AVERE
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# SUBAT-SSPI-CT-2003-502490

# Deliverable D 34 – Final report

Background and working documents of the study can be found as per Deliverables D1 to D26 as well as per the minutes of the 7 progress meetings that were held during the 15 months of the project.

The aim of this final report is to provide an overview of the conclusions by the 3 main Work Packages constituting SUBAT:

- WP1, dealing with the technological assessment, see Deliverable D27 as per APPENDIX I, page 3 of the report;
- WP2, dealing with the environmental assessment, see Deliverable D28 as per APPENDIX II, page 45 of the report;
- WP3, dealing with the economical assessment, see Deliverable D29 as per APPENDIX III, page 176 of the report.

In order to allow not only ranking of the different batteries but to also enable comparison in function of different criteria WP5 has used the Promethee software. Technical results are to be found as per APPENDIX IV, page 292 of the report.

Due to the confidentiality agreements the SUBAT consortium had to sign in order to get the relevant data to perform the study, these individual reports have to remain confidential.

A public report has however been compiled. It has also the advantage to integrate the results coming from the individual assessment fields into one single overall assessment approach.

This document, Deliverable D31, to be found as per APPENDIX V, page 371 of the report, was presented at the SUBAT final conference that took place on 6th April 2005 just after the closing ceremony of EVS-21. Copies pf the slides that were presented on this occasion are to be found as per APPENDIX VI, page 436 of the report.

To be noted that the public report had first been submitted to EUROBAT for validation and that all their comments have been integrated.

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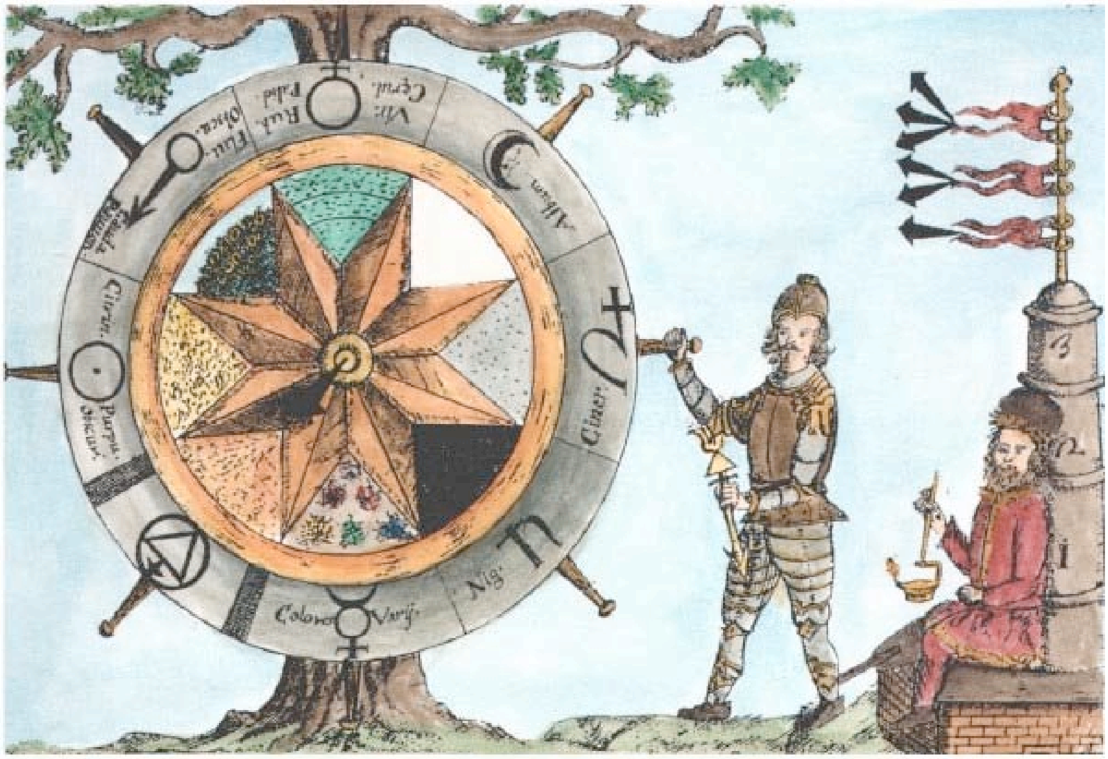
APPENDIX I



# SUBAT

## SSPI-CT2003-504290

## WP1: Technical Assessment Final Report

# Table of Contents

# Introduction

In urban traffic, due to their beneficial effect on environment, electrically propelled vehicles are an important factor for improvement of traffic and more particularly for a healthier living environment. The electrically propelled vehicle makes use of energy sources which are particularly suitable for use in urban or suburban areas.
The use of electric energy on board of a vehicle designed to operate independently of an external electric power supply such as an overhead wire raises the necessity of providing a means of electric energy storage on board the vehicle. Although one can design an electrically propelled vehicle without on-board storage of traction energy (e.g. a diesel-electric transmission or a "pure" fuel cell vehicle), the presence of an on-board electrical storage allows for clean and silent mobility in electric mode, and, in the case of hybrid vehicles, for optimizing the exploitation of the combustion engine in order to reduce energy consumption and emissions.

The device which is foremostly suited for storing electric energy is the secondary battery., the basic operating of which is the potential difference occurring between two different metal electrodes immersed in an electrolyte. At the anode (negative plate), the electrode metals are exalted to a higher valence, through a oxidizing reaction, which liberates electrons providing the electric current through the load. The electrons flow to the kathode (positive plate), where a reducing reaction of the active material takes place. The reversibility of the reactions allows charging and discharging of the battery which acts as an accumulator. The traction battery thus becomes the "electric fuel tank" of the electrically propelled vehicle, that is where the energy needed for driving is stored. It is also considered the most critical component of the vehicle.

Numerous battery types have been developed over the years, only a small number of these can be taken into consideration for traction purposes however. The following paragraphs will present these batteries; in the scope of the SUBAT project the focus will be on traction batteries only (i.e. Batteries intended to store energy used for moving the vehicle), auxiliary and starting batteries not being considered.

# General parameters of traction batteries

In order to define a common terminology and to allow a clear comparison, it is useful to explain the main figures and magnitues describing battery systems.

- The *cell voltage* V, this is the nominal voltage of one single cell in the battery, expressed in Volts. The complete battery consists of series-connected individual cells; the total battery voltage equals the sum of the cell voltages. This voltage is a nominal value, being a suitable approximate value of the voltage used to designate or identify the electrochemical system. It corresponds to the voltage of a fully charged battery at no load, but does not necessarily reflect the actual battery voltage during the any phase of the use of the battery.

- The *capacity* C, this is the amount of charge, or in other words the amount of electricity the battery can deliver under specified discharge conditions, usually expressed in Ampère-hours (Ah). 1 Ah corresponds to a current of 1 A which is

delivered during 1 hour. The capacity is given for a certain discharge time (in most cases 5 hours), which reflect the fact that the actual capacity is dependent on the discharge current. A battery rated at $C_5$=100Ah will thus deliver 20A during five hours, but if discharged at 100A (one hour rate) the actual capacity will be less.
The relationship between battery capacity, discharge current and discharge time is given by the formula of *Peukert*:

$$C_p = I^k \times t$$

where k is the *Peukert* constant, which is equal to one for an ideal battery, and the value of which is typically between 1,10 and 1,30 for a lead-acid battery.

- The *energy content* E, this is the amount of electric energy the battery can deliver under specified conditions, expressed in watthours (Wh). Roughly approximated it equals the product of capacity and nominal voltage. This is only an approximation because the battery voltage is not constant during the discharge phase.

- The *specific energy* or gravimetric energy, expressed in watt-hours per kilogram (Wh/kg), being the quotient of the battery energy by its mass. The energy density allows a relationship to establish between battery mass and energy content.

- The *energy density* or volumic energy, expressed in watt-hours per litre (Wh/l), being the quotient of the battery energy by its volume. This is a measurement for the battery volume in function of the energy content.

- The *specific power*, expressed in watts per kilogram (W/kg). This is a measure for the maximum power (or the maximum current) the battery can deliver, and thus for the performances (acceleration, maximum speed) of the vehicle.

- The *power density*, expressed in watts per litre (W/l).

- The *internal resistance*, expressed in milli-ohms (mΩ). This quantity is the quotient of the change of voltage by the corresponding change in discharge current under specified conditions, and gives the apparent electrical resistance of the internal parts of the battery. It varies in function with the state of charge and will have an influence on voltage variations during discharge and on the power density.

- The *energy efficiency*, expressed in %, this is the ratio of the electric energy provided from the battery during discharge to the electric energy supplied to the battery during the preceding charge. This value gives an image of the energy losses in the battery.

- The *charge efficiency,* expressed in %, this is the ratio of the electric charge discharged from the battery to the electric charge provided during the preceding charge. The percent value of the energy efficiency is lower than for the charge-efficiency, since voltage during discharge is lower than voltage during charge. Both quantities are fundamentally different and should never be compared with each other!

- The *charge factor*, expressed in %, this is the factor by which the quantity of electricity on discharge has to be multiplied to determine the quantity of electricity on charge required for the battery to recover its original state of charge. It is the reciprocal of the charge efficiency.

- The *service life* of the battery, usually expressed in number of cycles. A cycle is a charge followed by a discharge; the life cycle is considered as terminated when the battery capacity falls under a predefined value (e.g. 70 % of nominal capacity).

# The Lead-Acid Battery

## Basic principles

The lead-acid battery was invented by Gaston Planté in 1860. Today, as the oldest and best known electrochemical couple, it is still the most widely used traction battery for industrial electric vehicles.

In its basic form, the lead-acid battery consists of a negative plate made from lead metal and a positive plate made from brown lead dioxide, submerged in an electrolyte consisting of diluted sulphuric acid.

During discharge, the lead at the negative plate is oxidized and combines with a sulphate ion from the electrolyte solution to form lead sulphate:

$$Pb + SO_4^{2-} \rightarrow PbSO_4 + 2e^-$$

The negative plate sees the lead oxide reduced to lead sulphate:

$$PbO_2 + 4H^+ + SO_4^{2-} + 2e^- \rightarrow PbSO_4 + 2H_2O$$

The overall reaction during discharge thus becomes:

$$Pb + PbO_2 + 2H_2SO_4 \rightarrow 2PbSO_4 + 2\,H_2O$$

The sulphate ions will migrate from the electrolyte to the plates during discharge, leading to a reduction of the density, which is 1,30 g/cm$^3$ for a fully charged battery and 1,10 g/cm$^3$ for a discharged battery.

During charge, the reactions are inversed. Illustration 1 shows the reactions occurring during charge and discharge processes

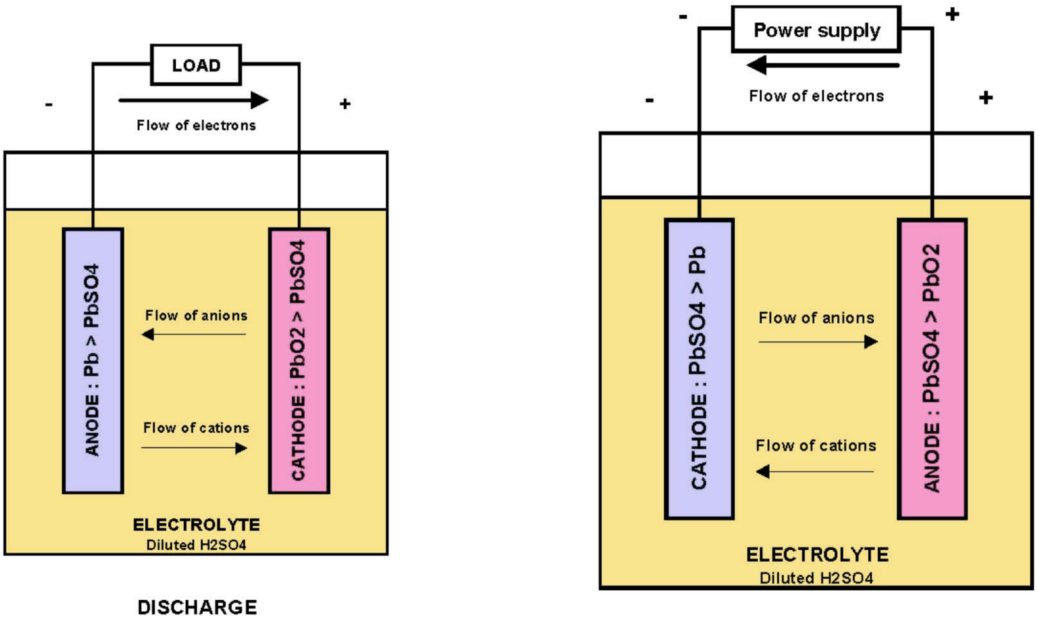


*Illustration 1: Lead-acid battery*

## Types

Lead-acid batteries are manufactured in different types and sizes according to their application. For electric vehicle traction purposes the following types have been considered:

### *Flat plate vented batteries*

In flat plate batteries, the positive plates consist of lead grids pasted with the active mass, lead dioxide. The negative plates consist of spongy lead. Each cell consists of alternate positive and negative plates with separators in between, as shown in Illustration 2.

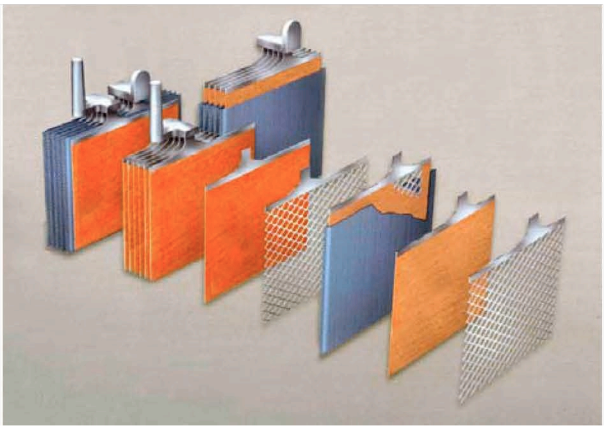


*Illustration 2: Flat plate battery*

The best known example of such a battery is the SLI battery (Starting, Lighting, Ignition), used in internal-combustion engined vehicles. Car batteries are designed to deliver high current bursts for cranking; to this effect, their plates are very thin to obtain a large active surface and a large current. A SLI battery is not designed for repetitive deep cycling (charge/discharge) needed in an electric vehicle, as it will not last for long.

Flat plate batteries for electric vehicle traction purposes have thicker plates and withstand deeper discharges. Such batteries are called "semi-traction" batteries.

They are cheaper than real traction batteries with tubular plates. Their service life is rather limited (500 cycles) however and their use today is limited to low-performance vehicles on the lower end of the market. They are not used for more advanced vehicles or hybrids.

### *Tubular plate vented batteries*

In this type, the positive plates consist of tubes made from a porous fabric and filled with lead dioxide. A central lead spine serves as current conductor. The stucture of such plates is shown in Illustration 3.

These are the archetypal traction batteries and are recommended for heavy-duty industrial purposes. Their cycle life can be up to 1500 cycles, with an energy density of 28-30 Wh/kg. Such cycle life is only attainable in controlled operating conditions (e.g. industrial vehicles), where the batteries can benefit of caring maintenance by knowledgeable personnel, and not for road vehicles in general use. Furthermore, one should take into account the difference in operating conditions: whileas industrial vehicles generally use moderate discharge rates (five to eight hours), high-performance road vehicles typically use a one or two hour discharge rate and thus put a heavier strain on the battery.

The most advanced cells on the market give up to 35 Wh/kg. It should be stated however that "tuning-up" the energy density of a battery in most cases decreases the cycle life.

A disadvantage of the tubular plate battery is its relatively high internal resistance compared to the flat plate battery, which leads to a somewhat lower lower power density.

*Illustration 3: Tubular plate lead-acid battery*

Vented batteries, both flat plate and tubular plate, need regular maintenance: topping up with distilled water. The consumption of water is due to the electrolysis of the electrolyte during charging. This maintenance work is essential to a good keeping of the battery, but represents a burden for introducing such batteries for consumer applications like passenger cars. For this reason, the use of vented traction batteries for electrically propelled vehicles is now largely limited to heavy-duty fleet vehicles such as buses, where the exploitation mode of the battery is comparable to industrial vehicles.

Furthermore, the emanation of hydrogen from the vented battery during this process may create hazardous situations which necessitate appropriate measures in the field of ventilation and implanation of the battery.

### *VRLA batteries*

The quest for a maintenance-free lead-acid battery has led to the development of the valve-regulated lead-acid battery (VRLA). This is sometimes called a "sealed" battery. This name is not correct however: the battery is not hermetically sealed, but is fitted with a safety valve to release overpressure (e.g. in case of a surcharge).
In this maintenance free lead acid battery, the amount of electrolyte is limited ("starved" electrolyte) and is immobilized in one of the following ways:

- AGM battery: the electrodes are separated by an absorbent glass fibre mat which acts as both the separator and the electrolyte reservoir
- Gel battery: the electrolyte has a gel shape due to the addition of silica. After some initial charges, the gel dries and a network of fine fissures develops between the cathode and the anode. These openings provide the path for the hydrogen/oxygen recombination reaction.

Water consumption, and thus the need for maintenance, is avoided through the use of hydrogen/oxygen recombination techniques and through the use of special alloys (such as lead-calcium). The recombination process during final charge is facilitated by the excess of anode active material combined with the starved electrolyte. The cell capacity of the VRLA battery is usually limited by the amount of cathode active material.

The maintenance-free character and the lack of topping-up make these batteries very popular for electric road vehicles; most of today's electric vehicles which make use of lead-acid now come with VRLA batteries.
They are more expensive however then vented bateries, and their cycle life is shorter (600-800 cycles stated by the manufacturers; 300-500 cycles in practical use).

The VRLA batteries are available in different forms, they can be prismatic cells either with absorbent glass mat (AGM) or gelled electrolyte; in the latter case, also traction cells with tubular plates have been presented. A typical example of a VRLA battery used for electric vehicle applications is shown in Illustration 4.

*Illustration 4: VRLA battery for EV (Exide)*

This battery is a 6 V, 180 Ah monobloc with a weight of 31 kg and a specific energy of

35 Wh/kg. Cycle life at 75% DOD is stated at 700 cycles.

A special mention has to be made of cylindrical VRLA cells (Illustration 5) with spiral-wound electrodes. The cylindrical containers can maintain a higher internal pressure without deformation. These present a high specific power value and are used in applications where a high discharge current is sought, like in specialist vehicles such as electric karts, but also in hybrid applications.

Other advanced lead-acid designs include semi-bipolar concepts such as the "Horizon" battery, with plates consisting of a pasted woven lead grid, have been experimented for traction purposes. It is clear that the lead-acid battery, even when it can rightfully be considered as the most mature of battery technologies, is not at the end of its evolution and that some improvements can still be expected. One can state that a reasonable maximum specific energy for advanced lead designs can be estimated at 40 to 45 Wh/kg.

*Illustration 5: Lead-acid with spiral electrodes*

Lead-acid batteries come in a variety of sizes, both as individual 2V cells and 6V or 12V monoblocs. Batteries made up from individual cells are mostly used for large electric vehicles (e.g. buses) and for industrial applications (e.g. lift trucks), their sizes are heavily standardized. For advanced lead-acid technologies, the status of today's technology precludes a full standardization of cell sizes, although such might be desirable for the future.

An overview of the overall market for lead-acid batteries, which is very large with cell sizes rating from less than 1 Ah to over 10000 Ah, is given in Table I.

| Market segment | Type | Construction | Applications |
|---|---|---|---|
| *Automotive* | SLI: starting, lighting, ignition | Flat-pasted plates (option: AGM VRLA) | Automotive, marine, aircraft, stationary power |
| *Motive power* | Industrial traction | Flat-pasted plates, tubular plates | Industrial trucks, material handling, milk floats |
|  | Road vehicle traction | Flad-pasted plates, tubular plates, composite construction, VRLA | Electric vehicles, hybrid vehicles, golf carts, neighbourhood vehicles, personnel carriers, mine vehicles |
|  | Submarine propulsion | Tubular plates, flat-pasted plates | Submarines |
| *Stationary* | Energy storage (charge retention, solar photovoltaic, load levelling, peak shaving) | Planté; tubular plates; flat-pasted plates; VRLA | Standby emergency power: telephone exchange, uninterruptible power systems, load levelling, signalling |
| *Portable* | Consumer and instrumentation | Flat-pasted plates VRLA; spiral wound; tubular plates | Portable appliances, lighting, emergency lighting, radio, TV, alarm systems |

*Table I: Overview of lead-acid batteries*

## *Charging*

Charging the batteries should be done apprpriately in order to obtain best results and a long cycle life. A typical charging profiles for vented lead-acid batteries is IUI$_a$, with a limit voltage of 2,5 V per cell. The final charge phase, with a small current, is essential for conditioning the battery and for balancing the cells. Gassing will occur at voltages exceeding 2,4 V; although this causes water consumption it has the desirable side effect of mixing the electrolyte and balancing its density to avoid acid stratification with the denser acid accumulating at the bottom.

A special charging procedure called equalizing charge should be performed at regular intervals in order to bring all cells to the same level and ensure they are all fully charged. Differences between single cells, which tend to increase during use, are in fact one of the most common causes of degradation of a battery. The equalizing charge consists of a prolonged charge at high voltage (up to 2,7 V per cell), albeit at a tiny current.

With VRLA batteries however, the charging has to be organized differently. Since the recombination potential of the VRLA cell is limited, charging voltage has to be controlled to avoid excessive gassing, which would result in a loss of electrolyte (through the pressure relief valve), that can not be replaced, and thus in a loss of capacity. VRLA batteries should thus only be used with specially designed battery chargers; in most cases, an IU charging profile is used.

Since a standard equalizing charge can not be performed, it is highly advisable for VRLA applications to provide a battery management system controlling each cell. Such systems are typically able to provide each cell with an individual charge in order to maintain the balance between the cells.

During storage periods, lead-acid batteries shall be charged regularly and it shall be avoided to leave them in a discharged state, as this may lead to the formation of large lead sulphate crystals that take difficultly part in the electrochemical reaction, and thus to a loss of capacity (sulphatation).

### *Safety aspects*

The main safety hazard in a lead-acid battery is the electrolyte: sulphuric acid is a corrosive liquid. The diluted acid present in a battery is still very dangerous for the eyes.

During normal use of the battery, the risk of coming into contact with the acid is very limited; during maintenance operations however, necessary precautions have to be taken (wearing of protective clothes, safety goggles).

In an accident, the battery may be damaged and acid may escape. This acid shall not cause any hazard for the occupants of the vehicle. Particulary when the vehicle might roll over, no acid shall penetrate the vehicle interior.

In maintenance free batteries, the electrolyte is fixed in a gel or in a glass fibre mat, which makes the contact with liquid acid very unlikely and represents an additional safety aspect of these batteries.

The lead in the battery is a toxic metal of course, but the user of the battery does not come in direct contact with it.

There can also be risks identified involved with hydrogen gas emissions during charging, particularly with vented batteries, where the final charge is accompanied with gassing and electrolysis of the electrolyte. To this effect, particular care has to be given to the design of battery enclosures, where potential sources of ignition have to be avoided,

With VRLA batteries, these hydrogen emissions are absent in normal conditions; they can however occur in fault conditions: when during an overcharge condition more gas is being generated than can be absorbed through recombination, this is emitted through the overpressure valve.

# Alkaline batteries

Batteries with alkaline electrolytes have been developed starting from the late 19th century. Most of these batteries use nickel oxide as positive plate material, with negative plates based on cadmium, iron, zinc, or hydrogen (the latter under form of metal hydrides).

## The Nickel-Iron battery

The nickel-iron battery has a positive electrode is made from nickel oxide and a negative electrode from metallic iron, with a lye solution as electrolyte. It was the first alkaline battery to be commercialized, being invented by Thomas Alva Edison. In the early 20th century, it was one of the most popular types of secondary battery, its higher specific energy and longer cycle life being distinct advantages over lead-acid batteries. The traditional design of nickel-iron batteries made use of steel jars and a pocket-plate design.

The nickel-iron battery received a renewed interest during the 1980s, with new developments, typically using sintered plate designs, both in Europe and the USA. The high specific energy and the lower decrease in specific energy with increasing discharge current compared to lead-acid presented this battery as a valuable contender for electric vehicles. A typical example of this battery is the 6 V monobloc developed by SAFT and deployed in the electric Peugeot 205 prototype in 1986.With a specific energy of 60 Wh/kg and a specific power of 170 W/kg it offered good performance, with a battery life of up to 1500 cycles.

The nickel-iron battery presented a number of drawbacks however. Its low-temperature performance was quite weak, and its energy efficiency low, and water consumption high. Furthermore, the production price of the electrodes remained high. Due to this effects, nickel-iron batteries today have been abandoned as an energy source for electrically propelled vehicles.

## The Nickel-Cadmium battery

### *Generalities*

The nickel-cadmium battery also presents a positive electrode made from nickel oxide; the negative electrode however is made of metallic cadmium. The electrolyte consists of a lye solution of potassium hydroxide with an addition of lithium hydroxide, the latter having a stabilizing effect during cycling. The nominal cell voltage is 1,2 Volt.

The reactions are as follows:
negative plate:
$Cd + 2OH^- \rightarrow Cd(OH)_2 + 2e^-$
positive plate:
$2NiOOH + 2H_2O + 2e^- \rightarrow 2Ni(OH)_2 + 2OH^-$
overall reaction:
$2NiOOH + Cd + 2H_2O \rightarrow 2Ni(OH)_2 + Cd(OH)_2$

One should note that the lye electrolyte does not take part in this reaction; one can thus not measure the state of charge via the density of the electrolyte which is constant.
Its historic development was parallel to nickel-iron, with similar technologies being used for its manufacture. It offers the same characteristics as nickel-iron, such as a quite high specific energy compared to lead-acid, a good resistance to abuse and a very good cycle life. Its particular advantages however are a better operation at low temperatures, a good acceptance of fast charging, a slow self-discharge and a higher electrical efficiency (compared with nickel-iron) leading to less maintenance and water consumption.

Traditionally, nickel-cadmium batteries have been manufactured with steel jars and pocket-plates; in order to decrease weight and thus increase energy density for demanding applications like electric vehicles, advanced plate designs have been proposed.

The sintered electrode design makes use of a porous mass of active material (nickel powder) sintered on a steel grid. This process is used by SAFT in France. The elements are packed in polymer jars, either as single cells or as monoblocs, the latter design being the favourite one for electric vehicles. The single cells have widespread applications as railway and aircraft batteries. These batteries are now the most popular for battery-electric road vehicles in Europe. They present in fact interesting opportunities for this application: good cycle life and specific power, ability for fast charging and operating in a wide temperature range. The current cost of these batteries remains high however; this fact has caused several electric vehicle manufacturers, particularly in the USA and Japan, not to consider the use of this battery. Furthermore, the toxicity of cadmium has been cited as an aspect affecting the societal acceptation of this battery, as can be seen from the SUBAT study itself.

The sintered plate cells can be made in various configurations, according to the chosen application:

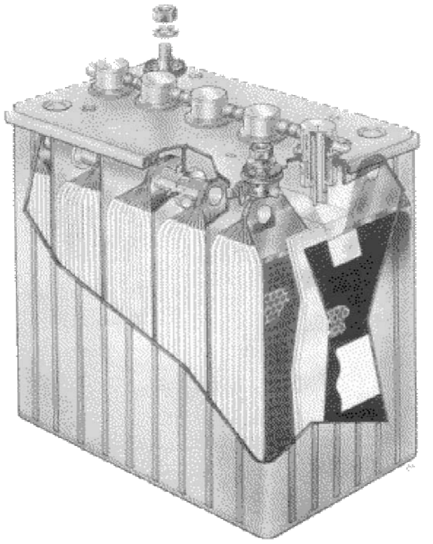


*Illustration 6: NiCd battery for EV (Saft)*

- emphasising a high energy density, for traction applications where range is paramount A commercial example of this type is the STM range (Illustration 6) manufactured by SAFT. These batteries, specifically designed for battery-electric vehicles, come in 6V monoblocs with capacities of 100 or 140 Ah. The 100 Ah type is the most commonly used, it is available in an air-cooled or water-cooled version, the latter having a water cooling jacket. The 140 Ah types are air-cooled only. The specific energy of these batteries is 51 Wh/kg at C5 rate and 45 Wh/kg at C1 rate. Specific power is 9,5 W/kg at C5 rate and 44,8 W/kg at C1 rate. However, the monoblocs are able to deliver a peak power of 2,7 kW during a 30 second burst; this corresponds to a peak power of 209 W/kg.

- emphasising a high power density, for applications such as hybrid vehicles, where the batteries must be able to deliver power bursts but where deep discharges are less frequent. An example of this technology is the STH range manufactured by SAFT. These batteries, mainly aimed at hybrid heavy-duty vehicles, come as single 1,2 V cells, with capacities from 16 to 190 Ah. The specific energy of these batteries is lower than for the STM ones however (29 Wh/kg at C5 rate and 27 Wh/kg at C1 rate).

Another nickel-cadmium technology makes use of fibrous electrodes consisting of porous conductive fibres which contain active material. This process, developed in Germany, is used by Hoppecke, as well as by Asian manufacturers. These types of batteries have known limited use for electric vehicle applications however.

Maintenance free versions of the nickel-cadmium battery have also been developed. These have a much lower energy density than the conventional, vented types however; their specific energy is comparable to a lead-acid battery. The high cost of these batteries precludes, as for now, their deployment in electric vehicles.

### *Charging*

Charging of nickel-cadmium batteries typically is done with a constant current up to a voltage level corresponding to 1,63 V per cell. A small final charge current (typically 0,05 $C_{5)}$ can then be applied without voltage limitation; at such low current, the battery can be overcharged for a long time without damage to the plates, although this will of course cause consumption of water and thus a waste of energy. Such long overcharges are periodically to be applied to obtain an equalising charge, which manufacturers recommend after 150 deep-discharge cycles.
The batteries can be fast-charged up to a state of charge of 80%; to fully charge the battery a low current is needed.
According to manufacturers, the nickel-cadmium batteries for electric vehicle applications can have a lifetime of 1500 to 2000 cycles; real-life experience however shows that values of 1000 cycles are realistic.

### *Maintenance*

As all vented batteries, nickel-cadmium batteries need periodic watering. The watering frequency depends on the use of the battery and the amount of overcharging; according to the manufacturer, it has to be performed once or twice a year. Due to the large number of individual cells usually present, automatic watering systems are necessary in a commercial environment. Other maintenance is limited to routine tasks such as keeping terminals and connectors clean, checking cell voltage and visual inspection of the battery.

### *Specific safety aspects*

The lye contained in the battery is caustic for the skin; when installing or maintaining the batteries the same protective measures as for lead-acid batteries apply, such as the use of personal protective equipment.

When lead-acid and nickel-cadmium batteries are used in the same vehicle fleet, contact between the electrolytes must be avoided: not only can this cause hefty and potentially hazardous reactions, but adding acid in a nickel-cadmium battery means its certain death.

The presence of toxic metals (cadmium) in this battery has given rise to a certain amount of adverse publicity; the cadmium however never leaves the battery and can be recycled completely at the end of the cycle life. Accidental exposure to cadmium in case of a crash-damaged battery is unlikely to present an acute health hazard.

Overcharge of the battery, as well as the final charge phase, causes the emission of hydrogene gas, the necessary ventilation procedures for battery compartments and charging rooms must be taken. The manufacturer states however that the nickel-cadmium batteries are intrinsically safe at cell level. Hazardous conditions such as thermal runaway can only occur in extreme conditions such as complete cell dry-out.

## The Nickel Zinc battery

The nickel-zinc battery uses the same type of positive electrode as the nickel-iron and nickel-cadmium, this time with a metallic zinc negative plate. One of its advantages is the higher cell voltage (1,6 V) compared with other alkaline battery types. This allows a specific energy 25% higher than nickel-cadmium, with values up to 80 Wh/kg.

Nickel-zinc has been the subject of extensive research focusing on its application in electric vehicles. The main drawback of this electrochemical couple however proved to be its unacceptably short cycle life, which is a result of the formation of zinc dendrites on the negative electrode during charging. These dendrites will eventually perforate the separator and short the cell. The phenomenon is caused by the fact that the discharge product, zinc oxide, is highly soluble in the alkaline electrolyte.

A number of research projects on nickel-zinc batteries has been performed in the USA, Korea and the former USSR. A recent research project (PRAZE) funded by the EU aimed at the development of advanced nickel-zinc batteries for use in electric scooters. Although promising results were obtained with the prototype cells, this research has not been continued however due to the French company involved, Sorapec, ceasing its activities.

Also in France, current work on nickel-zinc is being performed by SCPS, aiming at developing new types of zinc electrodes allowing an extended cycle life. The characteristics of this electrode are as follows:

- a conductive collector network, constituted by a specific "3D" structure (a copper foam), in which is pasted a plasticized active mass,
- particles of conductive ceramics, creating a secondary conductive "micro" network in the active mass,
- specific co-additives, linked with the ceramic particles, in charge of increasing zincate retention in the anode

SCPS claim promising results as to cycling ability and lifetime, with values exceeding 1000 cycles; their research is still focused at the cell level however and complete batteries have not yet been experimented for deployment in vehicles, which means that real-life experience is not yet available.

It is thus unlikely that nickel-zinc batteries will be available as a commercial product for electric vehicle applications in a short-term future.

## The Nickel Metal Hydride battery

The use of hydrogen as negative active material gives a good energy to weight ratio. Storing and maintaining hydrogen gas can be cumbersome however; to this effect, hydrogen can be stored in metal alloys, and one obtains the nickel-metal-hydride battery.

The reactions become as follows:

metal hydride:

$MeH_2 \rightarrow H_2 + Me$

negative plate:

$H_2 + 2OH^- \rightarrow 2H_2O + 2e^-$

positive plate:

$2NiOOH + 2H_2O + 2e^- \rightarrow 2Ni(OH)_2 + 2OH^-$

overall reaction:

$2NiOOH + MeH_2 \rightarrow 2Ni(OH)_2 + Me$

The metal alloys (shown in the reactions as "Me") used for this purpose are mostly proprietary, and are usually of the types AB5 (e.g. $LaNi_5$) or AB2 (e.g. $TiN_2$). The process of manufacturing these alloys is quite complicated, which is a key limiting factor to the widespread development of these batteries.

The positive electrode behaves in the same way as a nickel-cadmium battery; the reactions at the negative electrode are comparable with those in a fuel cell, releasing, during discharge, hydrogen from the metal to which it was attached, and producing water and electrons.

Nickel-metal hydride batteries possess some characteristics which make them suitable for use in electrically propelled vehicles. The fact that they are cadmium free is a selling argument in some markets where the use of cadmium is seen as an environmental concern. From a technical viewpoint however, their specific energy is somewhat higher than nickel-cadmium, and ; furthermore, they are well suited to fast charging.

A disadvantage however is their tendency to self-discharge, due to hydrogen diffusion through the electrolyte. Furthermore, high-current operation during charging (which is an exothermic reaction), makes thermal management and cooling of these batteries essential.

Because of this, they have been subject of substantial research and development activities, particularly in the field concerning electrically propelled vehicles. The technology receives interest worldwide, through companies such as SAFT (Europe), Cobasys (USA) and Panasonic (Japan).

It is considered a very promising battery, particularly for hybrid applications and is used in advanced hybrids like the Toyota Prius. The battery for hybrid use is a typical power battery with limited capacity.

The battery pack shown in Illustration 7 is a typical assembly for hybrid vehicles encompassing its battery management system. Specific energy is only 32 Wh/kg, whileas the specific power reaches 800 W/kg. The power nature of such batteries is further reflected in their low Ah capacity (8,5 Ah), at system voltages of 288 V.

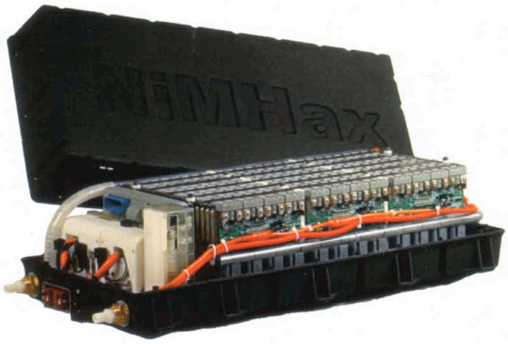


*Illustration 7: NiMH battery pack for HEV (Cobasys)*

Batteries optimised for energy and fit for deployment in battery-electric vehicles have been implemented in a number of experimental or small series vehicles, such as the ill-fated GM EV1, but are not now widely available. Illustration 8 shows a typical example: this 12 V, 85 Ah module from Cobasys has a specific energy of 60 Wh/kg and a specific power of 250 W/kg.

*Illustration 8: NiMH battery for BEV (Cobasys)*

One must thus recognize that this battery, as for the battery-electric vehicle application, is not yet to be considered a commercial product comparable to nickel-cadmium or lead-acid.

## The Silver Zinc battery

Alkaline batteries can also be made with the positive plate material being silver. More particularly the silver-zinc battery is characterized by a very high specific energy and is used in special defence applications such as torpedo propulsion. Its high material cost and low cycle life however make this battery unsuitable for general use such as in road vehicles.

# Lithium batteries

Lithium is the lightest metal element known and is under full consideration for high energy batteries. The main advantage of the lithium based battery is the high specific energy and the high cell voltage. Disadvantages are that lithium can not be used with aqueous electrolytes, but only with organic electrolytes, molten salts or solid polymer electrolytes. The cost of the electrolyte increases and new battery security problems are appearing.

Several secondary battery technologies using lithium have been developed, the principal ones being the lithium-ion and the lithium-polymer battery.

## The Lithium-Ion battery

Lithium-ion batteries work through the migration of lithium ions between a carbon anode and a lithium metal oxide alloy cathode. The electrode is an organic solution; no metallic lithium is used.

The electrochemical reactions in this battery during discharge are as follows:

negative electrode:

$$LiC_6 \rightarrow Li^+ + 6C + e^-$$

positive electrode:

$$Li^+ + Li_xMeO_2 + e^- \rightarrow Li_{x+1}MeO_2$$

overall reaction:

$$Li_xMeO_2 + LiC_6 \rightarrow Li_{x+1}MeO_2 + 6C$$

The reactions in the battery during discharge are shown in Illustration 9.

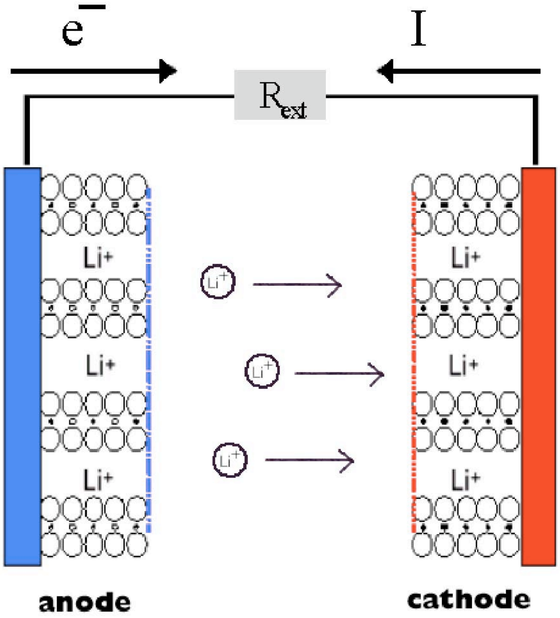


*Illustration 9: Li-Ion battery*

The anode material in the lithium-ion battery is usually carbon; for the cathode, different lithiated transition metal oxides have been considered:

- Lithium manganese oxides, which have good electrochemical properties and are less toxic than LiNiO or LiCoO materials. Their main problem however is a poor cycling life due to manganese dissolution in the electrolyte. Futhermore, the LiMnO compounds have low specific capacity and are structurally unstable for lithium ion intercalation and de-intercalation.
- Lithium nickel oxides, which offer a large specific capacity, but are less environmentally friendly and more expensive than LiMnO. Cycling life is poor however for the same reasons as with LiMnO. The structurally ordened LiNiO materials are difficult to synthesize.
- Lithium cobalt oxides, which have the best electrochemical properties and cycle life, but which are less environmentally friendly due to the toxicity of cobalt. Futhermore, cobalt is an expensive resource with limited availability. This battery is now the most widely used for portable lithium-ion; for larger scale production, such as for traction batteries, other cathode materials are sought as to avoid the cost of the cobalt.

Commercial lithium ion batteries often make use of one or a combination of these chemistries, with a nickel oxide doped with 15-30 % cobalt being popular with many manufacturers, some using additional elements such as aluminium in their proprietary electrode compositions.

Lithium-ion cells are offered for electric vehicle applications, either as energy or power batteries. High-energy batteries typically offer 150 Wh/kg and 420 W/kg, whileas high-power versions have 85 Wh/kg and 1350 W/kg, with an intermediate version of 135 Wh/kg and 650 W/kg also available. These data refer to Saft Li-Ion batteries and are calculated at cell level (not complete battery system level).

## The Lithium-Polymer battery

In the lithium-polymer technology, the electrolyte is a solid conductive polymer; the batteries are completely dry and do not contain liquid electrolytes. Several chemistries are being proposed.

- The lithium-ion polymer battery makes no use of metallic lithium; its electrochemistry is comparable with the lithium-ion battery with liquid electrolyte.
- The lithium-metal-polymer battery however uses lithium foil as its negative electrode, with a positive electrode of metal oxide foil (typically vanadium oxide) and a polymer foil that is conductive for lithium ions as electrolyte (Illustration 10).

The electrochemical reactions in this battery are as follows:
negative electrode:

$$xLi \rightarrow xLi^{+} + xe^{-}$$

positive electrode:

$$xLi^{+} + Me_yO_z + xe^{-} \rightarrow Li_xMe_yO_z$$

overall reaction:

$$xLi_x + Me_yO_z \rightarrow Li_xMe_yO_z$$

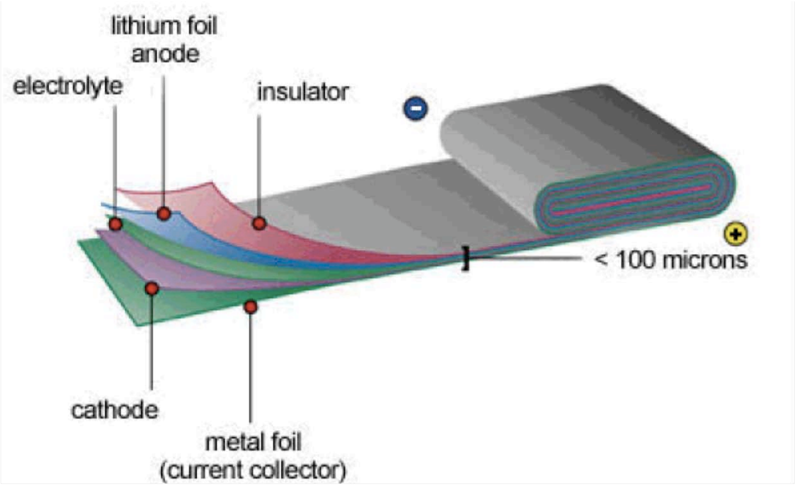


*Illustration 10: Lithium-polymer cell construction*

Development work on the lithium-metal-polymer battery is being performed by Avestor in Canada and Batscap in France. Avestor (Illustration 11) is now focusing on stationary (telecom) applications, for which there is a ready market, rather than on traction. It has in the past developed some prototypes for electric vehicle applications, which came at 120 Wh/kg and 240 W/kg.

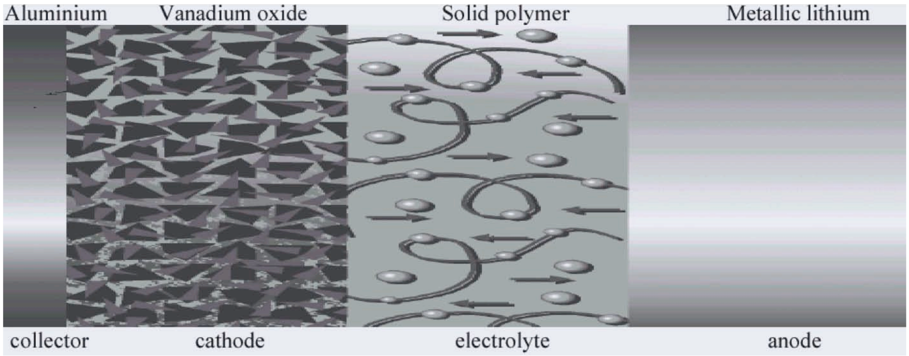


*Illustration 11: Lithium metal polymer battery (Avestor)*

## Applications and Problems

Lithium-ion batteries have been proposed for both battery-electric vehicles, where they benefit of their excellent specific energy of up to 200 Wh/kg, and hybrid vehicles, making use of cells specifically designed for high power, where values exceeding 2000 W/kg can be reached. Furthermore, an interesting property of the lithium battery is its long life, where cycle lifes up to 3000 cycles are announced, having been observed at cell level.

The lithium-ion battery for electric vehicle applications is being produced at small scales for prototype and pilot developments.

## Lithium safety

One main issue to be considered with lithium batteries is safety. Lithium is very reactive, and uncontrolled overcharge of the battery may give rise to uncontrolled energy releases which pose hazardous situations. The implementation of cell-level management systems is thus a dire necessity for any lithium-based system.

Although lithium batteries have taken a considerable share of the portable battery market, one has to recognize that high-power applications such as traction present different challenges. Lithium batteries for traction are now available as prototypes and are on the brink of series production; further optimisation as to life, system safety and stability and production cost is still being performed however, and the lithium systems can today not be considered yet as a commercially available product on a par with lead-acid or nickel-cadmium. This is also due to their expensiveness; some cheaper lithium-ion batteries are now available from Asian manufacturers, but their reliability still has to be proven.

# High-temperature batteries

## The Sodium-Nickel-Chloride Battery

### *Introduction*

Of the batteries a high operating temperature (around 300 °C), the sodium-nickel-chloride battery (known under its brand name Zebra) presents interesting opportunities for electrically propelled vehicles due to its high specific energy of typically 100 Wh/kg. After initial design work in South Africa (which is reflected in the trade name ZEBRA, standing for "Zero Emission Battery Research Activity") and was further developed by AEG-Anglo Batteries. Now the technology is further developed and manufactured by MES-DEA in Switzerland where a pilot plant is in production.

The electrodes of this battery consist, in charged state, of molten sodium and molten nickel chloride; the electrolyte is a solid aluminium oxide (beta alumina) ceramic. In discharged state, the electrodes are sodium chloride and nickel. The batteries are assembled in a discharged state which avoids having to handle reactive sodium metal.
This beta-alumina electroltye is conductive for $Na^+$ ions but an insulator for electrons.Because both of beta alumina and nickel chloride are solids, a second liquid electrolyte is needed to allow the sodium ions to reach the nickel chloride reaction sites from the beta alumina. This electrolyte is sodium tetrachloroaluminate ($NaAlCl_4$) which melts at 157°C and dissociates into $Na^+$ ions and $AlCl_4^-$ ions.

The basic electrochemical reactions during discharge are as follows:
negative electrode:

$$2Na \rightarrow 2Na^+ + 2e^-$$
$$2Na^+ + 2Cl^- \rightarrow 2NaCl$$

positive electrode:

$$NiCl_2 \rightarrow Ni^{2+} + 2Cl^-$$
$$Ni^{2+} + 2e^- \rightarrow Ni$$

global:

$$2Na + NiCl_2 \rightarrow Ni + 2NaCl$$

Batteries consist of individual cells of 2,58 V, 38 Ah enclosed in steel cans. The batteries are assembled in a discharged state, avoiding the handling of metallic sodium. A number of cells are enclosed in a thermally insulating package constituting a battery of approximately 20 kWh, which can be fitted, through series and parallel connections of individual cells, for output voltages of 140 to 560 V, allowing for specific applications.
The structure of the cell is shown in Illustration 12.

Failure of the cell can be caused by the following:

- Gross closure weld defects.
- Bursting of the beta alumina tube if the positive electrode volume is too great.
- Cracking of the beta alumina tube due to flaws.
- Failure of the thermocompression bond (TCB) seal.
- Corrosion of the alpha alumina /beta alumina glass seal by the cell reactants.

An interesting property is that failure of a cell results in a short circuit with low resistance, allowing further operation (albeit at a slightly reduced voltage) of the battery.

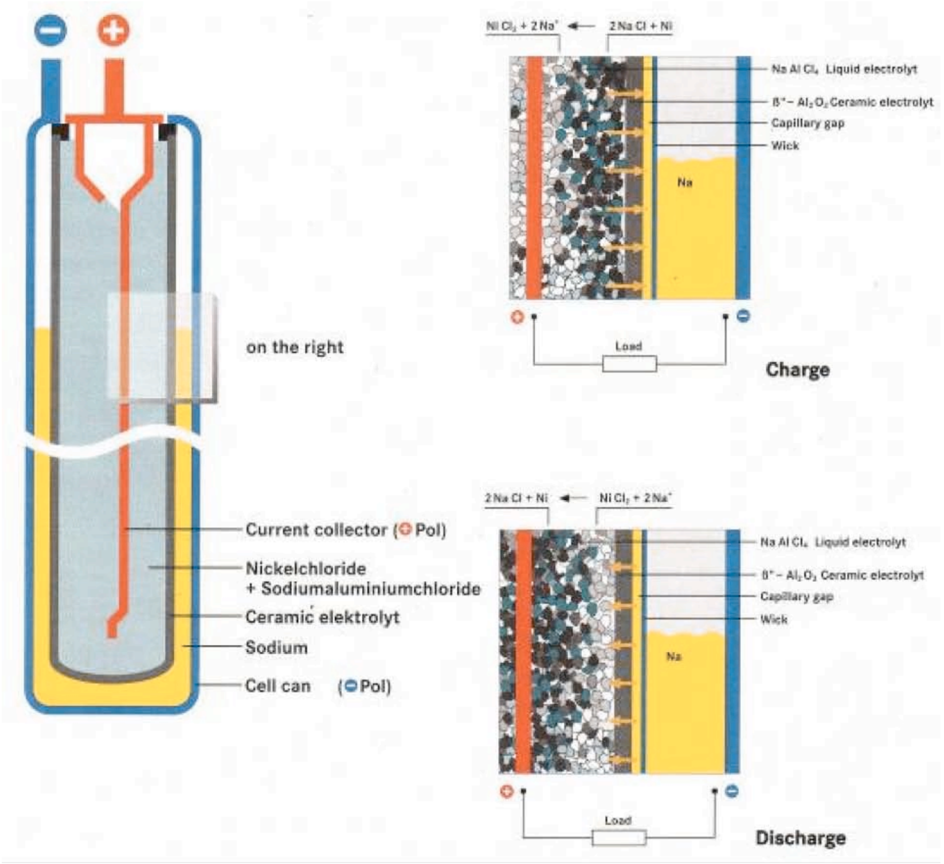


*Illustration 12: Zebra cell*

*Illustration 13: Beta alumina electrolyte tube*

Apart from the reversible cell reaction, there are no side reactions, so that the charge efficiency of the ZEBRA cell is 100%.

The ZEBRA battery can be put on fast charge. Half of the discharged energy can be replaced in about 30 minutes. Starting from a completely discharged battery, a 90% charge takes 3.5 hours and 5 hours are required for a 100% charge.

A fully assembled Zebra battery is shown in Illustration 14

*Illustration 14: Zebra battery*

## *Thermal management*

Heat insulation is provided by an  cavity wall housing filled with a highly efficient insulation material on the principle of a thermos flask. Electrical heating elements and, where required, a cooled ventilation system are built into the battery to control the temperature.

The lowest operating temperature of the ZEBRA battery is theoretically 157°C because, above this temperature, the liquid electrolyte is molten and the battery could carry current. At this temperature, the internal resistance of the battery is still too high to operate so that, in practice, the internal temperature was set to within the range of 250 ÷ 350°C. The residual heat loss through the battery case is typically 85-100 W depending upon the size of the battery and the load capacity of the connections. This heat loss is compensated by the built-in electrical heating system during prolonged stand-by periods, and, when in operation, by the losses through the battery internal resistance. Under heavy load, the internal losses lead to heat being generated in the battery. The heat is regulated by an electronically controlled cooling system .

Due to its wide operating temperature range in combination with its heat capacity, the ZEBRA battery not only functions as a storage medium for electrical energy, but also for heat. For example, for the winter service of an electrically driven vehicle, in addition to the electrical energy, up to 10% of the electrically stored energy can be stored additionally as heat, similar to that of a storage heater. This is effected by heating the battery from the mains, regulated by the outside temperature. This heat is then immediately available in the passenger compartment, making exhaust-free driving also possible in winter, without any emissions or limitation on the vehicle's range.

For summer operation too, the increased operating temperature is advantageous, as the battery cooling is fully and reliably functional indepentently of ambient temperatures.

If the battery is fully cooled, it has to be brought to operating temperature again, which takes 24 hours using the heating resistors. This thermal cycle does not harm the ZEBRA battery in any way, as has been proven in a durability trial.

### *Battery control unit*

A programmable control unit (Battery Management Interface, BMI) connected to the battery, communicates with the elements of the whole system, e.g. the engine electronics of an electrically driven vehicle, across a serial interface. All these elements are powered by the battery.

The BMI fulfils the following functions:

- Battery temperature regulation
- Measurement of the present state of battery charge
- Measurement of the cumulative charge
- Measurement of the insulation resistance
- Measurement of the battery terminal voltage
- Battery heating during operation.

These data are available to a superordinated system via a serial interface.

### *Safety aspects*

The battery is tolerant of excess current, so that a brief short circuit (which can occur during installation, for example) does not immediately result in cell failure.

Repeated cooling of the battery again is well tolerated, as is overheating within certain limits as the steel cell cups will normally remain intact even at temperatures of 500°C to 600°C with no leakage of reactant.

The ZEBRA cells are so constructed that any violent distortion of the cell case will first break the ceramic. Any liquid sodium present mixes with the liquid electrolytes and rapidly reacts to form common salt and aluminium, thus virtually excluding the possibility of the egress of liquid sodium. This reaction releases only about half as much energy as the normal discharge reaction which is to a large extent prevented.

In serious accident situations, the whole battery could be mechanically destroyed. Even in such cases however, the battery should not constitute any additional source of danger.

To this end, safety test programmes were run such as crashing the battery. The ZEBRA battery did pass all these tests satisfactorily.

### *Application to EV*

ZEBRA batteries has been used in several on EV experimentation and demonstration fleets, with over 400 batteries in service by the end of 2003. CITELEC has been involved in several of these projects, including the "Electric Vehicle Fleet Demonstration with Advanced Batteries" and the hybrid bus projects in Trento.

The ZEBRA battery comes out to be a valuable candidate to power electric vehicle, not only because its energy density three-fold that lead-acid batteries (50% more than NiMH), but also because of all the other EV requirements such as power density, non maintenance summer and winter operation, safety, failure tolerance and low cost potential are fulfilled. The battery management system, including battery controller, main-circuit breaker and cooling system, is engineered for vehicle integration and ready to be mounted in a vehicle.

There are limitations to the ZEBRA battery, in particular the need to heat the battery during long standstill periods, which means that this battery will be most advisable for applications where vehicles are used intensively, such as fleet vehicles (buses, goods delivery, etc.).

## The Sodium-Sulphur battery

Another high-temperature battery couple which has been investigated for electric vehicle applications is the sodium-sulphur battery. It has a similar operation principle than the sodium-nickel-chloride battery, the negative electrodes consisting of molten sodium and the positive of molten sodium polysulphides. The electrolyte is also a solid beta alumina ceramic. With specific energies of 100 Wh/kg and specific power of 200 Wh/kg, the sodium-sulphur technology was very promising, being pursued independently by ABB in Germany and Chloride in the UK.

The development of these batteries has been completely abandoned however due to reliability and safety problems. The batteries poorly resisted thermal cycling ("freezing") and cell failure mode was high resistance, disabling entire batteries with a single cell failure. Furthermore, cases of thermal instability leading to vehicle fires have been observed.

# Metal-air batteries

## Introduction

Metal-air batteries are not strictly secondary rechargeable electric batteries, but can rather be considered as fuel cells which are "recharged" with new metal electrodes.
If a reactive anode is coupled to an air electrode the resulting electrochemical system has an inexhaustible cathode reactant and, in some cases, very high specific energy and energy density. The system capacity is determined by the charge capacity of the anode and the technique for handling and storage of the reaction products.
Because of this performance potential, a significant research effort has been done to develop metal-air batteries.

Several metals have been investigated as electrode materials for metal-air batteries and electrically rechargeable and mechanically rechargeable battery configurations have been developed. Because of their attractive energy densities, lithium-air, calcium-air, and magnesium-air batteries have been studied, but problems such as high cost, anodic polarization or instability, parasitic corrosion, non uniform dissolution, safety and practical handling have so far inhibited the development of commercial products. Aluminium is very attractive because of its high geological abundance and its relatively low cost but this metal requires a too high recharge voltage if the battery have to be electrically recharged. Consequently, the development of aluminium-air battery has been focused on mechanically rechargeable configuration.
At present the mainly considered metal into metal-air batteries development is zinc because it is environmental friendly, of moderate cost and intrinsically safe. Zinc is also attractive for electrically rechargeable metal-air systems because of its relative stability in alkaline electrolytes and also because it is the most active metal that can be electrodeposited from an aqueous electrolyte. The development of a practical rechargeable zinc-air battery with an extended cycle life would provide a promising high-capacity power source for many portable applications (computers, communications equipment) as well as, in larger sizes, for electric vehicles.

## The Zinc-Air battery

### *Generalities*

Zinc-air batteries are constituted with a zinc anode and an oxygen cathode in an alkaline electrolyte, generally concentrated KOH.
The reactions during discharge are as follows:
negative electrode:

$$2Zn + 4OH^- \rightarrow 2ZnO^- + 2H_2O + 4e^-$$

positive electrode:

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$$

overall reaction:

$$2Zn + O_2 \rightarrow 2ZnO$$

The theoretic energy density, referred to the overall reaction, is 1.350 Wh/kg.
High power requires an appropriate catalyst on the electrodes, impregnated with transition metal oxides.
The overall capacity is determined from the anodic capacity because the electrode is

continuously fed by oxygen from the air.
The advantages are :

- safety;
- high energy density;
- moderate cost;
- environmental compatibility.

Disadvantages:

- self discharge for high zinc corrosion (more than 6% per month) because of zinc relative stability in alkaline electrolyte.
- slow kinetics, depending from ion diffusion and charge exchange at the interface.
- the battery capacity, and then the vehicle autonomy, decrease with the normal use of the vehicle and it only can be restored from recharging of spent zinc anodes.
- the system behaviour is highly dependent from the temperature. The power is strongly decreasing with the temperature and the capacity is decreasing over 60°C for the zinc oxidation
- degradation of capacity due to deposition of $ZnCO_3$ by reaction with $CO_2$ from air.

Zinc-air systems has been developed by different manufacturers: Electric Fuel Ltd from Israel, Powerzinc Electric Inc. from United States and Zoxy from Germany.

The EFL zinc-air cell includes a zinc anode in a potassium hydroxide electrolyte . IN Illustration 15, the anode is partially withdrawn from the plastic case of the cell.

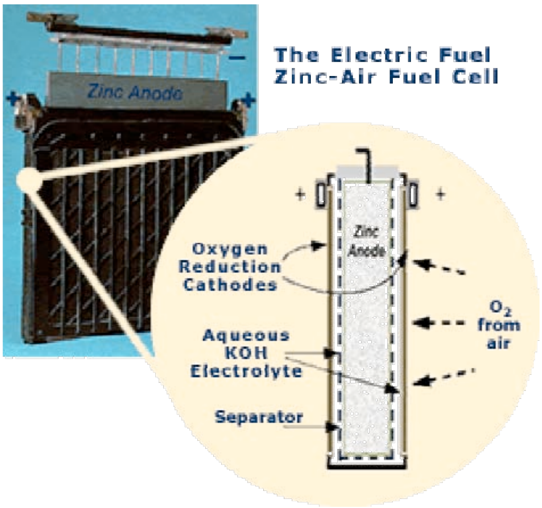


*Illustration 15: Zinc-air cell*

The cathode is an oxygen reduction membrane. During discharge on board an EV, the zinc is converted in zinc oxide.
Electrodes are multistage on a porous carbon base, an air diffuser and hydrophobic membrane. Metal grids act as positive conductors.

## *Zinc-air logistics and regeneration*

The EFL zinc-air battery is mechanically recharged, substituting the exhausted zinc with fresh anodes. The spent zinc anodes are electrochemically recharged in a regeneration plant. Mechanical recharge is better than electrical recharge because it has no problem

of zinc dendritic growing and allows to the E.V. to quickly regain the autonomy.
The use of the mechanical recharging necessitates a logistic supply chain as illustrated in Illustration 16.

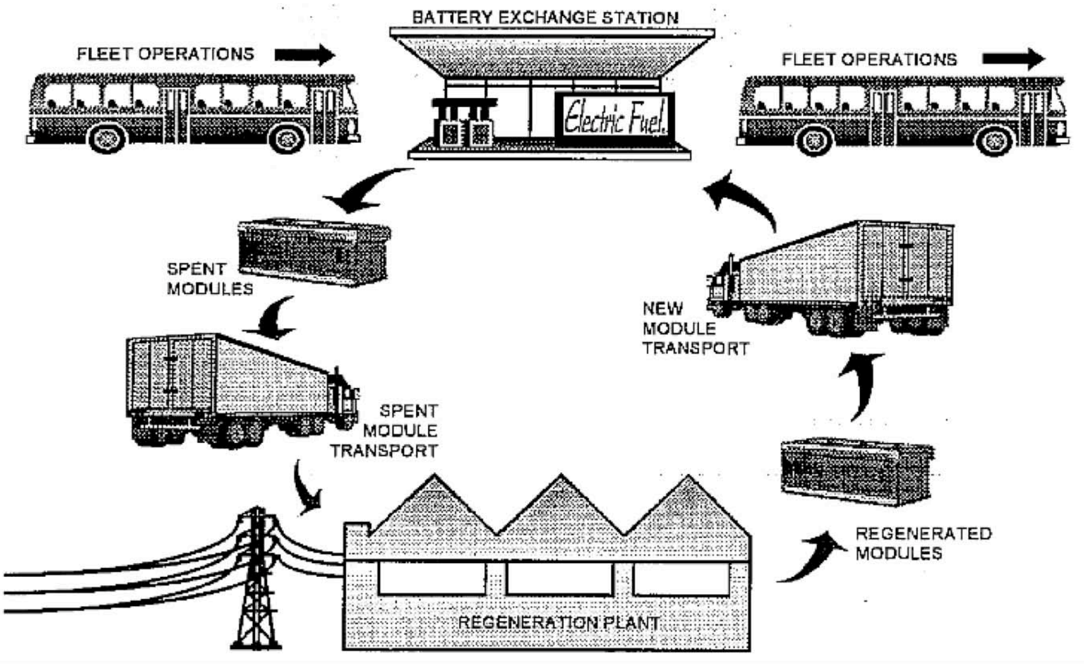


*Illustration 16: Zinc-air logistics chain*

The link among these elements depends from the territorial distribution of the EV: the refuelling station can be near the regeneration plant or far, but with problems connected with battery storage and electrodes transportation. Operations at the refueling stage can be focused on removing spent electrodes or on exchanging whole batteries, or refueling can take place on the vehicle exploitation site for larger fleet operations.

The regeneration of the spent anodes is an electrochemical process ("electrowinning") shown in Illustration 17.

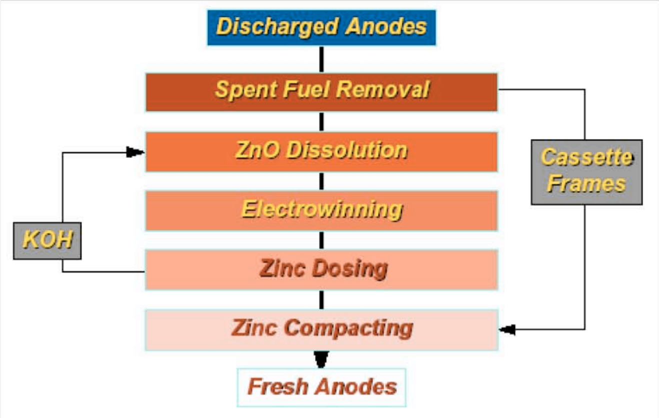


*Illustration 17: Zinc-air regeneration*

The zinc oxide is dissolved in a KOH solution:

$ZnO + 2KOH + H_2O \rightarrow K_2Zn(OH)_4$

with the zinc being electroformed from the solution:

$K_2Zn(OH)_4 \rightarrow Zn + 2KOH + H_2O + \frac{1}{2} O_2$

This process takes place at a cell voltage of 2,1V; the discharge voltage of the zinc-air cell of 1,15 V gives a voltage efficiency of 55%; real energy efficiency of this process is evaluated between 40 and 50%.

To overcome the poor efficiency of this process, other recycling strategies have been proposed, among which the disposal of the zinc oxide as a secondary resource. There is in fact a market for zinc oxide which is used for various applications like pigments, pharmaceuticals, ... The successful collection and marketing of zinc oxide from batteries would also represent a major logistical burden however.

### *Applications to electric vehicles*

The zinc-air system allows to build batteries with a specific energy exceeding 200 Wh/kg, an unprecedented value. It has therefore been extensively studied for deployment in electric vehicle applications.
The energy density allows in fact long operating ranges: from an Edison's report, a van type EV of 950 kg (without battery) equipped with zinc-air batteries had a distance covered of 447 km, more than 6 times the range of the same EV equipped with lead-acid batteries, for the same overall weigh (1950 kg).
The theoretical life of a zinc-air battery is about 400 charge-discharge cycles, which means in distance, 4 times greater than lead-acid and comparable with nickel-cadmium.

Large-scale experiments with zinc-air have been performed by the Deutsche Post in Germany and by Edison in Italy. The logistical problems associated with the mechanical recharging have hampered further development and use of this technology however.

### *Battery-battery hybrids*

The zinc-air battery may have an exceptional specific energy; its specific power however is rather modest at 90 W/kg, making it less performant in high-power applications. To this effect, batttery-battery hybrids have been proposed, where an high energy zinc-air battery is coupled with a high power auxiliary battery.
The main zinc-air batteries are designed for energy carrying capacity, reaching an extremely high specific energy (> 200 Wh/kg). The auxiliary "power" battery has been selected for its power and cycling characteristics with minimal reference to its energy density. The high power density Ni-Cd batteries provide acceleration and a "power" absorption function during vehicle deceleration or regenerative retarding.
The Ni-Cd batteries can be used in parallel with the main zinc-air battery, providing "topping" power whenever high power is demanded. Several variations on these basic configurations are possible. The optimal hybrid configuration will reference system characteristics as well as battery characteristics such as cycle life and efficient charge/discharge rates.
This propulsion system has been experimented in urban buses in the United States and has the ability to drive a transit bus for a full day's uninterrupted service at the same power and performance levels as a conventional diesel powered vehicle.

### *Conclusions*

Zinc-air batteries can be considered as a solution for electric vehicles, particularly for fleet operators, such as public transport companies or firms with a vehicle fleet, when it is feasible to achieve zinc anodes regeneration on-site.

The battery has a good energy density, about 4 times the lead-acid battery energy, with a comparable cycle life.

The system is intrinsically safe because the mechanical recharge is not requiring electrical recharge that is affected with parasitic reactions (hydrogen evolution) and it is using environmental friendly materials, that is a great advantage in comparison with others battery systems. Also the recharging process is not leading to polluting materials. The only metal used is zinc, a metal of moderate cost and easily recyclable.

The weak points of this battery consist in the low specific power, the low efficiency of the regeneration process and the logistic burden associated with mechanical recharging.

# Redox batteries

## Generalities

The so-called "redox" or "flow" batteries are complex electrochemical systems with circulating electrolytes. The heart of the system can be considered as a reversible fuel cell stack, able at both generating electricity from the electrochemical reaction of the electrolytes (discharge), and restoring the original composition of the electrolyte through the injection of electric current (charge).
A schematic view of such a system can be seen in Illustration 5.

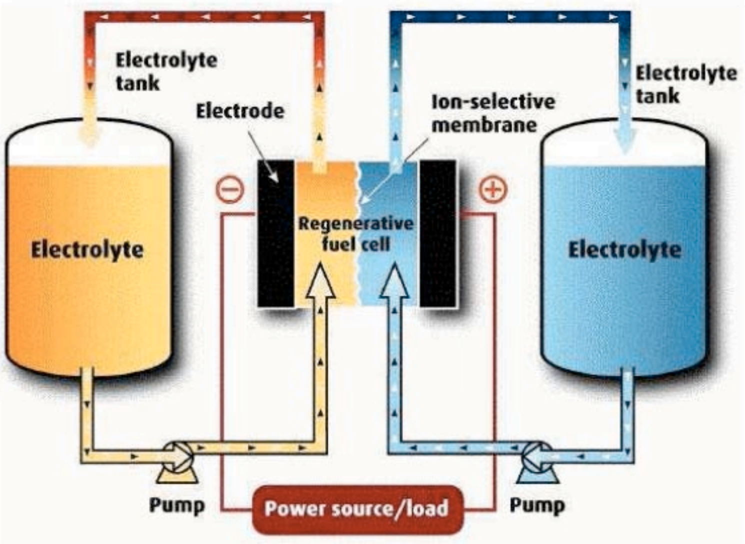


*Illustration 18: Redox battery*

It is characteristic for these systems that the electrochemical energy storage is actually performed in the external reservoirs and not in the cell stack proper. The storage capacity (Wh) is thus determined by the volume of electrolyte in the tanks, whileas the power rating (W) is deterined by the size of the stack.
Electrochemical systems which have been investigated for such batteries include the zinc-bromine battery, the vanadium-redox battery and the polysulfide-bromine battery.

## The Zinc-Bromine battery

The ZnBr battery has been considered for electric vehicle applications since the 1970s, both in the US, Europe and Japan. The electrolyte is an aqueous solution of zinc bromide; reactions during discharge are as follows:
negative electrode:

$Zn \rightarrow Zn^{2+} + 2e^-$

positive electrode:

$Br_2(aq) + 2e^- \rightarrow 2Br^-$

overall reaction:

$Zn + Br_2(aq) \rightarrow ZnBr_2$

The reactions during the charge are inversed; the bromine produced at the cathode is mixed with quaternary ammonium salts in the electrolyte and forms a complex which is less reactive than pure bromine, thus improving overall system safety.

The zinc-bromine battery presents a number of interesting features for electric vehicle applciations:

- specific energy of 65-85 W/kg, two to three times the value for lead-acid. (These values are system-based and not just cell-based)
- capability of full (100%) discharge without damaging the battery
- long cycle life (up to 2000 cycles)
- stack modules can be connected as desired for the application
- simple plastic construction

In this framework, extensive experimentations have been performed with ZnBr batteries, particularly by SEA in Austria. Further developments have taken place in the USA (where it has been dubbed the "Zinc-Flow" battery, probably to avoid mentioning bromine) and Japan.

## The vanadium-redox battery

The development of this technology was started by NASA for stationary energy storage applications. The electrolyte in the positive and negative electrode compartments are different valence states of Vanadium sulphate. On one side of the battery is a solution of Vanadium (II) ions dissolved in sulphuric acid. In the other side is a solution of Vanadium (V). The reactions during discharge are:

negative electrode:

$$V^{2+} \rightarrow V3^{+} + e^{-}$$

positive electrode:

$$V^{5+} + e^{-} \rightarrow V^{4+}$$

The Vanadium (II) is oxidized to a solution of Vanadium (III) and returns to the anode reservoir. The Vanadium (V) is reduced to a solution of Vanadium (IV) and returns to the cathode reservoir. Hydrogen ions may cross the membrane to maintain charge balance. The cell has a potential of 1.6 V when fully charged. Under same cell conditions, open-circuit cell voltage at 50% state of charge decreases to 1.4 V.

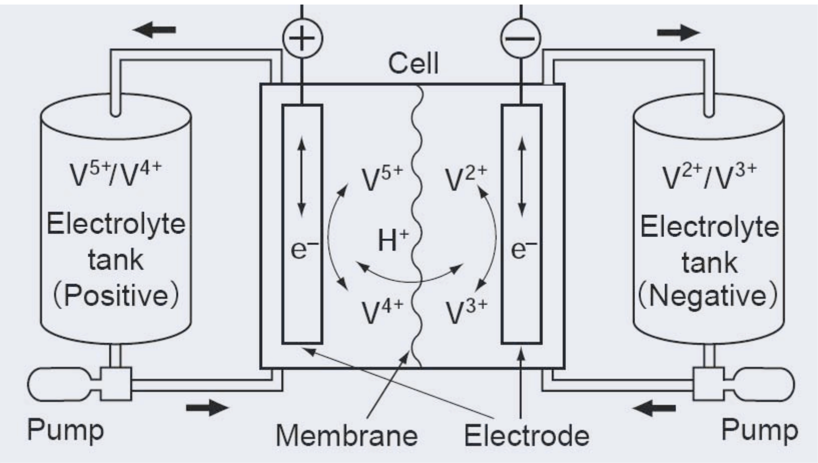


*Illustration 19: Vanadium battery single cell*

The vanadium battery has a significant advantage over the other flow battery because a possible mix of the electrolytes does not damage the battery. If some of Vanadium leaks through the membrane, the only disadvantage is energy loss, that have to be regenerated from the transfer of electrons through the graphite. Once the battery is recharged, the Vanadium ions will returns to their charged oxidation states. The electrolyte solution is not permanently contaminated.

Vanadium-redox batteries have been experimented for electric vehicle applications, particularly in the USA.

## The polysulfide/bromine (Regenesys) battery

This battery was developed in the early 1990's and is also known under its trade name Regenesys. A polysulfide-bromine battery is similar to a redox system but both the positive and negative reactions involve neutral species. The two electrolytes are sodium bromide (NaBr) as the anode and sodium polysulfide ($Na_2S_4$) as the cathode. The chemical couples involved are bromine/tri-bromine and polysulphide-sulphide in aqueous solution. The electrochemical reactions during discharge can be simply represented as follows:
negative electrode:

$$Na_2S_4 + 2Na^+ + 2e^- \rightarrow 2Na_2S_2$$

positive electrode:

$$3NaBr \rightarrow NaBr_3 + 2Na^+ + 2e^-$$

overall reaction:

$$3NaBr + Na_2S_4 \rightarrow NaBr_3 + 2Na_2S_2$$

Sodium ions pass through the cation exchange membranes in the cells to provide electrolytic current flow and to maintain electro-neutrality. The sulphur that would otherwise be produced is discharged dissolved in excess sodium sulphite that is present to form sodium polysulfide. The bromine produced at the positives on charge dissolves in excess sodium bromine to form sodium tri-bromide. One drawback of this system is the risk of cross-contamination of the electrolytes, due to the cross-over of ionic species through the membrane, from one compartment to the other.

The system is organised as a bipolar module with an electrode shared between two cells; their system used a number of these modules linked electrically in series to reach the required voltage. The electrolytes are distributed to the modules in parallel.
Few applications of this battery for traction purposes have been recorded.

## Conclusions

The main characteristic of the redox batteries is that, differently from conventional batteries, system energy and power can be defined independently at the value more adequate for practical application. This is due to the structural propriety to store energy not inside electrodes but inside electrolytes flowing through the stack cells. So simply energy is proportional to electrolyte volume in tanks and power is proportional to stack volume. This typical characteristic together others advantages such as ambient operation temperature, very high cyclelife, no self-discharge, tolerance to deep discharge, instant recharge, make redox batteries very attractive for applications on board of vehicles.
Despite these virtues, the complexity of the system and its needs for ancillary equipment have been major drawbacks for further consideration of these batteries for actual vehicle traction purposes.

# Industrial batteries for non-road vehicle applications

## Introduction

Although the SUBAT action is focused on traction batteries, it seems interesting to briefly highlight the situation with industrial batteries in general. This excludes portable batteries on one hand and SLI batteries on the other hand.
The industrial battery market is dominated by the lead-acid battery, due to its low cost. There are some applications however in which nickel-cadmium batteries can compete with lead-acid batteries due to better high-rate performance and longer life combined with low maintenance costs.

The typical technologies for industrial nickel-cadmium are as follows:

1. The pocket-plate battery has the lowest cost and is used when are required high reliability and for fail-safe operation. However, the energy and power density limit its use in some areas. This battery is still used only for that applications in which are required ruggedness and long durability.
2. The fiber plate battery has lower internal resistance than the pocket-plate battery and is also available both in ultra-high and low-rate cells.
3. Where very high energy and power density are required, the plastic-bonded plate may be the choice.

Non-road vehicle application fields, where industrial-type nickel-cadmium batteries are used, can summarized as follows:

- Aircraft or aerospace application.
- Cycling application: lightning, medical, professional electronic, power tools, home appliances.
- Permanent charge application: stand-by, back-up and emergency lightning.
- Stationary applications: electricity and general industries, water, oil & gas industry, buildings, hospitals, airports, boats, and rail infrastructure.
- Rail and mass Transit: on board applications.
- Telecom network.

For industrial electric vehicles, today lead-acid batteries are the most frequently used due to their low cost and their good cycling performance in this type of application. The heavy weight of the battery is no problem in applications such as fork lifts which are in need of counterweight mass anyway.

## Aircraft and aerospace applications

Aircraft currently use rechargeable battery to provide power for a large number of auxiliary electrical functions including lightning, emergency power, load-levelling fill-in, APU (Auxiliary Power Unit) and engine starting. Battery types used are typically either vented or valve-regulated nickel-cadmium or lead-acid. Vented batteries tolerate better over-charge and over-discharge abuse, but require expensive maintenance. The valve-regulated configurations overcome the maintenance expenses, but are subject to failure when poor charge regulation in encountered. Fibrous electrode and sintered plate NiCd batteries are used in advanced applications with high power demands.
Current developments of battery systems for aircraft applications are concerning low maintenance nickel-cadmium, nickel metal hydride and lithium ion batteries, that would supplant completely VRLA batteries. The reasons for this trend is essentially for the weight reduction.

## Batteries in stationary applications

In stationary applications, nickel-cadmium batteries are used in standby and emergency installations where life and great economic values would be endangered by a power failure. For examples, emergency power in hospital operating theatres, standby power for all vital functions on off-shore oil rigs, uninterruptible power supplies (UPS) for large computer systems in banks and insurance companies, standby power in process industries, and emergency lighting and landing systems in airports.

In applications with short-duration discharges - standby and emergency equipment are usually used for less than a half-hour - the rated capacity of a battery is of little importance. The size of the battery is chiefly determined by the power need. The nickel-cadmium battery performs well in industrial applications when reliability and durability are considered in a life-cycle cost calculation.

### *Electric energy storage*

Electric energy storage is a broad term that covers a group of stationary applications in which battery capacities are often measured in megawatt hours. However these applications can be grouped in three main categories:

- Power Quality: Stored energy, in these applications, is only applied for seconds or less, as needed, to assure continuity of quality power.
- Bridging Power**:** Stored energy, in these applications, is used for seconds to minutes to assure continuity of service when switching from one source of energy generation to another.
- Energy Management: Storage media, in these applications, is used to decouple the timing of generation and consumption of electric energy. The batteries are used for load levelling, in this application the batteries are charged when energy cost is low and are discharged when loads require more power than available on grid.

In many cases, energy storage systems are expected to satisfy more than one of these requirements. These applications are steadily increasing in importance, particularly in a newly-deregulated environment in which distributed generation is becoming prevalent.

The nickel-cadmium battery is used in power-generating stations and power distribution networks where power supply needs to be not broken down. The batteries are used in switchgear applications and for control and monitoring functions.

In case of failure of the primary power supply, diesel generators or gas turbines are installed to take over the power supply. For a reliable and fast-acting start-up of these engines, nickel-cadmium batteries have proven to be the best emergency power source.

By virtue of their technology, Ni-Cd batteries are reliable in terms of construction, performance and maintenance.

The advantages of nickel-cadmium for stationary applications are:

- long life and the optimum reliability to protect vital equipment in substations,
- it is the only battery type that does not suffer sudden failure,
- low life-cycle cost, especially under adverse conditions.

Reserve batteries for uninterruptible systems usually use lead acid batteries over 100 Ah or nickel-cadmium batteries for higher reliability plants (nuclear plants).

Nickel metal hydride technology is extremely expensive for large applications. These batteries are used only when environmental aspects became important.

Efforts to scale up lithium-ion to larger capacities are not easy, since the current technologies mostly use cobalt oxides in the cathode material and this material would be too expensive for the larger cells. Development is proceeding on a wide range of cathode materials and one of the early successes is with doped nickel oxides. Using this technology SAFT has developed a range of cells up to 44 Ah and high-power, high-

energy and mid range designs. The high-power types can be discharged at rate of 10 times the battery capacity.
The lithium-ion polymer technology has been under development for over 20 years. One major disadvantage to the use of this technology is that it is aimed at energy applications and cannot be used in power application without special management. In fact this battery cannot sustain heavy damage if exposed to high discharge rates for more than a few seconds. Safety concerns with lithium also remain an issue.

Others interesting storage systems are flow battery systems. There are several flow battery technology that are near to commercial stage for utility stationary applications.
A major advantage of a flow technology is that power and energy functions are decoupled.

### *Photovoltaic and wind generations*

Solar and wind-powered generation systems are used for many applications including lighthouses, beacons and cathodic protection. The systems, composed by a solar panel or wind generator, electronic controllers and a back-up battery, are often installed in remote areas, at sites accessible only in good weather and with only limited skilled maintenance labour available.
For these systems, sinter/plastic bonded Ni-Cd batteries are used but they are limited in cell size to about 440 Ah per cell. Lead-acid batteries are used for capacity over 100 Ah. Alkaline batteries are also used for applications requiring smaller capacities (10 to 50 Ah).

## Railway applications

The nickel-cadmium pocket-plate battery was the first alkaline battery used for railroad applications. In recent years, plastic-bonded and fiber-plate batteries are used since they can perform higher energy per unit weight and volume. This characteristic is particularly important for high-speed trains, mass-transit cars, subway cars, and light rail vehicles.

### *Starting batteries for diesel locomotive*

Starting diesel engine calls for a reliable high-current power source for a short period of up to 30 seconds. Engine starting batteries must be able to supply an high current to the starter motor. They must be able to work over a wide temperature range and to withstand heavy vibration. Engines normally need to be started once a day.

### *Electric locomotive, high-speed trains, light rail vehicles and metros*

On-board electric locomotives, batteries are supplying not only the energy for emergency lighting and ventilation, but also for different low voltage systems when the main power is not available, for example when the pantograph in not connected to the grid. To raise the pantograph requires discharges from a few seconds to 2 minutes.
In these applications the batteries have to power the low voltage system in the event of emergency shutdown of the high voltage system or converter failure. This function needs batteries with 20 to 90 minutes of power supply in a metro and up to 2 hours in a high-speed train.
Like other mass transport systems, Light Rail Vehicles require an independent power source to back-up the on-board low voltage system, for door control, lighting and air conditioning, radio communication, and computing systems, typically for 30 min.
In a metro, the battery typically has a buffer function to meet sudden demand for

power (peaks for emergency braking) or to compensate for high voltage interruptions (particularly during change of section or gaps in the track).

### *Passenger Coaches*

Batteries are used onboard conventional train passenger coaches to provide a reliable emergency power supply in case of failure of the main power supply.

They may come into operation not only for emergency purposes, but also whenever the train is at a standstill with the engine still running.

These batteries power lighting, ventilation, air-conditioning and switching & transmission systems.

### *Signalling systems*

Signalling is crucial for all rail transport systems, and reliability of the standby power source is essential. Signalling batteries must be able to withstand a wide range of temperatures and rugged operating conditions. Railways are continually fine-tuning their signal lighting systems to regulate the traffic and to improve vehicle and passenger safety.

Train lamps and track signals use air-depolarized batteries (saline and alkaline) as stand-alone lighting power sources. Standby batteries are required for signalling functions at highway level crossings, wayside signals and switch-point operations.

Signalling standby batteries must be able to withstand severe conditions and to provide reliable, predictable energy. High-energy batteries providing lower currents over longer periods are required for standby power supply for various monitoring and control functions with telecommunications equipment, electronic devices of various kinds, closed-circuit television and computers.

In many applications along the track, batteries are used to meet peak electricity demand and to provide back-up power to all security systems in case of emergency.

### *Substations*

Battery systems are installed in substations to close and to trip high-voltage circuit breakers, for transformer protection and safe isolation during normal or fault conditions. These switchgear and transmissions systems are frequently installed in unattended operation and must be capable of operating for long periods with total reliability and without maintenance.

These applications require high reliability, long life, low maintenance, and proper operation in uncontrolled environments.

In addition, substations require UPS systems and auxiliary generator. These systems require a set of batteries to protect their control system and emergency and security systems.

## Telecom network applications

In telecommunications infrastructures, every site must be fully reliable. Industrial batteries for telecommunications ensure power reliability in a wide variety of terminals, such as central offices, remote terminals, cellular base stations and photovoltaic powered sites.

For this application lead-acid batteries over 50 Ah are generally used. ZEBRA batteries are beginning to be used for their higher reliability and long life.

### *Battery rooms in central offices*

Traditionally, central office equipment is supported by parallel strings of flooded lead-acid batteries. Batteries in central office are generally well maintained and operated under ideal conditions, therefore they provide many years of reliable and economical service.

However, in some areas of the world, temperatures are so high that lead-acid batteries, although located in air-conditioned buildings, may suffer from sudden failures. Nickel-Cadmium batteries represent an excellent alternative to flooded lead-acid batteries, for a more reliable, safer and longer lasting power backup in the central office. Most central offices are equipped with diesel generators as protection against long utility power outages. These generators are of little use if they do not start when needed, so the starting battery is a critical component.

Starting problems, frequent battery replacements and high maintenance costs reduce the difference in price between a lead-acid battery and a Ni-Cd battery.

### *Emergency phones and radio repeaters*

Emergency phones and radio repeaters are another type of terminals that can be very remote. Difficult access and distance from the closest operation and maintenance office are often aggravated by poor power quality. Therefore batteries with the low maintenance and reliable backup are the most preferable.

Lithium-metal-polymer batteries are now being offered as commercial products for telecom applications.

## Conclusions

Industrial-type electric vehicles normally use lead-acid batteries. The main reason for this is that lead-acid batteries are less expensive than others battery systems. In these application performances are not the most important aspect, but cost is prevailing.

Nickel-cadmium batteries are used in those applications in which a high performance and long-life is required.

In the next years, the developments of other technologies such as nickel-metal hydride, lithium, ZEBRA and redox could make them as a valid alternative to nickel-cadmium batteries in a lot of segment markets.

Lithium-ion and nickel-metal hydride batteries are used for portable applications in which low weight is important and the cost is relatively low because the energy required is not high, even though the cost per kWh is high.

ZEBRA batteries can be utilized for which applications that require high energy density and can replace nickel-cadmium battery in telecom, railways and energy storage applications.

Redox flow battery is an attractive technology for the stationary applications. In fact, if electrolyte tanks are not considered, their energy density can reach very high values. This is possible if tanks were placed underground (for example in electricity plants to load-levelling).

## Comparison of battery types

In order to allow the SUBAT project as a whole to compare the different battery technologies on a common basis, the following assumptions have been made which reflect the state of the art. To this effect, it is advisable to consider on one hand "energy" batteries (aimed at BEV use) and on the other hand "power" batteries for hybrid vehicles. Within the same electrochemistry, widely different batteries can indeed be designed for specific applications.

For battery-electric vehicle applications, battery types can be considered as shown in Table II

| Type | Spec. energy Wh/kg | Spec.power W/kg | Cycle life | Efficiency (energy) | Maintenance | BMS | Status |
|---|---|---|---|---|---|---|---|
| Pb vented | 30-35 | 200 | 700 | 80-85 | yes | available | C |
| Pb VRLA | 40 | 250 | 500 | 80-85 | no | advisable | C |
| NiCd | 50-60 | 200 | 1350 | 75 | yes | advisable | C |
| NiMH | 60-70 | 350 | 1350 | 75 | no | advisable | P |
| NiZn | 70-80 | 200 | 300? | 75 | no | advisable | L |
| LiIon | 100-120 | 400 | 1500 | 90 | no | essential | P |
| LiMetPol | 100-120 | 250 | 1500 | 90 | no | essential | P |
| NaNiCl | 100-120 | 200 | 1000 | 86 | no | integral | C |
| ZnAir | 200 | 70 | 2000 | - | yes | advisable | P |
| ZnBr | 80 | 100 | 1000 | - | yes | integral | L |

*Table II: BEV batteries*

Status codes:

- C: commercially available products (from catalog)
- P: batteries available as pre-series or prototype for experiments – not a commercial product
- L: laboratory stage – cell level available

It has to be noted that the values for the cycle life in this table have been taken quite conservative, since practical experience shows that manufacturer's data (based on standard cycling tests) are often quite optimistic compared with real life data.

For hybrid vehicles it is difficult to express battery life in cycles, as the cycling mode strongly depends on the design of the hybrid and no standard test cycles exist. Another approach has been chosen here, with the cycle life in hybrid service expressed in relative values, with lead-acid equalled to one.
This gives the results in Table III One should note that some electrochemistries which are less suited for this purpose are not reproduced in this table.

| Type | Spec. energy Wh/kg | Spec.power W/kg | Cycle life | Efficiency (energy) | Maintenance | BMS | Status |
|---|---|---|---|---|---|---|---|
| Pb VRLA | 25 | 350 | 1 | 80-85 | no | advisable | C |
| NiCd | 30 | 500 | 3 | 75 | yes | advisable | C |
| NiMH | 55 | 1500 | 3 | 75 | no | advisable | P |
| LiIon | 70 | 2000 | 3 | 90 | no | essential | P |
| LiMetPol | 60 | 1000 | 3 | 90 | no | essential | P |
| NaNiCl | 125 | 200 | 3 | 86 | no | integral | P |

*Table III: HEV batteries*

In order to compare the different battery types on the level of their performances, one can make use of the so-called Ragone chart (Illustration 20), which plots specific energy versus specific power (the latter usually represented on a logarithmic axis), where one can compare easily the different batteries suitable for use in either battery-electric vehicles (which need foremostly energy) and hybrid vehicles (which need foremostly power).

In this framework, one should note that the coloured areas on the chart each represent an electrochemical couple, but that several design options are possible to optimize the battery for its application and to locate it in these areas.

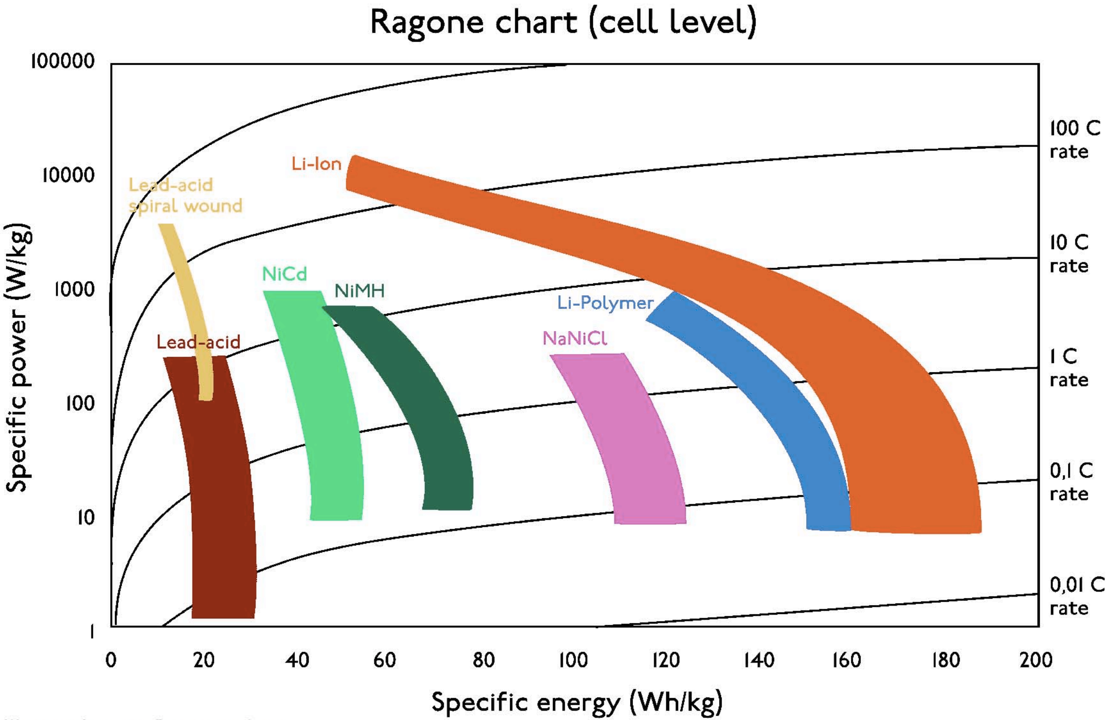


*Illustration 20: Ragone chart*

APPENDIX II

# SUBAT: SUSTAINABLE BATTERIES

## Work package 2: Environmental Assessment: Final Report

**Report prepared by**

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# Abbreviations list

BEV = Battery Electric Vehicle

BMS = Battery Management System

DOD = Depth of discharge

EV = Electric vehicle

EQ = Environmental Quality

F.U. = Functional Unit

HEV = Hybrid Electric Vehicle

HH = Human Health

ICE = Internal Combustion Engine

ISO = International Standardisation Organisation

LCA = Life Cycle Assessment

LCI = Life Cycle Inventory

LCIA = Life Cycle Impact Assessment

Li-ion = Lithium-Ion Battery

NiCd = Nickel-Cadmium Battery

NiMH = Nickel-Metal Hydride Battery

NiZn = Nickel-Zinc Battery

NiNaCl = Sodium-Nickel Chloride Battery

Pb-acid = Lead-acid battery

Pt = Eco-indicator point

R = Resources

SUBAT = Sustainable Batteries

VSP = Vehicle Simulation Program

# I. Introduction

The SUBAT-project is a specific targeted research project, evaluating the opportunity to keep nickel-cadmium traction batteries for electric vehicles on the exemption list of Directive 2000/53 on End-of-Life Vehicles. Right now, Annex II to the Directive has exempted nickel-cadmium batteries for electric vehicle applications until December 31, 2005.

The aim of the SUBAT-project is to deliver a complete assessment of commercially available and forthcoming battery technologies for battery-electric and hybrid vehicles. This assessment will include a technical (work package 1), an environmental (work package 2) and an economical (work package 3) study of the different battery technologies, including the nickel-cadmium technology. These studies are performed using data gathered in work package 4, while the overall results and conclusions are presented in work package 5.

Battery and hybrid electric vehicles, in substitution of internal combustion engine (ICE) vehicles, are a part of the solution to problems such as urban air pollution, fossil fuel depletion and global warming [1,2,3]. When analysing electric vehicles, the battery is often considered to be the main environmental concern, be it pertinent or not. Anyhow, the environmental impact of the battery should be assessed. Many batteries contain heavy metals, each with their specific toxic properties to environment and human health. The impacts of the different battery technologies should be analysed individually to allow the comparison of the different chemistries and to enable the definition of the most environmentally friendly battery technology for battery electric vehicles (BEV) and hybrid electric vehicles (HEV). This can be done in a qualitative or a quantitative way.

The impacts of the most widespread technologies (NiCd, NiMH, NaNiCl, Li-ion and Pb-acid) are analyzed quantitatively in the first part of the report. Life Cycle Assessment is used for these quantitative analyses. Other less widespread technologies (like Zn-air, NiZn, Li-polymer…) were assessed in a qualitative way in the second part of this report, as their development does not allow a complete assessment (comparable with the previously described technologies).

The first step of the analysis was to list the available technologies for battery and hybrid electric vehicle appliances. Afterwards, a model for the different battery types has been developed and introduced in an LCA software tool. This model allows an individual comparison of the different phases of the life cycle of traction batteries. This makes it possible to identify the heaviest burden on the environment for each life phase of each battery. The main difficulty encountered while performing this study was the gathering of appropriate, comparable and accurate data.

# Part 1. Quantitative analyses

# 1. LCA

## 1.1. LCA Methodology

Life cycle assessment (LCA) studies the environmental aspects and potential impacts of a product throughout its life from raw material acquisition through production, use and disposal [4]. Other instruments exist to assess some environmental impacts of products or services. But its so-called "cradle-to-grave" approach makes LCA unique.

A schematized overview of the life cycle of a battery is shown in Figure 1.

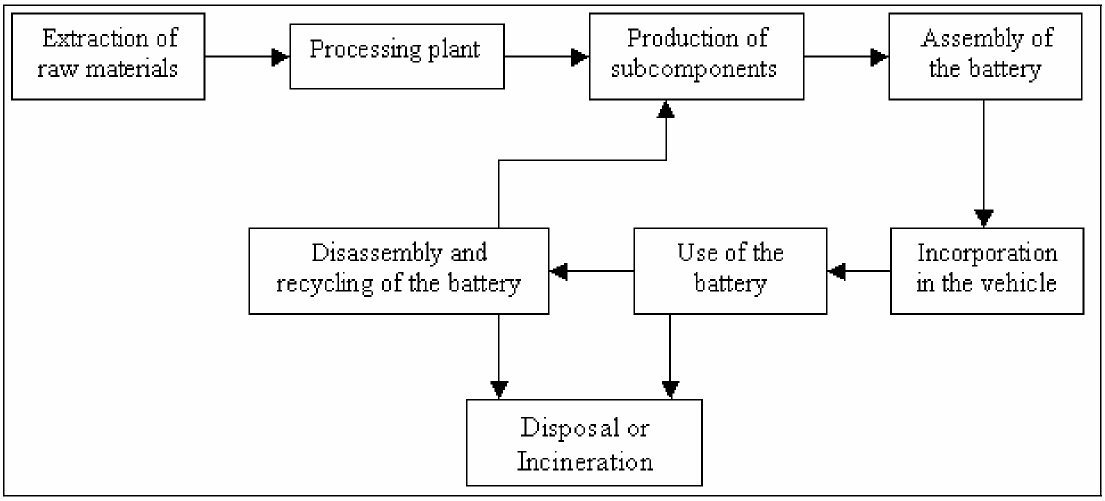


**Figure 1: The schematized life cycle of a battery.**

An overall approach is a must when wanting to compare different products in an appropriate way. LCA is the most adapted tool to compare the complete environmental burden of different products. This can be explained by the fact that different products may have burdens in different parts of their life cycle. For example, one product may use more resources (for example energy) compared to another product during the use phase, but this may be at the cost of more resources used in its production phase [5].

The life cycle assessment of a product will probably never be completely exhaustive; as a consequence the analyst has the freedom to choose to which degree of detail he or she will try to model the assessed life cycle. However, it should be clear that, the choice of a more or less detailed model determines the degree of precision and correctness of a study to a certain extent. However, most studies don't go into so much detail [6].

There are four ISO standards specifically designed for LCA applications, they are summarized below:

ISO 14040: Principles and framework
ISO 14041: Goal and Scope definition and Inventory Analysis
ISO 14042: Life Cycle Impact Assessment
ISO 14043: Interpretation

## 1.2. Software selection

### 1.2.1. Selection of the Software

The performing of an LCA study is a complex process and it involves an important number of calculations. As a consequence, software had to be acquired to perform the study. Additionally, many of the software applications are delivered including a number of databases (optional or not) including an important amount of information. As the collection of data is a very labour intensive process, these databases are essential to relieve the data collection work.

Due to the important number of specialized software available on the market, the choice of the software hasn't been a straightforward issue. The software tool was selected following a thorough market review of different commercial software tools.

After a preselection, three software tools were kept and analyzed in more detail on the basis of a questionnaire sent to the developers, of a demonstration proposed by the companies and of experiences reported by LCA software users.

The preselection of the software tools has been done according to the following criteria:

- Availability as a commercial product
- Origin of the software: European
- Specificity of studies covered by the software: applications
- Reference users: manufactory industry, chemical and metal sector

The three pre-selected software tools were:

- Gabi 4 (PE Consulting group)
- SimaPro 5.1 (PRé Consultants)
- TEAM 4.0 (PriceWaterhouseCoopers - Ecobilan).

After the demonstration and the comments, TEAM seemed to be slightly more adequate than SimaPro to perform this study. Gabi was eliminated because of its lack of user-friendliness and poor visibility when working with various windows. An overview of the advantages and disadvantages of these software tools is given in appendix 1.
In the end, the SimaPro software was chosen, because the TEAM software exceeds the budget allocated for this study.

Several updates of SimaPro were released during the performing of the SUBAT-study. The final LCA's were accomplished with the most recent update of the software (SimaPro 6.01).

## 1.2.2. SimaPro

### 1.2.2.1. Different versions of SimaPro

The LCA studies were performed using the Analyst Multi-User version of SimaPro 6.01. In the Multi User version different people can share data in one central database and work together on a project. Software Manuals can be downloaded from the SimaPro Website.

### 1.2.2.2. Data processing in SimaPro

There are many different results visualization modes in SimaPro. In each mode you can also choose the variable (impact indicator, damage indicator, weighted indicator, substance…).

### Visualization of the process structure

There are two different graphical representations of the process structure in SimaPro: a hierarchical tree or a network. Both have some advantages and disadvantages. In both representations you can choose a cut-off range i.e. the level from which to include or exclude the representation of a given input.
In each step (in the tree or network representation), the cumulative impact of each stage is given as a percentage of the global impact or as a real value of the indicator. Additionally, the length of a bar in each box represents the proportional impact of each life-stage to the overall impact:

- In the **hierarchical tree** representation, all relevant inputs and outputs (larger than the cut-off range) are shown for each process.

- In the **network representation,** each process is only represented once, irrespectively of the number of times it's used in the tree. In this representation you can easily identify the importance of each process. Contrarily to the hierarchical tree representation, this representation can contain loops.

Additionally all the final and intermediate results of the LCA can also be shown in a table or in a chart.

## 1.3. Life Cycle Impact Assessment (LCIA) method

### 1.3.1. Selection of Impact Assessment Method

Life cycle impact assessment (LCIA) methods try to link each life cycle inventory (LCI) result (elementary flow or other intervention) to its environmental impact(s) [7]. According to ISO 14042, LCI results are classified into impact categories, each with a category indicator.

Often the impact assessment methodologies differ and the choosing of one of the methods remains a difficult decision. Previous studies demonstrated that in some cases the choice of the used method actually has got an influence on the results of the study [8].

In the past, two classic schools of methods have been used [7]:

- Classical impact assessment methods (ex. CML, EDIP…) which restrict (quantitative) modeling to relatively early stages in the cause-effect chain (or environmental mechanism) to limit uncertainties and which group LCI results in so-called midpoint categories, according to themes. (Themes are common mechanisms, such as climate change, or are generally accepted groupings, such as ecotoxicity).
- Damage oriented methods (ex. eco-indicator 99, EPS…), which try to model the cause-effect chain up to the endpoint (damage), sometimes with high uncertainties.

A general overview of the structure of an Impact Assessment Method can be seen in Figure 2.

LCIA aims to evaluate the significance of potential environmental impacts using the results originating from the LCI phase. The ISO14040 standard suggests to divide this phase of an LCA into the following steps:

- **Classification**: Once the different impact categories are defined, the LCI results have to be assigned to these impact categories. For example $CO_2$ and $CH_4$ can be allocated to the impact category “Global Warming”, while $SO_2$ and $NH_3$ are assigned to the impact category “Acidification”.

- **Characterization**: Once the different LCI results are assigned to the different impact categories, one should define the characterisation factors. These factors define the relative contribution of the different LCI results to the impact category. As an example, as the contribution of $CH_4$ to global warming is 21 times higher than the contribution of $CO_2$ this means that if the characterisation factor of $CO_2$ is 1, the characterisation factor of $CH_4$ would be 21. Characterization can shortly be described as the conversion of LCI results to common units within each impact category, so that results can be aggregated into category indicator results.

The following elements are optional:

- **Normalization:** the magnitude of indicator results is calculated relatively to reference information.
- **Weighting:** indicator results coming from the different impact categories are converted to a common unit by using factors based on value-choices.
- **Grouping:** impact categories are assigned into one or more sets (on a nominal or a hierarchical basis).
- **Sensitivity analysis:** in order to be able to evaluate the influence of the most important assumptions, it is strongly recommended to perform a sensitivity analysis during and at the end of the LCA. The principle is simple. Change the assumptions and recalculate the LCA. With this type of analysis you will get a better estimation of the effects of the assumptions you make.

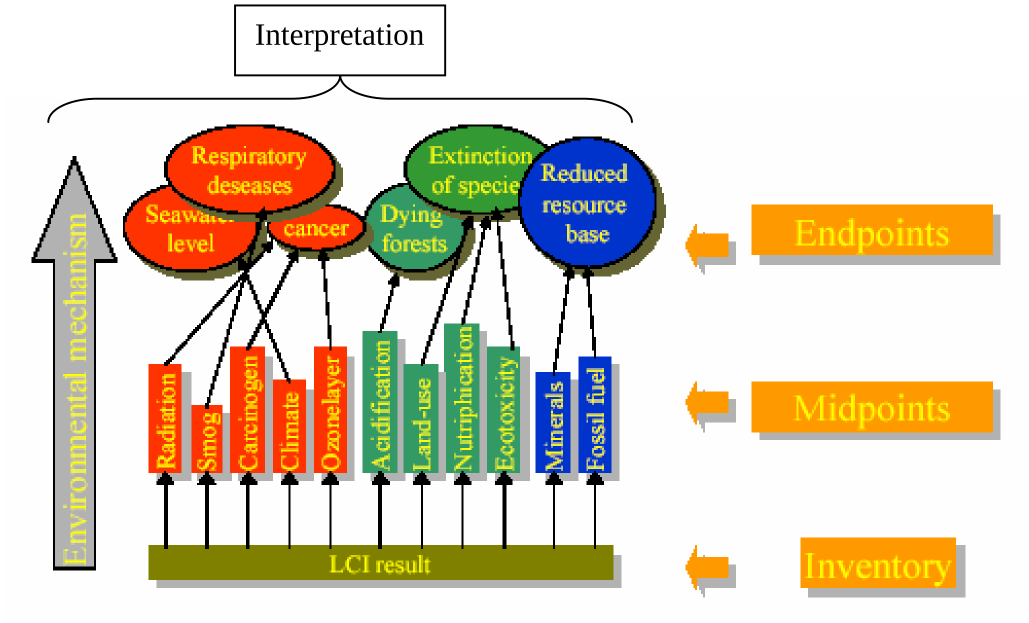


**Figure 2:General overview of the structure of an Impact Assessment Method [9].**

## 1.3.2. Eco-Indicator 99

Several LCIA methods are included in SimaPro. In this study, the only LCIA to be used is Eco-indicator 99. Eco-indicator 99 was chosen, for it’s a quite standard and widespread methodology.

### 1.3.2.1. General

The figure below gives an overview of the structure of Eco-indicator 99 [10].

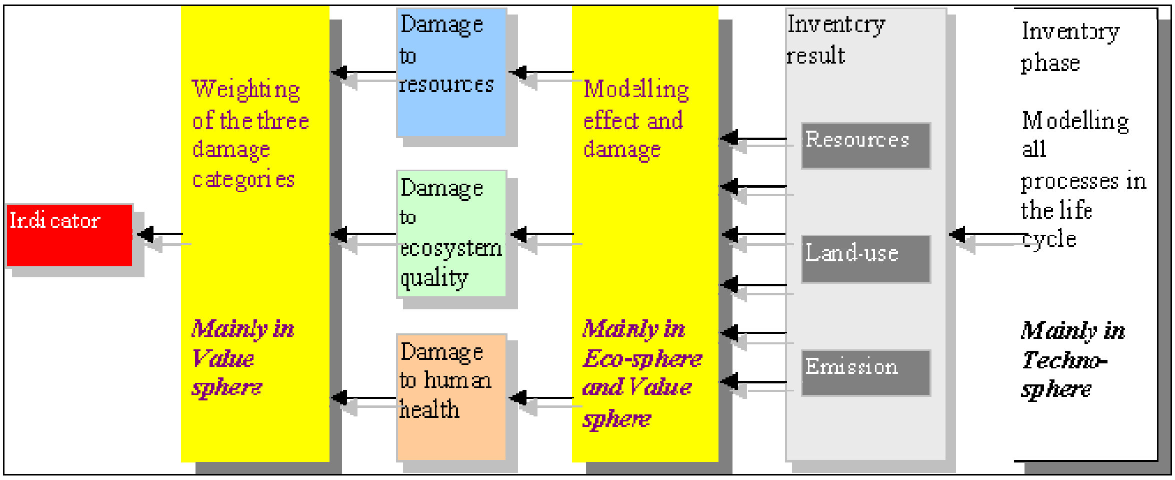


**Figure 3: Global structure of Eco-indicator 99.**

In this life cycle impact assessment method basically three types of models are used (Figure 3):

- Modelling of the Technosphere in the inventory phase (modelling of all processes in the life cycle). The inventory result divides the impact of the processes in impact on resources, on land use and on emissions).
- Modelling of the Eco-sphere in the impact assessment phase (modelling of the effects and damages of these events to obtain three categories of effects and damages: resources, ecosystem quality and human health).
- Modelling of the Value sphere in the weighting and ranking phase, as well as in order to deal with unavoidable value choices (leads to the indicator).

### 1.3.2.2. Impact categories

All the inventory results are linked with one or more of the impact categories: i.e. emissions, land use or resources. The subdivision of these impact categories is given next table [10].

**Table 1: Impact categories in Eco-indicator 99.**

| | |
|---|---|
| *Emissions* | • Carcinogens: Carcinogen effects due to emission of carcinogenic substances to air, water and soil.<br>• Respiratory organics: Respiratory effects, resulting from summer smog, due to emissions of organic substances to air.<br>• Respiratory inorganics: Respiratory effects caused by winter smog resulting from emissions of dust, sulphur and nitrogen to air.<br>• Climate change: Damage resulting from an increase of diseases and death caused by climate change.<br>• Radiation: Damage resulting from radioactive radiation.<br>• Ozone layer: Damage due to increased UV-radiation as a result of emission of ozone depleting substances to air.<br>• Ecotoxicity: Damage to ecosystem quality, as a result of emission of ecotoxic substances to air, water and soil.<br>• Acidification/Eutrophication: Damage to ecosystem quality as a result of emission of acidifying substances to air. |
| *Land use* | Damage as a result of either conversion of land or occupation of land. |
| *Resources* | • Minerals: The additional energy required for mining or obtaining new ores as a result of decreasing ore grades.<br>• Fossil fuels: The additional energy required for the extraction of fossil fuels as a result of lower quality resources. |

As in all other impact assessment methods, it’s not possible to take all the impacts (for every impact category) into account in Eco-indicator 99. This is due to the especially large number of small impacts caused by virtually every human activity. It is important to know which components are included in the different impact categories and which are not. This is required to evaluate the eventual influence on the results when including and/or excluding them. As an illustration, the category ‘Resources’ is determined by thirteen different components.

#### 1.3.2.3. Damage categories

The results of the impact categories are used to quantify the damages in each of the three damage categories (Human Health, Ecosystem Quality, Resources). This is done by fate analysis, exposure analysis, effect analysis and damage analysis, etc.

- Human health (HH): this category includes the number and duration of diseases, as well as the life years lost due to premature death caused by environmental pollution. Following effects are included: climate change, ozone layer depletion, carcinogenic effects, respiratory effects and ionising (nuclear) radiation.

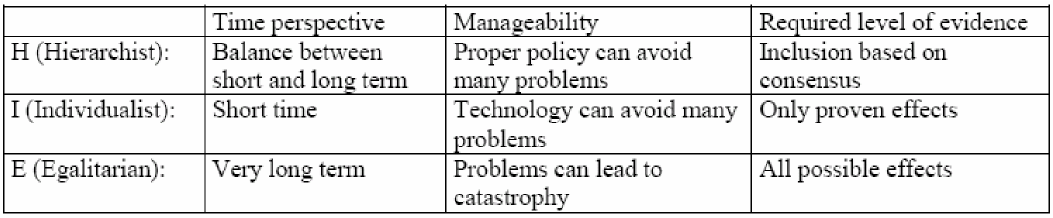
- Ecosystem quality (EQ): this category includes the effect on species diversity, especially vascular plants and lower organisms diversity. Following effects are included: ecotoxicity, acidification, eutrophication and land use.

- Resources (R): this category includes the surplus energy needed in the future to extract lower quantities of mineral and fossil resources. The depletion of agricultural and bulk resources, such as sand and gravel, is considered under land use.

### 1.3.2.4 Weighting

In the Eco-indicator 99 method, the weighting step is performed by a panel, which has been selected according to a series of strict criteria. In debates about the significance of environmental effects opinions are usually very diverse. This may be due to varying knowledge, but fundamental differences in attitude and perspective play an important role too. To take these differences into account three archetypes/perspectives were defined: hierarchist, individualist and egalitarian. The main characteristics of these perspectives are summarized in the table below.

**Table 2: The three archetypes of the Eco-indicator 99.**



| | Time perspective | Manageability | Required level of evidence |
|---|---|---|---|
| H (Hierarchist): | Balance between short and long term | Proper policy can avoid many problems | Inclusion based on consensus |
| I (Individualist): | Short time | Technology can avoid many problems | Only proven effects |
| E (Egalitarian): | Very long term | Problems can lead to catastrophy | All possible effects |

In general, value choices made in the hierarchist perspective are politically and scientifically accepted. As a consequence, the LCA in this study will be performed using Eco-indicator 99 from a hierarchist perspective. The contribution of the different impact categories to the final value is shown in Figure 4:

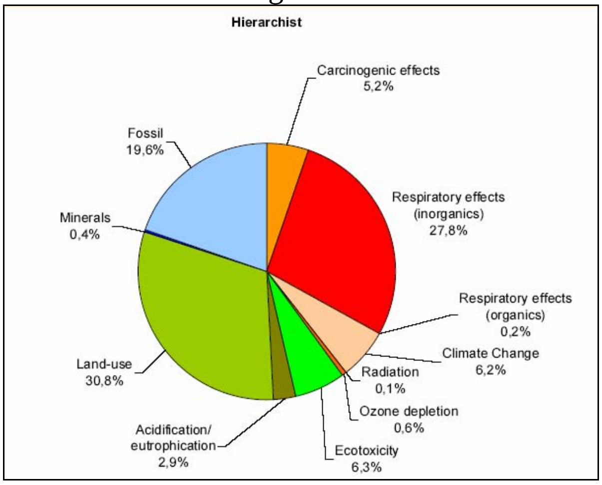


**Figure 4: Relative contribution of the impact categories to the European damage according to the hierarchist perspective, using the default weighting set (HH= 40%, EQ=40%, R=20%)**

### 1.3.2.5. Eco-indicator points

The data of the different stages of the life cycle are linked, processed and weighted in the impact assessment and Eco-indicator points are obtained.

The standard Eco-indicator values, the **Eco-indicator points** (Pt), can be regarded as dimensionless figures. As the size of the milli-point (mPt) is more convenient, Eco-indicator lists usually use this unit.
The scale has been chosen in such a way that the value of 1 Pt is representative for one thousandth of the yearly environmental load of one average European inhabitant. However, the absolute value of an eco-indicator point is not very relevant as the main purpose is to compare relative differences between products or components.

# 2. Model

Before assessing the environmental impact, the analyst has to possess a clear view of the object he or she is studying. Therefore an analysis of the composition of the product, of its production, use, recycling and disposal processes must be undertaken.

The composition of the BEV and HEV batteries, the assembly and recycling processes are presumed to be identical for both types of batteries. Actually, this does not comply completely with reality, but as far as environmental analyses are concerned, the differences are minor. These common characteristics are discussed in this paragraph. The data were obtained through questionnaires and by intensively studying of the available literature [11,12,13,14,15,16,17]. On the other hand, the technical specifications differ for BEV and HEV batteries. These aspects are discussed later on in this report.

The system boundaries of the LCA were defined. The considered area is the western world. Concerning the assessed time period, the current state of the technology was considered. The related other life cycles (trucks, industrial buildings, electric power plants, roads etc.) have not been considered, since they will not influence the results significantly. Other boundary conditions will be described further in this chapter.

## 2.1. Composition

Each substance or compound can be allocated to one of the major components of the battery: electrode, electrolyte, separator, case and other components. Lists of the substances with major importance, as well as their assumed mass (in m%), are given in the next tables. These tables are subdivided in components. The Battery Management Systems (BMS) are not taken into account in the present compositions of the different batteries.

**Table 3: Composition of the different parts of the Pb-acid battery.**

| **Pb-Acid** | | |
|---|---|---|
| | Substance | Weight percentage |
| Electrodes | Antimony (Sb) | 0.71 |
| | Arsenic (As) | 0.03 |
| | Copper (Cu) | 0.01 |
| | Lead (Pb) | 60.97 |
| | Oxygen ($O_2$) | 2.26 |
| Electrolyte | Sulphuric Acid ($H_2SO_4$) | 10.33 |
| | Water ($H_2O$) | 16.93 |
| Separator | Glass | 0.20 |
| | Polyethylene (PE) | 1.83 |
| Case | Polypropylene ((PP) | 6.73 |

Table 4: Composition of the different parts of the NiMH battery.

| NiMH | | |
|---|---|---|
| | Substance | Weight percentage |
| Electrodes | Nickel (Ni) | 20.59 |
| | Rare earth metals | 10.07 |
| | Nickel hydroxide ($Ni(OH)_2$) | 21.48 |
| | Cobalt (Co) | 4.85 |
| Electrolyte | Potassium hydroxide (KOH) | 3.35 |
| | Sodium Hydroxide (NaOH) | 0.88 |
| | Water ($H_2O$) | 11.67 |
| Separator | Polypropylene (PP) | 2.57 |
| Case | Polypropylene (PP) | 4.53 |
| | Polyethylene (PE) | 4.53 |
| Other | Copper (Cu) | 1.20 |
| | Other | 6.29 |
| | Steel | 7.99 |

Table 5: Composition of the different parts of the NiCd battery.

| NiCd | | |
|---|---|---|
| | Substance | Weight percentage |
| Electrodes | Nickel (Ni) | 13.23 |
| | Nickel hydroxide ($Ni(OH)_2$) | 15.44 |
| | Cadmium hydroxide ($Cd(OH)_2$) | 20.73 |
| | Cobalt hydroxide ($Co(OH)_2$) | 1.43 |
| Electrolyte | Potassium hydroxide (KOH) | 4.89 |
| | Sodium hydroxide (NaOH) | 0.35 |
| | Lithium hydroxide (LiOH) | 0.63 |
| | Water ($H_2O$) | 16.47 |
| Separator | Polypropylene (PP) | 4.47 |
| Case | Steel | 14.78 |
| | Polyethylene (PE) | 4.47 |
| | Polypropylene (PP) | 3.11 |

**Table 6: Composition of the different parts of the NaNiCl battery.**

| NaNiCl | | |
|---|---|---|
| | Substance | Weight percentage |
| Electrodes | Nickel (Ni) | 17.62 |
| | Sodium chloride (NaCl) | 11.58 |
| | Copper (Cu) | 3.52 |
| | Iron (Fe) | 16.45 |
| Electrolyte/Separator | Beta-alumina (Bohmite, $Al_2O_3$) | 16.45 |
| | Sodium aluminum chloride ($NaAlCl_4$) | 14.26 |
| Case | Stainless | 9.79 |
| Other | Steel | 4.08 |
| | Silicates ($SiO_2$) | 4.08 |
| | Polypropylene (PP) | 2.18 |

**Table 7: Composition of the different parts of the Li-ion battery.**

| Li-ion | | |
|---|---|---|
| | Substances | Weight percentage |
| Electrodes | Carbon | 14.96 |
| | Lithium metal (Co/Ni/Mn) oxide (LiMO2) | 23.63 |
| | Polyvinylidene fluoride (PVDF) | 1.19 |
| | Styrene Butadiene rubber (SBR) | 1.19 |
| Electrolyte | Propylene Carbonate (PC) | 3.15 |
| | Ethylene Carbonate (EC) | 6.30 |
| | Dimethyl carbonate (DMC) | 3.15 |
| | Lithium hexafluorophosphate (LiPF6) | 3.15 |
| Separator | PP/PE | 0.00 |
| Case | Other | 21.23 |
| Other | Aluminium (Al) | 12.60 |
| | Copper (Cu) | 9.45 |

## 2.2. Assembly

The current state of the technology is considered for the production and assembly of the batteries. The raw materials are purchased by the manufactures and are processed in the factory to form the battery components.

*Energy consumption for assembling.*

The energy consumption for assembling the different batteries is shown in the next table. The electricity production mix used in this study is the European Mix (EU-25) in the year 2002 [23]. The detailed composition is shown in paragraph 2.4.

**Table 8: Energy for the assembly of the different types of batteries (in MJ/kg)**

| | Assembly (MJ/kg) |
|---|---|
| Pb-acid | 10.71 |
| Ni-MH | 9.79 |
| NiCd | 19.60 |
| Li-ion | 42.75 |
| NaNiCl | 20.86 |

The data regarding the energy needed to assemble the batteries were provided by important battery producers and were matching some data found in the literature. The only gap in the information regards the sodium-nickel chloride battery, but as the only producer (MES-DEA) didn't provide realistic energy consumption data, some estimations had to be made to perform the calculations. The emissions of the energy production are the only emissions taken into account in the assembly stage. No other air and water emissions are assumed in this stage of the life cycle, because these data are not available for all the technologies. This allows comparing the different technologies in an unbiased way.

## 2.3. Use of the battery in the vehicle

To determine the environmental impacts of the different battery technologies during the use phase, some assumptions have been made. Concerning the use phase of the BEV, the only environmental impact to be considered are the electricity losses of the batteries due to the battery masses and their efficiencies. Concerning, the use phase of the batteries in HEV, the environmental impacts have been neglected, as the electricity input originates from the ICE (internal combustion engine). More details concerning these aspects are provided in chapter 3 (BEV) and 4 (HEV).

## 2.4. Recycling

An equivalent recycling level is considered for each battery technology. As an illustration, this means that if the plastic is recycled for one battery, the case is assumed to be recycled for each battery technology.

We assume that the recycled materials have the same quality as the original materials. The impact of the produced slags and other by-product is not taken into account, because the influence of these slags on the environmental score of the battery is negligible.

A collection rate of 100% was assumed, which means all the spent batteries are recycled at the end of life. These data are realistic considering the weight and volume of the BEV and HEV batteries and considering the answers of various stakeholders to our questionnaires. A recycling rate of 95% of the recuperated materials was assumed for the different technologies (except for lead because of the high maturity of lead recycling; recycling rate = 98.3%). It is assumed the electrolyte is neutralized before disposal. The only exception is the sulphuric-acid of the lead-acid batteries, which is recuperated for 90%. The first step in the recycling process of the batteries is the separation of the electrolyte from the rest of the battery.

The next table shows the recuperated materials of the different parts of the batteries for each of the assessed technologies.

**Table 9: Recuperated materials for the different battery technologies (MJ/kg).**

| Technology | Recuperated material | Part of battery |
|---|---|---|
| Pb-Acid | Lead | electrodes |
| | plastic (PP) | case |
| NiCd | Cadmium | electrodes |
| | Nickel | electrodes |
| | Steel | case |
| | plastic (PP + PE) | case |
| Li-ion | Nickel | electrodes |
| | Cobalt | electrodes |
| | Plastic | case |
| NiMH | Steel | case |
| | Nickel | electrodes |
| | Cobalt | electrodes |
| | plastic (PP + PE) | case |
| | Steel | other |
| NaNiCl | Nickel | electrodes |
| | Iron | electrodes |
| | stainless | case |
| | Steel | other |

*Energy and recycling*

The energy consumption (European Mix) for the recycling process for the different technologies is presented in the next table.

**Table 10: Energy for the recycling of the different types of batteries (in MJ/kg).**

| | Recycling (MJ/kg) |
|---|---|
| Pb-acid | 2.83 ↔ 4.1 |
| Ni-MH | 4.7 |
| NiCd | 4.72 ↔ 3.28 |
| Li-ion | 4.7 |
| NiNaCl | 4.7 |

Two recycling processes have been assessed for the Pb-acid and for the NiCd batteries. In the first scenario, the complete battery is fed into a furnace and the burning of the plastics is used as a kind of heat supply. This implies reduced energy consumption compared to the second scenario. In the second scenario, (a part of) the plastic is separated before the rest of the battery is sent to the furnace. The plastics are recycled in this scenario. This explains why two values are displayed in Table 10 for the energy consumption related to the recycling of lead-acid and nickel-cadmium batteries.

NiMH and NiNaCl batteries can be recycled in a similar way as the NiCd batteries [18]. As a consequence, the same energy consumption is assumed. This is due to the fact that no data are available for eventual recycling plants dedicated solely to one of these technologies.
At this moment there is no valuable, large-scale recycling process available for Li-ion batteries. Equivalent energy consumption is thus assumed for the Li-ion batteries.

## 2.4. Electricity production

The electricity production mix used in this study (European Mix) is a proportional mix of the different electricity production methods of the actual EU-25 member states in the year 2002 [23]. This choice has been made to remain objective, as the different electricity production methods have got varying impacts on the environment. As a consequence, the choice of one specific electricity production method or one specific country mix would potentially influence the results of the study, and should thus be avoided. Consequently, the results of this study can be seen as a European average.

**Table 11: Contribution of the different energy sources to the global energy production.**

| | Gross electricity generation (EU-25) |
|---|---|
| | (in %) |
| Hydro (+geothermal) power plants | 11.06 |
| Nuclear power plants | 31.90 |
| Wind turbines | 1.18 |
| Coal-fired power plants | 21.62 |
| Lignite-fired power plants | 9.76 |
| Oil-fired power plants | 6.50 |
| Natural gas fired power plants | 17.98 |
| Total | 100 |

## 2.5. Transport

Regarding the transportation phases, the SUBAT questionnaires included a question to assess the different distances (from and to the factories) to be covered for transportation of raw materials, new batteries, used batteries, etc. However, these distances are not always relevant when comparing the real impact of one battery technology to another, should these technologies have the same degree of development (as the different technologies would be equally widespread). The distances to be covered would be approximately the same when considering the distance from the manufacturer to the final user for example.

The only differences which should be taken into account when considering the transportation phases are the distances from the extraction point of the ore to the manufacturing unit and the load factor of the trucks (or other transportation modes) when transporting the different types of batteries/components.

Additionally, the analysis showed that the transportation phase only played a minor role in the total environmental impact of each individual battery technology and did not differ in any significant way between the different technologies. As a consequence the transportation of intermediate products, complete batteries and used batteries has not been taken into account in this study. A similar approach has been chosen in most of the available studies in the literature.

## 2.6. Results reliability

To perform a reliable study, the relevant process parameters (emissions, used resources, energy consumption…) have to be imported for all the different substances (raw materials etc.) and energy sources. Most of the time, these parameters are not known very well. These data can be found in the commercially available databases or can be estimated if there is no appropriate database available. The reliability of the data can thus vary and influence the results. The level of reliability for all the used components is given in the next table. The used databases or estimations for each specific process can be found in appendix 2 of this report.

**Table 12: Data reliability (the value between brackets represents the proportion of the global battery mass).**

| | No data | Estimated data | Weak data | Relatively accurate data |
|---|---|---|---|---|
| Pb-Acid | | Antimony (0.71%)<br>Arsenic (0.03%) | | Copper (0.01%)<br>Lead (60.97%)<br>Oxygen (2.26%)<br>Sulphuric acid (10.33%)<br>Water (16.93%)<br>Glass (0.20%)<br>Polyethylene (1.83%)<br>Polypropylene (6.73%) |
| NiMH | | Rare earths (10.07%) | Nickel hydroxide (21.48%)<br>Potassium hydroxide (3.35%) | Nickel (20.59%)<br>Cobalt (4.85%)<br>Sodium Hydroxide (0.88%)<br>Water (11.67%)<br>Polyethylene (4.53%)<br>Polypropylene (13.39%)<br>Copper (1.20%)<br>Steel (7.99%) |
| NiCd | | Lithium hydroxide (0.63%) | Nickel hydroxide (15.45%)<br>Cadmium hydroxide (20.73%)<br>Cobalt hydroxide (1.43%)<br>Potassium hydroxide (4.90%) | Nickel (13.23%)<br>Sodium Hydroxide (0.35%)<br>Water (16.47%)<br>Polyethylene (4.47%)<br>Polypropylene (7.57%)<br>Steel (14.77%) |
| NaNiCl | | Sodium aluminium chloride (14.26%) | | Nickel (17.62%)<br>Sodium chloride (11.58%)<br>Coppper (3.52%)<br>Iron (16.45%)<br>Beta-alumina (16.45%)<br>Stainless (9.79%)<br>Steel (4.08%)<br>Silicates (4.08%)<br>Polypropylene (2.17%) |
| Li-ion | Ethylene Carbonate (6.30%)<br>Dimethyl carbonate (3.15%)<br>Lithium hexafluorophosphate (3.15%)<br>Propylene Carbonate (3.15%) | Lithium metal oxide (23.63%) | Polyvinylidene fluoride (1.19%) | Carbon (14.96%)<br>Styrene Butadiene rubber (1.19%)<br>Polypropylene (21.23%)<br>Aluminium (12.60%)<br>Copper (9.45%) |

# 3. Common analyses to BEV and HEV batteries

## 3.1. Impact of the different battery technologies

The same composition (in proportional weights), production and assembly process as well as recycling process, have been assumed for BEV and HEV batteries. This makes it possible to describe their impact per kg of battery to the impact and damage categories first, while the global environmental score can be described consequently. Accordingly, the proportional contributions of the different damage categories are the same for the overall environmental scores shown further in this report. This chapter gives an overview of the common environmental characteristics of the BEV and HEV battery technologies. Chapters 4 and 5 specifically discuss the environmental implications of BEV and HEV respectively, while chapter 6 assesses the reliability of the results.

### 3.1.1. Assembly battery

#### 3.1.1.1. Assembly and the total score for the different technologies

The Eco-indicator 99 score per kg battery can be found in Table 13. When multiplying these scores with the total amount of batteries required for the F.U., the overall environmental score is obtained. The impact of the production of the materials is included in these calculations.

**Table 13: Impact of the assembly (/kg) of the different technologies**

| | Impact per kg battery |
|---|---|
| Lead-acid | 0.53 |
| Nickel-cadmium | 1.53 |
| Nickel-metal hydride | 1.92 |
| Lithium-ion | 1.31 |
| Sodium-nickel chloride | 1.27 |

**To check the reliability of these results, a sensitivity analysis is performed as described in chapter 6 of this report.**

The contributions of the different impact categories of Eco-indicator 99 are presented in Figure 5.

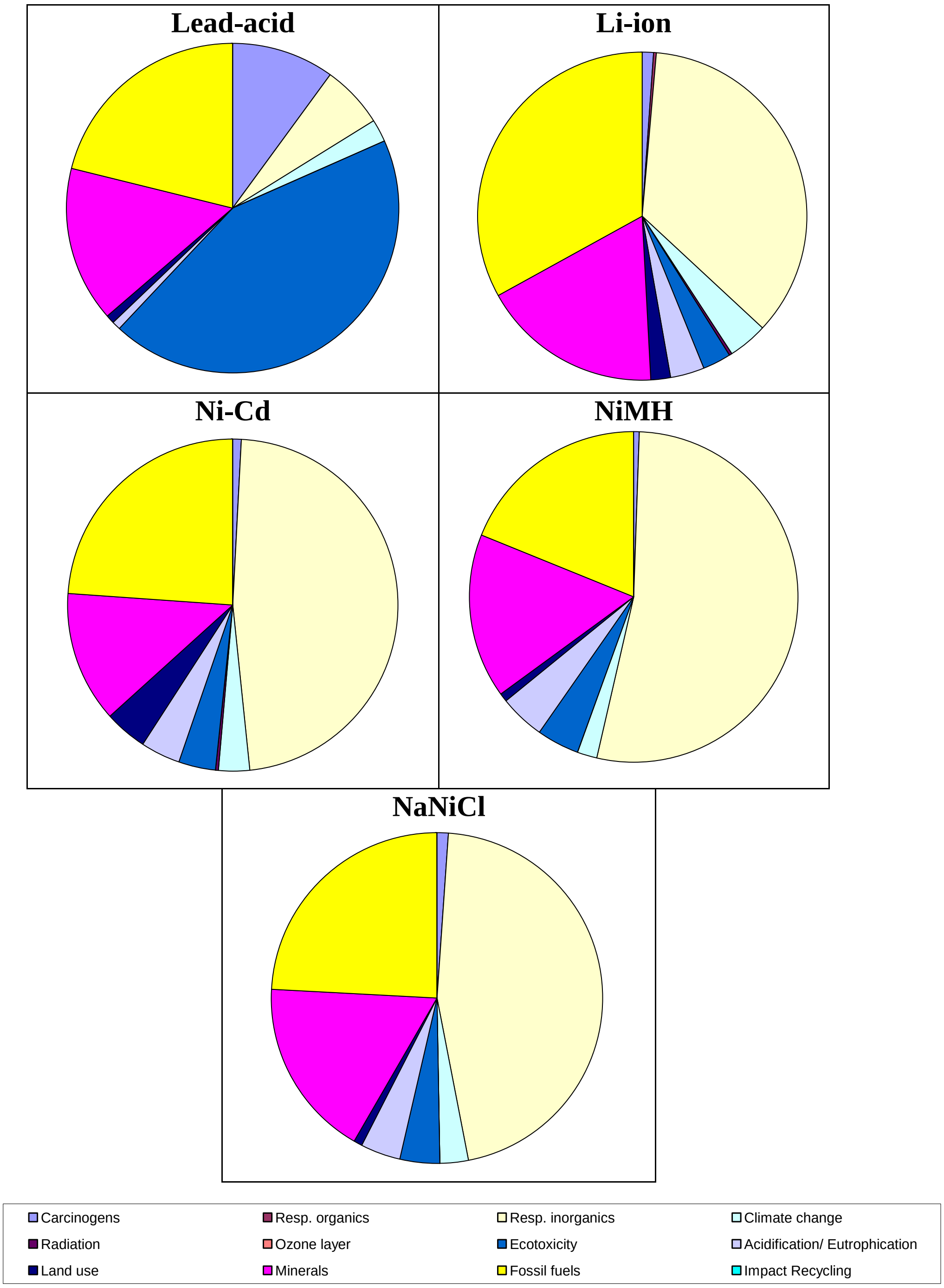


**Figure 5: Relative contribution of the different impact categories to the total score (assembly) for the different batteries.**

The graphs show that four impact categories (respiratory inorganic, minerals, fossil fuels and ecotoxicity) determine at least 80% of the total impact of all the different technologies. The impact of ecotoxicity in lead-acid batteries is responsible for 40% of the total lead-acid battery production and assembly impact.

The contribution to the three damage categories of Eco-indicator can be found in Figure 6. This figure shows the contribution of the different damage categories to the total score.

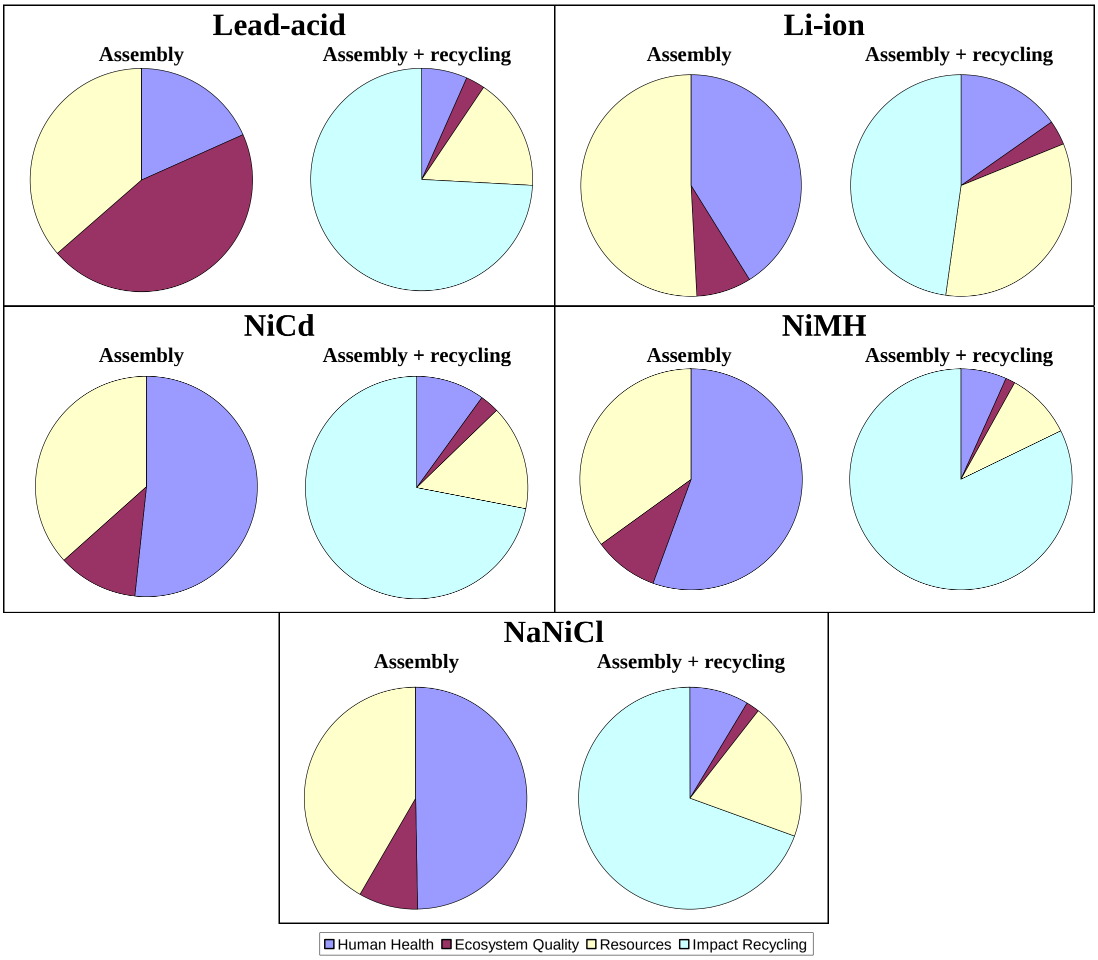


**Figure 6: Contribution of the different damage categories to the total score (left figure = assembly, right figure = assembly +recycling).**

### 3.1.1.2. Assembly scores per component for the different technologies

A battery is composed of several components (electrodes, electrolyte, separator, case and other parts). In this chapter, the contribution of the different subcomponents of the battery will be discussed. The contribution of the different components to the total impact is composition of these components is also given in Table 14 (in % of the total impact) for each battery type. The weight-related given to be able to analyse the relative impacts of the components compared to their respective masses. It's noticeable that an important part of the environmental impact is imputable to the electrodes.

The presented eco-indicator scores include the part of the life cycle from the raw materials to the ready-to-use battery components. The indicated impact due to the energy consumption (European Mix) is the energy needed in the manufacture to process the materials to the battery components.

**Table 14: Contribution of the components of the different technologies to their respective global impact and mass.**

| | | Electrode | Electrolyte | Separator | Energy | Total Assembly |
|---|---|---|---|---|---|---|
| Pb-acid | % of battery impact | 76.45 | 0.45 | 1.51 | 14.32 | 100 |
| | m% | 63.98 | 27.26 | 2.03 | | |
| NiCd | % of battery impact | 86.43 | 0.19 | 1.66 | 8.62 | 100 |
| | m% | 50.84 | 22.34 | 4.47 | | |
| NiMH | % of battery impact | 90.04 | 0.09 | 0.76 | 3.44 | 100 |
| | m% | 56.99 | 15.90 | 2.57 | | |
| Li-ion | % of battery impact | 47.59 | 0.00 | 0.00 | 22.00 | 100 |
| | m% | 40.97 | 15.75 | | | |
| NiNaCl | % of battery impact | 73.95 | 6.39 | | 10.81 | 100 |
| | m% | 49.17 | 30.70 | | | |

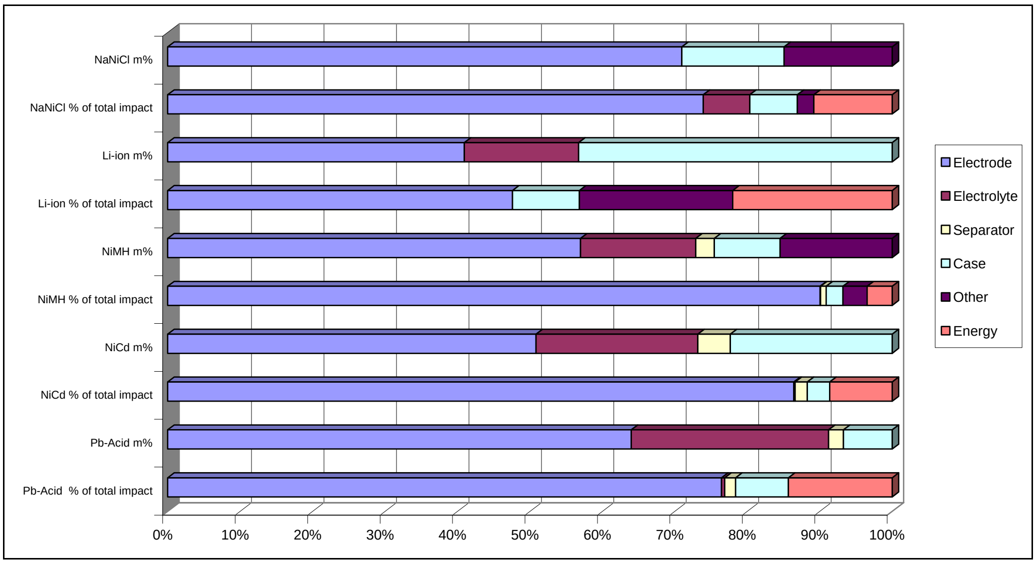


**Figure 7: Contribution of the components of the different technologies to their respective global impact and mass**

The impact of the electrodes is clearly a dominant element to the global impact (up to 90%) of the assembly phase. This can be explained by the important mass of this component of the battery and by the toxic properties of the used materials (metals) compared to the other components (electrolyte, separator and cases). It's noticeable that the impact of the electrolyte of the lithium-ion battery is zero as no data have been obtained for this technology. This is due to the fact that this technology is pretty recent and that the electrolytes are so specific that virtually no environmental data are available for these elements.

### 3.1.2. Assembly + Recycling

The global environmental impact of the assembly *and* recycling for 1 kg of the different battery technologies is illustrated in the next figure.

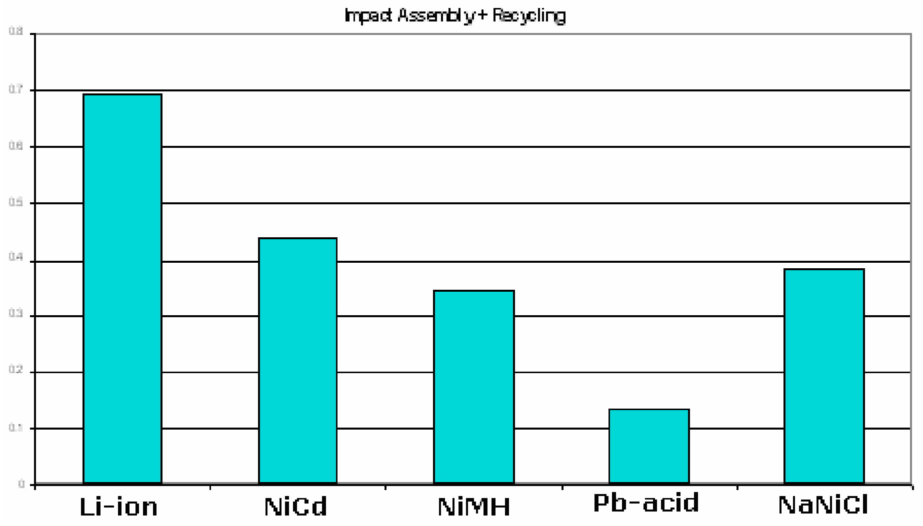


**Figure 8: Graphical overview of the environmental scores for the assembly of 1 kg of the different batteries.**

The next figure shows the impact of the assembly and recycling stages on the different damage categories. It's noticeable that the recycling phase allows compensating the environmental impacts of the production phase to a great extent (Figure 6).

As can be seen in Figure 6, Regarding 4 out of 5 of the battery technologies (lead-acid, nickel-cadmium, nickel-metal hydride, sodium-nickel chloride), at least 70% of the impact of the assembly phase is compensated during the recycling phase. Table 15 summarizes the proportions of the impacts that can be compensated by the recycling process. The important differences observed between the different technologies can be explained by the varying metal contents of the different battery technologies. This is due to the fact that metals can be recycled more easily than many other components. For instance, when an important part of the impact is due to energy consumption, this contribution to the impact cannot be recovered during the recycling.

**Table 15: Proportions of the impact of the assembly compensated by the recycling process.**

| | % of impact compensated by the recycling process |
|---|---|
| Lead-acid | 74.1% |
| Nickel-cadmium | 72.0% |
| Nickel-metal hydride | 82.3% |
| Lithium-ion | 52.2% |
| Sodium-nickel chloride | 69.6% |

Table 16 presents the reduction of the different damage categories obtained recycling (in % of the environmental impact of the assembly).

**Table 16. Proportions of impact of the assembly (in the different damage categories) compensated by the recycling process.**

| | Human Health | Ecosystem quality | Resources |
|---|---|---|---|
| Lead-acid | -63.2% | -94.4% | -54.5% |
| Nickel-cadmium | -80.6% | -77.7% | -58.4% |
| Nickel-metal hydride | -88.4% | -84.1% | -72.1% |
| Lithium-ion | -63.4% | -53.5% | -34.3% |
| Sodium-nickel chloride | -82.6% | -77.5% | -51.8% |

Table 16 shows that an important part of the damage to human health and to the ecosystems can be annihilated thanks to recycling processes. On the other hand, the damage to resources seems to be undone in a less important way. This can be explained by the fact that fossil energy sources are included in the depletion of resources. Of course, the energy put into the process of producing metals cannot be recovered and additionally the recycling processes consume a certain amount of energy too. Both last raisons explain the lower proportions of the compensations of resource depletion thanks to recycling compared to the other damage categories. The depletion of minerals and metals on the other hand is diminished drastically thanks to recycling.

# 4. Battery Electric Vehicles (BEV)

The composition, assembly and recycling of the different batteries have already been described in the previous paragraphs. The relevant technical data of the different BEV batteries and the choice of a suitable functional unit will be described in this chapter.

## 4.1. Technical characteristics

The technical parameters (specific energy, number of cycles, energy efficiency) of the different technologies are shown in the next table. These data have been obtained through contacts with the battery industry and through literature research (see WP1 report). The technical performances play an important role in the environmental impact of the batteries as these parameters determine the required quantities of batteries for each technology as well as the number of times the batteries should be replaced during the vehicles lifetime.

**Table 17: Technical characteristics of the different battery technologies (see report of WP 1).**

| | $E_{specific}$ (Wh/kg) | Number of cycles | Energy efficiency | Losses due to heating |
|---|---|---|---|---|
| Pb-Ac | 40 | 500 | 82.5% | |
| NiMH | 70 | 1350 | 70.0% | |
| NiCd | 60 | 1350 | 72.5% | |
| Li-ion | 125 | 1000 | 90.0% | |
| NaNiCl | 125 | 1000 | 92.5% | 7.2% |

The environmental impact of the maintenance has been assumed to be negligible. The depth of discharge (DOD) of the battery is said to reach 80% each cycle (DOD = 80% = deep cycling). The self-discharge of the batteries is neglected for all the technologies.

The NaNiCl battery is the only warm battery amongst the assessed technologies. As a consequence extra energy is needed to keep the battery at an appropriate temperature. We calculated the additional energy consumption needed for the heating of the battery to be 7.2% of the capacity[1].

---

[1] If we use the battery 250 times a year, the batteries will not be used during the remaining 115 days. When the car is not used, 85 W per hour are needed for the heating of the battery. This corresponds to an annual consumption of 234,6 kWh. To drive 250 cycles of 60 km, we needed 3000kWh (15000km at 200 Wh/km). So the extra consumption for heating the battery is 7.8%, which implies the energy consumption rises to 107.8% of the net energy needed to move the car. As a consequence, the losses due to the heating of the battery amount to 7.2% (1-100/107.2).

## 4.2. Reference car

Our model is based on a small car like the Peugeot 106. The net weight of the car, including the driver's weight (75kg), is 888 kg. Basically, this kind of car is equipped with a 250kg, 12 kWh, NiCd battery (47 Wh/kg)[19].

## 4.3. Energy consumption to drive

The energy consumptions to drive are calculated for the ECE cycle [20]. As the battery masses will be depending on the applied battery technology, this implies different energy consumptions for each battery technology. These different energy consumptions can be simulated and calculated by the Vehicle Simulation Program (VSP) developed at the Vrije Universiteit Brussel [21]. These simulations lead to the following equations, which allow us to determine the specific energy consumption for each battery technology:

$$E = mass\ .\ 0.0541 + 132.93 \qquad \textbf{(1)}$$

E (in $\frac{Wh}{kg}$)

Mass (in kg)

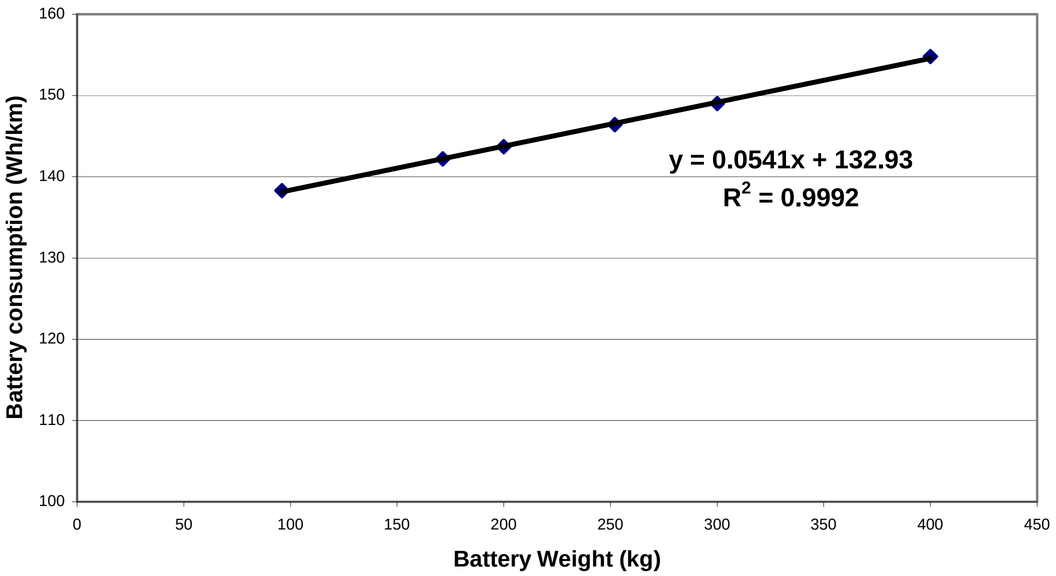


**Figure 9: Energy consumptions versus battery mass.**

When considering the use of the batteries in the vehicle, this phase can be subdivided in 3 parts. First of all, the use phase was studied for an ideal battery (mass = 0 kg, energy efficiency of the battery = 100%). In other words, this is the energy used to move the car (excluding the battery). In a second step, the influences of the varying masses and energy efficiencies of the different battery technologies have been taken into account. This allowed taking the influence of these battery characteristics on the electricity consumption

## 4.4. Functional unit

The functional unit is the central hub of any life cycle assessment, since it provides the reference to which all other data in the assessment are normalised. Basically, a functional unit (F.U.) is the basis on which different products are to be compared. The existence of the functional unit is requested because of the need to compare products in an appropriate and objective way.

### 4.4.1. Different possibilities

The F.U. has to be chosen in a way that the different batteries can be compared in an objective way: amongst others, the lifetime range of the car has to be identical for all the technologies. Different technical parameters play an important role when defining the F.U., for example: the number of cycles, the range, the energy content of the battery, the specific energy, etc.

There are different possibilities to define an F.U., but not all of them are appropriate. An overview of different potential F.U. can be found in Table 18.

**Table 18: Different possible F.U.**

| |
|---|
| F.U. constant energy content of battery + constant lifetime range of vehicle |
| F.U. constant battery mass + constant lifetime range of vehicle |
| F.U. constant range of the vehicle (+ constant lifetime range of the vehicle) |

These three F.U. will be described and discussed in the next paragraphs.

### 4.4.2. F.U. Constant energy content and constant lifetime range of the vehicle

*Advantages and disadvantages of the choice of this F.U..*

☺ The same global energy content

😐 The useful energy output can differ from technology to another (because of the battery efficiencies)

☹ Ranges differ from one technology to another (because of the different battery masses and battery efficiencies)

☹ Energy consumption differs from one technology to another (because of the different masses of the batteries)

- ☹ The number of cycles required to cover the total distance differs from one technology to another (because of the varying energy consumptions)

This functional unit corresponds to an equal energy content of the different batteries. The output energy however, can be different for each technology (cf. different energy efficiencies of the different batteries).

A 12kWh energy content and a life time distance of 160000 (159292km to be exact) to be covered by the car have been taken as a reference for the F.U.. 160000km is the covered distance during the lifetime of the vehicle when using lead-acid batteries (200 cycles a year, during 15 years). The number of cycles required for the other technologies is calculated by using the following equation.

$$\text{Required number of cycles} = \frac{\text{Distance to cover during lifetime}}{\text{Range per cycle}} \qquad \textbf{(2)}$$

The range per cycle is calculated by using next equation:

$$\text{Range} = \frac{\eta_{\text{battery}} \text{ x DOD x } E_{\text{battery}}}{\text{EC}} \qquad \textbf{(3)}$$

Where $\eta_{\text{battery}}$ stands for the efficiency of the battery, DOD for the depth-of-discharge, $E_{\text{battery}}$ for the energy content of the battery and EC for the energy consumption per km. The energy consumption for 1 km is mass dependent and can be calculated using equation (1). The required battery mass to obtain a 12kWh battery can be found using next equation:

$$\text{Mass of the battery} = \frac{\text{Required energy content}}{\text{Energy density}} \qquad \textbf{(4)}$$

The number of batteries needed to cover the total distance can easily be calculated by next formula:

$$\text{Required number of batteries} = \frac{\text{Required number of cycles to cover total distance}}{\text{Number of cycles delivered by battery during lifetime}} \quad \textbf{(5)}$$

The required number of batteries will always be an integer in daily life (as when the battery is out of order, but the vehicle is nearly at its end-of-life, the battery will not be replaced anymore). However, it was chosen to perform the study using the obtained real numbers of needed batteries in our calculations. This allows obtaining results that are not dependent of the arbitrary choice of a lifetime car range (Table 19).

Characteristics of the F.U. assuming constant energy content and a constant lifetime range can be found in Table 19.

**Table 19: F.U. constant energy characteristics.**

| | Mass (kg) | $E_{density}$ (Wh/kg) | Number of cycles per battery | Energy content of battery pack (kWh) | Range per cycle (km) | Number of cycles (life time) | Number of batteries | Lifetime range (km) |
|---|---|---|---|---|---|---|---|---|
| Pb-Ac | 300 | 40 | 500 | 12 | 53 | 3000 | 6.00 | 159292 |
| NiMH | 171 | 70 | 1350 | 12 | 47 | 3371 | 2.50 | 159292 |
| NiCd | 200 | 60 | 1350 | 12 | 48 | 3290 | 2.44 | 159292 |
| Li-ion | 96 | 125 | 1000 | 12 | 63 | 2547 | 2.55 | 159292 |
| NaNiCl | 96 | 125 | 1000 | 12 | 60 | 2670 | 2.67 | 159292 |

### 4.4.3. F.U. Constant battery mass

*Advantages and disadvantages of the choice of this F.U..*

- ☺ The energy consumption of the vehicles is the same for the different battery technologies
- ☺ The most appropriate battery mass can be selected as a function of the size and the energy consumption of the vehicle
- ☹ Ranges differ from one technology to another
- ☹ The energy contents of the batteries differ from one technology to another
- ☹ The number of cycles required to cover the total distance differs from one technology to another

When using the second functional unit, the different batteries are assumed to have the same mass. The reference mass is set to 300 kg and a lifetime distance of 160000 km (159292 km to be precise) has been put forward. The choice of the lifetime distance, as well as the calculations related to the different parameters is similar to the ones explained in the previous paragraph.

**Table 20: F.U. Constant mass characteristics.**

| | Mass (kg) | Energy content of battery pack (kWh) | Range per cycle (km) | Number of cycles (life time) | Number of batteries | Lifetime range (km) |
|---|---|---|---|---|---|---|
| Pb-Ac | 300 | 12.0 | 53 | 3000 | 6.00 | 159292 |
| NiMH | 300 | 21.0 | 79 | 2020 | 1.50 | 159292 |
| NiCd | 300 | 18.0 | 70 | 2276 | 1.69 | 159292 |
| Li-ion | 300 | 37.5 | 181 | 880 | 0.88 | 159292 |
| NaNiCl | 300 | 37.5 | 173 | 923 | 0.92 | 159292 |

### 4.4.4. F.U. Constant range and constant lifetime distance covered by the vehicle

*Advantages and disadvantages of the choice of this F.U..*

- ☺ The vehicle is able to cover the same distance independently of the technology. As a consequence, the same number of cycles is needed to cover the lifetime distance of the vehicle.
- ☺ The payload delivered by every battery technology is exactly the same (the driver gets exactly the same “service” out of each battery technology)
- ☹ The masses and energy contents differ from one battery technology to another.
- ☹ The assumptions are conceptually more complicated, compared to the other F.U.

When using the third functional unit, the battery enables the vehicle to cover a determined range, with one charge. The one-charge range was chosen to be 60 km.

The mass of the battery can be calculated using next equation:

$$\mathrm{Range} = \frac{E_{\mathrm{content}}}{E_{\mathrm{consumption}}} = \frac{\%_{\mathrm{DOD}}.E_{\mathrm{specific}}.m_{\mathrm{battery}}.\eta_{\mathrm{battery}}}{m_{\mathrm{battery}}.0.0541+132.93} \qquad \textbf{(6)}$$

Where $E_{specific}$ stands for the specific energy of the battery,
$m_{battery}$ stands for the mass of the battery,
and $\eta_{battery}$ stands for the energy efficiency of the battery.

Besides this parameter, it was decided that the environmental impacts were going to be compared for a lifetime distance covered by the vehicle of 180000 km, corresponding to 3000 charge-discharge cycles. Depending on the technology, the required number of batteries needed for the functional unit was determined.

**Table 21: F.U. constant range characteristics.**

| | Mass (kg) | Energy content of battery pack (kWh) | Range per cycle (km) | Number of cycles | Number of batteries | Lifetime range (km) |
|---|---|---|---|---|---|---|
| Pb-Ac | 344 | 13.78 | 60 | 3000 | 6 | 180000 |
| NiMH | 222 | 15.53 | 60 | 3000 | 2.22 | 180000 |
| NiCd | 253 | 15.16 | 60 | 3000 | 2.22 | 180000 |
| Li-ion | 92 | 11.49 | 60 | 3000 | 3 | 180000 |
| NaNiCl | 97 | 12.07 | 60 | 3000 | 3 | 180000 |

### 4.4.5. Overview

Only three F.U. seemed to be an appropriate choice to compare the different battery technologies. Each of these F.U. (constant energy content, constant mass or constant range, all coupled to a constant life time distance) implies some advantages and disadvantages. The importance allocated to these advantages and disadvantages by the investigator will obviously be determinant when having to decide which F.U. to choose. These advantages and disadvantages are summarized in the next table.

**Table 22: Advantages and disadvantages of the different F.U. with constant life time range of the car.**

| F.U. | Advantages | Disadvantages |
|---|---|---|
| Constant mass | - The energy consumption of the vehicles is the same for the different battery technologies<br>- The most appropriate battery mass can be selected as a function of the size and the energy consumption of the vehicle | - Due to the different masses of the batteries, the ranges differ from one technology to another<br>- The energy contents of the batteries differ from one technology to another<br>- The number of cycles required to cover the total distance differs from one technology to another |
| Constant energy content | - The same global energy content | - Ranges differ from one technology to another<br>- Energy consumption differs from one technology to another (different mass)<br>- The number of cycles required to cover the total distance differs from one technology to another |
| Constant range | - The vehicle is able to cover the same distance independently of the technology. As a consequence, the same number of cycles is needed to cover the lifetime distance of the vehicle. | - The masses and energy contents differ from one battery technology to another.<br>- The assumptions are conceptually more complicated, compared to the other F.U.<br>- The same payload is delivered |

The total environmental impact calculated using each of these three F.U. is shown in next graph for all the technologies. The contribution of each of the different stages of the life cycle of the battery (assembly + recycling, use due to the battery mass and use due to energy efficiency of the battery) is shown in next figure.

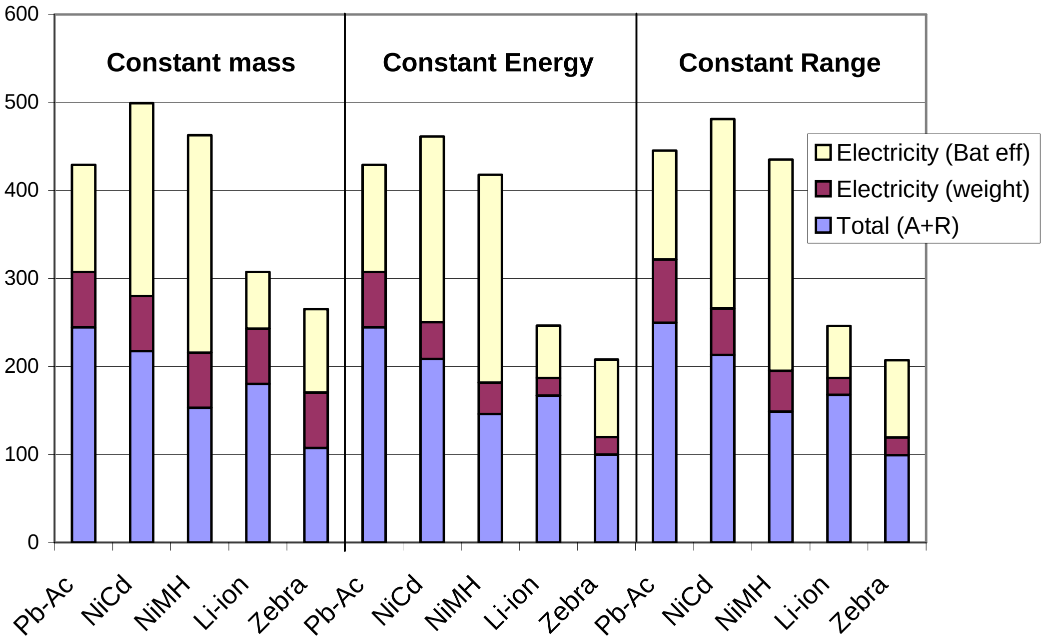


**Figure 10: Environmental impact of the assessed technologies for the different F.U..**

This figure clearly shows that similar results are obtained for the three different F.U. and that the choice amongst these F.U. has got no significant impact on the result[2]. The F.U. assuming a constant range seems to be the most appropriate, as it compares the batteries on the basis of the same delivered performances (all the vehicles can deliver exactly the same payload). As a consequence, the discussion concerning the environmental impacts will be almost exclusively restricted to this F.U. all along the remainder of this chapter.

## 4.5. Results for BEV batteries

### 4.5.1. Impact of the different stages

The impacts due to the different stages of the life cycle are shown in Table 23 and Figure 12 considering the constant range F.U..

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[2] Please note that these results were obtained without environmental data concerning the electrolyte of the li-ion technology and with (optimistic) estimations concerning the energy consumption to produce the sodium-nickel chloride batteries. As a consequence, the environmental rating of these technologies could be worse than the score obtained in this study.

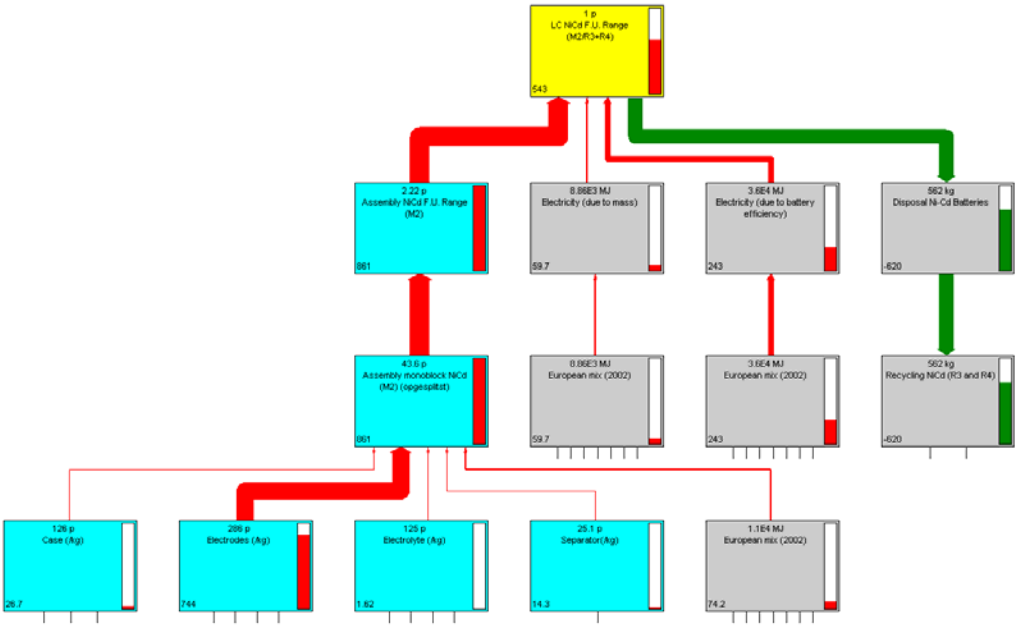

**Figure 11. An illustration of a typical basic process tree in SimaPro®.**

**Table 23: Environmental scores (eco-indicator points) of the life stages of the assessed battery technologies.**

| | Production | Use (weight) | Use (battery efficiency) | Recycling |
|---|---|---|---|---|
| Lead-acid | 1091 | 81.4 | 140 | -809 |
| Nickel-cadmium | 861 | 59.7 | 243 | -620 |
| Nickel-metal hydride | 945 | 52.4 | 271 | -777 |
| Lithium-ion | 361 | 21.7 | 66.9 | -172 |
| Sodium-nickel chloride | 368 | 22.8 | 99.5 | -256 |

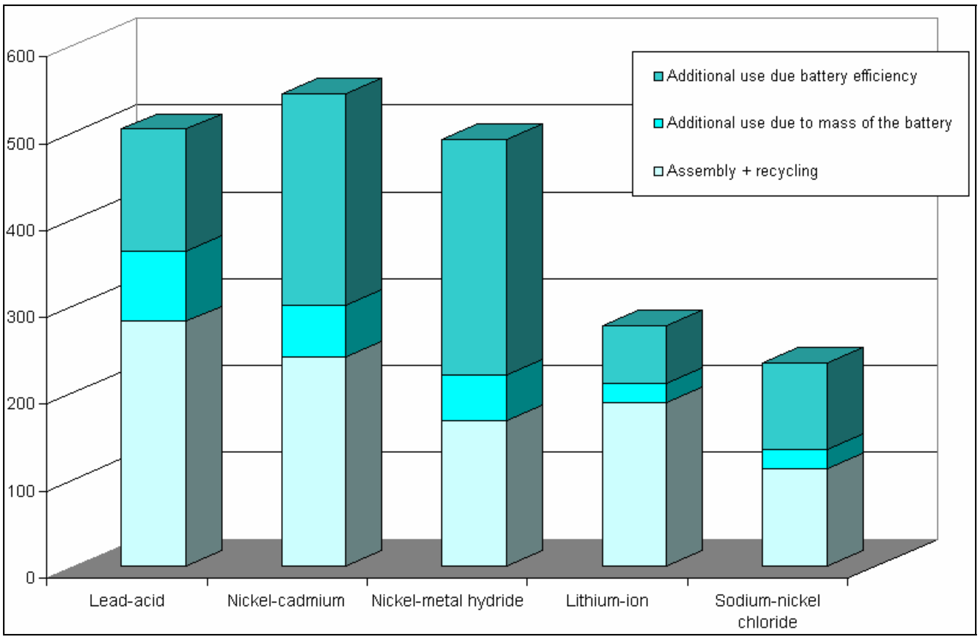

**Figure 12: Environmental impact of the assessed technologies, including the losses due to the battery during the use of the battery.**

When considering the life cycle of the batteries, it appeared that the energy losses in the battery have a very significant impact on the environment. However, this impact is strongly dependent on the way electricity is produced. In the present calculations the European electricity production mix has been used, but the impact would be strongly decreased if renewable energy sources were used more intensively. It can be concluded that the use of the European electricity production mix is a pessimistic scenario. In the future, the electricity production will most probably imply less emissions and thus a lesser impact on the environment. However, these issues should be assessed by a specific electricity production policy and cannot be handled through battery specific policies only.

When looking at the environmental impact of the battery, it appears that the lead-acid battery has got the highest impact, followed by nickel-cadmium, lithium-ion, nickel-metal hydride and sodium-nickel chloride[3].

When including the effects of the losses due to the battery (battery efficiency and battery mass), three battery technologies appear to have a somewhat higher environmental impact compared to the other two. The inclusion of the battery efficiencies results in a higher environmental impact for nickel-cadmium and nickel-metal hydride batteries and a lower one for lithium-ion batteries comparatively to the others.

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[3] Please note that these results were obtained without environmental data concerning the electrolyte of the li-ion technology and with (optimistic) estimations concerning the energy consumption to produce the sodium-nickel chloride batteries. As a consequence, the environmental rating of these technologies could be worse than the score obtained in this study.

# 5. Hybrid Electric Vehicles (HEV)

The composition of the different batteries, as well as their assembly and recycling have already been described in paragraph 2. The technical data of the different HEV batteries and the choice of a suitable functional unit will be described in this chapter.

Hybrid vehicles are defined as vehicles having either at least two different on-board energy sources or at least two different drivelines. They allow to integrate both electric and combustion drive technology, combining the benefits of both. Several configurations of hybrid drivetrains can be designed.

The "series hybrid" vehicle represents a hybridisation of energy sources. The wheels of the series hybrid vehicle are driven exclusively by one or more electric motors, which are fed by either an on-board electricity storage (battery) or an on-board electricity generator (combustion engine or fuel cell). Series hybrid drives are particularly suited for heavy-duty vehicles.

The "parallel hybrid" vehicle represents a hybridisation of drivelines, with both the electric motor and the combustion engine mechanically coupled to the wheels. The vehicle can be operated in thermal, electric or hybrid mode. Parallel hybrids are suited for applications where both zero-emission urban driving and long-distance highway driving are desired.

The "combined hybrid" vehicle integrates features of both series and parallel hybrid structures. A typical example is the Toyota Prius passenger car.

In this work package, the studied battery corresponds to the battery used in the Toyota Prius (combined hybrid).

## 5.1. Technical characteristics

The main technical characteristics of the different battery technologies are shown in the next table. The role of the battery in an HEV is different from its role in a BEV. In an HEV the ICE (Internal Combustion Engine) delivers the energy, while the battery delivers sudden power boosts. As a consequence, the power plays a more important role when analyzing HEV batteries. The data were obtained through questionnaires and by intensively studying of the available literature.

**Table 24: Technical characteristics of the different HEV battery technologies.**

| | Power (W/kg) | Relative number of cycles |
|---|---|---|
| Pb-Ac | 350 | 1 |
| NiMH | 1500 | 3 |
| NiCd | 500 | 3 |
| Li-ion | 2000 | 3 |
| NaNiCl | 200 | 3 |

The maximal number of cycles in a battery's lifetime is strongly dependent on the way the battery is used and on the type of cycles we assess (which DOD is assessed). Therefore, and as the main aim of work package 2 is to *compare* the environmental burden of the batteries, the numbers of cycles are given as a relative number. This method has no impact on the ranking and on the relative environmental burdens of the batteries.

## 5.2. Reference car

As a reference, the required battery power is similar to the power of the Toyota Prius (21kW), which is the best-sold HEV in the world up to now [22].

## 5.3. Functional unit

### 5.3.1. Definition of F.U.

As the application of a battery in a battery electric vehicle is completely different from the function of a battery in a hybrid electric vehicle, another F.U. has to be defined. The definition of an appropriate F.U. seems to be slightly more complex in the case of HEV batteries. The HEV technology is more intricate and several different hybrid structures are possible.

The choice of a simplified model, determining the installed power of the battery pack and the relative number of cycles for each battery technology, makes it possible to overcome this problem. Batteries characterized by a similar power will thus be considered.

The different battery technologies are compared on the basis of the assembly and recycling of the required amount of batteries needed to obtain the specified power.

### 5.3.2. Characteristics of the F.U.

The different battery technologies will be compared for hybrid vehicles on an equal power basis of the battery (21 kW). The quantity of batteries required to obtain this power basis, is obtained by dividing the desired power by the specific power. Assuming an HEV will require one battery during its lifetime[4], the environmental impact of one NiMH battery is calculated. Taking the technical properties of the other battery technologies into account (via an estimation of the number of cycles deliverable by each technology), it's assumed the same number of batteries is needed for the other technologies, except for the Pb-acid, which will provide three times less cycles.

---

[4] Toyota provides an 8-year-warranty on its Prius batteries.

Table 25: F.U. hybrid characteristics.

| | Mass (kg) of F.U. | Number of batteries |
|---|---|---|
| Pb-Acid | 60 | 3 |
| NiMH | 14 | 1 |
| NiCd | 42 | 1 |
| Li-ion | 10.5 | 1 |
| NaNiCl | 105 | 1 |

An example of the calculations to obtain the results in Table 25, is given for the lead-acid battery. This battery technology has a specific power of 350W/kg. As a consequence, to obtain a 21kW battery, 60kg of battery are needed (21kW : 350 W/kg). Similar calculations were performed to obtain the masses of the other technologies.

It should be noted that some of the calculations are purely theoretical, as the technical properties (mainly low specific power) of some technologies exclude them from being used for HEV applications.

## 5.4.Results for HEV batteries

### 5.4.1. Impacts of the different stages

The different impacts for the different parts of the life cycle are shown in the following table[5].

Table 26: Environmental scores (eco-indicator points) of the life stages of the assessed battery technologies.

| | Production | Recycling | Total |
|---|---|---|---|
| Lead-acid | 95.0 | -70.5 | 24.5 |
| Nickel-cadmium | 64.4 | -46.4 | 18.0 |
| Nickel-metal hydride | 26.8 | -22.1 | 4.8 |
| Lithium-ion | 13.7 | -6.6 | 7.2 |
| Sodium-nickel chloride | 133.0 | -92.6 | 40.8 |

The bars in Figure 13 represent the relative environmental impacts of every battery type, considering the lead-acid as a reference. The overall environmental score of the lead-acid battery has been set to 100. It appears that next to the important mass of the sodium-nickel chloride and lead-acid batteries, these technologies appear to present the worst environmental scores of the quantitatively assessed HEV battery technologies.

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[5] Please note that these results were obtained without environmental data concerning the electrolyte of the li-ion technology and with (optimistic) estimations concerning the energy consumption to produce the sodium-nickel chloride batteries. As a consequence, the environmental rating of these technologies could be worse than the score obtained in this study.

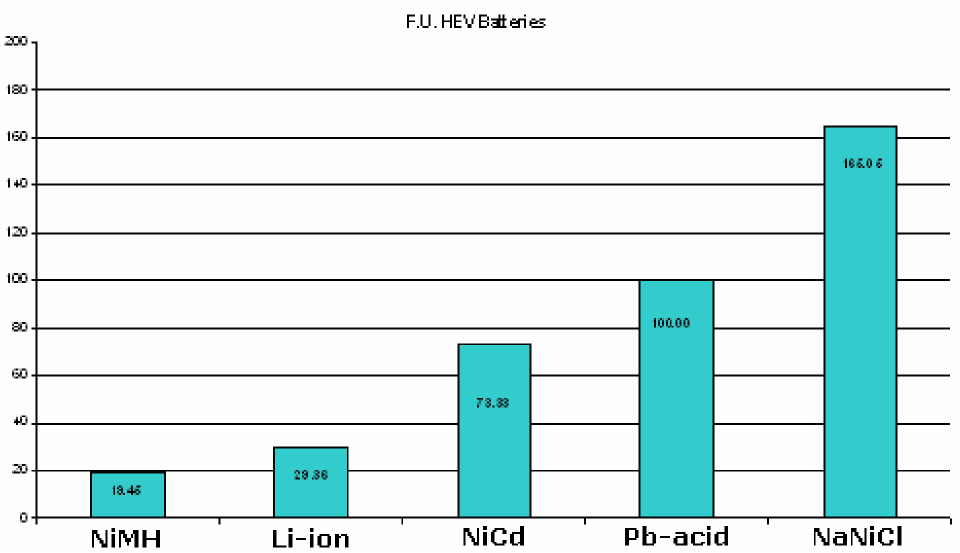

**Figure 13: Graphical overview of the relative environmental scores of the HEV batteries.**

The global results as well as their contributions to the different damage categories are shown in the next figure.

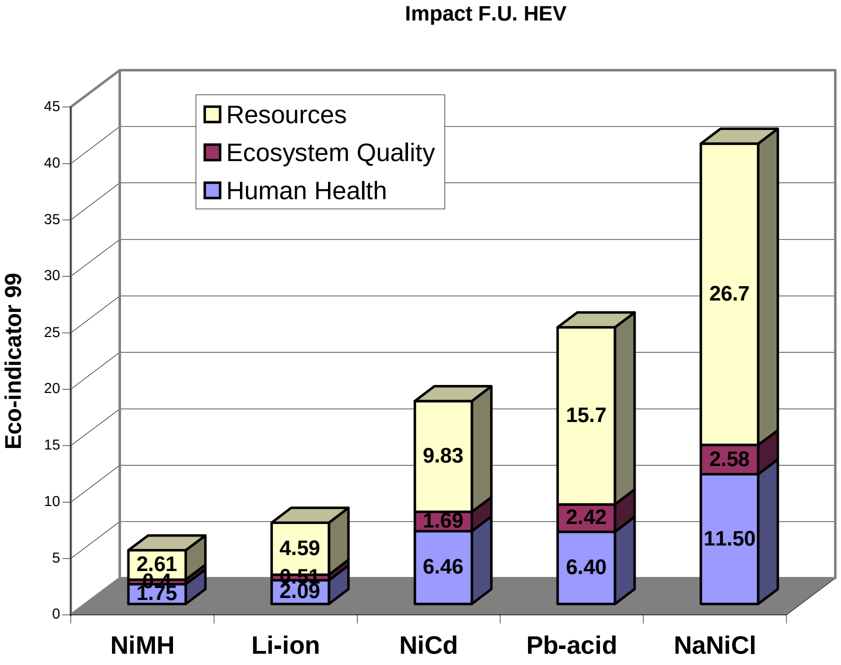

**Figure 14: Environmental impact of the assessed technologies for HEV.**

Table 26 and Figure 14 show the relative impact of the different technologies. The NiMH obtains the best environmental rating, followed by the Li-ion, NiCd, Pb-acid and NaNiCl.

# 6. Discussion

## 6.1. Correctness of the model

We should be aware that the results are influenced by the type of charger, charging curves, the outdoor temperature, the method of electricity production, the assumed driving cycle and conditions, etc. are important parameters.

### 6.1.1. Definition of F.U.

It is important to define a good F.U. Three valid F.U. could be used to compare the different battery technologies for BEV. Small differences occur between these different models, but their relative impact stays almost the same. As far as HEV are concerned, the most appropriate F.U. rapidly appeared to be a battery with a specific amount of power.

### 6.1.2. Reliability of the data

Ideally, to perform an LCA, reliable data are needed for all the components used in a battery and for all the process parameters involved in the manufacturing of these components.

Table 12 shows an overview of the reliability of the used data. Regarding four of the five discussed technologies (Pb-acid, NiMH, NiCd and NaNiCl) data concerning over 80% of the mass of the battery are considered to be accurate. Concerning Lithium-ion batteries, data regarding over 60% of the mass of the different components of the different technologies are accurate. The proportionally lower accuracy for lithium-ion batteries can be explained by the use of very specific chemicals and metal alloys in this technology.

A zero-impact has been allocated to the lithium-ion electrolyte. This is due to the fact that this technology is pretty recent and that the electrolytes are so specific that virtually no environmental data are available for these elements (see used data(bases) in appendix 2). As these synthetic chemicals are quite complex, it is not unrealistic to consider they have a relatively high score per kg compared to the other electrolytes. As a consequence, we can assume that the real environmental score of the Li-ion battery will be slightly worse than the score obtained with these calculations.

No realistic data were obtained from the sodium-nickel chloride battery manufacturer producer. As a consequence, an estimation of the energy consumption has been used to perform this study.

### 6.1.3. Boundary conditions

The system boundaries were defined.

The interaction of the functional unit with nature is assessed considering the following life stages of the battery:

- The **extraction** of raw materials,
- The **processing activities** of the materials and components,
- The **use** of the battery in the vehicle,
- The **recycling** of discarded batteries,
- The **final disposal** or **incineration**

When considering **geography**, the considered area is the western world. Concerning the assessed **time period**, the current state of the technology was considered. The related **other life cycles** (trucks, industrial buildings, electric power plants, roads etc.) have not been considered, since they will not influence the results significantly.
**Self-discharge** of the battery was not included for any of the assessed technologies because of the great dependence of this parameter on the way of using the vehicle. Neither was the **maintenance** of the batteries because of the presumption this impact is relatively small. Regarding **electricity** consumption, the European (EU-25) electricity production mix has been considered [23]. It has been considered that the **recycled materials** have the same quality as the original data. A **collection rate** of 100% was assumed (these data are realistic considering the weight and volume of the BEV and HEV batteries and considering the answers of various stakeholders to our questionnaires) and a recycling rate of 95% was used for the recuperated materials (except for the lead-acid recycling technology, which exists since much longer and which is very mature, where the lead metal recycling rate is 98.3%). It was assumed that the electrolyte is neutralized before disposal (except for the lead-acid technology where 90% is recuperated and 10% is neutralized before disposal).

### 6.1.4. Limitations of the used Impact Assessment method

Each Impact Assessment method implies some advantages and disadvantages. The hierarchist version of Eco-indicator 99 was chosen as impact assessment method for it’s a quite standard and widespread methodology.
It should be noted that, as it is the case for all the other impact assessment methods, not all of the emissions and used resources are included in Eco-indicator. Important is also to know which damage models are included and excluded in the model.

## 6.2 Sensitivity Analysis

LCA studies are based on a lot of assumptions. These assumptions can create important variations on the final results. A sensitivity analysis is used to assess the robustness of the obtained results.

As the results have to be reliable, the assumptions made during the development of the model have been modified and the consequences on the results were analysed.

### 6.2.1. Sensitivity analysis on common parameters

The sensitivity analysis assessed the effects of the assumptions (concerning average battery composition, energy consumption, etc.) and of possible variations in the collected data on the results. Varying the assumed parameters allowed the performing of this analysis. These implemented variations included calculations, using different relative sizes of the components of the battery (10% more weight of one component, compensated by an equivalent decrease of another component). The proportional masses of the electrodes, electrolytes and cases have thus been altered.

Figure 15 gives an overview of the environmental impact of the assembly of the different battery technologies, while Figure 16 summarizes the environmental impacts of the assembly and recycling of the different battery technologies.

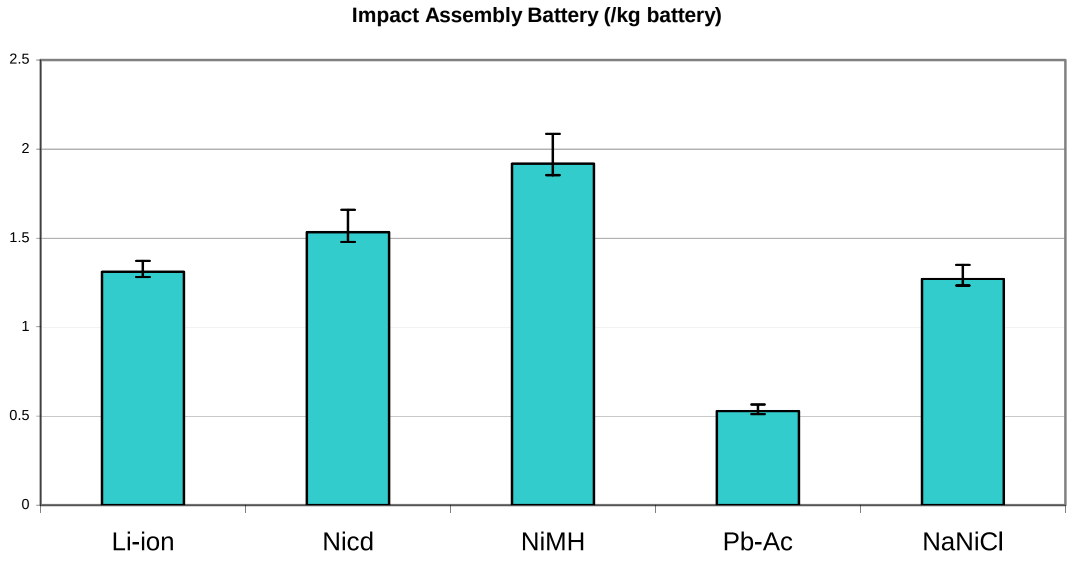

**Figure 15: Graphical overview of the environmental scores for the assembly of 1 kg of the different batteries (including the sensitivity analysis).**

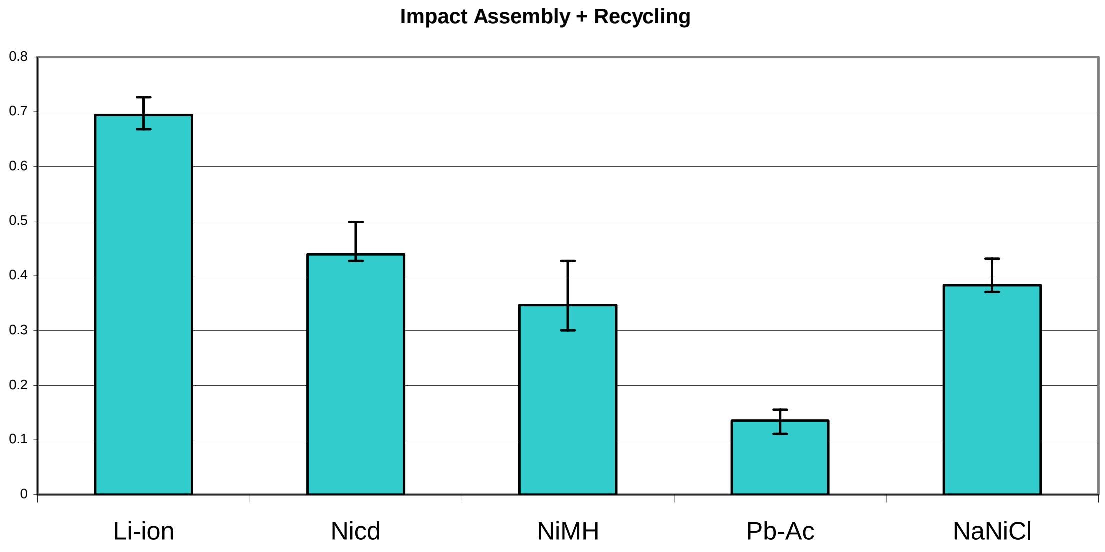

**Figure 16: Graphical overview of the environmental scores for the assembly of 1 kg of the different batteries (including the sensitivity analysis).**

Figure 15 and Figure 16 demonstrates that the assumptions did not have any significant impact on the results in the sense that the conclusions regarding the environmental of 1kg of each battery type remain the same. The error bars represent the intervals containing all the results obtained during the sensitivity analysis.

### 6.2.2. BEV battery

The sensitivity analysis assessed the effects of the assumptions (concerning average battery composition, energy consumption, etc.) and of possible variations in the collected data on the results. Varying the assumed parameters allowed the performing of this analysis. These implemented variations included calculations, using different relative sizes of the components of the battery (10% more weight of one component, compensated by an equivalent decrease of another component). The proportional masses of the electrodes, electrolytes and cases have thus been altered. Also, the recycling rates and recycling efficiencies have been modified as well as the required amounts of energy to produce and recycle the different types of batteries. Finally, other “one-charge ranges” have been assumed (50 or 70 km instead of 60 km).

Some data can not be altered in a sensitivity analysis without implying the assessment of a different F.U.. As a consequence, the number of cycles, specific energy, DOD, energy efficiency and different consumption of the vehicle are not included in the sensitivity analysis.

### 6.2.2.1. Different scenarios sensitivity analysis

Figure **17** demonstrates that the assumptions mentioned in the previous section (except for the different one-charge ranges) did not have any significant impact on the results in the sense that the conclusions remain the same. This demonstrates that the results of this study are reliable and illustrates the robustness of the model.

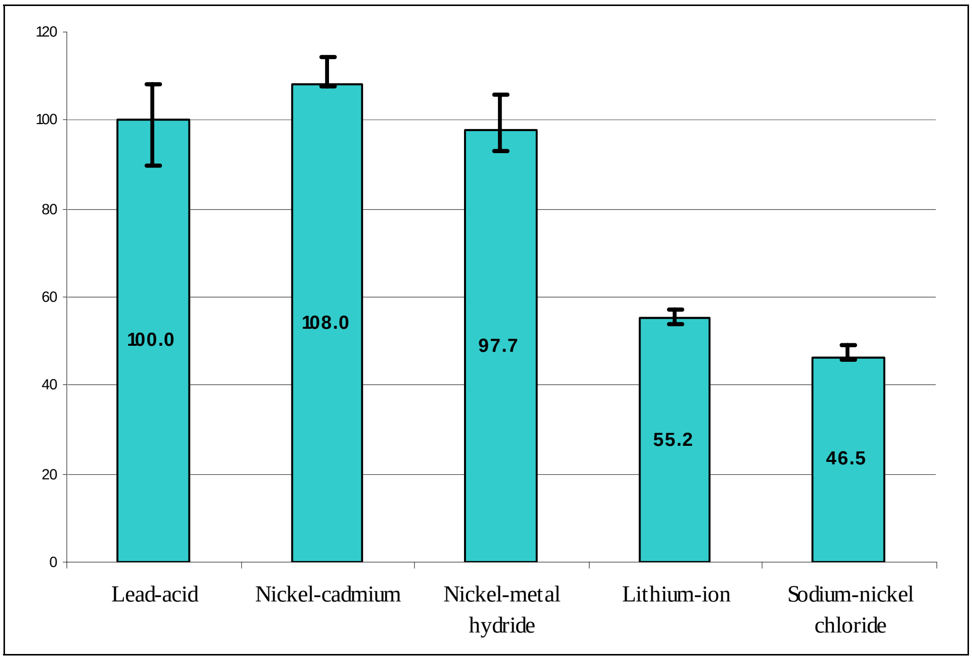

**Figure 17: Graphical overview of the relative environmental scores (including the sensitivity analysis).**

The bars in the figure represent the relative environmental impacts of every battery type, considering the lead-acid technology as a reference. The overall environmental score of the lead-acid battery has been set to 100. The error bars represent the intervals containing all the results obtained during the sensitivity analysis.

Figure **17** summarizes the sensitivity analysis. It should be mentioned that Figure **17** includes the results originating from production, recycling and the energy losses due to the battery mass and to the battery efficiency.

### 6.2.2.2. Different ranges

In the constant range F.U., the standard "one-charge range" was set to 60 km. The impacts of other one-charge ranges (50 or 70 km) have been investigated and the results are shown in Figure 18.

The results of the changes in the "one-charge range" are discussed separately from the other results of the sensitivity analysis, because they implicitly lead to the creation of new and different functional units.

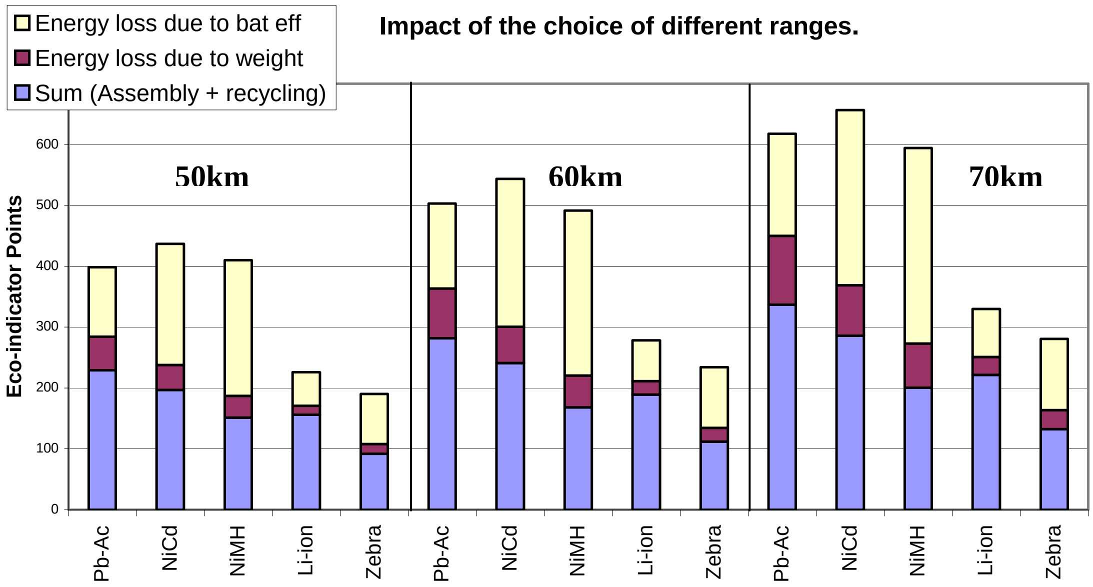

**Figure 18: Environmental burden when the "one-charge range" is modified to 50 or 70 km.**

It's noticeable that the absolute environmental impacts are different from the ones obtained using the 60 km range. But the main trends and thus the conclusions stay the same within each of the assessed "same-range batteries".

### 6.2.2.3. Different electricity production methods

The European electricity production mix was used in all of the calculations mentioned above. The environmental impact of the production of 1000MJ of electricity using the European Mix is summarized in Table 27. It should be mentioned that in these calculations the impact of the capital goods is included. Otherwise the impact of renewable energy sources (wind and water) would be zero.

**Table 27: Impact of 1000 MJ of the different energy sources.**

| | Eco-Indicator Points |
|---|---:|
| Wind power plant | 0.68 |
| Hydro power plant | 0.10 |
| Nuclear Power plant | 1.59 |
| Coal Power plant | 7.08 |
| Gas Power plant | 13.50 |
| Lignite power plant | 7.96 |
| Oil power plant | 22.40 |

These figures show that the number of eco-indicator points induced by the production of 1000MJ is the highest when using oil powered plants. The eco-indicator points allocated to the electricity production using lignite or coal powered plants are almost three times less than when using an oil powered plant and almost two times less when using gas powered plants compared to the oil powered plant. This is also due to the fact that the reserves of the different fossil fuels are taken into account. The more important the world reserves, the lower impact (the number of eco-indicator points) when consuming the fossil fuel. The impact of nuclear power plants (in eco-indicator points) is five times less than the average of the European Mix. Important to mention is that the nuclear waste is not taken into account in the eco-indicator methodology. The impact of the renewable sources is not zero, as the capital goods are included.

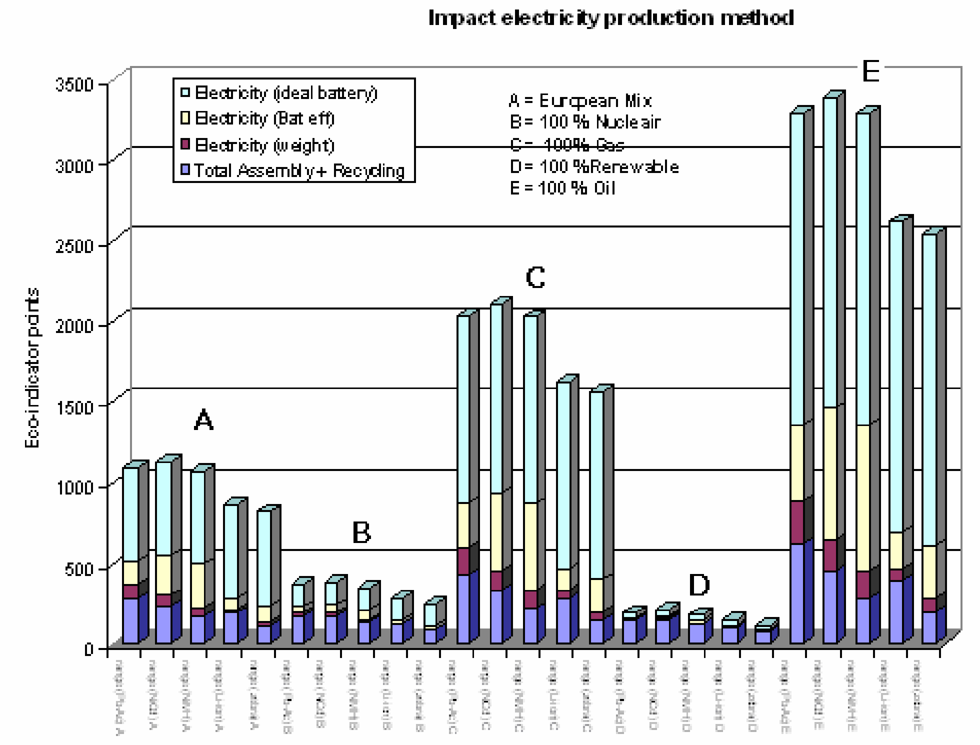

**Figure 19: Impact of the electricity production method on the global results.**

Figure 19 clearly shows the important influence of the electricity production method on the global results. The ranking of the different technologies remains unchanged, but the overall, specific impact of the different batteries varies strongly depending on the electricity production method.

The choice of the energy production method in the life cycle can thus have a great influence.

These figures show that sometimes, it’s more important to improve the environmental impact of the energy production method as the environmental impact of the energy production method can probably be improved more significantly than the environmental impact of the battery itself.

### 6.2.3. HEV battery

A sensitivity analysis has been performed for HEV. The sensitivity analysis mainly assessed the same variations of the assumptions for the BEV (concerning average battery composition, energy consumption, etc.). The implemented variations involved calculations, using different relative sizes of the components of the battery (10% more weight of one component, compensated by an equivalent decrease of another component). The proportional masses of the electrodes, electrolytes and cases have thus been altered. Also, the recycling rates and recycling efficiencies have been modified as well as the required amounts of energy to produce and recycle the different types of batteries.

The additional consumption due to differences in mass of the different batteries is not taken into account in the analysis of HEV batteries.

#### 6.2.3.1 Different scenarios sensitivity analysis

Figure 20 demonstrates that the assumptions mentioned in the previous section did not have any significant impact on the results in the sense that the conclusions remain the same. This demonstrates that the results of this study are reliable and illustrates the robustness of the model.

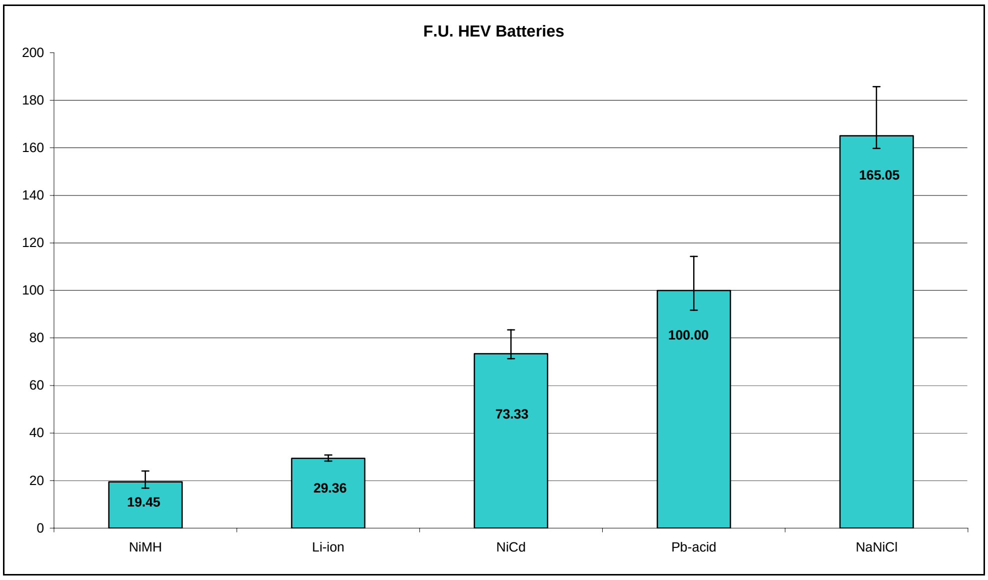

**Figure 20: Graphical overview of the relative environmental scores of HEV batteries (including the sensitivity analysis).**

### 6.2.4. Conclusion of the sensitivity analysis

The sensitivity analysis demonstrated that the non-technical assumptions did not have any significant impact on the results in the sense that the conclusions remain the same. This reveals the reliability of the results and the robustness of the model

## 6.3. Discussion of the results

- Importance of recycling

An important conclusion is that the impacts of the assembly and production phases can be compensated to a large extent when the collection and recycling of the batteries is efficient and performed on a large scale.

- Impact per kg for the different battery technologies

When analyzing the environmental impacts of the different technologies per kg, one could get the (wrong) impression that the technology having the lowest impact per kg is the most environmentally friendly one. However, several technical aspects play a significant role in the overall environmental impact of the batteries. As an example, a battery with a high specific energy (or a high specific power in the case of HEV) and a high number of cycles will involve a lower amount of batteries to allow identical performances.

- Application

As could be observed in the previous chapters, depending on he “application” (i.e. BEV or HEV) and the corresponding (technical) parameters, the global environmental rating of a specific battery technology will be different. This implies that it is nonsense to state that a certain technology <u>**is**</u> environmentally friendly, while the other is not. Actually, it can only be stated that a battery technology is environmentally friendly *compared to another* in a *particular application*. As a consequence, conclusions have to be drawn for each application specifically.

### 6.3.1. BEV

When excluding the energy losses during the use phase (due to the battery efficiencies and the additional masses of the batteries), the following environmental ranking is obtained (decreasing environmental impact): lead-acid, nickel-cadmium, lithium-ion, nickel-metal hydride, sodium-nickel chloride.
Looking at the global results, the following environmental ranking is obtained (decreasing environmental impact): nickel-cadmium, lead-acid, nickel-metal hydride lithium-ion and sodium-nickel chloride. Globally three battery technologies (lead-acid, nickel-cadmium and nickel-metal hydride) appear to have very comparable impacts on the environment. It can thus be stated that, taking the sensitivity analysis into account,

these technologies have a higher environmental impact than the lithium-ion and the sodium-nickel chloride technology.

When the calculations are performed with batteries that have different energy storage capacities (batteries allowing to cover different ranges with a single charge), the main conclusions stay the same. In other words, three of the assessed technologies (lead-acid, nickel-cadmium and nickel-metal hydride) have a comparable environmental burden and this burden is higher than the ones of the other two technologies, being lithium-ion and sodium-nickel chloride. However these results might be mitigated because of the great rareness of environmental data concerning some aspects of the lithium-ion and the sodium-nickel chloride batteries (for example concerning the electrolyte).

When analyzing the results of this study, it should be kept in mind that the environmental impacts of the batteries of electric vehicles are small (whatever the used battery technology might be) compared to the environmental burden caused by vehicles equipped with internal combustion engines. Therefore the results of this study should be seen as an indication on how to even enhance the environmental friendliness of electric vehicles.

### 6.3.2. HEV

Several types of HEV exist and the different configurations might have their own implications as far as batteries are concerned. An F.U. had to be determined and as a consequence, an identical power output of the battery seemed to be the best choice, as this parameter is essential in this type of vehicle.
Objectively, from a technical point of view, only three of the considered technologies (nickel cadmium, nickel metal hydride and lithium-ion) form a potential solution for HEV vehicles (like the Toyota Prius). Lead-acid and sodium nickel chloride batteries are not appropriate because of their high weight. For other kinds of HEV vehicles (for example busses), the weight not a big issue, and consequently, these technologies are technically more realistic for these applications. However, this study shows that these technologies are not advisable from an environmental point of view.

The results of the calculations for HEV lead to the following environmental ranking (decreasing environmental impact): sodium-nickel chloride, lead-acid, nickel-cadmium, lithium-ion, nickel-metal hydride.

## 6.4. General conclusion of the quantitative analysis

It is important to define the boundary conditions, the technical characteristics and the field of application of the different technologies when describing and discussing the impact of battery technologies on the environment. Indeed, the results of the LCA are strongly influenced by the performance characteristics of the battery.

A functional unit was chosen as a reference to compare the different technologies in an objective way. The analyses for BEV and HEV batteries result in quite different trends.

The three possible F.U. for battery electric vehicle resulted in similar conclusions. Lead-acid, nickel-cadmium and nickel-metal hydride batteries have a comparable and larger environmental impact than the lithium-ion and sodium-nickel chloride batteries.

The result of the F.U. for hybrid electric vehicles leads to the following global environmental ranking (decreasing environmental impact): sodium-nickel chloride, lead-acid, nickel-cadmium, lithium-ion and nickel-metal hydride.

These results illustrate that BEV and HEV batteries should be discussed separately.

# Part 2. Qualitative analysis

The most common battery technologies are discussed in the first part in a quantitative way. However, some other interesting but less widespread battery technologies were described in work package 1 and are described in this part of the study in a qualitative way. The following technologies are discussed:

- Nickel-zinc
- Lithium-ion polymer
- Lithium metal
- Zinc-air
- Vanadium redox
- Zinc bromine
- Polysulfide-bromine
- Nickel-iron
- Silver-zinc

Not all of the necessary data to perform a quantitative LCA study are available for these less widespread technologies. Regarding development, most of these technologies are on a research level and are not available commercially yet. Some of the (laboratory) technical data have to be confirmed in the real world experiments. Some of the data described below are not generally accepted yet and can change in the future.

A rough evaluation of the potential environmental impact for BEV or HEV applications of these technologies is given in the next sections.

# 1. Different technologies

## 1.1. Nickel-Zinc

### 1. 1.1. Composition

This battery consists of a nickel electrode (mainly nickel hydroxide) (20%), a zinc electrode (zinc oxide and calcium oxide) (30%), separators (6%), electrolyte (24%) and casting/connectors (~20%) (Investire, 2003).

### 1.1.2. Recycling

No detailed recycling plan has yet been formulated, but the battery does not contain any particularly hazardous materials. The untreated batteries would probably be considered as hazardous waste due to the corrosive (alkaline) electrolyte, but this could be recovered to eliminate that problem.
The nickel-zinc battery contains valuable raw materials, such as nickel, and is highly recyclable. Reclaiming and recycling nickel-zinc batteries is straightforward and makes

sense both from an environmental and an economic point of view. The NiZn batteries can be recycled using similar methods as for the recycling of NiMH and NiCd batteries

### 1.1.3. Technical parameters

Thanks to the relatively high specific energy (70-80Wh/kg), a relatively small battery pack is needed to obtain a given energy content. On the other hand, the relatively low specific power (200 W/kg) results in the fact that NiZn batteries do not form an optimal solution for HEV applications.
The limited number of cycles (300-500 deep cycles) is clearly a disadvantage when wanting to use the nickel-zinc batteries for electric vehicle applications.

### 1.1.4. Overall

The nickel-zinc technology intrinsically has some advantages to offer from an environmental point of view. However, these advantages are mitigated by the low number of cycles resulting in a high quantity of batteries needed during the vehicle lifetime in comparison with the other battery technologies. Specifically concerning the HEV, at this stage of development of this technology, the environmental impact can be assumed to be quite high, as the specific power of the nickel-zinc battery is low.

## 1.2 Lithium-ion-Polymer and lithium-metal

### 1. 2. 1. Composition

The lithium-ion-polymer batteries have cathodes consisting of lithium “Metal” oxides, where “Metal” stands for cobalt, nickel or manganese. They have carbon/graphite anodes and have a jelly, polymeric electrolyte.

Lithium metal batteries have a cathode consisting of vanadium oxide and an anode formed by a lithium foil, while their electrolyte is a solid polymer (Investire, 2003).

### 1.2.2. Recycling

The lithium-polymer battery recycling is an area where work is needed. These cells may be used in EV/HEV in the future as the polymer technology mitigates the safety issues related to the lithium-ion technology. It seems some work is underway to process the lithium-polymer batteries in an appropriate way, but no data have been published and no data were available for this study. Many constituents are common to this technology and the lithium-ion technology, but the use of a solid polymer could complicate the dismantling and recovery as new materials with new properties are introduced.

### 1.2.3. Technical parameters

The technical performances (specific power, specific energy and number of cycles) of Li-polymer and Li-metal are a bit lower than the performances of lithium ion batteries [24].

### 1.2.4. Overall

The technical characteristics involve that the environmental impacts of the lithium-polymer and lithium-metal batteries are expected to be somewhat higher than the environmental impact of the lithium-ion batteries. This is due to the higher amount of material needed to assemble these batteries.

## 1.3. Zinc-air

### 1.3.1. Composition

Zinc-air batteries are batteries, which can be **mechanically recharged** by replacing their zinc anodes (39% of the weight of the battery), have got carbon (air) cathodes (12%) and have potassium hydroxide as an electrolyte (28%) (Investire, 2003).
The recharging is done in a refuelling station. This is a plant where spent anodes are taken out of the vehicles and replaced with fresh ones. These spent zinc electrodes are electrically recharged.

### 1.3.2. Recycling

In this system, spent zinc anodes are removed from the battery and are processed electrochemically. The battery materials are non-toxic and should be quite easy to handle although no recycling scheme has been proposed yet. The cells contain KOH, which should be neutralized, but apart from the zinc anodes, which are recycled during the lifetime of the battery, the used materials are steel, carbon, plastic, copper and nickel.
A complete environmental impact assessment of the zinc-air system should take the emissions and waste due to batteries mechanical recharging (direct environmental impact) into account.

### 1.3.3. Technical parameters

Due to its relatively low specific power (70-100 W/kg), the zinc-air technology is not suitable for HEV applications. Nevertheless, thanks to their high energy densities (200 Wh/kg), Zn-air batteries are suitable for BEV applications. One of the disadvantages of this kind of batteries is the need for mechanical recharging.
Theoretically, the number of cycles of the Zn-air battery is very high, as the electrodes are refreshed every cycle.

### 1.3.4. Overall

Zn-air batteries can be a good choice for fleet applications, because in this case it is possible to use a centralized plant for zinc anodes regeneration. From an environmental point of view, there are no crucial concerns, as the components of the Zn-air battery don’t present any major toxicity. But the specificity of this technology (mechanical recharging) implies a difficult comparison of this kind of batteries with the others.

## 1.4. Vanadium redox, Zinc bromine, Polysulfide-bromine

### 1.4.1. Composition

A synonym for these batteries is: *Redox* batteries. This name is used only to indicate that the electrochemical systems where the oxidation and reduction take place involves only ionic species in solution and that the reactions take place on inert electrodes. Therefore the active materials are stored outside the cells of the battery and circulate through the battery to provide the energy.

### 1.4.2. Recycling

For a number of other storage technologies redox batteries recycling seems very feasible, although it has not yet been tested in practice (Investire, 2003).

### 1.4.3. Technical parameters

Prototypes of Zinc-bromine batteries have an specific energy of 80 Wh/kg and a specific power of 100 W/kg. Reliable data on the lifetime aren’t available for the moment due to the fact that this system has only been tested on a prototype scale in vehicle applications up to now and that research activities have been abandoned on motive power applications. The low specific power results in the conclusion that this battery seems inadequate for HEV applications. The other redox batteries have similar characteristics and accordingly similar conclusions can be drawn for these technologies.

### 1.4.4. Overall

The amount of data available concerning this technology is too low to discuss their potential environmental impact. What can be told for sure is that this application is not suitable for HEV application.

## 1.5. Nickel-iron

Nickel-iron batteries have similar performance characteristics as nickel-cadmium batteries. Therefore this technology theoretically can be a substitute for nickel-cadmium batteries. But, low energy efficiency (50-60%) causes excessive water consumption. This disadvantage compared to nickel-cadmium batteries makes this battery not accepted for commercial EV or HEV use.

The electrodes of this battery can easily be recycled and the recycled materials can be used in the steel industry.

### 1.6. Silver-zinc

Silver-zinc batteries have good specific energy and specific power characteristics. The lifetime cycles are very low compared to the other discussed technologies in this report (maximum 250 cycles).

## 2. Discussion

The less widespread technologies have been described and discussed qualitatively in the previous chapter.

Just like for the more widespread technologies, it’s important to define the application where the battery is going to be used and to choose an appropriate reference basis before comparing the different technologies. The comparison of the different technologies based on an equal mass is an inappropriate option. As previously discussed in the sections dedicated to the quantitative analyses, the technical parameters (specific energy, specific power, energy efficiency, number of cycles, etc.) influence the required battery mass and number of batteries needed for the functional unit. The technologies described in this part of the study are not commercially widespread. As a consequence, additional research will be needed in the future, if their overall environmental impact has to be lowered, through consequent technological improvements.

This qualitative analysis gave an overview of the composition of the batteries, their possible recycling methods, their main characteristics, etc. The short discussions summarized the practical feasibility for different applications.

As has been shown in the previous chapters of this study, recycling of the spent batteries is important, because it can save resources and lower the total environmental impact of the life cycle of the batteries. Of course this conclusion is valid for the batteries discussed in this chapter.

From an **environmental point of view**, following technologies (discussed in this section) are advisable for BEV applications: lithium-polymer, lithium-metal, zinc-air, redox-systems, nickel-iron.

From an **environmental point of view**, following technologies (discussed in this section) are advisable for HEV applications: lithium-polymer, lithium-metal, nickel-iron.

Of course, the technical and economical parameters should be taken into account too when determining which technologies are fitting the requirements of BEV or HEV.

# Appendix 1: Overview of the selection of the software tool.

## The selection

The choice of the software has been carried out after an analysis consisting of a questionnaire, a demo's test and comments from software's users.

## The questionnaire

At the end of February, a questionnaire was sent to the three providers. It was build on three technical sets of questions, service (maintenance and training), functionality and database content; and on specific questions relating to the use of software for similar LCA studies to our study (SUBAT project), the reference users, the principal assets of the software and an cost estimation of license.

Fields covered by the questions:

- *Service provided :*
    - *supported, updated*
    - *service hotline*
    - *do you propose a training (via seminar or personalised)?What would be the cost of the training? Are the trainings being organized on a regular base? Weekly? Monthly? Yearly? What is the maximal waiting period between the trainings?*

- *Functionality :*
    - *compatibility with PC and capacities required of the computer (processor, RAM...)?*
    - *working under Microsoft Windows operation system*
    - *process model unlimited in size and complexity*
    - *supporting inventory and impact assessment*
    - *graphical interface is implemented, graphical editor included*
    - *import and export possibilities (from/to MS Office tools? Others?)*
    - *possibility to change impact factors*
    - *possibility to change reference value (normalization)*
    - *possibility to change weighing factors*
    - *speed of calculation according to capacities of the computer?*
    - *time to master the software?*
    - *possibility to carry out other types of analysis (costs, socio-economic impacts...)?*
    - *user-friendliness?*

- *Database :*
    - *data on raw materials, power generation, transport and disposal is included,*
    - *up-to-dating*
    - *European and International validity*
    - *adjustable*

- *Has this software been used by a similar LCA study as ours? Could you provide us with a few examples of some organisations using your software? Is your software widely accepted as a reference tool?*
- *Which are the main assets of your software compared with the other software tools suggested on the market (SimaPro, TEAM, GaBi 4,)? What are the main disadvantages/problems encountered using the other software tools on the market?*
- *A full estimation for an academic license and multi-user of the software and various packs (database, training, service hotline, upcoming version upgrade...)?*

## Synthesis of the answers

Regarding the services (table 1), the three preselected companies provide more or less the same services. An important difference exists for the TEAM's software: the first year of the service is not free and is limited to 8 hours.
The three companies propose a training at home. The price of these trainings shows a rather widely amount (see appendix).

**Table 1 Answers to the questions about « service » (+: yes)**

| Service | | | |
|---|---|---|---|
| | **GaBi 4** | **SimaPro 5.1** | **TEAM 4** |
| Updating | Free | Service contract (free the first year) | Contract maintenance |
| Service hotline | Free | Service contract (free the first year) | Contract maintenance (8h) |
| Training | + | + | + |

Regarding the functionality of these three software tools (table 2), they are almost similar. Large differences appear nevertheless in the type of file which can be imported and exported and, in the other types of impact studies which each software can carry out. TEAM for instance, makes it possible to carry out a costs analysis.

**Table 2 Answers to the questions about « functionality » (+: yes, - : no and nc : not communicated)**

| Functionality | | | |
|---|---|---|---|
| | **GaBi 4** | **SimaPro 5.1** | **TEAM 4** |
| Recommanded requirements | PC 400 MHz<br>128 RAM<br>100 MB free hard disk | PC Pentium IV 2 GHz<br>96- 288 RAM<br>250 MB free hard disk | PC Pentium class<br>128 RAM or more |
| Compatibility with Microsoft operation system | Windows 95,NT,200,XP | Windows 95,98,ME, NT 4, 2000, XP | Windows 95 or NT 3.51, NT 4.0, 2000, XP |
| Limitation in size and complexity | no limit | no limit | no limit |
| Inventory and impact assessment | + | + | + |
| Import/export options | • Import: Excel<br>• Export: Excel | • Import : CSV (create via Excel), Spold99, SimaPro database<br>• Export: CSV, txt, Spold99, SimaPro database format,… . Copy and paste of results to Office applications | • Import : txt files (TEAM and Spold format), Ecoinvent 2000 formated data<br>• Export: txt files (TEAM and Spold format) |
| Changes in impact factors | + | + | + |
| Changes in reference value (normalisation) | + | + | + |
| Time to master the software | Depends on the complexity of the models analysed | 2 days to one week | 2 days to one week |
| Other types of analysis | +<br>(cost consideration and social conditions) | - | +<br>(cost analysis: fixed and variable) |
| User-friendly | + | + | ± |

Concerning the databases (table 3), each provider offers a great choice. Moreover, they all have an interface with the Ecoinvent database. The Ecoinvent database costs 1200 €.

**Table 3 Answers to the questions about the « database » (+: yes)**

| Database | | | |
|---|---|---|---|
| | **GaBi 4** | **SimaPro 5.1** | **TEAM 4** |
| Type of data (raw materials, power generation, transport and disposal) | + (see appendix) | + (see appendix) | + (see appendix) |
| Updating | + | + | + |
| Valid for Europe | + | + | + |
| Adjustability | + | + | + |

About the reference users (table 4), it seems that various studies were undertaken with each software. The reference users listed hereafter comprises only the companies quoted in the answers. In the appendix, other names of companies coming from the website of each software are shown.

**Table 4 Answers to the questions about the « similar LCA study, users references » (+: yes and nc : not communicated)**

| LCA study – reference | | | |
|---|---|---|---|
| | **GaBi 4** | **SimaPro 5.1** | **TEAM 4** |
| Similar study to SUBAT | + | nc<br>(studies are confidential) | +<br>(LCA of lead and zinc batteries) |
| User's reference | Bayer, BP Chemical, DaimlerChrysler, DuPont, EMPA, General Motors, Motorola, Nokia, Siemens, Solvay, Toyota, Volkswagen | Philips, Lear Automative, Gaz de France, TNO, VITO, United technologies, AgfaGevaert,… | EDF, Corus Steel, Arcelor, Unilever, … |

The table 5 synthesizes the answers to the question about "the main assets"; it is thus suggested to refer to the appendix for further information. Let us note that the companies' answers are limited to advertising. These answers are thus not always objective. Certain answers are even contradicted by the software's demonstrations test results (see 4.3).

**Table 5 Answers to the question about « the main assets »**

| **Principal assets** | |
|---|---|
| **Gabi** | Easy to understand structure and intuitive user interface<br>Possibility to use parameters for the calculation<br>Implemented of sensitivity analysis (Monte-Carlo Analysis), scenario analysis, parameter analysis<br>Possibility to create different types of diagrams<br>High quality LCI database, professional database, wide range data sets cover many industrial branches (metals, organic and inorganic intermediate products, plastics, mineral materials, energy supply, end of life, coatings, manufacturing and electronics)<br>Most used in the automobile and electronic industry |
| **SimaPro** | Intuitive interface<br>Very quickly learn how to work<br>Comparison of two pr more products and immediately analyse the difference<br>Sophisticated impact assessment and analysis options<br>Realtime analysis of impact assessment results<br>Support damage categories in impact assessment methods<br>Possibility to create easily his methods |
| **TEAM** | Implementation of global and local variables in the model so that it is possible to make easily sensitivity analysis using a control panel that runs as many simulation in batch as the user wish |

The table 6 shows the drawbacks which the providers accepted to communicate about their software.

**Table 6 Answers to the question about « the drawbacks» (nc : not communicated)**

| Drawbacks | |
|---|---|
| **Gabi** | Not available multi user capability of the software |
| **SimaPro** | Scenario analysis not supported |
| **TEAM** | nc |

The cost of the various software tools shows strong differences for the purchase of an academic license "university" (education, small-scale research project) or a professional license (consulting companies, large-scale research project, etc.)
An academic license for 2 users and one year of service cost 2 400 € from SimaPro and 5 300 € from TEAM. The cost for the same product is intermediary for Gabi.
The prices are also very different for the professional license. For one users and one year of service, the least expensive remains SimaPro with 3 600 €, followed-up of Gabi with 7 500 €. The cost for one professional license for TEAM and for the service is 10 000 € per year! For TEAM, the prices for two licenses haven't been asked because of the high price of one license.
After consultations with the providers, the license necessary for our study is a professional license.

**Table 7 License cost estimation (2004)**

| Estimation (tax not included) | | | |
|---|---|---|---|
| | **GaBi 4** | **SimaPro 5.1** | **TEAM 4** |
| **Academic license** | 3 750 € | 1 200 € (single user)<br>2 400 € (2 users) | 2 000 € |
| Additional license | 750 € | nc | 1 000 € |
| Service | Free | Free the first year<br>300 € (single user)<br>600 € (multi user) | 2 300 € (contract maintenance) |
| **Professional license** | 7 500 € | 3600 € (single user)<br>7200 € (2 users) | 10 000 € (consultant) per year ! |
| Additional license | 1 500 € | 1 800 € | nc |
| Service | Free | Free the first year<br>1 000 € (2 000 € for 2 and 500 € for each extra user) | Included (first year) |

From the result of the questionnaire, it appears that the three software tools show many similarities but they comprise also some specificities. The great differences are the possibilities of carrying out other types of analysis than environmental ones, the type of file for import and export possibilities and the cost of software tools.
In conclusion, at this stage, it is difficult to choose a software on the basis of the answers only, the test of the software's demonstrations and the comments must allow to determine the most adequate software and to improve judgement.

## Demonstrations

Besides the questionnaire, the choice of the software has been based on the test of the software's demonstrations. The comparison is not easy because each demonstration possessed its own characteristics.
Some demonstrations, like Gabi and SimaPro, propose to conceive a LCA following a specific tutorial. The software's demonstration provided by SimaPro presents a complete study of a simple wooden shed (time of the realisation: more than 2 hours) and an exploration of an example of LCA. The Gabi's demo is on the other hand much briefer (time of using is approximately 20 minutes).The software's demonstration of TEAM doesn't allow to undertake a LCA. It shows only the stages of a LCA's realization.
Thus, no unbiased comparison could emerge from the use of the three demonstrations tests. Moreover, any comparison starting from a random and easy LCA, imagined by our care, could not be realised. Indeed, each demonstration exercise has specific limitations of use.

In spite of these restrictions, some comments can be proposed. They can sometimes refute the answers to the question relating to the "principal assets" (see table 5).

Gabi

- no intuitive use
- good visibility of the process tree
- lack of visibility in the fitting of the running windows
- no modification existence in the event of error in the architecture of the processes?

SimaPro

- intuitive use
- graphically, the more well completed of the three softwares
- good visibility of the fitting of the running windows
- good visibility of the process tree
- construction of the software seems rigid
- seems to have an important amounts of tools for the study

TEAM

- intuitive use
- good visibility of the fitting of the running windows
- good visibility of the process tree
- seems to have an important series of tool for the study

From this test, the choice focuses on two software tools: SimaPro and TEAM.

## Comments of a SimaPro and TEAM's user

Here are the comments from an expert working at Procter & Gamble European Technical Centre. This company uses SimaPro since several years but now, they seem to prefer TEAM.

*The personal preference from this expert would go to TEAM for the following reasons:*

1. *TEAM is more flexible in terms of design of the LCI model. This is a considerable advantage over SimaPro, particularly in a ecodesign context and a fast moving goods sector where formulations change almost every day. You can assign variables to values in unit processes for which you know that they may change over time.*

2. *TEAM is also much more developed in terms of analysis of the model. It has the option of doing scenario and uncertainty analysis (Monte-Carlo with around 4 selections of distribution models). Since uncertainty in LCA can be of great importance, it is important to have a good understanding, particularly if you are making business decisions.*

3. *TEAM is slightly underdeveloped on the impact assessment, i.e. the interface to add new impact categories to the existing suite of impact categories is not very user friendly. However, most commonly used methods are available. SimaPro developments are mostly focused on building their suite of impact categories, rather than expanding the tools/features to analyse the LCI model. However, the last years they have improved, but still they are not where TEAM is.*

4. *Both software vendors are well connected to the LCA scene to monitor developments (e.g. both have an interface with the EcoInvent database).*

5. *In terms of database development, TEAM is also better equipped, since PriceWaterhouseCoopers (PWC) is providing LCA services with a lot of clients and therefore, their database is much more developed. When there is a need for a specific dataset, we can contact them and they can contact their clients to see if there is an interest to share data (even when there is a cost associated with this). This is something that does not exist in Pre. Specifically to your question on heavy metal industry and batteries, I know PWC have a dataset on rechargeable and disposable batteries.*

6. *Both vendors offer maintenance contracts (about same price) for support and updates on their software.*

According to these comments, following TEAM has more advantages than SimaPro. Nevertheless, SimaPro is slightly more developed on the impact assessment.

# Appendix 2: Used data

## A.1.1. Substances

The used data in the analyses are obtained from commercially available databases or from the literature. If the data could not be obtained by those means, the data were estimated.

An overview of the sources for the used data and databases is given in the following table.

**Table 28: Overview of the used data for each substance.**

| Substances | Used data | Used database/Estimation |
|---|---|---|
| Aluminum (Al) | Aluminum, primary at plant, RER S | Ecoinvent |
| Beta-alumina (Bohmite, Al2O3) | Epoxy resin insulator (Al2O3), at plant / RER S | Ecoinvent |
| Carbon | Carbon black, at plant GLO S | Ecoinvent |
| Cobalt (Co) | Cobalt, at plant / GLO S | Ecoinvent |
| Glass | Glass fibre / RER S | Ecoinvent |
| Polyethylene (PE) | PE, HDPE,Granulate RER S | Ecoinvent |
| Polyvinylidene fluoride (PVDF) | PVDC, granulate, at plant RER S | Ecoinvent |
| Silicates (SiO2) | Epoxy resin insulator (SiO2), at plant / RER S | Ecoinvent |
| Copper (Cu) | Copper ETH S | ETH-ESU 96 |
| Iron (Fe) | Cast iron ETH S | ETH-ESU 96 |
| Lead (Pb) | Lead ETH S | ETH-ESU 96 |
| Nickel (Ni) | Ni enriched ETH S | ETH-ESU 96 |
| Oxygen (O2) | O2 ETH S | ETH-ESU 96 |
| Polyethylene (PP) | PP ETH S | ETH-ESU 96 |
| Potassium hydroxide (KOH) | NaOH ETH S | ETH-ESU 96 |
| Sodium chloride (NaCl) | NaCl ETH S | ETH-ESU 96 |
| Sodium Hydroxide (NaOH) | NaOH ETH S | ETH-ESU 96 |
| Stainless | High alloy steel ETH S | ETH-ESU 96 |
| Steel | Low alloy steel ETH S | ETH-ESU 96 |
| Steel | Steel ETH S | ETH-ESU 96 |
| Sulphuric Acid (H2SO4) | H2SO4 (ETH S) | ETH-ESU 96 |
| Water (H2O) | Water demineralised | ETH-ESU 96 |
| Styrene Butadiene rubber (SBR) | SBR I (Idemat) | Idemat |
| Antimony (Sb) | Estimated data | |
| Arsenic (As) | Estimated data | |
| Cadmium hydroxide (Cd(OH)2) | Estimated data | |
| Cobalt hydroxide (Co(OH)2) | Estimated data | |
| Lithium hydroxide (LiOH) | Estimated data | |
| Lithium metal (Co/Ni/Mn) oxide (LiMO2) | Estimated data | |
| Nickel hydroxide (Ni(OH)2) | Estimated data | |
| Rare earth | Estimated data | |
| Sodium aluminum chloride (NaAlCl4) | Estimated data | |
| Dimethyl carbonate (DMC) | - | |
| Ethylene Carbonate (EC) | - | |
| Lithium hexafluorophosphate (LiPF6) | - | |
| Propylene Carbonate (PC) | - | |
| | | |

Rare earths include the following metals: Lanthanum, Cerium, Praseodymium and Neodymium.

The databases did not include data concerning KOH, but as the production processes and the properties of KOH and NaOH are very similar, the environmental impact of KOH has been replaced in the calculations by the impact of NaOH.

## Estimated data

The environmental impacts of the components for which no data are available in the databases are estimated by adding the impacts of their ores and an approximation of the impact of the energy consumption required to process these ores.

The energy needed for the smelting of the metals can be estimated using the minimum theoretical thermodynamic energy requirement ($E_{th,min}$). The following thermodynamic equation can be used [25]:

$$E_{th,min} = \left(m_{sample} . C_{spec} . (T_{melt} - T_{init})\right) + \left(m_{sample} . f_{spec}\right)$$

$m_{sample}$: Mass of material sample (kg)
$C_{spec}$: Specific heat capacity [J / (kg.K)]
$f_{spec}$: Specific heat of fusion (MJ/kg)
$T_{melt}$: Material melting temperature (K)
$T_{init}$: Initial temperature (K)

Of course, the actual energy requirement is probably much higher than the theoretical value. For example, the industrial energy efficiency for iron production is only 6%. When applying the above formula to other metals, we will assume an industrial efficiency of 10%.

The use of this formula was applied to obtain the data for the metals given in next table:

**Table 29. Overview of the estimations concerning energy consumption for metal production.**

| | **Electricity consumption** (MJ/kg) |
|---|---|
| Lithium | 7.21 |
| Lithium Hydroxide | 11.60 |
| Lanthanum | 0.90 |
| Cerium | 0.78 |
| Arsenic | 2.91 |
| Antimony | 1.47 |
| Cadmium hydroxide | 53.45 |
| Cobalt hydroxide | 44.15 |
| Sodium aluminium chloride | 5.47 |
| Neodymium | 0.68 |
| Praseodymium | 0.98 |
| Nickel Hydroxide | 43.99 |

### A.1.2. Energy sources

The used data in the analyses are obtained from commercially available databases and are summarized in the following table.

**Table 30: Overview of the used data for each substance.**

| | Used data | Used database |
|---|---|---|
| Electricity | European Mix | (based on) ETH-ESU 96 |
| Oil | Heat diesel B250 | BUWAL250 |
| Gas | Heat, natural gas, at boiler condensing .... /RER S | Eco-invent |
| LPG | Heat, natural gas, at boiler condensing .... /RER S | Eco-invent |
| Heat | Heat, natural gas, at boiler condensing .... /RER S | Eco-invent |

The environmental impact of the European electricity production mix, was obtained by adding, the environmental impacts of the different electricity production methods. Only data coming from the ETH-ESU database were added to obtain the European Mix impact.

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APPENDIX III

# SUBAT

## “Sustainable Batteries”

**STREP N° 502490**

## WP3 : Economical Assessment

## Final Report D29

FEBRUARY 28th 2005

cereveh

DEVELOPMENT AND INNOVATION CENTRE
ELECTRIC AND HYBRID VEHICLES

DSEA

*Department of Electrical Systems and Automation*

CEI CIVES

# APPENDIX III

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## A Abstract report (Subat public report)

## B Micro-economic Study

# A - Abstract report (Subat Public Report)

## TABLE OF CONTENT

# 1. Costs and Prices of Battery Technologies for Traction Applications and Relation with the world Market Trends.

For all types of electrically propelled vehicles (pure electric or hybrids), the battery is one of the most expensive components even when the power train configuration leads to a battery of small size. Investigations and studies have been performed for each type of technology showing a technical interest for the concerned applications. But, as the SUBAT purpose is to make an overall assessment (technical, environmental and economical) of all the battery technologies able to have an interest in the electric or hybrid vehicle field, the costs and prices comparisons becomes very difficult and specific hypothesis have to be assumed as well as specific evaluation methods must be developed.

## 1.1. Today Price Estimation for a Specific Technology

### 1.1.1. Estimation method used

Assuming the hypothesis of a well known technology, commercialized at a high production level (this level is a function of the technology) and produced by several battery manufacturers in the world under close design and chemical composition (case of NiMH for example), the today cost and price estimation can be made using the following steps:

- Technology study to establish the different types of materials needed and the relative amount of each for a typical battery cell,
- Technical performances study to establish the characteristics of the typical cells to be evaluated (if cells composition are different in the case of high power or high energy applications),
- Comparison of chemical composition of typical cells depending on the different battery manufacturers,
- Mean value estimation of the cells chemical composition (and impact on the cost calculation leading in some cases to a minimum and maximum values),
- Data collection and analysis of the raw material prices (leading in all cases to minimum and maximum values),
- Cell cost of goods estimation (two cases: high energy and high power, see table I),
- Cell cost evaluation taking into account the labour costs and the accessory costs in order to make the battery with a given number of cells,

At this stage of the evaluation, it becomes necessary to choose battery technical specifications for a given application in order to obtain reliable cost and price of the vehicle component. Depending on the application the calculated battery price can be different for several reasons:

- The size of the battery is different depending on the technical performances in energy (BEV) or power (HEV),
- The accessories costs are not always functions of the battery size,
- The battery design can be completely different.

We have chosen the following battery definitions leading to three different batteries (the two last columns lead to the same type of results)

| Vehicle type | Mild Hybrid | Full Hybrid | Full Hybrid with 40 km ZEV (Dual mode) | BEV |
|---|---|---|---|---|
| Energy (kWh) | 0,4 | 1,2 | 10 | 30 |
| Power (10s, kW) | 12 | 40 | 50 | 50 |
| Voltage (V) | 42 | 270 | 270 | 270 |
| Cost and Price units | €/kW | €/kW | €/kWh | €/kWh |

| **2004** | **W %** | **unit max (€/kg)** | **unit min (€/kg)** | **W (g)** | **Max Cost** | **Min. Cost** | **% (max)** | **% (min)** |
|---|---|---|---|---|---|---|---|---|
| Cathode active material | 33 | 45 | 38 | 330 | 14,85 | 12,54 | 47,00 | 45,44 |
| Collector (Al) & other Al | 8,5 | 21 | 19 | 85 | 1,79 | 1,62 | 5,65 | 5,85 |
| Anode active material | 17 | 21 | 18 | 170 | 3,57 | 3,06 | 11,30 | 11,09 |
| Collector (Cu) & other Cu | 12 | 15 | 14 | 120 | 1,80 | 1,68 | 5,70 | 6,09 |
| Separator | 1,5 | 140 | 120 | 15 | 2,10 | 1,80 | 6,65 | 6,52 |
| Electrolyte | 19 | 21 | 20 | 190 | 3,99 | 3,80 | 12,63 | 13,77 |
| Packaging (Al) | 9 | 3,5 | 3,1 | 90 | 3,50 | 3,10 | 11,08 | 11,23 |
| **Cell cost of goods** | | | | 1000 | **31,60** | **27,60** | | |
| | | | | **€/kWh** | **219** | **192** | | |

*Table I : Cost of goods estimation for a typical high energy cell in 2004*

The complete battery cost and price is then estimated using the two following steps:

- Battery production cost evaluation (BMS, assembly cost, labour cost and accessories costs),
- Battery price (other manufacturing costs, overheads and margin).

This last step causes a main problem in the price estimation. The manufacturing and Company costs used in this step have most often a value between 30 and 45% of the battery price. Data are not public and only estimation of the values can be made using the known habits of the Industrial Companies. In order to obtain reliable values the method used consists in choosing a minimum and a maximum value in agreement with the most common values.

Results are then expressed in terms of battery price, €/kWh for energy type batteries and €/kW for power type batteries.
These results are then compared to all known battery price (In the case of purchase by volumes) and cost studies made since 1999.

This method has been used in the case of NiMH, Li-Ion and $NaNiCl_2$. For Lead-Acid technology the method seems to be unusable. Because of a very high number of technology improvements made since several years by all the specialized companies, it becomes impossible to analyse the relations between the improved technical performances and the resulting price of the battery. A standard VRLA AGM battery with classical performances announced at a price of about 120 €/kWh is sold at more than 300 €/kWh in the case of advanced bipolar VRLA type. But as the technical performances of Lead-Acid are always poor compared with the other technologies, the hypothesis has been assumed that Lead-Acid is of interest for vehicle manufacturers only if the price remains low.
Only one manufacturer in the world (SAFT) commercializes NiCd batteries for traction application and this market is continuously decreasing since 2000. Prices of this manufacturer have been chosen without any complementary estimation.
Concerning more recent (or less developed) technologies like Lithium-Metal-Polymer, new type of Ni-Zn, Zn-Air, Redox batteries, prices could not be evaluate with a reasonable level of reliability and comparisons with the other technologies become impossible taking into account the great difference in industrial development levels.

### 1.1.2 Production costs, manufacturing costs and prices

All results are expressed in terms of battery prices but only production costs evaluation are really reliable and mainly function of the active material costs. But in order to obtain an order of magnitude of the future real price we have estimated the price corresponding to a given production cost using a mean value of the overheads and company costs. These results are made to be compared between each other and very carefully used as absolute value because of the close relation between the market situation and their values (in case of great competition overheads and margin decrease).

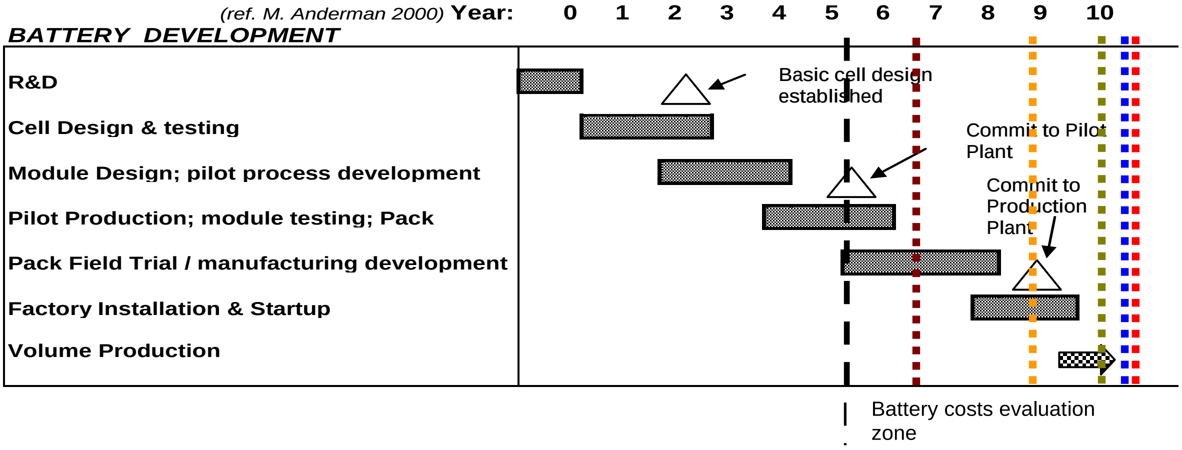
### 1.1.3 Notion of minimum and maximum price values

The minimum and maximum price (and cost) values have not the same meaning than usually and are function of the technology studied. In fact, most often, the maximum price value is a value taking into account the mean value of all the criteria. The minimum price value can be very different following the type of technology. For a mature technology, produced since a long time like Lead-Acid, minimum price is really the minimum value of price that can be found on the market. For an advanced technology like Lithium based, this minimum price is the result of the minimization of all the criteria. Then, the result is not an estimated minimum price but the lower boundary of the estimation (it seems impossible to find a price under this value).

## 1.2. 2012 price estimations

All the 2012 prices estimations are made in € (2004) with a standard ratio of 1.25 for €/$.
These evaluations are made using all the known data and several market trends analysis. Assumptions are made in each technology case taking into account the different factors able to have an influence on the results. These factors are different following the different technologies studied and will be given in a specific chapter after the main results presentation.

### 1.2.1 Today’s Battery level of development



*(Lithium based, NaNiCl2, NiMH, NiCd, Lead-Acid)*

### 1.2.2 The “scale effect” (or volume effect)

One of the main factors is the “scale effect” corresponding to the decrease of price as a result of the increase of production volume for a battery manufacturer. This “scale effect” has been studied by many specialists for more than ten years in order to define a relation between battery price and production volume. This relation is a function of the type of process (technology) and probably of the type of organization of the manufacturer. But in all the cases the relation obtained is of “asymptotic” shape with a fast decrease of price for low volume and after a given value of production volume a very slow decrease of price when volume increase.
This fact leads to the following conclusion:

- It is impossible to compare different technology prices if the stages of industrial development are too different,
- Price evaluations and comparison can only be made if the technology studied have reached the pilot production scale and have already a market even small (the uncertainty becomes too high for more recent technologies). But some qualitative forecasting can be made,
- Prices given or estimated for a new technology at the laboratory level are not reliable,

Our purpose is to estimate a value of the potential prices in 2012 of the different battery technologies assuming that they are used for large vehicle production volumes (it seems that this production volume value is of about 10 000 vehicles/year for BEV, and 50 000 vehicles/year for mild hybrids) called "mass production". The "scale effect" is then always in the asymptotic part of the relation between price and production volume.

### 1.2.3 Active material costs and production volume

Active material costs are the main part of the production costs for a battery in "mass production" (between 60 to 80% following the costs of battery assembly and BMS). Two very different cases have to be studied:

- For Lead-Acid and Nickel based (NiCd, NiMH, etc), the battery industry consumption of raw material is a minor part of the whole world industry consumption of this material, and the prices are set by the market without any relation with the battery production volume,
- For Lithium based in case of mass production the raw material consumption of lithium based traction battery industry will be the greatest of this type of product in the world. The prices are then function of the battery production volume, and a decrease of these raw material prices can be forecasted if the battery market grows.

### 1.2.4 Improvement of technical performances

If a battery for a given application decreases in weight because of an improvement of the technical performances (specific power for hybrids or specific energy for BEV), then the battery cost decrease as well (not always the price). This fact is the result of a decreasing need in active material for a given application. The active material used for a given technology can be also substituted by other giving the same performances for a lower price.
Taking into account the following elements:

- Technology improvements potential are very different following the different technologies,
- Relations between prices and performances are impossible to foresee,
- It is impossible to forecast more than 5 years before the material changes that can occur for a technology at the pilot stage as Lithium based,

Today's best known performances were chosen as the base of our estimation without any future improvement consideration. These potential improvements will be discussed in a second phase for each technology studied.

## 1.3 Main results

### 1.3.1 Today prices comparison

In all cases a standard ratio of 1.25 for €/$ has been chosen.

#### 1.3.1.1 Lead-Acid

Because of a high number of new design and new types of material introduced during the last ten years in this type of old technology, it becomes very difficult to make a reliable relation between price and performances. As the main interest of Lead-Acid is its low price, we have chosen a mean value of the prices given by many battery manufacturers for VRLA type convenient for the given applications today available. For hybrid applications, as power and life cycle seem to be not acceptable for the standard VRLA, many major companies have started R&D programs in order to increase the Lead-Acid properties. But corresponding increase of costs (and prices) seems to be high (prices of about 250 €/kWh can be found in the literature).

**BEV Battery of 30 kWh**

| | weight (kg) | min. price € | max. price € | €/kWh min. | €/kWh max. |
|---|---|---|---|---|---|
| **Lead-Acid** | 850 | 3 480 | 4 530 | 116 | 151 |
| **Ni-Cd** | 550 | 14 700 | 21 600 | 490 | 720 |
| **NiMH** | 430 | 16 770 | 19 980 | 559 | 666 |
| **NaNiCl$_2$** | 270 | 13 500 | 15 000 | 450 | 500 |
| **Li-Ion** | 270 | 21 000 | 25 800 | 700 | 860 |

**Mild Hybrid Battery of 12 kW, 0.4 kWh**

| | weight (kg) | min. price € | max. price € | €/kW min. | €/kW max. |
|---|---|---|---|---|---|
| **Lead-Acid** | 66 | 144 | 180 | 12 | 15 |
| **Ni-Cd** | 23 | 624 | 648 | 52 | 54 |
| **NiMH** | 15 | 552 | 720 | 46 | 60 |
| **$NaNiCl_2$** | 60 | 2 976 | 3 372 | 248 | 281 |
| **Li-Ion** | 7 | 528 | 624 | 44 | 52 |

**Full Hybrid Battery of 40 kW and 1.2 kWh**

| | weight (kg) | min. price € | max. price € | €/kW min. | €/kW max. |
|---|---|---|---|---|---|
| **Lead-Acid** | 111 | 480 | 600 | 12 | 15 |
| **Ni-Cd** | 75 | 2 080 | 2 160 | 52 | 54 |
| **NiMH** | 38 | 1 520 | 1 840 | 38 | 46 |
| **$NaNiCl_2$** | 200 | 9 920 | 11 240 | 248 | 281 |
| **Li-Ion** | 27 | 2 280 | 2 720 | 57 | 68 |

*Note : The grey rows (NaNiCl2 in the hybrid cases, and Lead-Acid in the full hybrid case) are given only for comparison. They do not have any technical reality because NaNiCl2 batteries are made only for energy applications (no power version today available) and the Lead-Acid battery weight (111kg) for full hybrid is not convenient for the design of this type of vehicle.*

#### 1.3.1.2 NiCd

NiCd batteries for traction applications are now produced by only one company in the world. Prices and costs are known and now only function of the active material prices. As these material prices are closely linked to Nickel price, their costs have increase of more than 100% since 1999. NiCd batteries are produced in a fully automated industrialized plant and only purchase volumes have an effect on the price. We have chosen a minimum value of the price corresponding to the purchase in volume price and a maximum value corresponding to the low volume price.

#### 1.3.1.3 NiMH

The NiMH battery production cost is a function of the active material prices closely linked with the Nickel market price. This market is very volatile since 1998 and it becomes very difficult to make any long term forecast. Our costs estimations are based on the today Nickel price (about 14$/kg) and an estimated ratio between Nickel (metal) price and active material of NiMH electrodes prices.

The power version of NiMH battery (for hybrids) is today in mass production and the technology is mature, it is not exactly the same for the energy version (BEV). We have assumed that all the estimated values of active material prices were the same in the two cases.

In the case of NiMH for hybrids battery, the battery assembly and BMS costs are a function of the battery and vehicle design, we have assumed reduced costs for the smaller one (mild hybrid) in agreement with the most common solutions chosen by the first industrial projects.

#### 1.3.1.4 Lithium based

Lithium based batteries are at the pilot stage for the most developed technologies (Li-Ion with liquid electrolyte), but the technology is not really mature today and many technologies are in competition in order to reduce the active material prices and to increase the safety. As it seems to be the technology with the highest potential, it is important to evaluate its potential price in the future. Today's price is not really a mass production price but only a price estimated with the today active material prices and a large production volume (mass production with no effect on the raw material prices).

All the known technologies (at the pilot stage) are taken into account by evaluation of a mean chemical composition (for each type of cells) and a minimum and maximum price of the active material as a function of their nature (Co, Mn, Ni Li(O)).

As the technical performances increase very rapidly for this technology, consequences on the cost estimations have been taken into account (number of cells for a given battery) based on the short term performances targets of several battery manufacturers.

#### 1.3.1.5 NaNiCl2 (ZEBRA)

Zebra battery is produced by only one battery manufacturer in the world (MES-DEA). For the today prices (as for NiCd), we have chosen the real today prices of the company for large orders.

## 1.3.2 2012 prices estimation

**2012 Battery Prices in € (2004)**

**BEV Battery of 30 kWh**

| | weight (kg) | min. price € | max. price € | €/kWh min. | €/kWh max. |
|---|---|---|---|---|---|
| **Lead-Acid** | 850 | 4 733 | 6 161 | 158 | 205 |
| **Ni-Cd** | 550 | 14 700 | 21 600 | 490 | 720 |
| **NiMH** | 430 | 16 770 | 19 980 | 559 | 666 |
| **$NaNiCl_2$** | 270 | 6 360 | 7 500 | 212 | 250 |
| **Li-Ion** | 270 | 10 800 | 14 310 | 360 | 477 |

**Mild Hybrid Battery of 12 kW, 0.4 kWh**

| | weight (kg) | min. price € | max. price € | €/kW min. | €/kW max. |
|---|---|---|---|---|---|
| **Lead-Acid** | 66 | 196 | 245 | 16 | 20 |
| **Ni-Cd** | 23 | 624 | 648 | 52 | 54 |
| **NiMH** | 15 | 552 | 720 | 46 | 60 |
| **$NaNiCl_2$** | 60 | 2 976 | 3 372 | 248 | 281 |
| **Li-Ion** | 7 | 276 | 384 | 23 | 32 |

**Full Hybrid Battery of 40 kW and 1.2 kWh**

| | weight (kg) | min. price € | max. price € | €/kW min. | €/kW max. |
|---|---|---|---|---|---|
| **Lead-Acid** | 111 | 653 | 816 | 16 | 20 |
| **Ni-Cd** | 75 | 2 080 | 2 160 | 52 | 54 |
| **NiMH** | 38 | 1 520 | 1 840 | 38 | 46 |
| **$NaNiCl_2$** | 200 | 9 920 | 11 240 | 248 | 281 |
| **Li-Ion** | 27 | 1 200 | 1 600 | 30 | 40 |

*Note : The grey rows (NaNiCl2 in the hybrid cases, and Lead-Acid in the full hybrid case) are given only for comparison. They do not have any technical reality because NaNiCl2 batteries are made only for energy applications (no power version today available) and the Lead-Acid battery weight (111kg) for full hybrid is not convenient for the design of this type of vehicle.*

### 1.3.2.1 Lead-Acid

For 2012 costs (and prices) evaluation, we have chosen as in the previous case lead-acid battery design that can be cost convenient. Prices evaluation has been made taking into account no real increase in power or energy performances and an increase of cost in relation with the high market price of lead and all the data given by the battery manufacturers (an increase of about 36% in 2012 and € (2004) has been anticipated by most of the lead-acid battery manufacturers).

### 1.3.2.2 NiCd

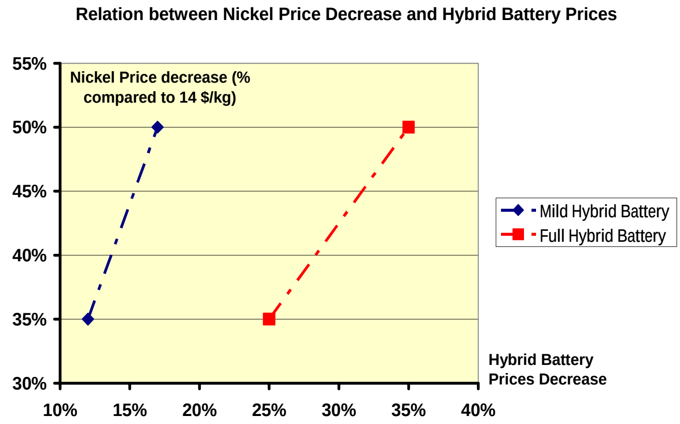
No real increase of the market of NiCd “traction” battery can be expected in the next years, on the contrary a decrease of the BEV NiCd batteries market can be anticipated in relation with the environmental Cd problems and regulations and the development of more efficient technologies.

In this situation no decrease of cost and price can be expected and the battery cost will be closely linked with the Nickel prices variation. We have chosen to keep the same prices between 2005 and 2012 (in 2004 €).

### 1.3.2.3 NiMH

The same prices (and costs) have been kept between 2005 and 2012 (in 2004 €) for NiMH technology assuming the following elements:

- Nickel market is very volatile but mean value will be high (between 10 and 15 $/kg) leading to nearly constant prices of active material,
- No “scale effect” can be expected for this technology,
- Technical improvements will not be high enough to have an influence on the price,
- The R&D activity for the development of advanced NiMH batteries for BEV applications has significantly decreased. No major battery manufacturer is now focusing on this technology for energy applications.



Two complementary results have to be considered:

- Relation between NiMH battery prices and Nickel price,
- Prices that could be used by the Chinese battery manufacturers specialized in this technology (see specific paragraph).

#### 1.3.2.4 Lithium based

Estimations are more difficult for this technology because of an intense R&D activity all over the world leading to an uncertainty concerning the technical performances and the type of active material (and cost) that will be used in 2012.

The following assumptions have been taken:

- Mass production of energy (BEV) and power versions (Hybrids) and decreasing active material costs,
- BMS and other electronic accessories are mass produced leading to a high decrease of price,
- For mild hybrid battery part of the electronic components has been included in the vehicle control unit,
- New technology developments lead to a decrease of active material costs and technical performances corresponding to the best laboratory performances known today,
- Comparison are made with the Lithium based portable battery market,
- The minimum price is calculated on the basis of the best known data of all the previous factors,
- The maximum price is calculated on the basis of mean value of the previous factors.

As for NiMH the special case of Chinese battery manufacturer has to be taken into account (see specific paragraph).

#### 1.3.2.5 NaNiCl2

The Zebra battery cost in mass production case have been studied and published by MES-DEA in 2002. Our estimations have been made using this published data and complementary evaluations taking into account the raw material price changes and some elements coming from a complete analysis of the technology and the production process. Results are only an order of magnitude of future prices because all the process costs can’t be checked up.

### 1.3.3 The specific case of Chinese Manufacturers

Since 1998, the Chinese Government and some private investor have started a dynamic politic of development of the battery industry. In relation with the national R&D program (863 program) many of the major Chinese battery companies have focused on traction battery development based on NiMH and lithium technologies.

This merging Chinese industry is in a very different situation compared to European, Japanese and American one for two main reasons:

- For NiMH and Lithium based a great amount of the raw material needed are coming from China,
- Chinese manufacturing costs (as for the other industries) are much lower.

It is today impossible to anticipate the prices that will be used by Chinese Manufacturers in 2012, but it seems probable that the technical performances will be of the same order compared to the other country companies and the prices will be lower.

A first estimation has been made using the information obtained during a special mission made recently for SUBAT project:

- NiMH for energy applications (BEV): a decrease of cost of about 50% seems to be possible, leading to a decrease of price of probably more.
- NiMH for power applications (hybrids) are not really developed in China for the moment,
- Lithium based for energy application: a decrease of cost between 20 and 30% seems to be possible ,

- Lithium based for power application: a decrease of cost between 30 and 40% seems to be possible.

## 2. World Traction Battery Market and Trends to 2012

As far as only the Battery Market for traction applications is concerned, the future battery market trends are closely related with the forecast of Hybrids and Battery Electric Vehicle Markets (Advanced Vehicles). The main purpose of this study is to evaluate the probability of mass production of each type of battery technology in 2012. It is then necessary to study the long term forecast for advanced vehicles and the corresponding battery needs. Taking into account only the passenger and light duty car market (96% of the total vehicle market) in a first step, the main factors that will drive the market are:

- Policy factors (laws, regulation and public subsidy) concerning the local pollution, the $CO_2$ emission (GHG) and perhaps the oil consumption,
- The oil market price pressure,
- The price of advanced vehicles compared to ICE one,
- The increase of sense of civic responsibility concerning the air pollution problems.

The consequences of these factors on the vehicle market can be studied only considering four different markets: Europe, Japan, America and China.

### 2.1 European Market

Market of about 17 million of vehicles in 2004, this market is mainly driven by three factors: the European Union laws and regulations concerning the local pollution (Euro IV and Euro V), fuel economy and CO2 emission incentives and price of vehicles. It is also characterised by small vehicles with small engines and a high amount of new type of eco-diesel engines.

A complete analysis of all the data made for several scenarios of development leads to the following conclusions:

- Advanced vehicle market will start and increase to a value between 3 and 8% of the total passenger car market (500 000 to 1.4 millions of vehicles) in 2012 depending on the scenario chosen,
- Mild hybrid type will prevail, probably equipped with a 42V battery pack of about 0.2 to 0.4 kWh and 9 to 12 kW (10s) leading to a battery weight between 1 800 to 4 000 t.
- Competition will prevail between advanced lead-acid, NiMH and Lithium based,
- Ratio will depend on relative cost for Lead-Acid and NiMH and of cost and safety for Lithium based.
- Market seems to be to small by itself to induce a world increase of the new technology battery market,
- BEV market will remain a niche market (between 30 000 to 100 000 vehicles/year) using probably mainly lithium based batteries.

### 2.2 Japanese Market

Market of about 13 millions of vehicles in 2004 (with Korea), this market is mainly driven by fuel economy, increase of comfort and vehicle price. It is also characterized by a great majority of small gasoline engines, midsize cars and strong incentives towards fuel economy and $CO_2$ emission reduction (a mean value of 25% in ten years). Laws and regulations for local pollution are less important (but standard values are comparable to European one) in relation with the type of fuel used.

A complete analysis of all the data made for several scenarios of development leads to the following conclusions:

- Advanced vehicle market has started in 2004 and will increase to a value between 5 and 10% of the total passenger car market (perhaps more) leading to values between 650 000 and 1.5 million of vehicles/year in 2012. But as this market is also driven by the US market these values can be higher if the US Car Manufacturers are not able to compete on this market,
- Full hybrid type will prevail equipped with high voltage batteries but probably all types of mild and full hybrids will be produced.
- Competition will prevail between NiMH and Lithium based batteries probably manufactured in China under (or not) Japanese licence (8 000 to about 30 000 t of batteries) and in the case of success of current lithium based development projects (cost and safety) lithium based have probably the best future,
- This market is enough to induce a mass production market for the new battery technologies concerned (in this case the consumption of active material is greater than the portable battery market),

- BEV market will remain very low and it seems to be too early to forecast any development of FC vehicle market.

## 2.3 The North American Market

Market of about 18 million of vehicles in 2004, this market is mainly driven by comfort and vehicle performances and for a part by incentives of several administrations (California and other states). It is also characterized by large cars (SUV, trucks etc), large gasoline engines and low fuel price. It becomes possible that very stringent regulations appear before 2012 concerning the local pollution, but no reliable forecast can be done.

A complete analysis of all the data made for several scenarios of development leads to the following conclusions:

- The advanced vehicle market has started in 2004 and will increase driven more by the increase of comfort and performances without any increase of consumption than other reasons. It will probably reach values between 4 and 8% of the total passenger car market (700 000 to 1.5 million of vehicles/year),
- On the opposite of European Market large or powered hybrid vehicles will prevail probably of all types depending on the market segment,
- Part of this production will come from Asia (Japan, Korea and perhaps China) and it seems that nearly all the corresponding battery packs will come from Asia too,
- Competition will prevail between Lead-Acid (for the smaller part), NiMH and Lithium based,
- This battery market can be considered as comparable to the Japanese one (manufacturers, volume and consequences),
- There is no reason to have any change of the BEV market that now nearly does not exist.

## 2.4 The Chinese Market

This Market is a new one, from about 4 million of vehicles in 2003 and with a yearly increase of more than 12%, it becomes possible to reach a size of more than 8 million of vehicles/year in 2012. As a new one, it is not so well known than the others and it becomes difficult to make reliable forecast. But some of the main characteristics can be described and consequences can be analysed assuming several different scenarios

This market will be mainly driven by fuel economy and governmental policy and hypothesis of a rapid growth of ultra-low-emission vehicles can be done for the following reasons:

- Chinese oil consumption increases very rapidly (about 30% per year) even though more than 50% is imported today,
- Local pollution has dramatically increased the last few years in all the main Chinese towns,
- China is one of the main world producer of active material for NiMH and Lithium based batteries,
- Development of advanced vehicle market could be a way to improve the development of Chinese car industry,
- On the opposite of all the other markets, Chinese authorities can have a direct impact on the vehicle market changes.

Consequences on the advanced vehicle market could be the following:

- Development of low prices little hybrids of all types, advanced electric vehicles and US type hybrids at the same time,
- Development of the electric two wheelers market (very important in China),
- Development of the hybrid and electric bus market.

In all cases the Chinese traction battery market will increase based on an internal production and consumption. This increase could have a consequence on the other markets (European and US) with an important decrease of the battery prices (NiMH, Lithium based).

# SUBAT FINAL REPORT

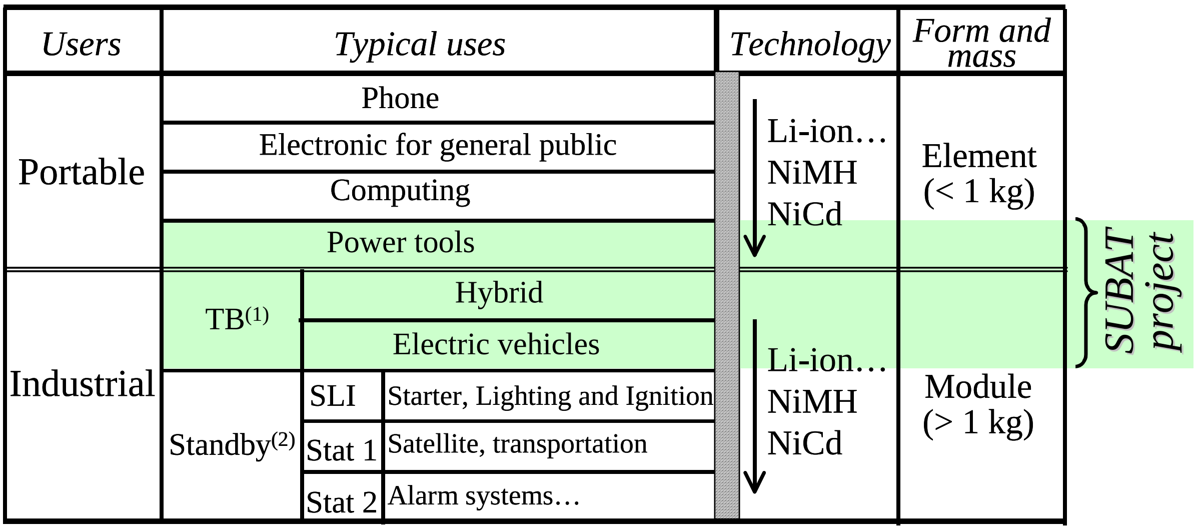
# Economical Assessment

# WP3

# B - Micro-economic Study

# 1. Battery Types Definition and related Markets

Batteries can be divided into two categories which are portable batteries (public and professional users) and industrial batteries (large batteries for transport and stationary applications), and according to batteries state-of-the-art, the electrochemical technologies (NiMH, NiCd, Li-ion…) are the same whatever the domain of application (cf. the overlapping hatched zone on Fig. 1-1). In this context, SUBAT project is placed at the portable and industrial batteries applications bound (green zone on Fig. 1-1).



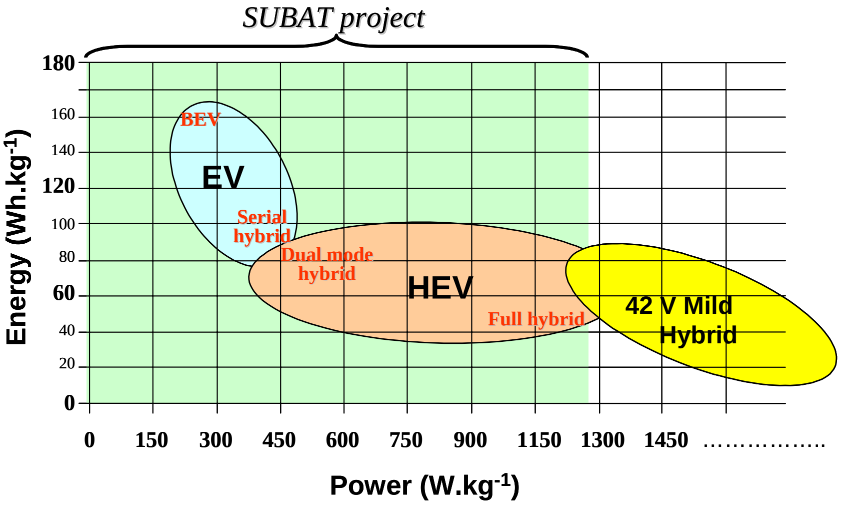
| Users | Typical uses | | | Technology | Form and mass |
|---|---|---|---|---|---|
| Portable | Phone | | | Li-ion…<br>NiMH<br>NiCd | Element<br>(< 1 kg) |
| | Electronic for general public | | | | |
| | Computing | | | | |
| | Power tools | | | | |
| Industrial | TB(1) | Hybrid | | Li-ion…<br>NiMH<br>NiCd | Module<br>(> 1 kg) |
| | | Electric vehicles | | | |
| | Standby(2) | SLI | Starter, Lighting and Ignition | | |
| | | Stat 1 | Satellite, transportation | | |
| | | Stat 2 | Alarm systems… | | |

(1): traction battery and (2): batteries for stationary applications

*Figure 1-1: Rechargeable batteries segmentation*

N.B.: In this report, the acronym SLI is applied to lead acid automotive batteries.

In a second point, the difficulty lies in defining the battery types according to their applications in the automotive industry (either pure electric vehicle field or hybrid vehicle field (Fig. 1-2)) when the same technologies are developed. Thus, the batteries for EV applications are “energy” batteries (strong specific energy and low specific power) and the ones for HEV applications are “power” batteries (strong specific power and low specific energy). Furthermore, the maximum specific energy and power values are not valid simultaneously (in some cases dual battery configuration is also developed showing intermediate values in energy and power).
To make the two types of batteries, the manufacturers adapt their production line to the batteries destination, for example, by changing active material and separator quantities.

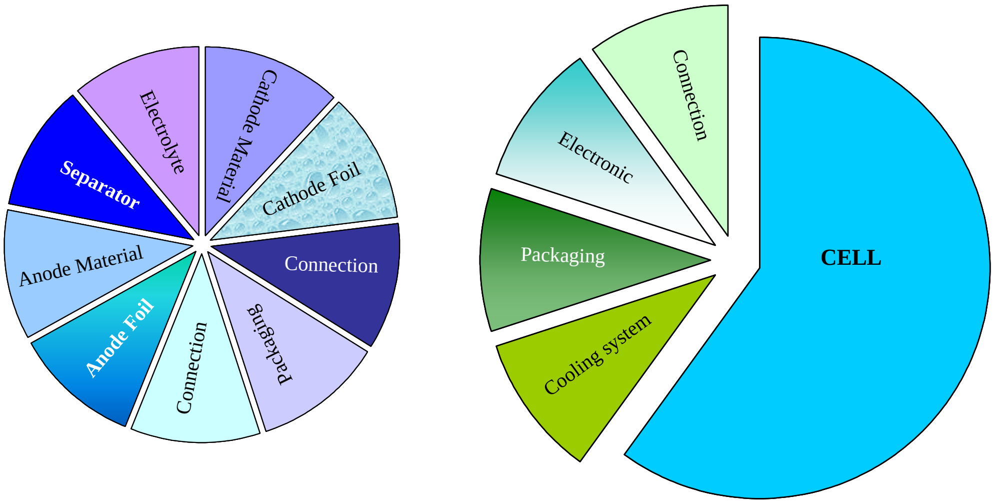


As in the previous table, the study area of SUBAT project is symbolised by a green zone (Fig. 1-2), including batteries for EV, HEV and power tools applications.

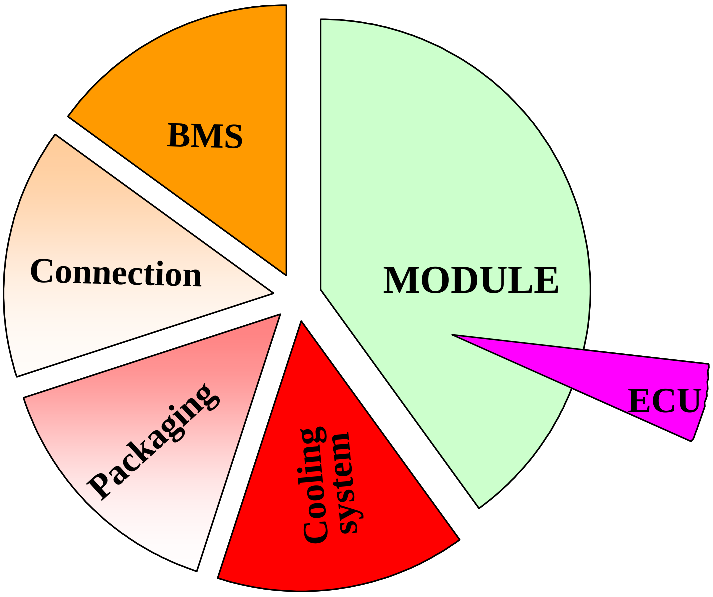
*Figure 1-2: Definition of EV, HEV and mild hybrid batteries according to specific energy and specific power*

## 2. Battery System Constitution for Automotive applications

In this section, various components of the battery pack (Fig.2-1) will be defined in detail in the aim to subsequently evaluate the potential evolution of the full battery cost.



(a)**Cell** (b) **Module**



(c) **Pack**

*<u>Figure 2-1</u>: constitution of HEV / EV battery's (a) cell, (b) module and (c) complete pack respectively.*

❖ An electrochemical generator or voltaic cell is a system which supplies an electric energy by using chemical energy produced by redox reactions. In the discharge state this electrochemical system is called accumulator (or more commonly battery) if the implicated redox reactions are reversible. Finally, two electrodes (a+e and b+e, see below) are in electronic and ionic (c) contact to generate current when a physic border called separator (d) exists.

❖ Electrochemical cell components:

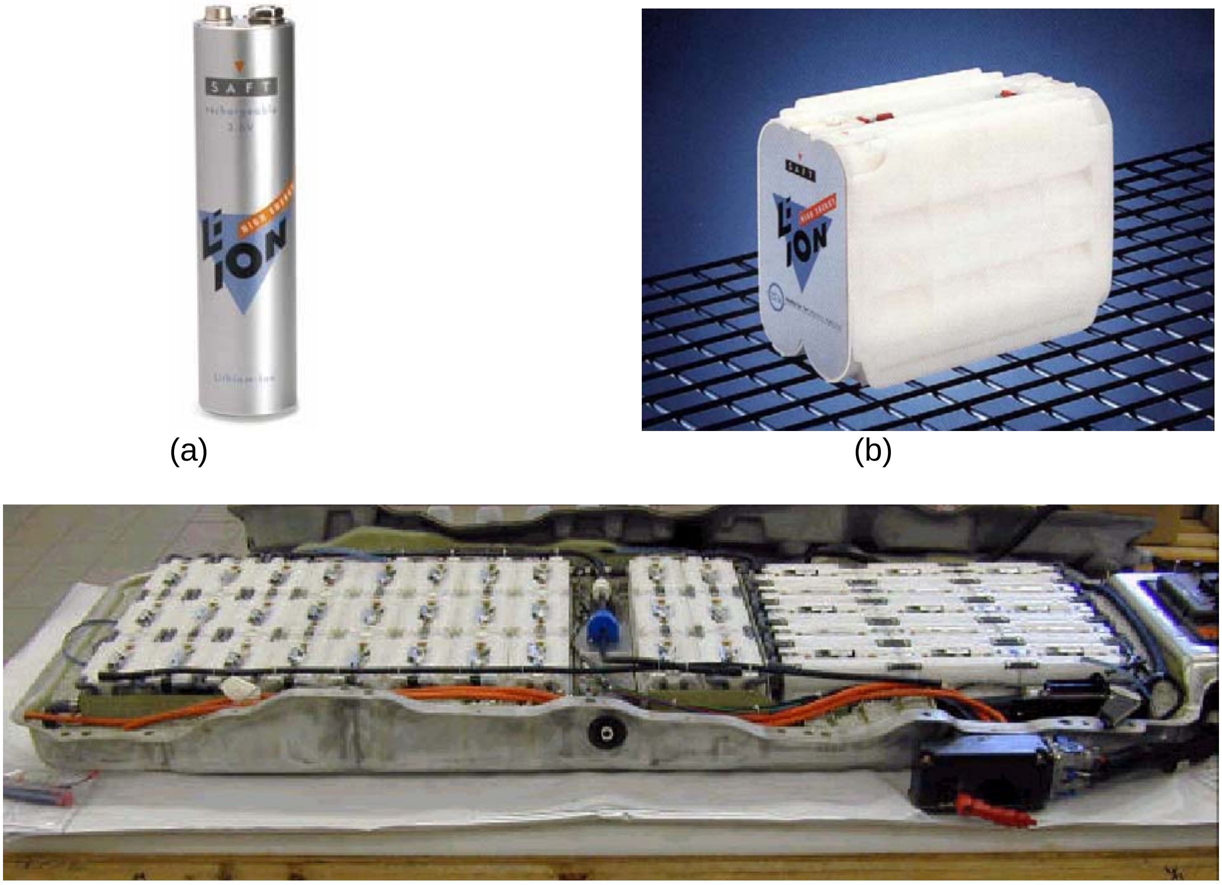
The electrodes are made up of electronic conductor materials in order to allow electron circulation.

*(a)* The reduction phenomenon takes place at the cathode (sometimes called active material) with electrons consumption. In the discharge state, this electrode is the positive pole.

*(b)* The oxidation phenomenon takes place at the anode with electrons production. In the discharge state, this electrode is the negative pole.
N.B.: the positive pole (cathode in discharge and anode in charge) relative voltage is higher than the negative one.
*(c)* The ionic conduction (ions migration) is provided by the electrolyte which can be a liquid or a solid material.
*(d)* The separator have two functions, the first is to keep the electrodes apart, and the second is to insure the electrochemical cell security (e.g. against short circuit).
*(e)* The cathode and the anode are in contact with the current collectors to provide the current circulation and the electrode cohesion.
The cell can design and size depend on the geometry cell choice (e.g. cylindrical or prismatic). Thus, the material used for the can making must be rigid and non-reactive (e.g. non corrodible) with electrolyte and active materials.

- Pack module and battery:

Whatever the electric vehicle's type, the battery manufacturing process is facilitated by the standardization of the module size and voltage.
*(a)* Module and battery packaging material: As for the cell can material, it is a rigid material and the shape must be kept during installation and vehicle use, moreover, the package must be lightweight and inexpensive, that is why plastics are usually chosen. For example, the Figure 2-2 shows a battery in cylindrical configuration.
The pack module contains cells and its electronic, sometimes a cooling system and inter-cell connection.
The packaging of the battery contains modules, the cooling system, some connectic and the BMS which is made and supported by car or battery manufacturers.



(a) (b)

(c)

*<u>Figure 2-2</u>: (a) cell to (b) module to (c) battery system (SAFT Lithium-ion BEV) [21].*

*N.B.: The elements size of previous pictures are not respected for the information, the cell, module and battery weight are 1.07 kg, 7.15 kg, 420 kg (including the cooling fluid), respectively.*

In order to respect the safety requirements, abuse tests are undergone (mechanical, thermal and electrical typical tests…); cell packaging, module and battery have to remain intact and must not emit any effluent and it will not catch fire.

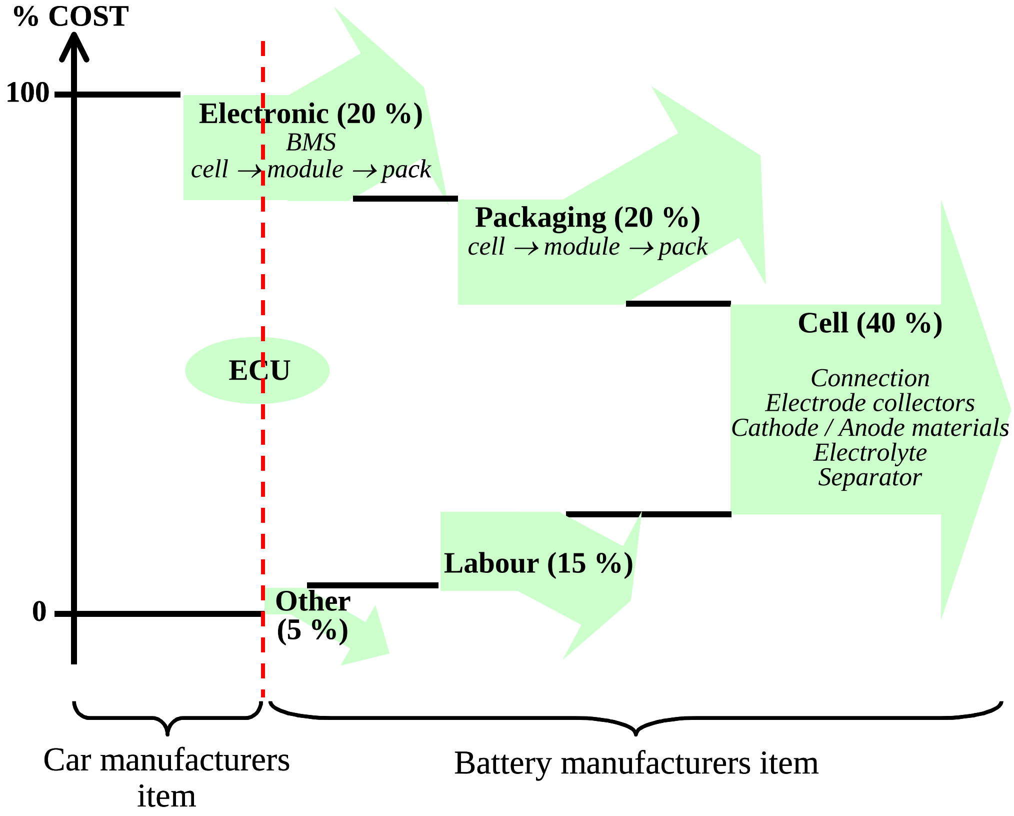
*(b)* Batteries used in electric and hybrid vehicles must naturally have high energy and power densities. In the aim to preserve cycling life and other fundamental characteristics of battery, it is important to improve the used technologies to obtain the best compromise between all these performances.

The internal electronic system of the battery is described by BMS, acronym of Battery Management System and its function is to control and to regulate the thermal, electrical and mechanical points within the cell, the module and the pack (measurement + intelligence device). This electronic system must insure the battery security.

*(c)* The cooling system can be of two types, liquid (water-based mode) and/or air device (cooling fan) in order to ensure a maximum cooling effect.

# 3. Cost analysis of a Battery System for Automotive Applications

This section concerns the cost of EVs and HEVs battery in the general case. Whatever the battery's technologies and their application, the highest contribution at the full cost are the cell active materials used for the electrodes (Fig. 3-1). Their Cost decrease will contribute mainly to a more competitive global cost. The figure 3-1 shows the different per cent contributions to the battery cost. The numbers are given in arbitrary per cent as an example.



*ECU : electronic control unit (vehicle interface)*

*Figure 3-1: flow diagram of various contributions at the full battery cost.*

N.B.: The design of the complete battery pack is often realized by the car makers, while it depends on the vehicle design and specifications. The financial charge of the packaging is supported by the car or the battery manufacturer.

The cost of advanced batteries for EVs and HEVs is highly dependent on production volume and a consistent market situation that encourages capital investment in production capacity and line automation. This phenomenon induces a “scale effect” which can lead to a decrease of the raw materials cost and of the corresponding batteries (case of new technologies). On the contrary for improved technologies and as the decrease of raw materials is no more possible it can lead to an increase of battery price or a margin decrease of the manufacturers (cf. market pressure in the lead-based battery case).

In order to compare reasonable estimations of the cost, in each battery technology and each automotive applications case, a specific study has to be made for each technology taking into account the raw material used and their quantities and costs, the labour cost for cells, modules and batteries, the margin, overheads and other company costs, the accessories costs (BMS, packaging) etc… In each case costs leading to a given price have to be detailed.

The results of these estimations have to be expressed in significant values and units also chosen to allow valuable comparison between the technologies studied. The following table summarized the way we have chosen to express the results and make the comparison.

*Table 3-2: Representative Battery Packs chosen*

| Vehicle type | Mild Hybrid | Full Hybrid | Full Hybrid with 40 km ZEV (Dual mode) | BEV |
|---|---|---|---|---|
| Energy (kWh) | 0,4 | 1,2 | 10 | 30 |
| Power (10s, kW) | 12 | 40 | 50 | 50 |
| Voltage (V) | 42 | >270 | >270 | >270 |
| Cost and Price units | €/kW | €/kW | €/kWh | €/kWh |

Light vehicles (e-bikes, scooters etc) and heavy vehicles are most often comparable to BEV vehicles exception made for some heavy duty vehicles where the battery power can become an important factor.

Estimations are always made using the following method:

1. Costs evaluation of materials of a basic Cell or Module ,
2. Global Costs evaluation of a basic Cell or Module
3. Costs evaluation of a battery Pack taking into account all the necessary accessories,
4. Price evaluation of the battery Pack chosen,
5. Specific Battery Pack Price indicator in the corresponding Unit.

Depending on the maturity of the technology studied some other hypothesis must be made. In the final global comparison (see last chapter of the micro-economic study) all these hypothesis are remained.

# 4. Technologies

## 4.1. Advanced Lead-Acid

### 4.1.1. Technology

In the lead-acid technology, the electrode reactions are both based on lead at two different oxidation states: $Pb^0$ to $Pb^{2+}$ at the anode and $Pb^{4+}$ to $Pb^{2+}$ at the cathode. The particularity of the lead-acid technology is the participation of the sulphuric acid used as electrolyte in the complete reactions at both electrodes. During the charge / discharge reactions, the concentration of the electrolyte is modified. Then, the both electrode materials are converted into lead sulphate inducing the "double sulphate reaction" name of the lead-acid chemistry.
N.B.: A solution of diluted sulphuric acid in water acts as electrolyte in the lead-acid technology.

At the cathode: $Pb^{4+} + 2e^- \xrightarrow{\text{Reduction/discharge}} Pb^{2+}$

$$PbO_2 + 2H^+ + H_2SO_4 + 2e^- \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftharpoons}} 2H_2O + PbSO_4$$

At the anode: $Pb \xrightarrow{\text{Oxidation/discharge}} Pb^{2+} + 2e^-$

$$Pb + H_2SO_4 \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftharpoons}} PbSO_4 + 2H^+ + 2e^-$$

Total cell reaction: $Pb + PbO_2 + 2H_2SO_4 \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftharpoons}} 2PbSO_4 + 2H_2O$

N.B.: The lead-acid cell have a nominal voltage of about 2.1 V *versus* NHE.

The theoretical energy density for the lead-acid cell is about 170 $Wh.kg^{-1}$. But the lead sulphate produced at the both electrodes by previously described reactions is not soluble and not conductor. Its accumulation at the electrodes induces a practical energy density only of about 40 $Wh.kg^{-1}$.

In the last few years electrochemical accumulators have been in large development and new battery typologies have became commercially available, especially for portable applications. Nevertheless the lead-acid battery is still the most used in a number of applications. Its major application in the automotive industry is to provide energy and power for engine starting, vehicle lighting, and engine ignition (called SLI batteries). It is also used extensively in telephone systems, power tools, communication devices, emergency lighting systems, and as power source for mining and material-handling equipment. Because of new applications for power batteries in energy storage, emergency power, its production and use continue to grow.
Their low cost and the ease in manufacturing often make this battery as the chosen option even in applications where high electrical performances are requested. Despite of its low efficiency (75-80%) and low specific energy (< 40 Wh/kg) and low lifecycle compared to other battery technologies, lead-acid batteries are still used frequently also in electric and hybrid vehicles.

New designs and fabrication processes are still introduced at significant rates, in order to increase the performances (power and lifecycle). Small individual lead-acid cells and batteries are now available for use in small electric appliances and electronics applications (portable Lead-Acid batteries). Lead-acid battery designs for many small portable and nearly all the SLI applications (since a few years) are often named as sealed and/or maintenance free, but actually no design has true hermetic seal and only a pressure release valve which limits outflow of gas from the cell. Batteries with release valve are also named as ''Valve Regulated Lead-Acid Batteries'' or VRLA.

The lead-acid technology has been developed considerably in design and construction over the decades but the basic chemistry remains the same. Advanced lead-acid battery technology is design in order to eliminate electrolyte spillage and hydrogen and oxygen gas emissions during charging.
Since 3 or 4 years maintenance free batteries as VRLA ones, have completely replaced “flooded” or “wet” ones (i.e. opened cells inducing a great amount of electrolyte in the battery) on the automotive market. VRLA batteries have only a limited amount of electrolyte (‘‘starved’’ electrolyte). In consequence the SUBAT study will be focused on VRLA and bipolar batteries.

- *Lead-acid batteries constitution*

As all technologies, the Lead-acid one is based on current collectors/active materials/electrolyte/separator device.

- Electrolyte

The electrolyte is a concentrated solution of sulphuric acid (i.e. $H_2SO_4$) in the flooded batteries case. In the VRLA and bipolar technologies, the electrolyte $H_2SO_4$ solution, is fixed using two methods:

1/ Gelled electrolyte: fumed silica (silicon dioxide $SiO_2$) and multiple additives are added to the electrolyte that becomes then a gel. After some initial charges some water is lost, and the gel dries developing a network of cracks and fissure between the cathode and the anode.

2/ Absorbed electrolyte or AGM (namely Absorbent Glass Material): The AGM batteries are the latest step in the evolution of Lead-acid batteries. The electrolyte is similar to the gel cell one (i.e. $H_2SO_4$), but instead of having an electrolyte in a gel form, it is a liquid one. The electrolyte is absorbed into a very fine glass material (i.e. borosilicate compound). The electrolyte will be in an unsaturated form. The AGM separator provides ideal wicking characteristics for electrolyte retention. The electrodes are separated by this material layer, highly porous and absorbent, made of fine glass microfibers; partially filled with electrolyte it acts as the separator/electrolyte reservoir. The larger pores of the AGM separator allow the transport of the gas.

3/ Gel and AGM electrolyte comparison:
- The amount of electrolyte in the gel case is greater than in the AGM one.
- A gel battery is charged slower than an AGM one, due to the high viscosity of the gel-electrolyte.
- The specific weight of the gel-electrolyte is lower than the AGM one, inducing a least corrosions to pole plates and a longest service life for the gel battery.
- The gel battery has excellent cyclic performances while problems of dendrite formation are met in the AGM structure.
- Under normal conditions of storage and transport, gel batteries have a self-discharge rate less than 2 % per month whereas it is about of 3-5 % per month for AGM type.
- Gel batteries have weaker charge efficiency than the AGM ones, allowing a reloading with more energy.
- The main problem of the Lead-acid battery technology (in flooded design) is the electrolyte acid stratification, but this phenomenon is impossible due to the immobilisation of the electrolyte in the gel. By the AGM use the influence of acid stratification can be minimised in horizontal assembly of the cells.

- Current collectors and active materials

Usually, the cathode is made of few sulphuric acid and pure lead that is partially oxidized by air under controlled conditions, inducing a cathode composition with lead and lead dioxide mixture powders. Mainly the anode is a sponge lead-based grid or a pure lead plate (namely Planté device).

- Separator

The separator is made of polyethylene or micro-fibreglass in the special case of AGM.

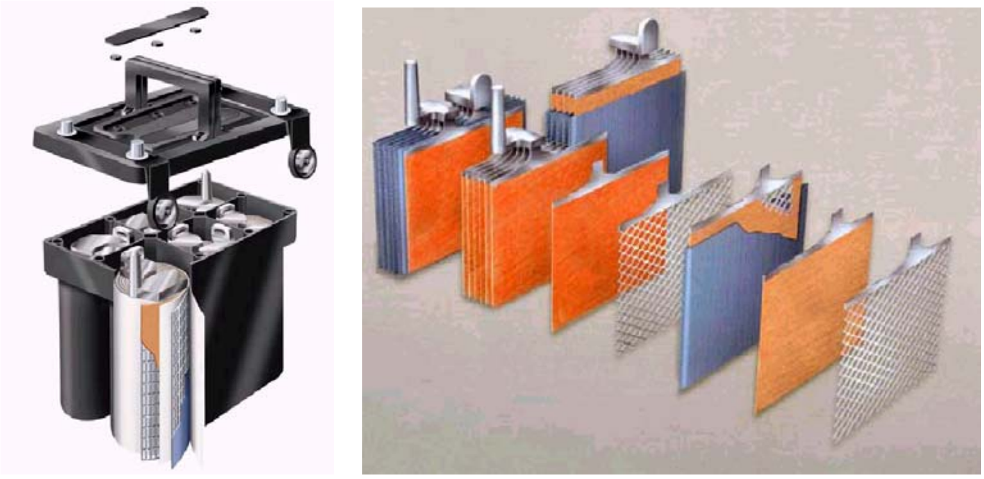
- *Basic Lead-acid batteries configuration*

The cell capacity is usually limited by the amount of cathode active material, while the excess of anode active material together starved electrolyte facilitate the recombination of oxygen produced during overcharge or ‘‘float’’ charge. The release valves are normally closed to prevent the entrance of oxygen from the outside air and the vent pressure depends on the manufacturer and mainly the case shape and material. VRLA batteries can have two usual shapes (1 and 2), but a specific configuration

is also adopted the tubular plate structure (3). The current collectors can be of two types: grids (the main used design for SLI appliances) or tubular.
(1) Spirally-wound electrodes: The cell elements are wound in order to adopt a cylindrical shape.

(2) For the flat plate electrodes, the battery design takes a prismatic shape.
In the two configurations, the use of gel or AGM electrolyte is allowed. The main used design of current collectors is grid.
Several electrode configurations can be used with grids current collector. The active material can be pasted with the grid and then the plates are wound in order to have a cylindrical shape (i.e. spiral pasted technology, Fig. 4.1.1a) or can be undergone with the grid to an extrusion process (i.e. flat plates technology, Fig. 4.1.1b). The cathode can also be obtained by electrolytic deposition of thick lead plate, (Planté plate, pure lead use) a high specific power and a long cycling life but a low specific energy are then achieved. In all cases the use of perforated or grooved plate increases the surface area. The cathode potential is so high that all metals are anodically dissolved. Only lead can be used because the lead corrosion due to the sulphuric acid electrolyte contact lead to the lead dioxide layer formation. Then, the dioxide lead active material is simply a product of corrosion process. Actually, the cathode is pasted on the current collector with an ABS (acrylonitrile butadiene styrene) co-polymer. At the anode, carbon black or expander graphite is added to the active material.
Sometimes, zinc is added to the anode because it has a strong ability to suppress hydrogen release at the negative plate. And at the cathode the addition of the mix antimony-iron can suppress the oxygen release effect of the transition metals contained in the cathode active material.

The material used for the grid is pure lead ingot, in which lead alloys as lead-antimony (i.e. usually about 11 % w. of Sb), lead-antimony-arsenic, lead-antimony-cadmium, lead-calcium-tin (the most used today), lead-calcium-tin-silver or lead-tin are added to harden it.
For example, FIAMM SpA works on Pb-Ca-Sn alloy grids by changing the relative amount of calcium/tin, and the best performances are reached with a low level of calcium and a high levels of tin. In practice, they are manufacturing advanced metal alloy with lead-calcium-tin or lead-antimony-selenium (cathode grid) and lead-calcium (anode one), namely *SLI Premium* or *Original* batteries.
In order to prevent grids manufacturing defects and to improve electrochemical properties, smalll quantities of arsenic, tin or selenium are added to the cathode active material. Indeed, this addition permits to form fine lead selenide particles, for example, in the molten alloy which act as nucleants during the solidification process inducing a lot of crystals formation and then a great hardening of the lead grid.



(a) Wound technology (b) Flat plates technology

*Figure 4.1.1: Different plates technologies used in Lead-acid battery.*

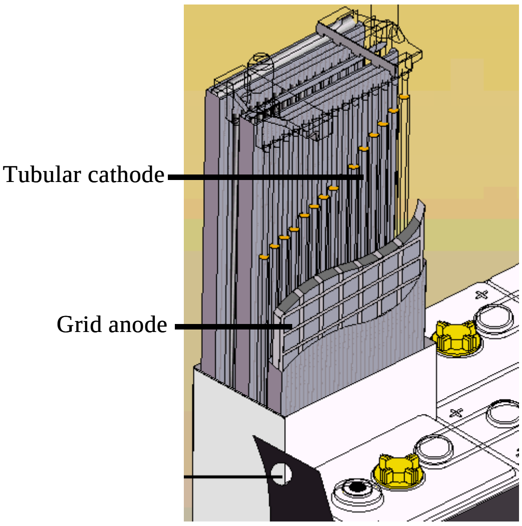
The cylindrical containers can maintain a higher internal pressure without deformation and they are designed to have a higher release pressure than the prismatic cells. In some design, an outer metal container is used to prevent deformation of the plastic cases at higher temperatures and internal cell pressures.

(3) In this last case, the tubular plate (i.e. gauntlet) adopts a prismatic shape and their operating is only possible with a gelled electrolyte suspension system or gel electrolyte. As the previous configurations, the electrolyte is based on concentrates $H_2SO_4$ solution.

The active material of the cathode is enclosed in a tubular plastic jacket (Fig. 4.1.2) in which there is a lead wire in their centre that acts as the current collector. These tubes, of diameter is about 8 mm, have a high retention capacity, inducing a long cycling life. The anode is constituted of flat grid or plate of lead-based support on which a dense paste of active material is deposited. The separator is a common porous polyethylene material (like the ones used in VRLA spiral-wound or flat plates configuration)

This tubular cell technology is of minor importance in the Starting Lighting Ignition (i.e. SLI) field but this technology is rather met in motive power and stationary applications. Indeed, for the heavy-duty industrial applications, tubular lead-acid battery is the most widely used type of battery.

Gauntlet and core Gauntlet and core front view Finished tubular plate



Complete assembly: tubular cathode and grid anode

*<u>Figure 4.1.2</u>: Different plates technologies used in Lead-acid battery.*

*Summary of different systems of Lead-acid batteries*

The technology of Lead-acid batteries is one of the oldest, inducing a lot of improvements made since many years. Researchers have worked on the battery configuration (cylindrical/prismatic), on the grids composition and thickness, and on the minimisation of the battery size (bipolar arrangement). On the figure 4.1.3 is shown a synthetic diagram of the Lead-acid batteries met nowadays in the automotive field.

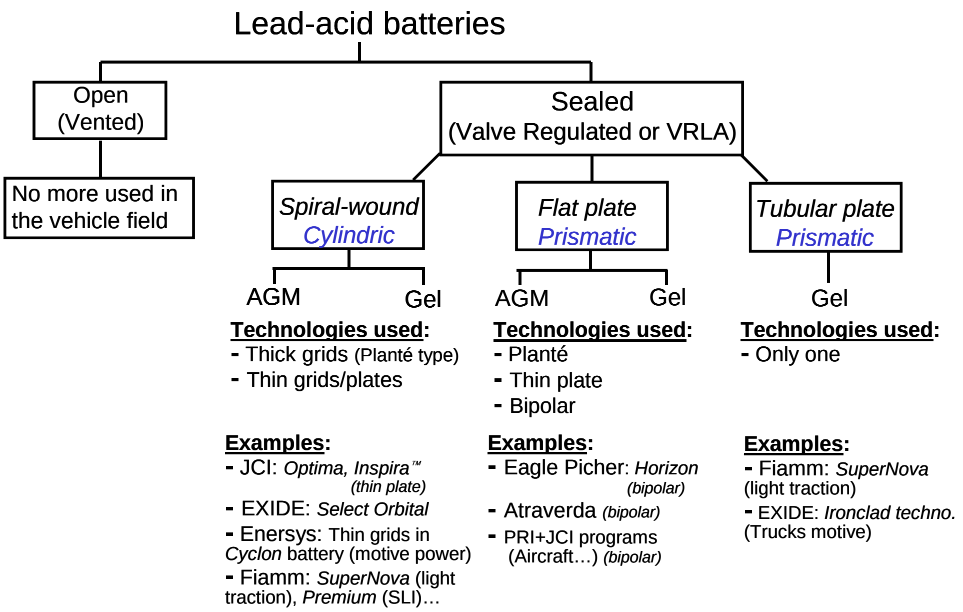


*Figure 4.1.3: Scheme of different Lead-acid batteries technologies.*

*Examples of today commercial batteries (Advanced Lead-Acid Batteries)*

* Spiral-wound design

The improvement of cylindrical batteries made by Johnson Controls Inc (JCI) lies in wounding tightly lead plates and separator (AGM one) together, and then in compressing the whole into a can. The cells and internal compounds are fixed in order to avoid any damage under severe operating conditions (shock, excess vibrations…). These batteries (Optima) are built to withstand the abuse use in Trucks, SUV etc. It seems that the optima battery have fifteen times more vibration resistance and twice more of cycling life than the classical spiral-wound battery. This new technology is named "Optima Spiralcell" Technology which is patented and registered trademarks of JCI.

JCI provides also Inspira battery for Hybrid Vehicle applications. Each battery contains six spiral rolls sealed in a small hard plastic case, and its weight is about 40 % less than the conventional batteries one. In traditional batteries, the electrolyte fills the cell can in aim to circulate through pasted metal grids but in Inspira technology two thin sheets of pasted lead foil allow to enhance the battery power. The thin solid lead foil has 20 times more surface area than the traditional grids reducing the electrical current path and the total weight. The separator used is of AGM type. JCI can obtain high power technology by using thin plates as current collector.

* Flat plate design

The greatest modification in this case is the bipolar Lead-acid construction. The principle is based on a single plate acting as anode and cathode at the same time. One side of the single plate is one electrode of one half of the cell and the other side of the plate is the opposite electrode for the other half of the cell. The complete cell is made by stacking of these plates (see Fig. 4.1.4). A microporous glass fiber, of AGM type, defines the inter-electrode gap and retains sulphuric acid electrolyte. The battery is sealed and maintenance free.

The biggest difference with traditional lead-acid batteries is the composition of the grids that are not metallic or lead-based in the bipolar construction. The grids of the electrode substrate can be in ceramic material, or polymer based on carbon-fluor or in fiber glass for reinforced a lead wire.

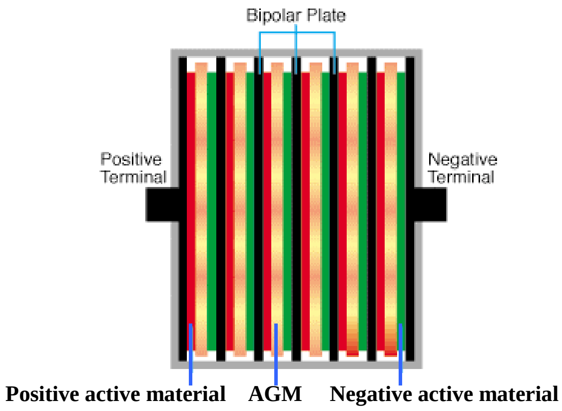


*Figure 4.1.4: Schematic cross-section view of a bipolar lead-acid battery.*

For example, the English Atraverda company uses current collectors based on titanium suboxide (e.g. $Ti_4O_7$) which is a metallic-type conductive ceramic compound (Ebonex®). These ceramic and carbon compound have a comparable conductivity but the oxidation resistance is higher in the Ebonex material due to their crystal structure. In conventional batteries, the use of grids, intercell connections made in lead increases the weight and reduces the electrochemical performances. The bipolar structure solves this problem and these batteries are smaller and lighter. It seems that the specific energy performances are much better than for the other Lead-Acid battery types. At the same time the production process of bipolar battery is simpler (reduced number of process steps).

*Note: A part of the 2004 research program of the US Advanced Lead-Acid Battery Consortium (i.e. ALABC) is devoted to the study of negative plate with an addition of Ebonex material.*

The well-known Horizon battery is also a bipolar Lead-Acid battery. Developed around 1995 for traction applications, this bipolar lead-acid system is made in order to reduce the internal cell resistance and so to charge/discharge with faster rates. The Horizon battery uses composite fiber glass filaments to weave an overlap grids made from a patented co-extruded lead wire and a special paste mixture. In fact, the electrodes are attached to a fiber glass core which eliminated the need of antimony, calcium or other alloys addition and which is highly resistant to grids corrosion. The grids are also based on a low tin alloy in order to minimise the charge gas release.

This new lead-acid construction permits to increase of approximately 35 % the specific energy and of around 400 % the specific power (about 50 $Wh.kg^{-1}$ and 450 $W.kg^{-1}$, respectively). And the Horizon battery has a predicted life of 1000 cycles at a moderate depth of discharge (about 36%).

Note: A tubular cell design can be found in some cases like Exide Ironclad batteries from Enersys Company with results of the same order.

The lead-acid battery is available today in a lot of sizes and designs, ranging from less than 1 to over 10 000 Ah. The overall market is usually divided in four main segments: automotive batteries (SLI), motive power batteries (traction batteries), stationary batteries and portable batteries [40]. Following table lists many of the various types of lead-acid batteries that are available.

*Table 4-1: Types, characteristics and applications of Lead-Acid batteries.*

| **Market Segment** | **Type** | **Construction Aspects** | **Typical Applications** |
|---|---|---|---|
| ***Automotive*** | SLI (starting, lighting, ignition) | Flat-pasted plates (today maintenance-free construction) | Automotive, marine, aircraft, diesel engines in vehicles and for stationary power |
| ***Motive Power*** | Traction | Flat-pasted plates; tubular and gauntlet plates (often maintenance free) | Industrial trucks (material handling) |
| | Vehicular propulsion | Flat-pasted plates; tubular and gauntlet plates; also composite construction (maintenance-free) | Electric vehicles, golf carts, hybrid vehicles, mine cars, personnel carriers |
| | Submarine | Tubular plates; flat-pasted plates | Submarines |
| ***Stationary*** | Energy storage (charge retention, solar photovoltaic, load levelling) | Planté; tubular and gauntlet plates; flat-pasted plates. | Standby emergency power: telephone exchange, uninterruptible power systems (UPS), load leveling, signaling |
| ***Portable*** | Consumer and instrumentation | Flat-pasted plates (gelled electrolyte, electrolyte absorbed in separator); spirally wound electrodes; tubular plates | Portable tools appliances, lighting, emergency lighting, radio, TV, alarm systems |

As mentioned above, this table does not take into account a recent change in the SLI battery market, where nearly all the new vehicles are with maintenance free batteries equipped.

The problem is more complicated for the motive power (traction) applications where conventional flooded lead-acid are often used in “professional” applications (industrial vehicles, golf carts etc) for their best performances in terms of power and lifecycle. But as for SLI batteries, maintenance free technology is most often used in “public” vehicles like Electric Cars and Hybrids.

### 4.1.2. Battery Manufacturers and today Market

All the companies producing Advanced Lead-Acid batteries are also manufacturers of classical SLI batteries for automotive industry. As a consequence the number of manufacturers is much larger than the others technologies case and it becomes impossible to build up an exhaustive list. Battery manufacturer can be found in nearly all countries developing advanced technologies almost of the same kind.
The following table has been built using two main criteria:

- The size and technological know-how of the companies involved
- The experience in EV, HEV battery development including heavy vehicles.

The production of the lead-acid batteries can be divided into approximately 88 % for the starting uses (i.e. 65 % car and 23 % motorcycle etc…), 8 % for deep cycle motive (wheelchairs, golf carts, trucks etc…) and about 4 % for the deep cycle stationary.

| Group name | Known name | Ownership | TM | Technologies | Products | comments |
|---|---|---|---|---|---|---|
| Enersys | Hawker, ESB | Yuasa Corp. | General Batteries, Hawker batteries, Enersys, Exide Ironclad, Cyclon | Advanced Lead-Acid all types | EV & HEV batteries (gel, VRLA) | Recycler |
| Johnson Controls | Varta, VB, Optima | Johnson Controls | Varta, Optima, VB, JC | Advanced Lead-Acid all types | EV & HEV batteries (gel, VRLA and solid state) | |
| Fiamm | Fiamm | Fiamm | Fiamm, Akuma, IBS, Baren, Premium, SuperNova | Advanced Lead-Acid all types | EV & HEV batteries (gel, VRLA) | Other products for auto Industry |
| Exide | Exide | Exide | Exide, Tudor, Fulmen, CEAC, Big, TS, Deta, Lion, GNB, Sonnenschein, Hagen, Champion, Select Orbital | Advanced Lead-Acid all types | EV & HEV batteries (gel, VRLA etc ) | Recycler |
| Delphi | Delphi | Delphi | Freedom batteries | Advanced Lead-Acid all types | EV & HEV batteries (gel, VRLA etc ) | |
| Eagle Picher | Horizon | Eagle Picher | Horizon | Advanced Lead-Acid (bipolar) | EV batteries | |
| East Penn | DEKA | East Penn | Deka batteries | Advanced Lead-Acid | EV batteries | Recycler |
| Hitachi | Shinkobe | Hitachi | | Advanced Lead-Acid | EV batteries | |
| GS Yuasa | JSB | GS Yuasa | GS, Yuasa, JSB | Advanced Lead-Acid all types | EV & HEV batteries | |
| Atraverda | | | | Bipolar battery | | |

During the 1990s, automotive battery producers such as EXIDE (USA-UK) and YUASA (Japan) moved into Europe, showing that this market sector could become a global market. From then, most of European automotive battery manufacturers is passed to foreign hands and the world market has became an oligopoly dominated by the major suppliers [35]. This is shown in the previous figure 4.1-1, where it can be seen that four big manufacturers dominate the worldwide market, among them three are American: Exide, Johnson Controls and Delphi Corp.
In *Europe*, Exide and Johnson Controls are the largest suppliers of automotive batteries, followed by Delphi, Fiamm and Enersys (USA/Europe).

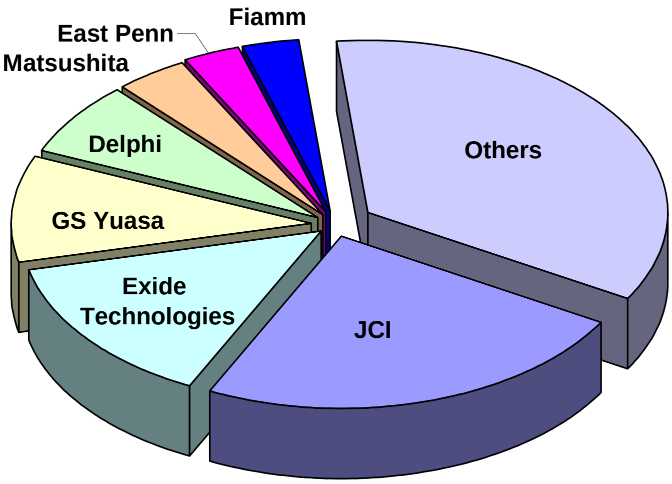


*Figure 4.1-1: Market Shares of major producers of automotive lead-acid batteries (2004)*

***Exide Technologies*** is one of the world’s largest producers and recyclers of lead-acid batteries. Its product range includes starting, lighting and ignition batteries for cars, trucks, off-road vehicles, agricultural and construction vehicles, motorcycles, recreational vehicles, boats and other applications. In North America and Europe, Exide is one of the largest manufacturers of transportation batteries.

***Johnson Controls***, with its Headquarters in Milwaukee (US), entered the North American battery market in 1978 through the acquisition of Globe Union, and it is today the largest automotive battery supplier in North and South America. In 2002, it expanded its battery operations into the European market through the acquisition first of Hoppecke Automotive GmbH and Co. KG (German automotive battery manufacturer, and then with its acquisition of the Automotive Battery Division of Varta AG).

***Delphi Corp*** sells batteries in 62 countries and produces for various industries, including the OE and aftermarket automotive, heavy-duty, farm and commercial vehicle, marine, motorcycle and recreational vehicles. Its R&D projects include a lithium-polymer battery for HEV applications.

The *North American market* of OE lead-acid automotive batteries is dominated by three big suppliers: the largest is Johnson Controls, which has over one-quarter of the market, followed by Exide and Delphi Corp.

In *South America*, the market situation is a bit different from one in Europe and North America.
The industry is still very nationalistic because of national currency instabilities in the past and sensitive language differences among area countries. As a consequence there is a number of small manufacturers that dominates the SLI battery market. Among big suppliers Delphi and Yuasa have been operated in this area with market shares lower than 10%. Among local producers the most important are Acumex and Baterias Moura.

The *automotive market of Asia-Pacific area* is dominated by the Japanese manufacturers, of which the majors are Yuasa, Japan Storage Battery, Matsushita and Shin-Kobe Electric Machinery Corp (a Hitachi group company).

**Yuasa,** with its Headquarters in Osaka (Japan), is one of the world's largest and most diversified manufacturers of batteries. In 2003 it started a new battery manufacturing operation in China. This means Yuasa will have its entire Japanese aftermarket battery production made in China. In 2004 Yuasa and JSB have joined to create the world's largest Battery Company for automotive applications: GS Yuasa.

***Japan Storage Battery***, which celebrated its centenary in 1995, produces lead-acid batteries for cars and electric vehicles. It has manufacturing plants in Thailand, Indonesia, the US, Taiwan, Pakistan, Italy, the Netherlands, the UK, China and Vietnam. Before the GS Yuasa Company appears JSB was dominating the Japanese market together with Yuasa. Currently it is working with Toyota Motors to develop advanced lead-acid batteries for hybrid vehicles.

### 4.1.3 Advanced Batteries for EVs and HEVs

Most of electric vehicles currently in service are powered by lead-acid batteries of type normally used in industrial traction applications as forklift trucks, mining locomotives, airport ground equipment, and other off-road applications. These batteries, also called *motive power batteries*, in most of cases have a thick flat or tubular positive plate and a flooded-electrolyte design with glass fiber separator; these construction characteristics provide them a relatively low specific energy (about 25 Wh/kg) and a cycle life up to 1500 deep-discharge cycles.
The increasing interest over the last two decade towards electric road vehicles (EVs), has stimulated research in order to improve this kind of battery and make it a more attractive candidate for this application. This research effort about lead-acid battery technology resulted in the development of the so-called valve-regulated lead-acid battery (VRLA). Differently from more conventional batteries, ones of VRLA type use low-gassing lead grid alloys and starved electrolyte designs; this construction characteristics permit internal gas recombination and to eliminate the need for periodic water addition (maintenance-free). In addition performances as 35-40 Wh/kg in specific energy and 300-400 cycles in cycle life have been reached (lower cycle life and power than conventional flooded one, see WP1).

Important developers and manufacturers of VRLA batteries for electric and hybrid vehicles are the following: HAWKER (Enersys), EXIDE, JOHNSON CONTROLS (VARTA-OPTIMA), YUASA (GS Yuasa), MATSUSHITA (PANASONIC), TROJAN BATTERY Co., U.S. Battery Manufacturing Co., FIAMM, EAST PENN and some others in Asian countries (Korea, China etc).

The table 4.1.2 shows the characteristics of some VRLA batteries suitable for electric vehicles.

*Table 4.1.2:VRLA batteries features for EV applications*

| **Manufacturer** | **East Penn** | **Matsushita (Panasonic)** | **Optima (Johnson Controls)** |
|---|---|---|---|
| Model | UX 168 | EV 1260 | D 750S |
| Voltage(V) | 8 | 12 | 12 |
| Capacity (Ah) | 85 | 60 | 57 |
| Weight (kg) | 19 | 21 | 19 |
| Volume (l) | 7,9 | 7,9 | 8,9 |
| Specific Energy (Wh/kg) | 36 | 34 | 36 |

For hybrids vehicles (see also C-3, C-4, C-5, C-6), Advanced Lead-Acid is only chosen for the less "electrified" vehicles, that means µ-hybrids and soft-hybrids (considered by some auto-makers as ICE vehicles with an electric option). As the hybrid vehicle industry is only starting, all the Lead-Acid batteries chosen today (as for Citroën C3 µ-hybrid) are SLI VLRA batteries for price reasons (the EV battery types have insufficient power).
For mild hybrids (perhaps the most developed type of hybrid in the next future) the competition is open between new technologies (NiMH and Lithium based) and advanced Lead-Acid batteries. The major competitive advantage of Lead-Acid is the reduced price compared to others, but specific power and

life cycle seem to be too low for this application. Many of the major manufacturers are developing modified advanced batteries in order to increase power and cycle life but the battery price seems to increase at the same time and the major advantage of Lead-Acid could disappear.

### 4.1.4 Battery Pack Costs Analysis, Market and Price Trends

Lead-acid batteries of type normally used in industrial traction applications, with conventional flooded-electrolyte design with glass fibre separator are sold at prices to customer from about 120 to 160 €/kWh. Battery less robust with prices ranging from 60 to 80 €/kWh and a cycle life of 200-300 cycles are also used [45] (2000).

FIAMM Italy [49] (2004) provided a price value of 100 €/kWh for a flooded electrolyte battery sold at a volume of 2600 modules/year. The battery has the following characteristics: nominal voltage of 6 V, capacity of 185 Ah at $C_5$, specific energy of 30 Wh/kg at $C_3$ and cycle life of 1000 cycles in deep-discharge application.

For advanced batteries like VLRA maintenance-free, Anderman et al. [45] (2000) reports that Panasonic sold approximately 18.000 modules/year in 1999 and 2000 at a sale price for EV manufacturers of about 285 €/kWh. For 2003, the company estimated a production volume of about 65.000 modules (corresponding to about 2500 battery packs/year) at a price of 230 €/kWh. Price could decrease further to 160 €/kWh and 95 €/kWh at production volumes of 130.000 and 390.000 modules/year respectively.

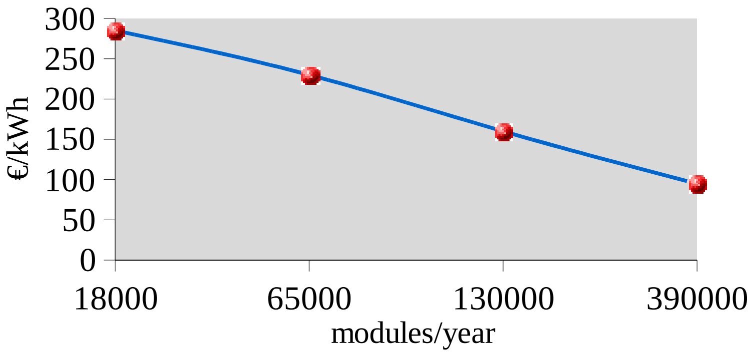


*Figure 4.1.2: Price estimation for Panasonic VRLA EV batteries as function of production volume [45].*

Other price data and estimations are reported in [39]. These data were provided by major EV battery manufacturers and have been used in this report to define a relationship between battery price and production volume. A good interpolation of this data is given by the following expressions:

$$p = p_o + p_1 \exp\left(-\frac{V}{V_o}\right) \qquad (1)$$

Where *V* is the battery volume in kWh/year, $p_o$ = 83.55 €/kWh, $p_1$ = 230.56 €/kWh and $V_o$ = 90000 kWh/year.

But these data have to be modified considering the lead market price evolution since 2000.

The following figure shows a comparison among data from [45], data from [39] and calculated values by means of relationship (1). At low production volumes the battery price decreases fast as volume increases. For a production volume higher than about 250000 kWh/year the price falls down to 100 €/kWh and as volume increases it decreases very slowly towards the limit of 83.55 €/kWh.

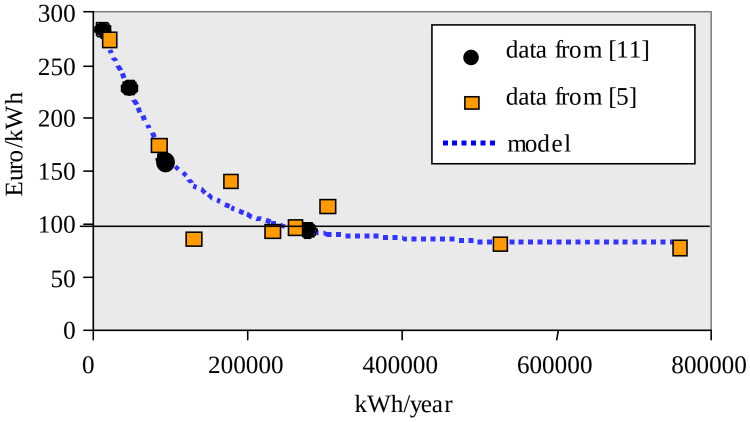


*Figure 4.1.3: VRLA battery price as function of yearly production volume.*

Piaggio and Microvett [51,52] (Italian EV manufacturers) provided price data for the VRLA battery model **GF 6 180 V** currently produced by EXIDE (Sonnenschein). The GF-V range monoblocks are suitable for hard industrial use. This includes applications for advanced guided vehicles, mobile elevating work platforms, cleaning machines, walk-behind pallet trucks, electric cars and buses. The characteristics of model **GF 6 180 V** are reported on the following figure. This battery model is used currently in OEM electric/hybrid vehicles produced by FIAT, IRISBUS-ALTRA, MICRO-VETT, PIAGGIO, MALAGUTI MOTO, TRANSTEQ, LTI, EBUS, REVA CAR.

| **Model** | **GF 6 180 V** |
|---|---|
| Voltage(V) | 6 |
| Capacity (Ah) at $C_5$ | 180 |
| Weight (kg) | 31 |
| Volume (l) | 12,75 |
| Specific Energy (Wh/kg) | 35 |
| Cyclelife at 75% DoD | 700 |

*Figure 4.1.4: Characteristics of the EXIDE VRLA model **GF 6 180 V**.*

Microvett sold from 1997 to 2004 about 500 electric Van vehicles per year. The vehicles were equipped with a lead-acid battery pack having a voltage of 84 V and a capacity of 180 Ah at $C_5$. The stored energy and the module number in the pack are respectively 15,12 kWh and 14 corresponding to a battery purchase volume of 7560 kWh/year and 7000 modules/year. The purchase price corresponding to this purchase volume as stated by Microvett was of 110 €/kWh, with a yearly rise price not higher than 10%. Following tables show more details on purchase price changes as stated by Microvett (price data provided by Piaggio agree with ones provided by Microvett).

*Table 4.1.3: Purchase price for Microvett as function of purchase volume in 2004.*

| **Purchase volume (modules)** | **1000** | **4000** | **7000** | **10000** |
|---|---|---|---|---|
| *Price per module* | *130 €* | *122 €* | *116 €* | *108 €* |
| *Price per kWh* | *120 €* | *113 €* | *107 €* | *100 €* |

*Table 4.1.4: Purchase price changes over last seven years for Microvett.*

| **Year** | **1998** | **2000** | **2002** | **2004** |
|---|---|---|---|---|
| *Price for 7000 modules/year* | *87* | *96* | *105* | *116* |
| *Price for 7560 kWh/year* | *80* | *88* | *97* | *107* |

A detailed manufacturing cost analysis of lead-acid battery is reported by Lipman in 1999. He considers, for the analysis, a VRLA battery of mono-block construction with electrolyte of AGM type. The battery has a nominal voltage of 12 V (six cells) and a capacity of 75 Ah, and a nominal energy of 900 Wh (0.9 kWh). Material composition of battery was estimated on the basis of battery physical characteristics and information's on battery manufacturing. Cost analysis was performed for two different production volumes (120.000 and 480.000 modules/year) and resulted in a total manufacturing cost of 70.66 €/kWh and 67.20 €/kWh for 120.000 and 480.000 modules/year, respectively. The estimate of sale price to customer was 88.31 €/kWh and 84 €/kWh, assuming a profit of 20 % on sale price. Following table reports the manufacturing costs as estimated for a production volume of 120.000 modules/year.

*Table 4.1.5: Manufacturing Costs of a VRLA Lead-Acid battery (120.000 modules/year).*

| **Type of manufacturing costs** | | **€/module** | **€/kWh** |
|---|---|---|---|
| Plate Production | | | |
| | *Materials* | 11.79 | 13.10 |
| | *Labour* | 2.22 | 2.47 |
| Module Assembly | | | |
| | *Materials* | 14.49 | 16.10 |
| | *Labour* | 1.85 | 2.06 |
| Battery Formation | | | |
| | *Labour* | 0.74 | 0.83 |
| | *Other* | 1.89 | 2.10 |
| | ***TOTAL Materials and Labour*** | **32.98** | **36.65** |
| Other factory costs | | | |
| | *Overheads on Labour and Materials* | 11.52 | 12.79 |
| | *Amortized Equip. cost and Rent* | 2.33 | 2.59 |
| | *Miscellaneous* | 0.38 | 0.42 |
| | ***TOTAL other factory costs*** | **14.22** | **15.80** |
| | ***TOTAL Production costs*** | **47.20** | **52.45** |
| Other expenses | | | |
| | *R&D, Distribution and Services* | 5.72 | 6.36 |
| | *Marketing* | 1.59 | 1.76 |
| | *Warranty* | 3.19 | 3.54 |
| | *Disposal* | 3.52 | 3.91 |
| | *License Fee* | 2.38 | 2.64 |
| | ***TOTAL other expenses*** | **16.39** | **18.21** |
| | **TOTAL Manufacturing costs** | **63.59** | **70.66** |

Table 4.1.6: Aggregate Manufacturing Costs of a VRLA Lead-Acid battery (120.000 modules/year).

| **Type of manufacturing costs** | **€/module** | **€/kWh** | **%** |
|---|---|---|---|
| Materials | 26.27 | 29.19 | 41.32 |
| Labour | 4.82 | 5.35 | 7.57 |
| Other process costs | 1.89 | 2.10 | 2.97 |
| Other expenses | 30.61 | 34.01 | 48.14 |
| **TOTAL Manufacturing costs** | **63.59** | **70.66** | **100** |

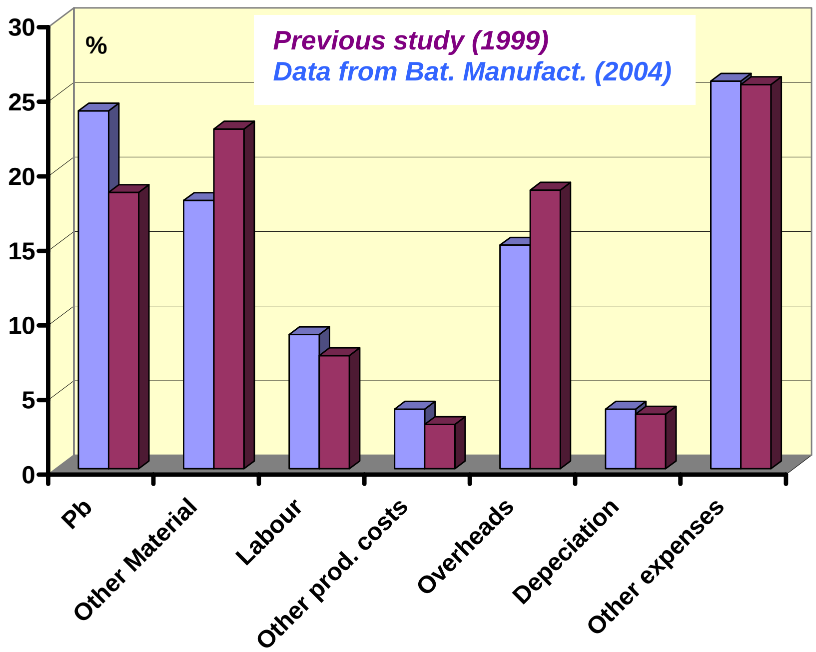


*Figure 4.1.5: Manufacturing costs of VRLA lead-acid battery estimations about two different sources.*

This study made in 2000 does not take into account the increase of lead market price. The other material prices are also to discuss and the other factory expenses are estimated. It seems then useful to compare these results with other data coming from Battery Companies most often given in relative costs (confidentiality of data).

As Lead prices have increased of more than 100% between 2000 and 2004 (0.45 $/kg in 2000 to about 1 $/kg at the beginning of 2005), the differences between these relative values seems to be very low. It is the result of several factors:

- The Lead-Acid Market is a very competitive Market compared to the other battery technologies, and Battery Manufacturer cannot easily pass this increase to the customer (reduced margin),
- Lead cost represents only about 13 % of the battery price to the customer,
- As battery Manufacturers data are from European Manufacturers the $/€ value change between 2000 and today is of about 25 %.

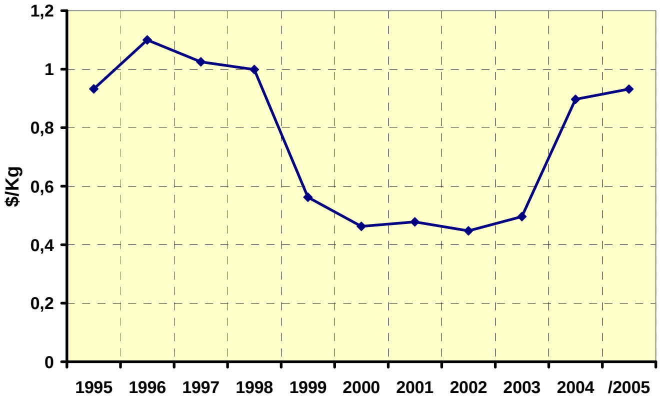


*Figure 4.1.6: Annual average Lead price in $/kg (Metal Prices Source).*

These evaluations are for conventional “advanced” Lead-Acid batteries, but since the first developments of the Hybrid Vehicle Market, more advanced Lead-Acid technologies (sealed type) are in development and their prices are a little higher than the conventional one.

Only Battery modules are not enough for an electric or hybrid vehicle. Battery auxiliaries must be added to the modules to create a complete pack (see B-2). They can include:

- a case and electrical connections,
- a bus bars and terminals,
- a cooling/ventilation system,
- a Battery Management System (BMS)
- a Charging Unit (often not included in the battery price)

Cost estimates for the battery auxiliaries are provided in [39] (2002). Dixon et al. estimate the costs of auxiliaries at 11 to 15 per €/kWh for a Lead-Acid battery pack between 2003 and 2007.

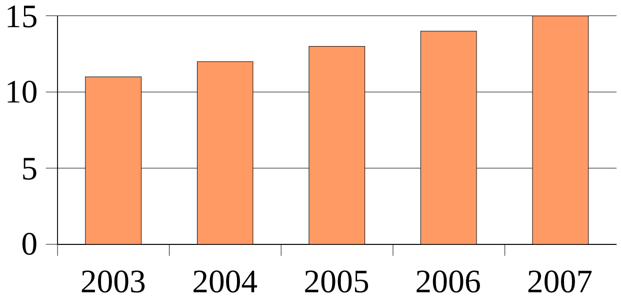


*Figure 4.1.7: Cost estimates for battery auxiliaries (from Dixon et al.).*

Piaggio provided costs data for assembling a lead-acid pack constituted of 14 modules EXIDE VRLA **GF 6 180 V** series connected. The assembling process provides following main steps:

- quality check (view check, production code check, module's voltage check),
- pack assembling,
- installation on board of vehicle,
- pack wiring.

An assembling overall cost equal to about 20% of modules cost was stated, with reference to a number of pack assembled equal to 500 per year. For this pack production volume (7000 modules/year) the module cost is 107 €/kWh, so the assembling cost results 21.4 €/kWh.

*Table 4.1.7: Summary of min/max costs estimations for EV and mild HEV applications (2005 prices).*

| | Min. value € | Max. value € | Battery weight |
|---|---|---|---|
| €/kWh | 116 | 151 | |
| €/kW | 11,8 | 15,4 | |
| €/Kg | 4,14 | 5,39 | 1 Kg |
| Mild hybrid vehicle | 142 | 185 | 60 kg |
| BEV | 3480 | 4530 | 880 kg |

With Mild hybrid vehicle battery of 400 Wh and 12 kW, and BEV battery of 30 kWh.

These calculated prices are for a production of up to 250 000 kWh/year (about 7 000 t) of one type of Lead-Acid battery usable for the concerned traction application in 2005, an increase of price of about 10% in 2005, 6% in 2006 and about 5% per year if the lead market price does not decrease. They do not take into account the last advanced developments introduce by several Battery Manufacturers in order to increase energy, power or life cycle. These developments increase the price of the Lead-Acid VRLA batteries from 20% to 60% at the prototype stage, but the consequences on the industrial price are not known.

# 4.2. Lithium based

## 4.2.1. Principle

The basic principle of Lithium-ion battery is described by the following global reaction:

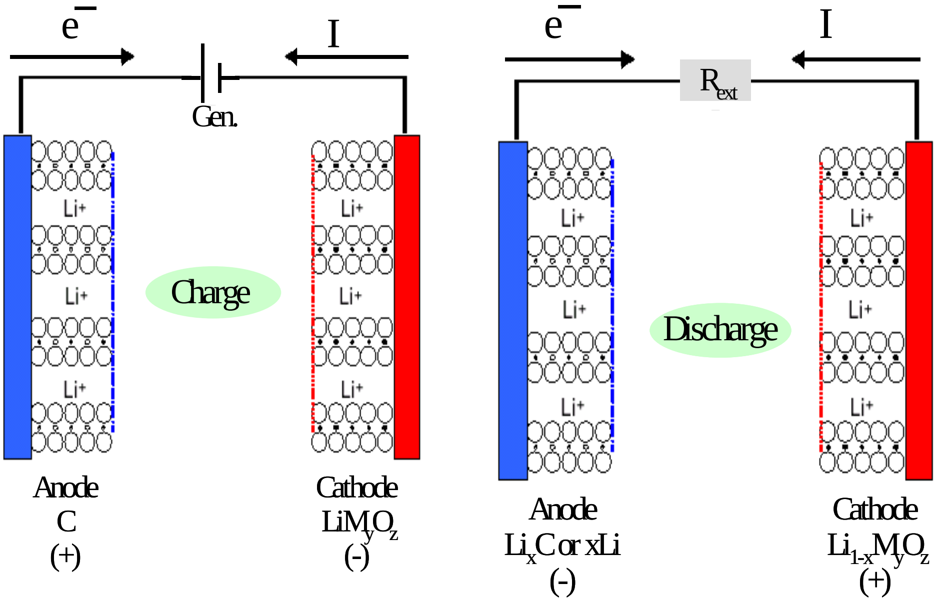
$$LiM_yO_z + C_n \underset{\text{Discharge}}{\overset{\text{Charge}}{\rightleftarrows}} Li_{1-x}M_yO_z + Li_xC_n$$

N.B.: In the lithium metal battery case, the electrochemical solid state reaction is simplified as:

$$AB + xLi^0 \underset{\text{Discharge}}{\overset{\text{Charge}}{\rightleftarrows}} Li_xAB \quad \text{in which AB is a cathode material}$$

(a) (b)

*Figure 4.2.1: Representation of a Lithium-based battery operating in (a) charge and (b) in discharge.*



## 4.2.2. Various technologies used

### 4.2.2.1 Lithium-ion

The understanding of the intercalation lithium-based compounds mechanism with several graphite types is fundamental in the rechargeable lithium-ion battery development.

The main advantage of the Lithium-based battery is their high storage density and their low weight. Moreover, it operates at room temperature with a [min / max] working range of [-30,-25 °C / 45, 55 °C] and the cell voltage is higher than the others (4 V).

On the contrary the disadvantage of the Lithium-ion battery system is that lithium cannot be combined with aqueous electrolytes but only with organic electrolytes or molten salts. The cost of the electrolyte increases and new battery security problems are appearing.

Lithiated transition metal oxides, such as lithium (manganese, nickel, cobalt) oxides are the typical materials used in Lithium-based battery for cathode materials. A comparison of the interest of each couple is proposed in the following chapters.

- **Li-Mn-O**

Today the use of spinel-type lithium oxide $LiMn_2O_4$ allows good electrochemical properties for cathode material (until recently it was not the case).

This material is cheaper and less toxic than Li-Ni-O and Li-Co-O materials. However, the main problem is the poor cycling life of Li-Mn-O battery due to the manganese dissolution in the electrolyte.

An acid dissolution of manganese ions is observed due to HF of the $LiPF_6$, $H_2O$ (i.e. trace) electrolyte. Some manganese ions are involved in solid-state material formation by re-precipitation, and the others manganese ions migrate to the negative electrode and are reduced in metallic manganese.
Another disadvantage of this material is that $LiMn_2O_4$ spinels have low specific capacity and are structurally unstable for lithium ion intercalation and de-intercalation.

- **Li-Ni-O**

One of the advantage of using lithium nickelate as a cathode material is the large capacity compared to lithium cobalt oxide. However, lithium nickelate is less environmentally friendly material and more expensive than lithium manganese oxide. The structurally ordered $LiNiO_2$ materials are difficult to synthesize and their cycling life is poor due to dissolution in the electrolyte solvents phenomenon as $LiMn_2O_4$ spinel.

- **Li-Co-O**

In practical, only $LiCoO_2$ material is widely competitive in lithium-ion battery production. The use of Li-Co-O cathode leads to the best electrochemical performance (i.e. stability *versus* electrolyte implying a good cycling life). However, this material is not environmentally friendly due to the toxicity of cobalt and is the most expensive (the cobalt market is indeed very uncertain since few years). This type of cathode material is the most commonly used in the Li-Ion portable battery industry. Since a few years portable battery manufacturers are trying to substitute Cobalt by manganese or iron (see C-7).

In conclusion, the cost of lithium-ion batteries, especially the cobalt-based ones, increases with the price of Cobalt oxide on a large scale production. A possible strategy is to replace cobalt by other ions, and as the structural integrity must be kept, the electrochemical properties will be maintained. Such new cathode materials are crucial for making large-scale lithium-ions batteries for electric vehicles and stationary energy storage application.

#### 4.2.2.2 Lithium-ion-Polymer and Lithium-Polymer

A lithium-ion battery becomes a lithium polymer battery by substitution of the liquid electrolyte for either a gelled electrolyte or a true solid electrolyte.
In many cases, this new technology can use laminated electrodes, these batteries are then lighter than lithium-ion batteries.
As lithium-ion technology, Li-(Mn, Ni, Co)-O oxides are used as cathode materials. But new intercalation materials are studied intensively for a few years: $LiFePO_4$ Olivine type.
The increase of the research activity on $LiFePO_4$ material is induced by the necessity of cobalt-based cathode substitution due to the high cost of cobalt and loss of $LiCoO_2$ capacity ($LiCoO_2$: theoretical capacity = 273 $mAh.g^{-1}$ when practical one ≈140 $mAh.g^{-1}$ and $LiFePO_4$: theoretical capacity = 170 $mAh.g^{-1}$ when practical capacity ≈150 $mAh.g^{-1}$).
(Fe, P)-based components are also cheaper and more environmentally friendly than cobalt one. Nevertheless, $LiFePO_4$ cathode has a working voltage of 3.5 V vs. $Li^+$ / Li (when 4 V vs. $Li^+$ / Li for $LiCoO_2$ cathode) implying a volumetric power lower than the $LiCoO_2$ one.

#### 4.2.2.3 Lithium-Metal-Polymer (LMP)

Lithium is the alkaline metal with the smallest molecular weight and with a standard potential equilibrium of –3.045 V. For this reason lithium as a material for negative electrodes allows a high storage capacity. The Lithium ions formed during the electron reaction are highly soluble. A lithium metal electrode is dissolved during the discharge process inducing a modified initial structure during the recharge. In charge, lithium dendrites can grow and induce short-circuits. The cycling stability is reduced dramatically by both effects. Lithium is then used more frequently as a metallic electrode in primary batteries.
However, in the rechargeable battery case, the lithium-metal is associated to a material based on vanadium oxides compound as cathode (e.g. $V_2O_5$, $VO_y$ blended...).

### 4.2.3. Battery Manufacturers and their specific Technologies

In this section, the specificities of each Lithium-based battery technology associated to a battery manufacturer are proposed (cf. summary in Tables 4.2.1, 4.2.2 and 4.2.4).

*PE = Polyethylene*
*PP = Polypropylene*
*SBR = Styrene-butadiene-rubber*
*CMC = Carboxy-methyl-celluluose*
*PC = Propylene carbonate*
*EC = Ethylene carbonate*
*DMC = Dimethyl carbonate*
*PVdF = Polyvinylidene fluoride*
*PEO = Polyethylene oxide*
*LiTFSI = Lithium (bis)trifluoromethanesulfonimide*
*MCMB = Mesocarbon microbead*
*DEC = Diethyl carbonate*
*PPE = Porous polymer electrolyte (= PVdF/HFP dissolved in NMP and de-ionized water)*
*AB = Acetylene black*
*NMP = N-methyl-2-pyrrolidone*
*MEC = Methyl ethyl carbonate*

*Table 4.2.1: List of Lithium-ion battery manufacturers and concise description of each production process.*

| Group name | Anode material | Electrolyte | Separator | Cathode material | Comments |
|---|---|---|---|---|---|
| SAFT | Carbon | Org. solvents + $LiPF_6$ | PE and PP | $Li\text{-}Ni_{0.8\text{-}y}Co_{0.2}Al_yO_2$ | Cylindrical cell |
| Hitachi Vehicle Energy, Ltd [17] | Synthetic graphite | Unknown (probably Org. solvents + $LiPF_6$) | polyolefin | $Li\text{-}Ni_{1\text{-}x\text{-}y}Co_xMn_yO_2$ | elliptical cylinder |
| | Hard carbon | Unknown (probably Org. solvents + $LiPF_6$) | polyolefin | Modified $LiMn_2O_4$ | Cylindrical cell |
| GS Yuasa Co. [18, 19] | Hard carbon | Unknown (probably Org. solvents + $LiPF_6$) | polyolefin | $Li(Ni\text{-}Co\text{-}Mn)O_2$ | Prismatic cell |
| | Hard carbon | Unknown (probably Org. solvents + $LiPF_6$) | polyolefin | $LiMn_2O_4$ | Prismatic cell |
| | Carbon | Org. solvents + $LiPF_6$ + PPE | Unknown (probably polyolefin) | $Li\text{-}Ni_{0.83}Co_{0.17}O_2$ | Prismatic cell |
| PEVE [12] | graphite | Unknown (probably Org. solvents + $LiPF_6$) | polyolefin | $LiMn_2O_4$ | Cylindrical cell |
| NEC Lamilion Energy, Co | Carbon | $LiPF_6$ | polyolefin | $LiMn_2O_4$ | Laminated type |
| Sanyo | Carbon | Unknown (probably Org. solvents + $LiPF_6$) | polyolefin | $Li\text{-}Ni_{1\text{-}x}Co_xO_2$ | |
| Toyota | Graphite | Org. solvents + $LiPF_6$ | polyolefin | $LiNi_{0.81}Co_{0.15}Al_{0.04}O_2$ | Prismatic cell |
| B&K | Unknown (probably carbon) | Unknown (probably Org. solvents + $LiPF_6$) | polyolefin | Probably Li-Co-O | |
| LG [22] | Carbon | Unknown (probably Org. solvents + $LiPF_6$) | Unknown (probably polyolefin) | $LiMn_2O_4$ | Cylindrical, prismatic and laminated cell |
| Thundersky Battery Ltd | Unknown (probably carbon) | Unknown (probably Org. solvents + $LiPF_6$) | polyolefin | Cr-F-Li ?<br>Li-Mn-O | Li-ion-polymer?<br>Li-ion+solid electrolyte |
| Samsung SDI | Artificial graphite | Org. solvents + $LiPF_6$ | polyolefin | $LiCoO_2$ | Cylindrical, prismatic and laminated cell |
| BYD | Unknown (probably carbon) | Org. solvents + $LiPF_6$) | polyolefin | Li-Co-O<br>Li-Mn-O and $LiFePO_4$ ? | Forecast of 200.000 vehicle/year |
| Wanxiang Group Power battery | Carbon | Solid polymeric electrolyte | / | Li-Mn-O<br>$LiFePO_4$ | Prismatic cell<br>(laminated process)<br>EV applications |

| Group name | Anode material | Electrolyte | Separator | Cathode material | Comments |
|---|---|---|---|---|---|
| Aucma New Power Tech. | Unknown (probably carbon) | Unknown (probably Org. solvents + $LiPF_6$)<br>Polymeric electrolyte | Unknown probably polyolefin<br>/ | Li-Co-O and Li-Mn-O<br>$LiFePO_4$ | Prismatic cell ? |
| Tianjin Lantian Hi-Tech Power Sources Joint-Stock Co. Ltd | Unknown (probably carbon) | probably Org. solvents + $LiPF_6$ | Unknown probably polyolefin | Li-Co-O<br>+ probably Li-Mn-O and $LiFePO_4$ | Cylindrical cell (+ a few prismatic cells) EV, HV appli. (863 program context) |
| Xingheng Phylion Battery Co. Ltd. | Unknown (probably carbon) | Unknown (liquid electrolyte) | Unknown probably polyolefin | Li-Co-O, then Li-Mn-O<br>$LiFePO_4$ | HV applications |

### 4.2.3.1. Lithium-ion technology

According to the literature, the Li-(Ni-Mn-Co)-O cathode-based choice is usually made. Nevertheless some battery manufacturers add some others element (as SAFT with aluminium addition).

- **SAFT [15]**

SAFT has developed a range of Lithium-ion batteries for industrial applications, both electric vehicles and different types of hybrid concepts, thus, three main types of cells can be described : high energy, medium range (dual) and high power. They all use the same basic electrochemistry and electrode compositions. The operating temperature range has been evaluated from -30 °C to +50 °C. The number of cycles in deep-discharge is demonstrated at 1 800 cycles leading to a 10 years EV battery life evaluation. For HEV type operation today evaluation are so that a 8 years warranty period seems to be the minimum.

In the cathode, SAFT still uses $LiNiO_2$ based active material chemically doped with cobalt (≈ 20 %) and aluminium in order to get the best performances in terms of capacity, life, abuse tolerance and cost. A suitable electronic conductivity and mechanical properties are insured by carbon powder and PVdF binder addition (14 % rate of the total loading) in the cathode material. This electrode is manufactured using an organic solvent process.

The anode contains a mixture of graphite and graphitised carbons selected for their electrochemical performance and their ability to be processed efficiently. Besides a lower cost, their new graphite powder brings higher capacity (330 $mAh.g^{-1}$ when 295 $mAh.g^{-1}$ for the mix used up till now) and higher rate capability during charge and discharge process. SBR and CMC are added as binders (4 % rate in total) using an aqueous process. In the aim to prevent metallic lithium plating at the surface of the carbon in normal operating conditions, the anode is provided with a 25 % charge reserve at an end of charge voltage of 4 V.

The separator is a three laminated layer membrane composed of PE and PP (polyolefin type). It has a mechanical integrity at least up to 165 °C (i.e. melting point of PP).

The electrolyte is composed of a mixture of organic carbonate solvents (PC, EC and DMC) containing 1 $mol.L^{-1}$ of $LiPF_6$. A proprietary additive is also used in small quantity in order to optimize cell formation and stabilize life characteristics.

After coating, drying, calendering and sizing operations, electrodes and separator are spirally wound using an automatic winding machine which also welds aluminium and nickel connecting tabs to the edge of each electrode. After winding, these tabs are welded to positive and negative terminals and the so-obtained jelly roll is introduced in an aluminium can with the positive terminal directly connected to this case. The negative polarity is isolated from the case using a sealed copper based terminal. Each cell is also fitted with two safety vents positioned at the positive terminal side of the cell.

- **Hitachi Vehicle Energy, Ltd**

In addition to their low cost, lithium manganese spinel material shows a better thermal stability than lithium cobalt oxide material. HITACHI has developed a manganese type lithium ion battery which has almost the same level of performance in energy density and cycle life than the cobalt type one, for EV applications. Indeed, HITACHI has focused on two types of modified manganese lithium ion batteries: one for pure-EV (needing high energy density) and the other for HEV (needing high power density).

HITACHI cathode is based on $LiMn_2O_4$ active material whose crystal structure has been modified.

A structured carbon compound (i.e. hard carbon) is used as the anode material in order to facilitate the release of lithium ions.

The use of new HITACHI electrolyte improves the low-temperature discharge rate and output power. This electrolyte is made from a solid material, as opposed to the flammable liquid electrolyte that many other lithium-ion batteries use. Indeed, the liquid electrolyte problem is its possible ignition by battery heat (or can simply evaporate). However, the idea of a solid, safer electrolyte is not new, but in the past this use was followed by a decrease in power output.

The modules for EVs and HEVs are composed of 8 and 48 lithium ion cells respectively serial connected. The specific characteristics of Lithium-ion HITACHI module for EVs and HEVs applications are proposed on figure 4.2.2 (a,b).

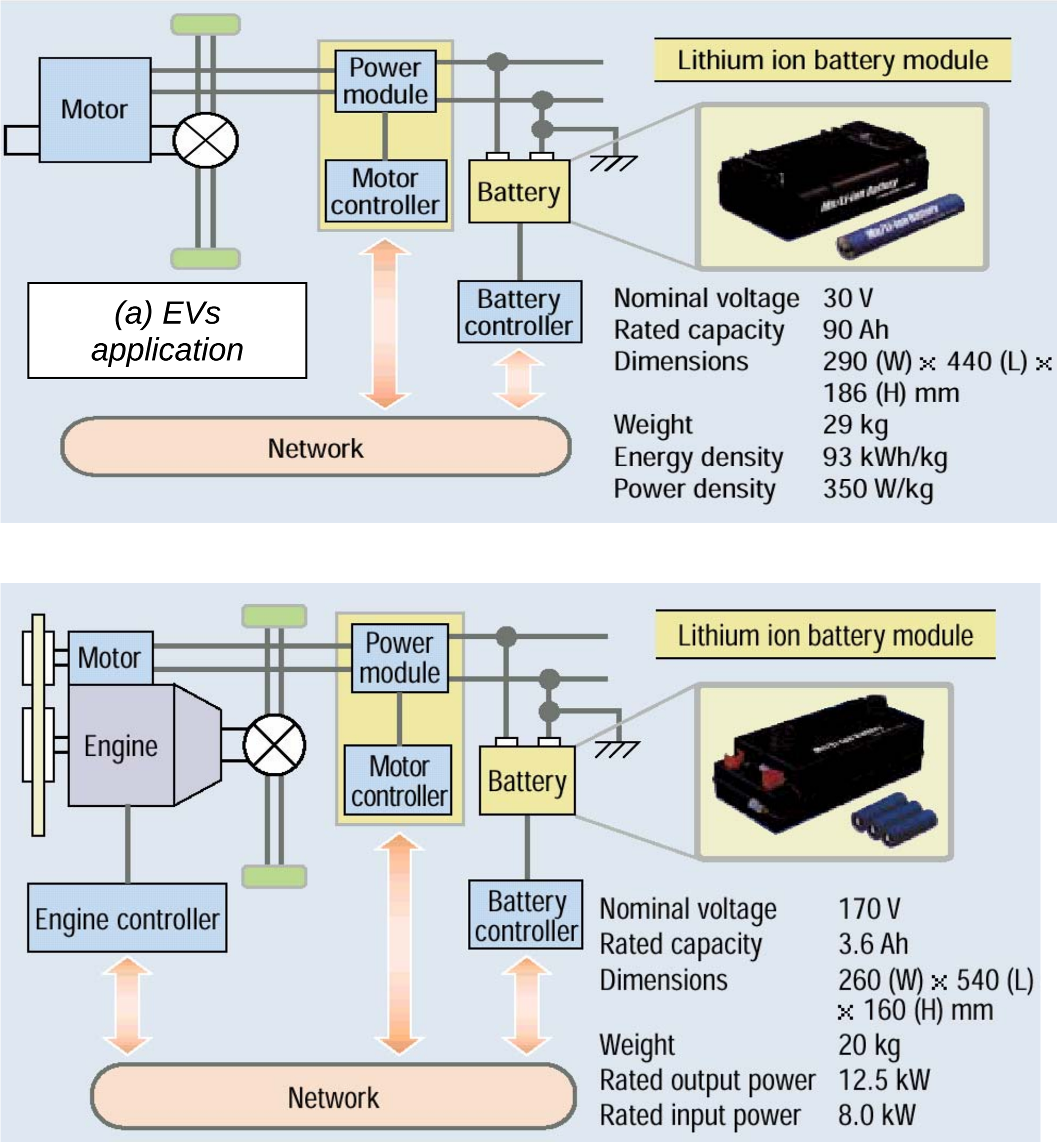


*Figure 4.2.2: System diagrams and lithium-ion battery modules for (a) EVs and (b) HEVs applications.*

HITACHI' EVs and HEVs batteries type had been used by Nissan to equip their EVs Hypermini (4 modules of 8 cells each) and HEVs Tino-Hybrid (2 modules of 48 cells each). Cells for EV and HEV batteries haven't the same size and weight (cf. Figure 4.2.2' characteristics).

N.B.: HITACHI group worked on the synthetic graphite/Li-(Ni, Co, Mn)-O system. In this case, the anode is composed of MCMB or MAG (=carbon type developed by HITACHI) and mixed lithium oxide as cathode material, but this technology seems withdrawn nowadays.

- **GS YUASA Co.**

GS YUASA, which realised a joint holding company with Japan Storage Battery (i.e. JSB), developed two types of cathode materials: one based on $LiMn_2O_4$ system and the other based on Li-(Ni, Co, Mn)-O system.
GS YUASA group compared various positive active materials with a number of compositions. The Ni-rich cathode showed an increase of the capacity but a poor thermal stability, when the Mn-rich one had superior thermal stability but poor capacity retention, and finally the Co-rich composition had good capacity retention, but required full consideration of cost and resource problems. This manufacturer found a cathode composition which concentrated the advantages of Ni, Mn, and Co, all together controlling the amount of each component. The real composition of their new cathode is not disclosed.

In the future the lithium-ion batteries with this new cathode active material will be used especially in HEVs applications.
Whatever the cathode type used, hard carbon as anode active material is associated by GS YUASA.

For EVs application, GS-YUASA has developed a new Li-(Ni, Co, Mn)-O / Carbon system with porous polymer electrolyte which contains smaller amount of liquid electrolyte compared to the other known lithium-ion batteries. The risk induced by flammable electrolyte is widely decreased. The porous polymer electrolyte technology is based on its higher diffusion coefficient of lithium ion and higher electro-conductivity compared with the polyolefin separator. The PPE is deposited on the surface of both electrodes in a thin film form. This technique leads to a superior discharge performance, reduce the irreversible capacity and increase the thermal stabilization of the anode.

N.B.: The small amount of liquid electrolyte is composed of a mixture of organic carbonate solvents (EC, DMC and DEC) and $LiPF_6$ salt.

- **NEC Lamilion Energy, Co.**

NEC Corporation and Fuji Heavy Industries Ltd. (FHI) have signed an agreement to create a joint venture company (NEC Lamilion Energy Ltd.) in the aim to enhance the development of laminated manganese lithium-ion type rechargeable battery for EVs / HEVs applications (Figure 4.2.3).

*Figure 4.2.3: $LiMn_2O_4$ lithium-ion battery pack of NEC Lamilion.*

They use an additives blending with Mn spinel as cathode material in order to prevent HF-generation and to stop the manganese dissolution. Results given recently show that they have been able to improve storage performance at elevated temperatures of their battery system.
The NEC & FHI anode is composed of graphite or amorphous carbon. Moreover, they work on the development of a new cell structure which is laminated type.
In the other hand, NEC develops a new product which could potentially be recharged in under a minute. Their cell was created by substituting the heavy cobalt, nickel and/or manganese metal oxide with an organic compound (i.e. polymer cathode) as the active cathode material which combined with a graphite anode. According to NEC this new organic battery retains 92 % of its capacity after 1000 cycles and the highest voltage reaches 3.5 V compared with 4.2 V in basic lithium-ion cells.

- **SANYO**

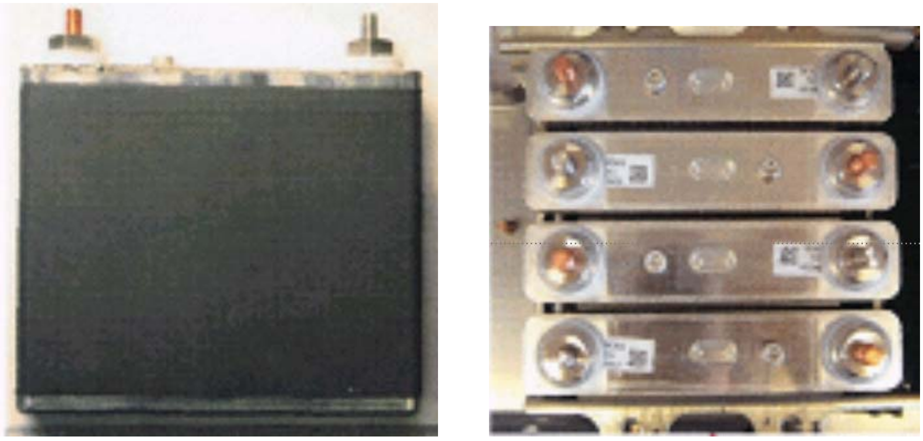
SANYO lithium-ion batteries is based on Li-(Ni, Co)-O / hybrid carbon system, in which the $LiNi_{0.7}Co_{0.3}O_2$ cathode shows the best electrochemical performances for electric vehicles application.
The anode is made of mixed material of natural graphite and coke (i.e. hybrid carbon electrode), in which the graphite : coke weight ratio is 4 : 1.
The electrolyte is composed of a mixture of organic carbonate solvents (EC/DEC) and $LiPF_6$ salt.

N.B.: This year, Sanyo changes its design of lithium-ion batteries to use less cobalt due to the increase of the cobalt prices about $ 25.00 per pound in early June 2004 from $ 9.30 early September 2003 (Metal Bulletin information).

### - TOYOTA

After some years of work on energy configuration (EV applications) TOYOTA has developed a range of Lithium-ion batteries for HEVs applications (high power batteries).
The active material cathode of TOYOTA is $LiNi_{0.81}Co_{0.15}Al_{0.04}O_2$ (i.e. the same as Saft one), in which an addition of carbon and PTFE is operated in 11 % and 5 % of the total weight, respectively. Suitable electronic conductivity and mechanical properties are insured. The anode contains a mixture of graphite (MPG, 98 % of graphitisation) and binders (MBS + CMC, in 2.5 wt%).
The cathode and the anode are put on aluminium and copper foil current collector, respectively.
The separator is a 27 µm three layer membrane composed of PP/PE/PP (polyolefin type). And, finally the electrolyte is composed of a mixture of organic carbonate solvents (EC/DMC/MEC) containing $LiPF_6$ salt.
Using its original industrial position (Battery Manufacturer and Car Maker) TOYOTA has equipped one of its micro-hybrid vehicle (Vitz, stop and start vehicle) with the first Lithium-ion module industrially used in the automotive industry.
The SUS case prismatic Lithium-ion battery of TOYOTA's Vitz is made of 4 single cells with the following characteristics (Figure 4.2.4).

- SUS case Prismatic LIB: 120x120x25mm 4 cell
- Typical 12 Ah, measured 13.2 Ah (4.1-3.0 V) with 580 g single cell
- Power output 1300 W/cell, 82 Wh/kg, 132 Wh/l, 2241 W/kg



(a) Element (b) Modules

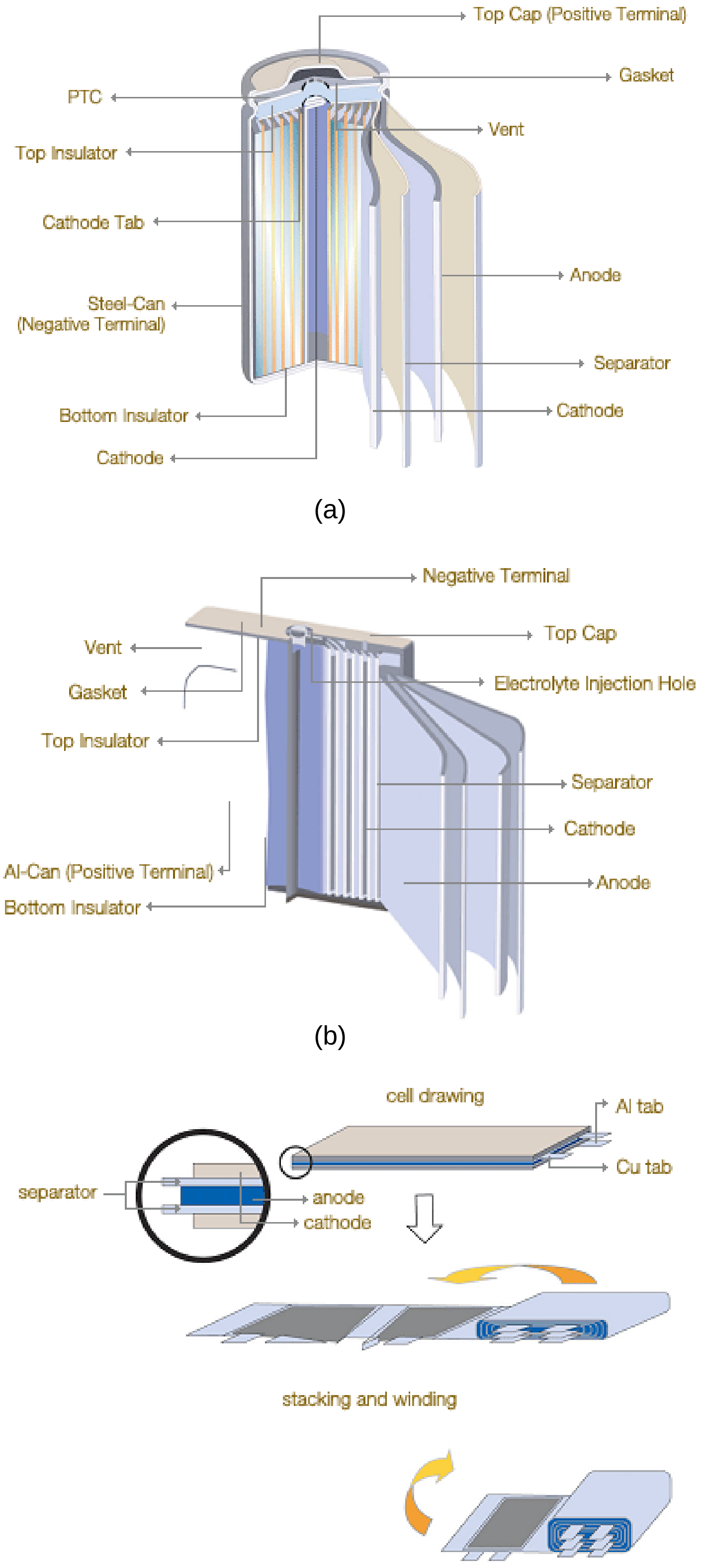
*Figure 4.2.4: Toyota SUS prismatic Lithium-ion (a) element and (b) modules.*

### - LG Chem.

In 2004, LG Chem. Ltd. has received a grant by USABC to develop advanced Lithium-ion polymer battery for Hybrid Electric Vehicles associated to CPI (Compact Power Inc. US subsidiary of LG Chem) in charge of the electronic development (BMS). LG Chem. is developing Lithium-ion batteries for electric vehicles, hybrid vehicles and military aerospace applications.

The LG Chem. cell system is based on a manganese-based cathode material, associated to blended-carbon or graphite anode material for HEVs or EVs applications, respectively. The new use of the blended-carbon anode in the large-sized Lithium-ion polymer battery allows to improve the power capability, same as at low temperature (-10 °C or below) and the cycling life.

They have developed two types of cells according to their industrial utilization (i.e. 5, 7.5 and 8 Ah-class whose are high power Lithium-ion polymer cells and 10 Ah-class which is high energy Lithium-ion polymer cell). No clear information's have been found on the technical characteristics of separator and electrolyte used by LG in this technology. They work on three different cell configurations (Figure 4.2.5 (a,b,c)): cylindrical, prismatic and laminated (i.e. lithium-ion polymer cell). In this last case, the ultra-slim and ultra-light design improve the battery safety and allow a big flexibility in size.



(a)

(b)

(c)

*Figure 4.2.5: LG Chem. lithium-ion cell in (a) cylindrical, (b) prismatic and (c) laminated configuration.*

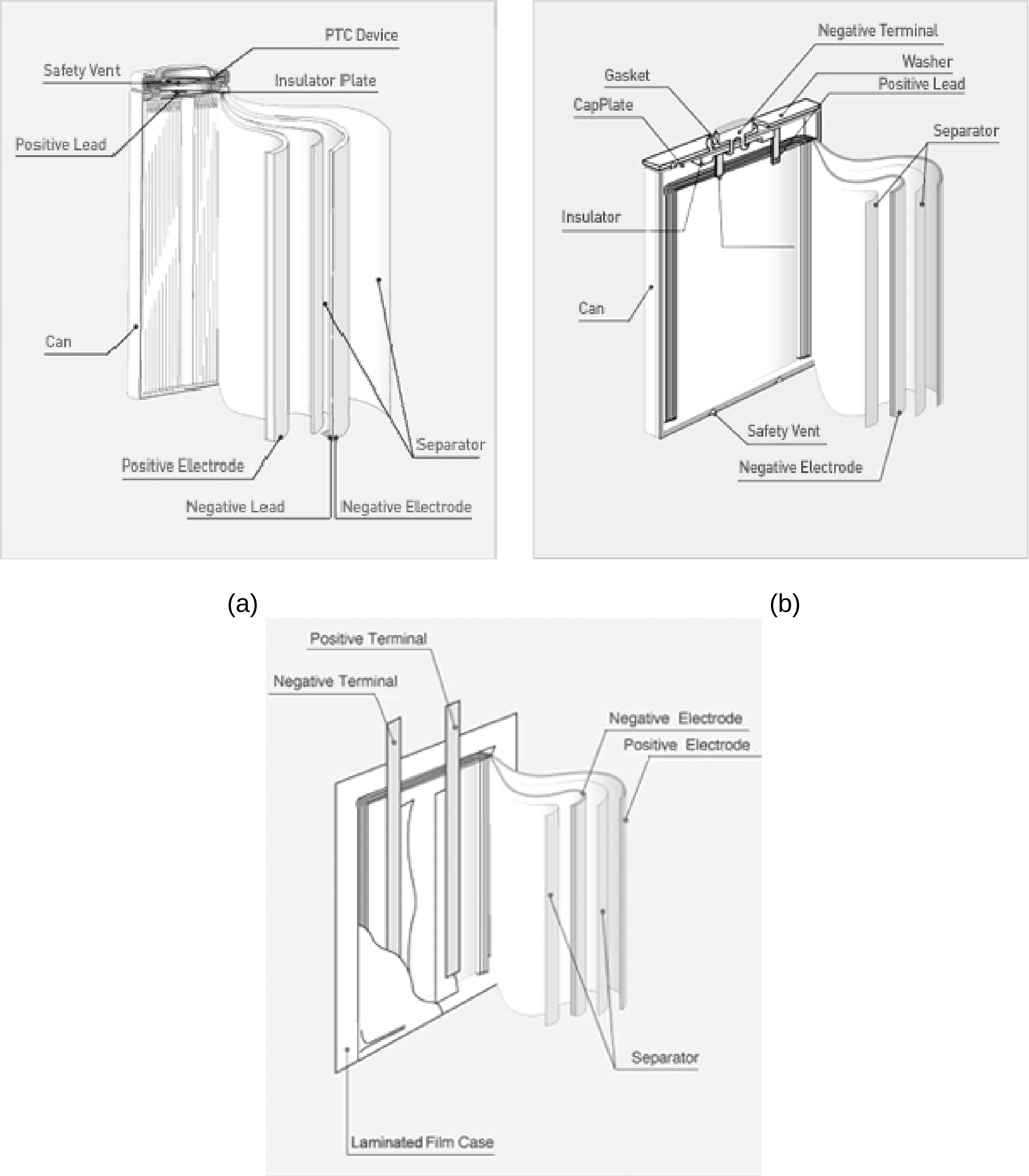
- **SAMSUNG SDI**

SAMSUNG SDI has recently developed rechargeable Lithium-ion batteries for HEV applications based on their large experience and know-how in the field of portable Lithium technologies.

The cathode active material of this manufacturer is a Lithiated Cobalt oxide deposited on aluminium foil. The anode is made of a mixture of carbon and graphite (or MCF anode) spread on a copper foil used as current collector.

A porous film used to prevent electrical contact of the battery between the cathode and the anode, namely the separator, is formed by PE and PP layers. The electrolyte is composed of a mixture of organic carbonate solvents (EC/DMC/MEC) containing $LiPF_6$ salt.

SAMSUNG Lithium-batteries are produced following different processes (i.e. stack or winding configuration) and cells are in a metal can (cylindrical, prismatic) or in an aluminised plastic pouch package (see figure *4.2.6*).



(a) (b)

(c)

*<u>Figure 4.2.6</u>: SAMSUNG SDI lithium-ion cell in (a) cylindrical, (b) prismatic and (c) laminated configuration.*

- **<u>The special case of Chinese manufacturers</u>**

In the SUBAT context, a mission to China has been organized in December 2004 (see appendix). Most of the visited laboratories and companies strongly depend on the development of the 863 Chinese R&D program and as a consequence, their activities have often been launched recently. The main Chinese actors in the lithium battery field are discussed in the following paragraph.

BYD, Shenzhen: BYD, a Chinese battery manufacturer created in 1995, is the second largest manufacturer of Lithium-ion rechargeable batteries for portable applications in the world. Recently BYD has bought one of the major Chinese automaker (a « government owned » Chinese car manufacturer), namely Xi’an Auto, becoming then BYD Auto.

Various electric and hybrid vehicle concepts have been developed using the BYD advanced batteries. They are based on the Li-Co-O type lithium-ion battery. A cycle life of 1000 cycles at 80% DOD is claimed. The BMS is produced on-site and it seems that it includes a complementary electronic cell equilibrating system. The cooling system is performed using air circulation.

At the beginning of 2004 they announced a new large project in order to develop and manufacture 100.000 EV per year in 2006 and a production of 200.000 vehicles in 2008. However, the company has no clear sight regarding the development of the electric vehicle market in China and this target seems to be forgotten. On the contrary, BYD confirms that the e-bike market is promising, but estimates the price of Li-Ion battery should drop in order to compete with Lead-Acid on the Chinese market.

Wanxiang Group Power battery: this manufacturer, located in Hangzhou, is the largest Chinese automobile OEM manufacturer and a well known supplier of the US car Industry..

The group diversified heavily and created a subsidiary, Wanxiang Electric Vehicle Centre in the framework of the 863 program, in 1999 and its subsidiary Wanxiang Power Batteries Co., Ltd. in 2000. The last one develops Li-Mn-O type lithium-ion polymer batteries from different sizes. The packaging is partially made of rigid plastics and partially made of metal.

Wanxiang also develops electric power train, BMS as well as the centralized BMS of the pack (not cooled). Three buses (2 electric and 1 hybrid) as well as 6 electric passenger cars (based on Mazda model) has been developed for the 863 program. The battery does not work on the basis of modules but on the basis of individual cells. The BMS is centralized and does not include any cell electronics or thermal control unit. These batteries have to be checked by the official battery test Laboratory and it seems that they are today at the pilot stage of production without any large scale experimentation.

Aucma New Power Technology, located at Qingdao, is the first household appliances and electricity components manufacturer.

The traction battery subsidiary has been created in 2000 with the support of the government and in the framework of the lithium-ion battery aspect of the 863 program.

Since 2003, AUCMA produces lithium-ion batteries (40 million cells/year) for cellular phone applications (amongst others Nokia or Motorola).These battery are nearly “hand made”. Only the fritting of the electrodes is performed using semi-automatic ovens. The company has created and uses a testing laboratory and a quality control laboratory. An automated production line should be installed next year to double the production capacity.

The development of the cells began with the Li-Co-O technology with liquid electrolyte and then evolved to the Li-Mn-O technology. However, this included serious problems regarding cycle life at high temperatures. It seems that the cycle life performances remain low with about 300 cycles and thermal problems are not solved.

Tianjin Lantian Hi-Tech Power Sources Joint-Stock Co. Ltd.: Tianjin Lantian Hi-Tech Power Sources Joint-Stock is a part of a complex group based principally in Tianjin. The main activity of this group is the production of batteries of all types (portable and traction with lead-Acid, NiMH and Lithium technologies)

The company provides CATARC (National Transport R&D Center) with lithium batteries and signed a joint venture with the Chinese car manufacturer Wuhan.

Prismatic and cylindrical cells of diverse capacities are produced, but mostly these capacities are quite high. These cells are based on a Li-Co-O cathode and a classic liquid electrolyte. Today, the research is mainly focussing on new cathode materials. The new production line is based on spiralling machines bought in Japan and in the USA, but the local machines remain quite outdated.

Nowadays, there are ten batteries of 250 kg (including BMS) produced each year mainly for the 863 program. In 2004, roughly 200 EV have been sold in China, while 1000 units are expected to be sold in 2008. A production capacity of 10 millions cells per year will be reached in 2006. Since recently, attention has been paid to hybrids but the cycle life is relatively low.

Xingheng Phylion Battery Co. Ltd.:

Phylion battery Co. Ltd, a joint stock company co-founded in 1995 by Institute of Physics of the Chinese Academy of Science and Chengdu Di Ao Group, is specialised in research, production and distribution of large capacity lithium-ion batteries.

In the 863 program framework, this battery manufacturer provides to Tongji University of Shanghai, (and other partners) some high power batteries for their fuel cells electric and hybrid vehicle development. Firstly, they have worked on Li-Co-O based cathode and then on Li-Mn-O cathode that show less safety problems than the Li-Co-O one. As far as it is possible to have exhaustive information, they seem to be the only Chinese Battery Manufacturer specialized in high power Lithium Batteries.

Thunder Sky

Thunder Sky has developed a new rechargeable Lithium-ion battery for industrial and military applications such as electric vehicles (buses, scooters, bicycles and cars). They are manufacturing a dynamic colloid solid-state Cr-F-Li battery (a patent protection is registered over 26 countries and regions). However, it seems that the Thunder Sky cathode is neither more nor less composed of $LiMn_2O_4$ possibly doped with chrome and fluorine. Finally, they use the same basic electrochemistry and electrode compositions: $LiMn_2O_4$ / carbon with a solid polymer electrolyte.

Since the establishment of Thunder Sky company in 1998, their commercial battery doesn't seem to have any battery management system (the results of the reliability tests are not clear), thus neither overcharge or overdischarge are controlled.

In this context, the Thunder Sky today production seems to be incompatible with the quality production standards of automakers industry (and any other road application).

- **Korean Consortium (Ssangyong Motor Co., SKC, Nexon Technology)**

Recently a large Korean consortium supported by Korean government had been created by linking Ssangyong Motor Co. (Korean automaker specialized in SUV and trucks), SKC and Nexon Technology (electronic company manufacturing different types of BMS and ECU) in the aim to develop a (i) specific battery for electric vehicle (BEV) based on Lithium-ion-Polymer technology (30 kWh) and (ii) an other Lithium-ion-Polymer products for automotive industry.

Another Korean Consortium with LG Chem, SamsungSDI and Hyundai Motor has been created at the same time for similar purposes (see LG Chem paragraph for more information)

#### 4.2.3.2 Lithium-Polymer technology

*Table 4.2.2: List of Lithium-Polymer battery manufacturers and concise description of each production process.*

| Group name | Anode material | Electrolyte | Separator | Cathode material | Comments |
|---|---|---|---|---|---|
| Valence | Unknow | gelled electrolyte (+EC:DMC, probably in ratio 2:1) | Without | $Li_xFePO_4$ | Cylindrical cell (Saphion® technology) |
| GAIA [11] | probably $LiTiO_2$ | conducting salt, org. carbonates | polyolefin | $LiMn_2O_4$ | Extrusion process |
| | synthetic graphite, carbon black | | | $LiMn_2O_4$ or $LiCoO_2$ | Prismatic cell |

- **VALENCE**

Valence technology is the leader in the development and commercialization of Saphion® technology. This company uses Lithiated metal Phosphates as cathode active materials such as Olivine $LiFePO_4$ (*J. Goodenough et al., 1996*) which is considered as a safe cathode material for large battery applications. A high thermal stability of $LiFePO_4$ and $FePO_4$ phases is observed thanks to the covalent P-O bonding which stabilizing the structure versus $O_2$. Phosphates may be classified as materials built up from one $PO_4$ tetrahedron or from the condensation of several $PO_4$ groups sharing one, two or three oxygen atoms. When atoms such as F, Cl, S and H replace one or more of the oxygen atoms in phosphates, substituted phosphates are created. The most common form, the monophosphate are salts derivated from orthophosphoric acid, $H_3PO_4$.

When fully charged, no excess lithium is left at the cathode (unlike $LiCoO_2$ where 50 % still remains), the redox voltage ($LiFePO_4$: 3.5 V *versus* $Li^+/Li$) is low enough to ensure no electrolyte decomposition (no free electrolyte). Under severe abusive conditions $LiFePO_4$ active material will not liberate oxygen and therefore does not pose any significant safety hazard.

- **GAIA**

GAIA is developing and producing lithium ion polymer batteries based on production processes adapted from the plastics industry. GAIA's proprietary extrusion process has been reported figures 4.2.7 and 4.2.8. The extrusion of all battery compounds has become the core element of GAIA's battery. This extrusion process allows the production of liquid free and flexible form batteries with a low thickness for industrial and automotive applications.

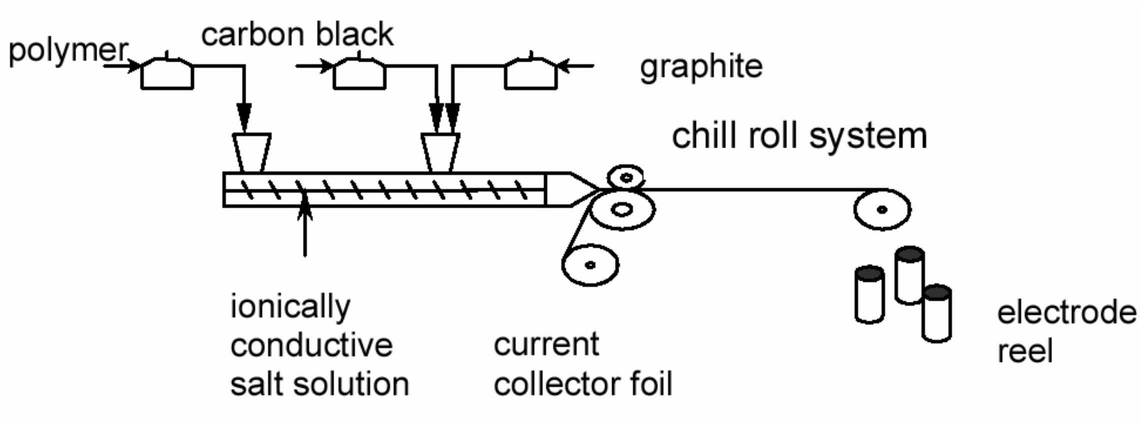


*Figure 4.2.7: Scheme of the extrusion process [11].*

In GAIA process, the foils are obtained in an extrusion process onto a chill roll system at high temperature and are stored on supply reels. Cells are currently manufactured on a winding machine to a cylindrical cell and are contacted and put into a housing immediately. A separate injection of electrolyte is not necessary. The dispersion, mixing and plasticizing of the materials steps are performed in only one machine representing the main advantage of the GAIA manufacturing process. In case of dry-blend use as a precursor, the dosing in the extrusion step is shut away to two positions: the first for the solids and the second for the electrolyte with plasticizers (which one is PC). Different possibilities are offered for the coating process: the simpler one uses a direct coating of the electrodes on the current collectors (only for single sided coating), nevertheless the demand of higher energy density requires double sided coating with an additional transfer-lamination step. In this case, the electrodes are coated on a separate carrier foil and are transferred on the current collector by a lamination step (Figure 4.2.8).

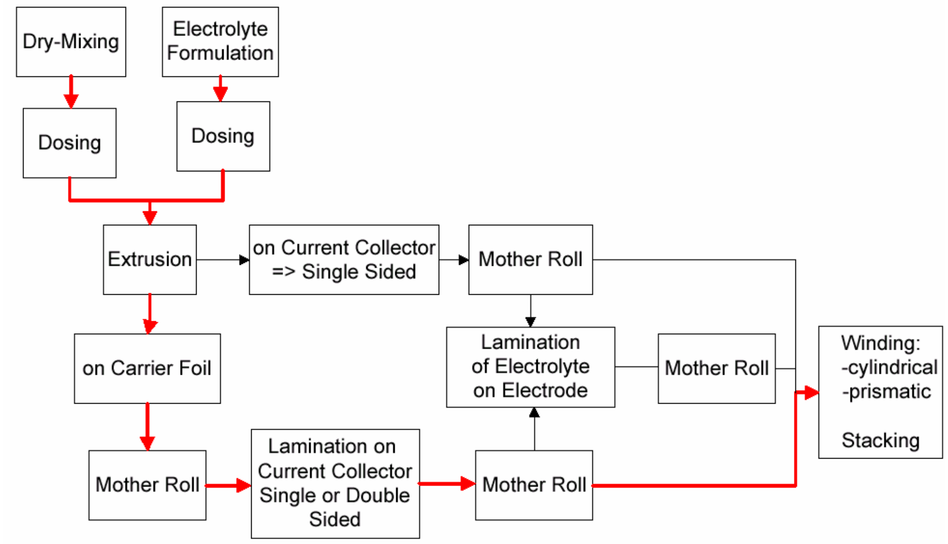
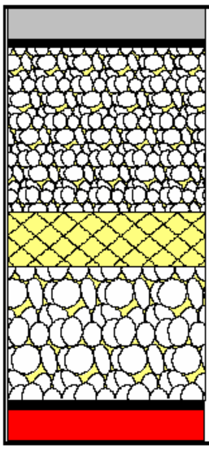


*Figure 4.2.8: Scheme of the coating process [11].*



| Layer | Thickness | Composition |
|---|---|---|
| Collector | 25 µm | Al-foil |
| Primer | 3 µm | carbon black, polymer |
| Cathode | 180 µm | $LiMn_2O_4$ or $LiCoO_2$, carbon black, electrolyte |
| Electrolyte | 50 µm | conducting salt, org. carbonates, polymer 1, polymer 2, stabilizers |
| Anode | 60 µm | graphite, carbon black, electrolyte |
| Primer | 3 µm | carbon black, polymer |
| Collector | 18 µm | Cu-foil |

*Figure 4.2.9: Cross-section of a GAIA lithium ion polymer cell.*

The GAIA technology focuses on the direct and complete extrusion of each battery component, i.e. the anode, cathode and separator electrolyte foil. This means that anode (i.e. intercalation graphites or MCMB) and cathode foil (i.e. spinel $LiMn_2O_4$, $LiCoO_2$ or mixed oxides depends on the required application, $LiMn_2O_4$ is chosen for automotive applications) already include the polymer electrolyte. In this one the conducting salt solution is immobilised (i.e. such as coating process) inducing a safe battery. All materials have to be dried before the production starts, so the polymers and the active materials are dried in a vacuum mixing drier. The extrusion pressure and temperature are critical parameters in the global process, which must be a compromise between the high melting point of the polymer and the decomposition temperature of the electrolyte.

The cylindrical cell is entirely edge contacted using a special bounding technique. This establishes low contact resistances which is necessary for high power applications. For the stainless steal housing the terminals are screwed to the lid with insulators (WIG welding process). The Lithium-ion polymer battery characteristics are summarized on the table 4.2.3.

*Table 4.2.3: Specific features of GAIA Lithium-ion polymer battery for automotives applications [23].*

| Battery Type | Specific Power (W/kg) | Specific Energy (Wh/kg) | Operating Temp. ($^oC$) | Calendar Life (In Vehicle/Yr) |
|---|---|---|---|---|
| Advanced Lithium Ion (LTC/GAIA) | 1300 | 150 | -30 to +80 | 8 |

A second new development of GAIA Lithium-ion polymer battery is realized by using a high power anode material such as $LiTiO_2$ associated to $LiMn_2O_4$ cathode material. This system has good electrochemical properties especially at low temperature (-20 °C).

#### 4.2.3.3 Lithium-metal technology

*Table 4.2.4: List of Lithium-metal battery manufacturers and concise description of each production process*

| Group name | Anode material | Electrolyte | Separator | Cathode material | Comments |
|---|---|---|---|---|---|
| AVESTOR | Lithium foil | Solid polymer conductor | / | $V_2O_{5-x}$ (x<1) | Prismatic cell |
| BatScap [16] | Lithium foil | Solid electrolyte | / | $V_2O_5$ | Prismatic cell |

PEO = Polyethylene oxide
LiTFSI = Lithium (bis)trifluoromethanesulfonimide ($(Li(CFSO_2)_2N)$)

- **AVESTOR**

This company is a leading organization in the development of large metallic lithium dry polymer-based electrolyte batteries for electric vehicles and stand-by power.

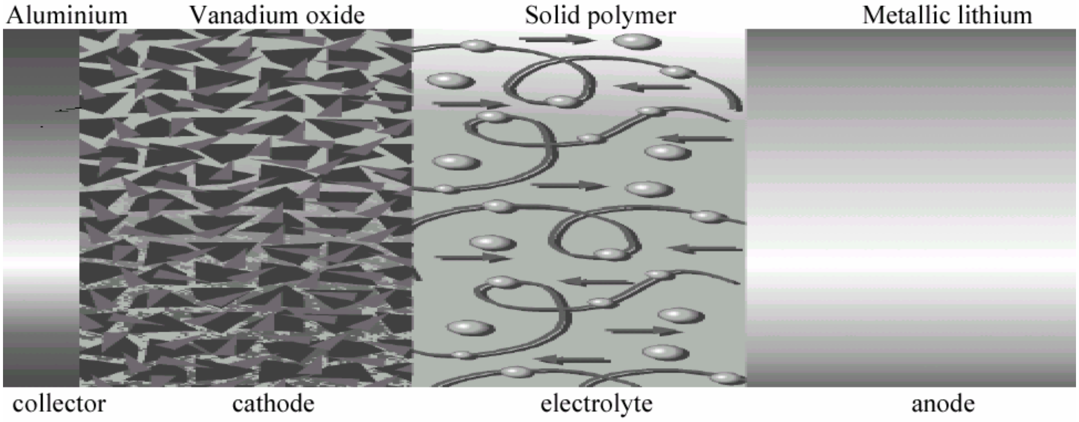


*Figure 4.2.10: Avestor Lithium-Metal-Polymer electrochemical cell.*

The electrochemical cell (figure 4.2.10) developed by AVESTOR is based on Li metal / Co-Polymer + TFSI salt / $V_2O_5$ system in which during the discharge, the anode, the Solid polymer electrolyte and the cathode are $Li^+$ source (+current collector), $Li^+$ carrier and $Li^+$ sink, respectively. The concept involves an all-solid-state cell made of two reversible lithium ions electrodes, separated by a thin ionically-conductive polymer membrane acting both as an electrolyte and as a separator. The cathode is a material based on a reversible intercalation compound of vanadium oxides which is blended with polymer electrolyte and carbon to form a plastic composite. It will be deposited on a metal foil current collector (i.e. aluminium foil). The Solid-state polymer electrolyte is obtained by dissolution of a LiTFSI salt in a solvating aprotic polymer such as PEO co-polymer. Finally, this Lithium-Metal-Polymer cell is made by stacking five thin layer materials.

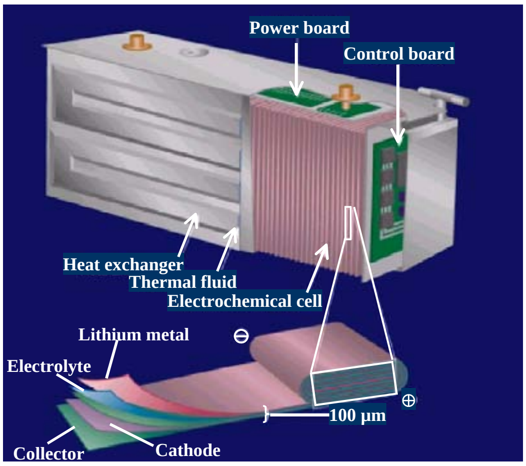


*Figure 4.2.11: Lithium-Metal-Polymer cell laminate construction and corresponding full pack.*

The total thickness of the laminated cell is less than 100 µm and it is wound into a prismatic shape to form an electrochemical cell. Since changes in the size of the cell or in the total amount of wound material do not affect the fundamentals of current uniformity or thermal control, the Li-M-P technology is suitable for a wide variety of applications. Various designs of this technology are shown on Figure 4.2.12 with highlight on the difference between the HEV and the EV thin films (variation of the thickness film for optimizing performances).

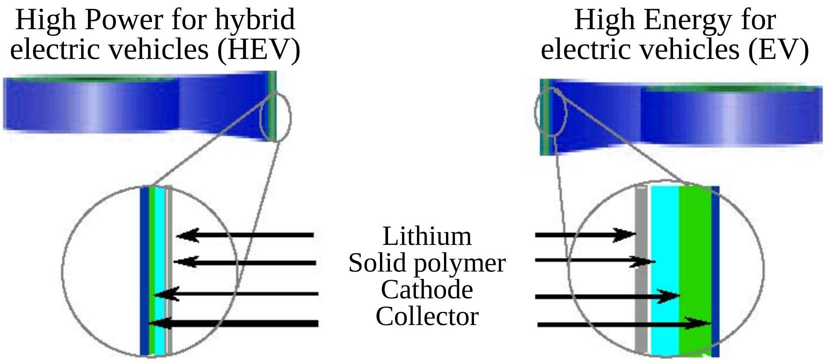


*Figure 4.2.12: AVESTOR LMP technology for EV and HEV [25].*

Li-M-P being in solid state, the optimal performances of the battery for EV applications is achieved when it operates at a temperature between 60 °C to 80 °C.
The Lithium-Metal-Polymer battery manufacturing process can be summarized by assembling three (anode, cathode and electrolyte) ultra-thin films to form an energy laminate.
The anode (Figure 4.2.13) starts from an ingot and is extruded down to a thick foil. The Lithium foil is rolled down to an ultra-thin foils and its length is directly proportional to the volume of lithium ingot which goes into the extruder when width and thickness remain the same. Both lithium extrusion and rolling processes are fast and the resulting components are about 10 µm.

The cathode is also extruded and this process (Figure 4.2.14) is free of solvents. The thin layer of cathode is extruded onto a corrosion resistant current collector and the cathode has a very high energy density, without porosity.

Finally, the electrolyte is a full solid polymer that is extruded directly onto the cathode and this electrolyte is combined on the cathode-current collector thin film by UV reticulation leading to the half-cell formation.

The anode and the half-cell dry films are laminated with the anode and cathode offset, the electrodes contacts are mechanically bound with integrated electrical wires for cell to cell interconnection.

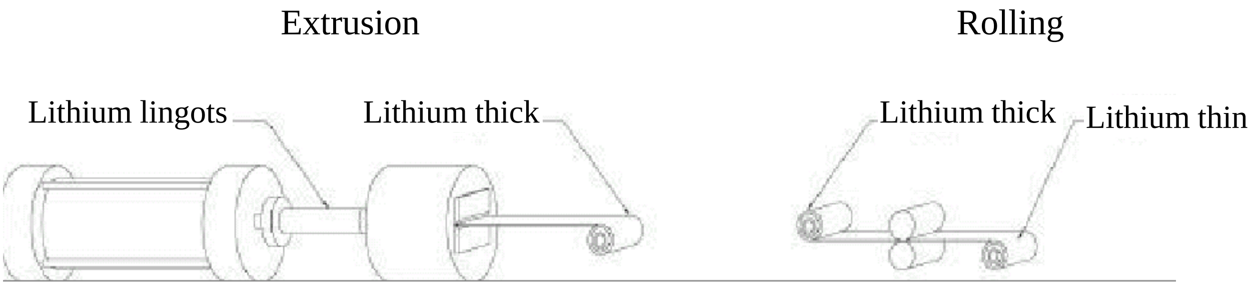


*Figure 4.2.13: AVESTOR Anode manufacturing process [24].*

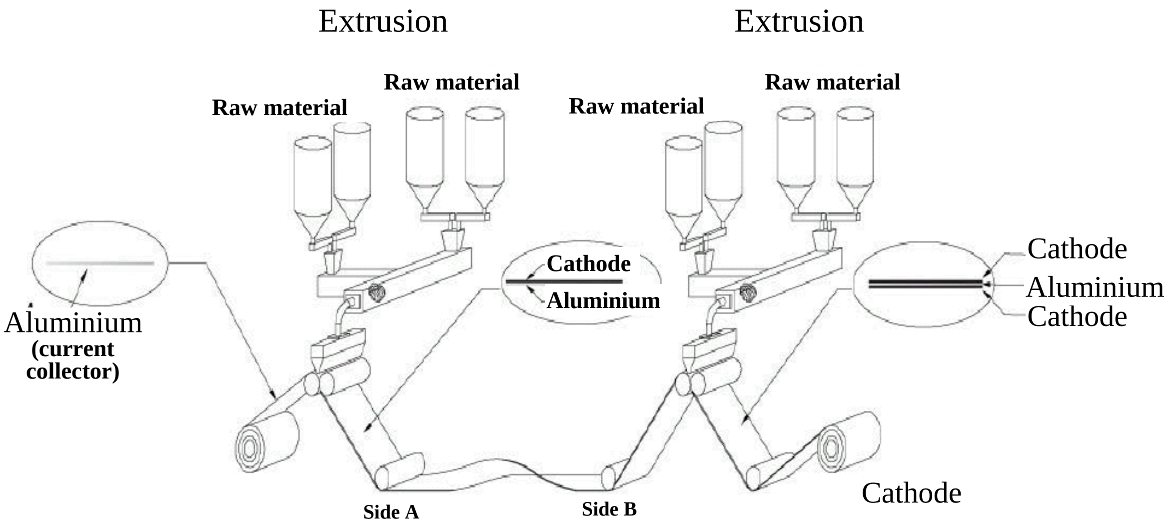


*Figure 4.2.14: AVESTOR  Cathode manufacturing process [24].*

This type of technology seems to be very attractive for automotive applications with high performances and a relatively cost of goods and process, but it seems that reliability is very difficult to obtain in the case of Hybrid or Electric Vehicles application. It's probably for this reason that recently a press release from AVESTOR announced that their company removes from the automotive market [26,27].

- **BatScap**

Bolloré Technologie (80 %) and Electricité de France (20 %) founded in 2001 the BatScap Company to manufacture and commercialize the Lithium-Metal-Polymer battery and corresponding super capacitors. This battery is an electrochemical system with a solid and dry polymer electrolyte in which there is no solvent. The electrolyte is made with PEO and LiTFSI salt and an ultra-thin lithium foil anode is chosen to take full advantage of lithium specific energy (3900 $Ah.kg^{-1}$). The lack of reaction between lithium metal and the electrolyte (no liquid and no vapour pressure) allows decreasing drastically the anode thickness. The cathode is a plastic composite of vanadium oxide blended with polymer electrolyte and carbon, some additives are added. Both cathode and electrolyte are extruded in ultra-thin porous films and elementary cells are created by coiling electrodes and electrolyte together. This technique facilitates the wounding process with current collector and it avoids the introduction of solvent during the production. The extrusion process has been developed to continuously produce thin films (single cells) with an excellent reproducibility and thickness profile (actually the thickness is about 150 µm).Thanks to the extrusion process, thickness of films can be different according to the various applications (energy storage, power density...) and this technology allows a large flexibility in cell and module design.

After more than eight years of development this technology has not been yet tested on vehicles (either Electric than Hybrid). Recently Batscap has announced the first vehicle tests in a next future (The Matra/Bolloré BlueCar to be shown during the 2005 Genève Auto Show). Results of these tests will be very important to demonstrate the reliability of these batteries [28].

### 4.2.4 Market Trends and Costs analysis

As Lithium based batteries are at different stages of development depending on the technology chosen and the Battery Manufacturer, the Cost and Price estimation of a future volume production must take many parameters into account. But the method used must allow comparison of the estimation in 2012, when most of Car and Battery Manufacturers think that the market could have begun.

The today price of Lithium-based batteries is not significant of a future industrial price in volume production but it will be used as a “starting” value useful for today car developers.

The following parameters will be studied:

- As the active materials of all the Lithium-based battery types are used only for battery (portable ones today), mass production will induce a decrease of the material cost,
- Lithium battery packs use much more electronic systems than the other technologies. A decrease of the electronic costs can be forecast following the increase of production volume,
- Several new Lithium-based battery technologies are in development with the aim to decrease the material and process costs (Li-Mn-O) spinel for the cathode, new carbon type material for the anode, new separator and electrolyte, laminated process etc…),
- Labour costs differences between European and Asian countries where battery manufacturers are taking place,
- Technical performances like specific power and know-how are continuously increasing, consequences on the cost and price estimations are taken into account (number of cells needed for a specific application).

The method used in this estimation is based on a minimum cost and price calculation where mass production and new technologies cost decrease are taken into account in the material and system cost evaluation and a maximum cost and price where only mass production cost decrease are considered.

Increasing technical performances are considered for all the technologies, the best performances reached in the world by any of all the Battery Manufacturers.

Data for the hypothetic costs in 2012 are obtained using reliable values coming for many sources as material producers, battery manufacturers, battery specialists and comparison with other materials used in comparable situation.

The evaluation is made in four steps:

- Cell cost of goods,
- Cell cost,
- Battery cost,
- Battery price.

The Cell specifications are chosen arbitrary according to the most used cell specifications for a given application:

- For high power cells a 10 Ah, 380 g 36 Wh cell is chosen,
- For high energy cells a 40 Ah, 1000 g 144 Wh is chosen.

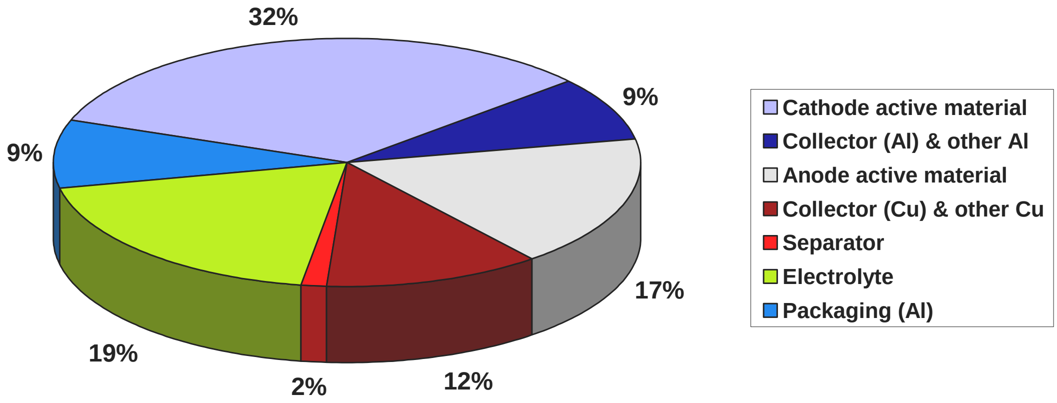
The Cell cost of goods evaluation needs the use of the chemical composition of the cell (in weight %), as this composition changes with the cell weight energy and power, with the technology used and with the corresponding process it would be necessary to make a great number of evaluation. But after

some simulations made on several well known examples it appears that the composition changes have a little influence on the calculated cell cost of goods (< 5 %).
As only a minimum and a maximum value are taken into account, only a mean value of the composition has to be considered.
The Lithium-Metal-Polymer batteries are not considered in this study because of a great difference of composition and process, this type of battery cannot be evaluated by the same method.

1. *Energy Cells and batteries for BEV and Full Hybrid with ZEV*

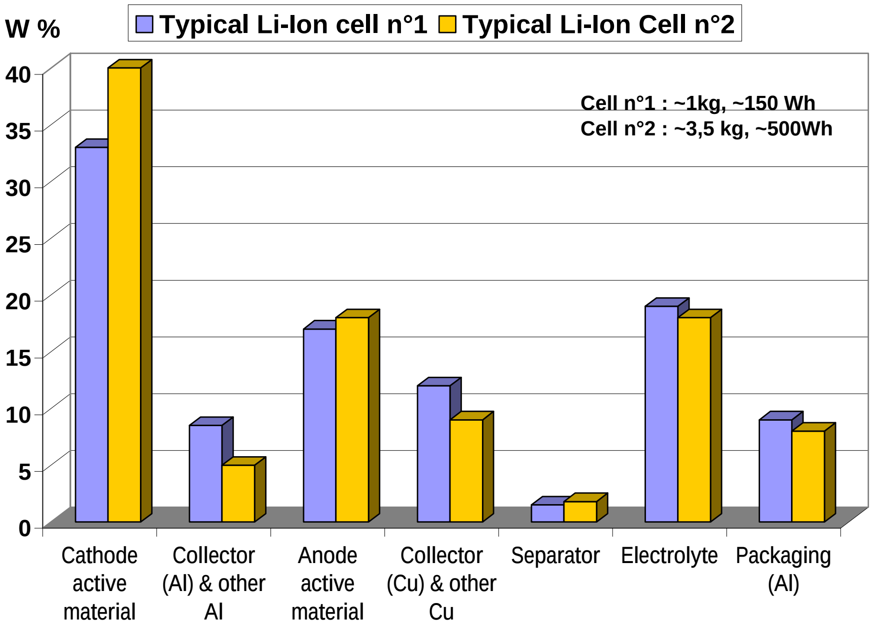
A typical composition of a Li-Ion cell for "energy" applications is shown on the following diagram (40 Ah, 1000 g).

*<u>Figure 4.2.15</u>: Composition in weight % of a Li-ion cell for "Energy" (typical 1 kg) applications.*



In order to evaluate the influence of Cell size two types of cells are compared on the following figure. This comparison shows that the influence of cell size is not important for the calculation of the cell cost of goods (it could be different for the battery pack cost).

*<u>Figure 4.2.16</u>: Influence of cell size on the weight (%) of Li-ion cell for "Energy" (typical 1 kg) applications.*



Cell costs of materials in 2005 are given in the following table for a typical 1kg cell (144 Wh and 40 Ah).

| 2005 | W % | unit max. (€/kg) | unit min. (€/kg) | W (g) | Max. Cost | Min. Cost | % (max.) | % (min.) |
|---|---|---|---|---|---|---|---|---|
| Cathode active material | 33 | 45 | 38 | 330 | 14.85 | 12.54 | 47.00 | 45.44 |
| Collector (Al) & other Al | 8.5 | 21 | 19 | 85 | 1.79 | 1.62 | 5.65 | 5.85 |
| Anode active material | 17 | 21 | 18 | 170 | 3.57 | 3.06 | 11.30 | 11.09 |
| Collector (Cu) & other Cu | 12 | 15 | 14 | 120 | 1.80 | 1.68 | 5.70 | 6.09 |
| Separator | 1.5 | 140 | 120 | 15 | 2.10 | 1.80 | 6.65 | 6.52 |
| Electrolyte | 19 | 21 | 20 | 190 | 3.99 | 3.80 | 12.63 | 13.77 |
| Packaging (Al) | 9 | 3.5 | 3.1 | 90 | 3.50 | 3.10 | 11.08 | 11.23 |
|  |  |  |  | 1000 | 31.60 | 27.60 |  |  |
|  |  |  |  | €/kWh | 219 | 192 |  |  |

Total Cost of a 30 kWh Battery for BEV

| 2005 |  |  | Max Cost | Min. Cost |
|---|---|---|---|---|
| Cell | Materials |  | 31.60 | 27.60 |
|  | Labour |  | 6 | 4.2 |
|  | Cell electr. |  | 5.4 | 5.1 |
|  | Other components |  | 1.6 | 1.5 |
|  | TOTAL |  | 45 | 38 |
| Cells Assembly | nbre | 208 |  |  |
|  | Total |  | 9 276 | 7 986 |
| Battery | BMS |  | 720 | 680 |
|  | Mechanical |  | 440 | 420 |
|  | Battery Ass. labour |  | 110 | 77 |
|  | Power devices |  | 1050 | 1010 |
|  | TOTAL |  | 11 640 | 10 212 |
|  |  | €/kWh | 388 | 340 |

Company Costs

| 2004 |  |  | Max. Cost | Min. Cost |
|---|---|---|---|---|
|  | Total Cost of a 30 kWh Battery |  | 12 028 | 10 552 |
|  | Other Manufacturing Costs |  | 4 210 | 2 955 |
|  | Overheads |  | 3 609 | 2 638 |
|  | Total Cost |  | 19 847 | 16 144 |
|  |  | €/kWh | 662 | 538 |

|  |  |  |  |
|---|---|---|---|
| Margin |  | 30% | 30% |
| Price |  | 25 801 | 20 988 |
|  | €/kWh | 860 | 700 |

These estimations (in €/kWh) made for BEV 30 kWh battery can also be applied to a full hybrid with 40 km ZEV 10 kWh battery with a little extra-cost for the BMS and mechanical hardware leading to an equivalent price.

They are close to those announced by Battery Manufacturers able to produce energy Lithium-Ion batteries at a pilot plant stage (between 850 and 950 €/Wh)
Note: Results are expressed in terms of battery prices but only production costs evaluation are really reliable and mainly function of the active material costs. But in order to obtain an order of magnitude of the real price (and future real price) we have estimated the price corresponding to a given production cost using a mean value of the overheads and company costs. These results are made to be compared between each other and very carefully used as absolute value because of the close relation between the market situation and their values (in case of great competition overheads and margin decrease).

Evaluations for a 2012 production are the following.

| 2012 | W % | unit max. (€/kg) | unit min. (€/kg) | W (g) | Max. Cost | Min. Cost | % (max.) | % (min.) |
|---|---|---|---|---|---|---|---|---|
| Cathode active material | 33 | 15 | 9.8 | 330 | 4.95 | 3.23 | 28.17 | 24.32 |
| Collector (Al) & other Al | 8.5 | 21 | 19 | 85 | 1.79 | 1.62 | 10.16 | 12.14 |
| Anode active material | 17 | 15 | 8 | 170 | 2.55 | 1.36 | 14.51 | 10.23 |
| Collector (Cu) & other Cu | 12 | 15 | 14 | 120 | 1.80 | 1.68 | 10.24 | 12.63 |
| Separator | 1.5 | 60 | 40 | 15 | 0.90 | 0.60 | 5.12 | 4.51 |
| Electrolyte | 19 | 11 | 9 | 190 | 2.09 | 1.71 | 11.89 | 12.86 |
| Packaging (Al) | 9 | 3.5 | 3.1 | 90 | 3.50 | 3.10 | 19.91 | 23.31 |
|  | 100 |  |  |  | 17.58 | 13.30 |  |  |
|  |  |  |  | €/kWh | 122 | 92 |  |  |

**Total Cost of a 30 kWh Battery in 2012**

| **2012** |  |  | **Max. Cost** | **Min. Cost** |
|---|---|---|---|---|
| Cell | Materials |  | 17.575 | 13 |
|  | Labour |  | 5.5 | 4.2 |
|  | Cell electr. |  | 3.24 | 3.24 |
|  | Other components |  | 1.3 | 1.3 |
|  | **TOTAL** |  | **28** | **22** |
| Cells Assembly | nbre | 208 |  |  |
|  | **Total** |  | **5 744** | **4 584** |
| Battery | BMS |  | 540 | 500 |
|  | Mechanical |  | 370 | 280 |
|  | Battery Ass. labour |  | 110 | 77 |
|  | Power devices |  | 900 | 750 |
|  | **TOTAL** |  | **7 692** | **6 213** |
|  |  | **€/kWh** | **256** | **207** |

**Company Costs**

| **2012** |  | **Max. Cost** | **Min. Cost** |
|---|---|---|---|
| **Total Cost of a 30 kWh Battery** |  | **7 948** | **6 420** |
| Other Manufacturing Costs |  | 2 384 | 1 605 |
| Overheads |  | 1 590 | 963 |
| **Total Cost** |  | **11 922** | **8 988** |
|  | **€/kWh** | **397** | **300** |

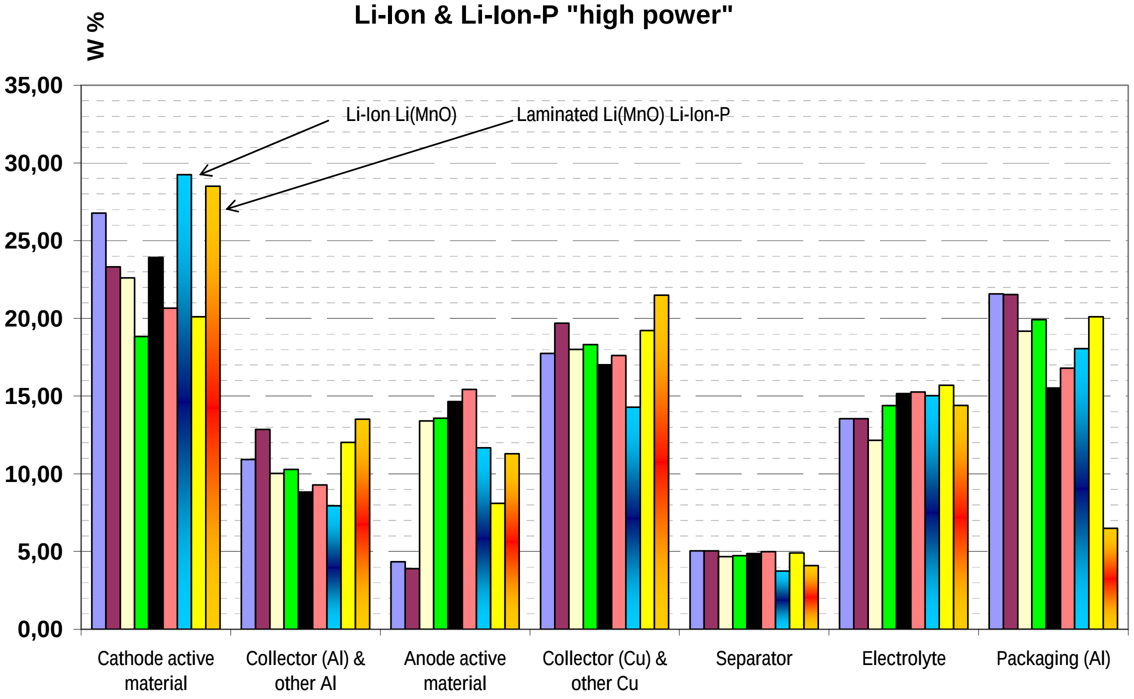
|  |  |  |  |
|---|---|---|---|
| Margin |  | 20% | 20% |
| **Price** |  | **14 306** | **10 786** |
|  | **€/kWh** | **477** | **360** |

These results are close to the values announced by several Battery Manufacturers and seem to show that it will be difficult to forecast a Li-Ion battery price under 360 €/kWh in the future. As this price is more than 50% higher than the expected price by the Car Industry it is difficult to forecast a great development of the BEV market without any other contribution (like oil price or governmental directives).

## 2. *High power Cells and battery for Hybrids Vehicles*

As shown chapter B.3, the Hybrid Vehicle Market seems to have begun to grow with the Toyota Prius II and the Honda Civic put on the Market in 2004. NiMH batteries are now used for all these vehicles, but for Battery Manufacturers and Car Makers it seems that Lithium based could be the most promising system to compete with NiMH. All Companies able to develop Lithium based battery with high performances at low cost are now working hard for this future market with less interest to high energy one. Several types of technology (see previous chapter) are in competition and it becomes more difficult to make a synthesis in order to obtain a typical high power cell.

*<u>Figure 4.2.17</u>: Comparison of composition (weight %) of different manufacturers Li-ion & Li-ion-P cell for "power" (typical 1 kg) applications.*



But, as shown on the previous diagram where composition of 9 high power cells from 7 different companies have been described, only two of them are showing a different composition. These two high power cells are made using Li-Mn-O spinel (Li(Co-Ni-Mn)-O for the others) where the cathode active material is often in greater quantity than for the others and one of them is of laminated type where the packaging weight decreases a lot.

In such conditions we have chosen as typical composition the mean value of the more "traditional" battery types and laminated with Li-Mn-O spinel are described in the minimum values.
The typical cell chosen is 10 Ah, 380 g corresponding to a mean value of the most often size chosen by the Battery Manufacturers.
Two applications are evaluated:

- A battery pack for mild hybrid vehicle of 12 kW (10 s) and 0.4 kWh where two hypothesis are studied (thermal cooling system is assumed to be very simple):
  - Hypothesis n°1: The BMS and part of the accessories are included in the battery pack cost,

- Hypothesis n°2: The BMS and part of the accessories (electrical and mechanical ones) are not included in the battery pack cost and developed by the Car
- Manufacturer in the ECU of the vehicle.

- A battery pack for full hybrid vehicle of 40 kW (10 s) and 1.2 kWh (all accessories included)

Results are shown on all following tables.

| 2005 | W % | unit max (€/kg) | unit min (€/kg) | W (g) | Max. Cost | Min. Cost | % (max.) | % (min.) |
|---|---|---|---|---|---|---|---|---|
| Cathode active material | 25 | 45 | 38 | 95.00 | 4.28 | 3.61 | 32.09 | 30.34 |
| Collector (Al) & other Al | 13 | 21 | 19 | 49.40 | 1.04 | 0.94 | 7.79 | 7.89 |
| Anode active material | 12 | 21 | 18 | 45.60 | 0.96 | 0.82 | 7.19 | 6.90 |
| Collector (Cu) & other Cu | 17 | 15 | 14 | 64.60 | 0.97 | 0.90 | 7.27 | 7.60 |
| Separator | 4 | 140 | 120 | 15.20 | 2.13 | 1.82 | 15.98 | 15.33 |
| Electrolyte | 14.5 | 21 | 20 | 55.10 | 1.16 | 1.10 | 8.69 | 9.26 |
| Packaging (Al) | 14.5 | 2.8 | 2.7 | 55.10 | 2.80 | 2.70 | 21.02 | 22.69 |
|  | 100 |  |  | 380.00 | 13.32 | 11.90 |  |  |
|  |  |  |  | €/kWh | 370 | 331 |  |  |

Cell costs of materials in 2004 become the following:

And for a mild hybrid battery of 12 kW (10 s) and 0.4 kWh costs could be as following

|  |  |  | hyp. N° 1 |  |  | hyp. N°2 |  |
|---|---|---|---|---|---|---|---|
|  | 2005 |  | Max. Cost | Min. Cost |  | Max. Cost | Min. Cost |
| Cell | Materials |  | 13.32 | 11.90 |  | 13.32 | 11.90 |
|  | Labour |  | 4 | 3.6 |  | 4 | 3.6 |
|  | Cell electr. |  | 2.8 | 2.4 |  | 2.8 | 2.4 |
|  | Other components |  | 1.2 | 1.1 |  | 1.2 | 1.1 |
|  | TOTAL |  | 21 | 19 |  | 21 | 19 |
| Cells Assembly | nbre | 15 |  |  |  |  |  |
|  | Total |  | 320 | 285 |  | 320 | 285 |
| Battery | BMS |  | 18 | 17 |  | 0 | 0 |
|  | Mechanical |  | 9 | 8 |  | 4 | 4 |
|  | Battery Ass. Labour |  | 6 | 4.5 |  | 2 | 2 |
|  | Power devices |  | 25 | 24 |  | 18 | 16 |
|  | TOTAL |  | 378 | 338 |  | 344 | 307 |
|  |  | €/kW | 31 | 28 |  | 29 | 26 |

|  |  | **hyp. N° 1** |  | **hyp. N°2** |  |
|---|---|---|---|---|---|
| **2004** |  | Max. Cost | Min. Cost | Max. Cost | Min. Cost |
| **Total Cost of a Mild Hybrid Battery** |  | **378** | **338** | **344** | **307** |
| Other Manufacturing Costs |  | 57 | 41 | 52 | 37 |
| Overheads |  | 94 | 68 | 86 | 61 |
| **Total Cost** |  | **529** | **447** | **481** | **405** |
|  | **€/kW** | **44** | **37** | **40** | **34** |

|  |  |  |  |  |  |
|---|---|---|---|---|---|
| Margin |  | 30 % | 30 % | 30 % | 30 % |
| **Price** |  | **688** | **581** | **626** | **527** |
|  | **€/kW** | **57** | **48** | **52** | **44** |

Evaluations for a 2012 production are following.

| 2012 | W % | unit max. (€/kg) | unit min. (€/kg) | W (g) | Max. Cost | Min. Cost | % (max.) | % (min.) |
|---|---|---|---|---|---|---|---|---|
| Cathode active material | 25 | 15 | 9.8 | 95 | 1.43 | 0.93 | 16.90 | 16.51 |
| Collector (Al) & other Al | 13 | 21 | 19 | 49.4 | 1.04 | 0.94 | 12.31 | 16.64 |
| Anode active material | 12 | 15 | 8 | 45.6 | 0.68 | 0.36 | 8.11 | 6.47 |
| Collector (Cu) & other Cu | 17 | 15 | 14 | 64.6 | 0.7 | 0.90 | 11.49 | 16.04 |
| Separator | 4 | 60 | 40 | 15.2 | 0.91 | 0.61 | 10.82 | 10.78 |
| Electrolyte | 14.5 | 11 | 9 | 55.1 | 0.61 | 0.50 | 7.19 | 8.79 |
| Packaging (Al) | 14.5 | 2.8 | 1.4 | 55.1 | 2.80 | 1.40 | 33.21 | 24.82 |
|  | 100 |  |  |  | 8.43 | 5.64 |  |  |
|  |  |  |  | €/kWh | 234 | 157 |  |  |

For the mild hybrid battery studied

|  |  |  | hyp. N° 1 |  | hyp. N°2 |  |
|---|---|---|---|---|---|---|
|  | **2012** |  | Max. Cost | Min. Cost | Max. Cost | Min. Cost |
| Cell | Materials |  | 8.43 | 5.64 | 8.43 | 5.64 |
|  | Labour |  | 4 | 2.5 | 4 | 2.5 |
|  | Cell electr. |  | 1.6 | 1.6 | 1.6 | 1.6 |
|  | Other components |  | 0.8 | 0.8 | 0.8 | 0.8 |
|  | **TOTAL** |  | **15** | **11** | **15** | **11** |
| Cells Assembly | nbre | 15 |  |  |  |  |
|  | **Total** |  | **223** | **158** | **223** | **158** |
| Battery | BMS |  | 13 | 12 | 0 | 0 |
|  | Mechanical |  | 5 | 5 | 4 | 4 |
|  | Battery Ass. Labour |  | 3 | 2 | 2 | 2 |
|  | Power devices |  | 13 | 13 | 12 | 12 |
|  | **TOTAL** |  | **257** | **190** | **241** | **176** |
|  |  | **€/kW** | **21** | **16** | **20** | **15** |

Leading to the following prices:

|  |  | hyp. N° 1 |  | hyp. N°2 |  |
|---|---|---|---|---|---|
| **2012** |  | Max. Cost | Min. Cost | Max. Cost | Min. Cost |
| **Total Cost of a Mild Hybrid Battery** |  | **257** | **190** | **241** | **176** |
| Other Manufacturing Costs |  | 31 | 23 | 29 | 21 |
| Overheads |  | 38 | 29 | 36 | 26 |
| **Total Cost** |  | **326** | **241** | **305** | **224** |
|  | **€/kW** | **27** | **20** | **25** | **19** |

|  |  |  |  |  |  |
|---|---|---|---|---|---|
| Margin |  | 20 % | 20 % | 20 % | 20 % |
| **Price** |  | **391** | **290** | **367** | **268** |
|  | **€/kW** | **33** | **24** | **31** | **22** |

For the full hybrid battery costs of cell materials are the same and:

| 2005 | | | Max. Cost | Min. Cost |
|---|---|---|---|---|
| Cell | Materials | | 13.32 | 11.90 |
| | Labour | | 4 | 3.6 |
| | Cell electr. | | 2.8 | 2.4 |
| | Other components | | 1.2 | 1.1 |
| | **TOTAL** | | **21** | **19** |
| Cells Assembly | nbre | 58 | | |
| | **Total** | | **1 237** | **1 102** |
| Battery | BMS | | 72 | 70 |
| | Mechanical | | 43 | 42 |
| | Battery Ass. Labour | | 13 | 8 |
| | Power devices | | 119 | 105 |
| | **TOTAL** | | **1 484** | **1 327** |
| | | **€/kW** | **37** | **33** |

Leading to the following values in 2005:

| **2005** | | Max. Cost | Min. Cost |
|---|---|---|---|
| **Total Cost of a Full Hybrid Battery** | | **1 484** | **1 327** |
| Other Manufacturing Costs | | 223 | 159 |
| Overheads | | 371 | 265 |
| **Total Cost** | | **2 077** | **1 752** |
| | **€/kW** | **52** | **44** |

| | | | |
|---|---|---|---|
| Margin | | 30 % | 30 % |
| **Price** | | **2 701** | **2 277** |
| | **€/kW** | **68** | **57** |

And for the 2012 evaluations:

| 2012 | | | Max. Cost | Min. Cost |
|---|---|---|---|---|
| Cell | Materials | | 8.43 | 5.64 |
| | Labour | | 4 | 2.5 |
| | Cell electr. | | 1.6 | 1.6 |
| | Other components | | 0.8 | 0.8 |
| | **TOTAL** | | **15** | **11** |
| Cells Assembly | nbre | 58 | | |
| | **Total** | | **860** | **611** |
| Battery | BMS | | 61 | 58 |
| | Mechanical | | 36 | 34 |
| | Battery Ass. Labour | | 13 | 8 |
| | Power devices | | 92 | 78 |
| | **TOTAL** | | **1 062** | **789** |
| | | **€/kW** | **27** | **20** |

And battery price evaluation:

| 2012 | | Max. Cost | Min. Cost |
|---|---|---|---|
| **Total Cost of a Full Hybrid Battery** | | **1 062** | **789** |
| Other Manufacturing Costs | | 127 | 79 |
| Overheads | | 159 | 118 |
| **Total Cost** | | **1 349** | **987** |
| | **€/kW** | **34** | **25** |

| | | | |
|---|---|---|---|
| Margin | | 20 % | 20 % |
| **Price** | | **1 619** | **1 184** |
| | **€/kW** | **40** | **30** |

| | | | Mild Hybrid Battery* | Full Hybrid Battery |
|---|---|---|---|---|
| **2005** | **min.** | **€** | 527 | 2 277 |
| | | **€/kW** | 44 | 57 |
| | **max** | **€** | 626 | 2 701 |
| | | **€/kW** | 52 | 68 |
| **2012** | **min.** | **€** | 268 | 1 184 |
| | | **€/kW** | 22 | 30 |
| | **max** | **€** | 367 | 1 619 |
| | | **€/kW** | 31 | 40 |

Results are summarized in the previous table where for the Mild Hybrid battery evaluation only the cheaper hypothesis is shown.
These results must be compared to the Car Manufacturers point of view concerning the battery technology choice for each type of electric propelled vehicle. It is also of great interest to compare these results with USABC goals even if these goals are often so high (low cost) that they are loosing part of their interest.

| | Mild Hybrid Battery | Full Hybrid Battery |
|---|---|---|
| **USABC Goals** | **300 $** | **800 $** |

*Note : the USABC goals are for a 0.3 kWh 13 kW mild hybrid and a 0.5 kWh 40 kW full hybrid*

This comparison shows that for mild hybrid the evaluations made lead to value of the same order than the goals while these goals have been calculated by the car manufacturers without any references to the known price of battery technologies.
These performances are especially the result of a great increase of specific power performances of Li-Ion cells that allow a decrease of the cell number used for a given battery in the mild hybrid application.

### 3. *Lithium Metal Polymer Batteries*

As shown in the technology description chapter, this technology has to be tested on vehicles and developed more than today in order to be really evaluated as a competitor for automotive applications. AVESTOR (one of the two Manufacturers in the world) is no more involved on the automotive market but Batscap seems to have important projects in this field. They announced a potential price of the BEV battery of 250 €/kWh but without any validation on a vehicle it is impossible to know what is included in this price (accessories, pack mechanical design etc). No HEV battery production is planned and the today specific power do not allow optimistic forecast.

### 4.2.5 The special case of Chinese Lithium based batteries

As seen in the 4.2.3 Chapter, Chinese Manufacturers are working hard since 1999 on the development of Lithium based batteries for BEV or HEV. No industrial products are today really available and it is very difficult to have a precise idea of the performances of the batteries built for the 863 national program. But the Chinese Companies have two major advantages on this promising Market :

- Nearly all the key raw materials needed for the constitution of a Lithium based battery are available in China (China is one of the biggest lithium based material producer in the world),
- The Chinese production costs are several times lower than the corresponding European, Japanese or American one.

Knowing these two facts, the prices announced by some of he Chinese Battery Manufacturers could become credible and they could become soon an important competitor.

Examples of prices announced by Chinese Battery Manufacturers:

- For three Manufacturers, energy version (BEV) prices could be between 250 to 300 €/kWh,
- For the only Manufacturer specialized in power version (for FC applications) announced a cost of 400 €/kWh, that means a projected price of 630 €/kWh.

In terms of batteries for specific vehicles:

| | **Mild Hybrid Battery** | **Full Hybrid Battery** | **BEV battery (30 kWh)** | |
|---|---|---|---|---|
| **€** | **441** | **1 472** | **7 500** | **Min.** |
| **€/kW** | **36.8** | **36.8** | | |
| **€/kWh** | **630** | **630** | **250** | |
| **€** | **525** | **1 752** | **9 750** | **Max.** |
| **€/kW** | **43.8** | **43.8** | | |
| **€/kWh** | **750** | **750** | **325** | |

*Note: Prices for hybrid batteries are higher than those calculated previously for a kWh price lower because the power performances of the Chinese batteries are lower (1 200 W/kg instead of 2 400 W/kg) and then the Chinese hybrid batteries are heavier.*

## 4.3 NiMH Batteries

### 4.3.1 Principle

A nickel-metal hydride (NiMH) cell consists of a nickel hydroxide ($Ni(OH)_2$) cathode, a hydrogen storage alloy anode (positive electrode and negative one, in discharge case, respectively), a separator and an alkaline electrolyte. The charge-discharge reactions of NiMH batteries for the positive and negative electrodes are shown in following equations and the complete process of this type of battery is schemed on Figure 4.3.1:

At the positive electrode: $Ni(OH)_2 + OH^- \underset{\text{Discharge}}{\overset{\text{Charge}}{\rightleftharpoons}} NiOOH + H_2O + e^-$

At the negative electrode: $M + H_2O + e^- \underset{\text{Discharge}}{\overset{\text{Charge}}{\rightleftharpoons}} MH + OH^-$

Total cell reaction: $Ni(OH)_2 + M \underset{\text{Discharge}}{\overset{\text{Charge}}{\rightleftharpoons}} NiOOH + MH$

Where M is hydrogen storage intermetallic alloy and MH is metal hydride.

The charge reaction at the positive electrode is based on the oxidation of nickel hydroxide in nickel oxy-hydroxide as the nickel-cadmium (NiCd) couple working.
At the negative electrode, in the presence of the hydrogen storage alloy and with the application of an electrical potential, the water in the electrolyte is decomposed into hydrogen atoms and hydroxyl ions. Thus, the hydrogen atoms are absorbed and stored into the alloy as a hydride phase.
During discharging state, the reactions are reversed. The nickel hydroxide of the positive electrode is reduced to its lower valence state and at the negative one; the hydrogen atom is desorbed and combined with a hydroxyl ion to form water.

As it appears in the total cell reaction, the water does not participate; consequently there is no change in electrolyte concentration during the charge / discharge process, unlike the nickel cadmium battery. Besides, no short-circuit may be caused by dendrites formation (because of dissolution and precipitation reactions). The operating voltage of the cell is about 1.2 V almost the same as that NiCd cell.

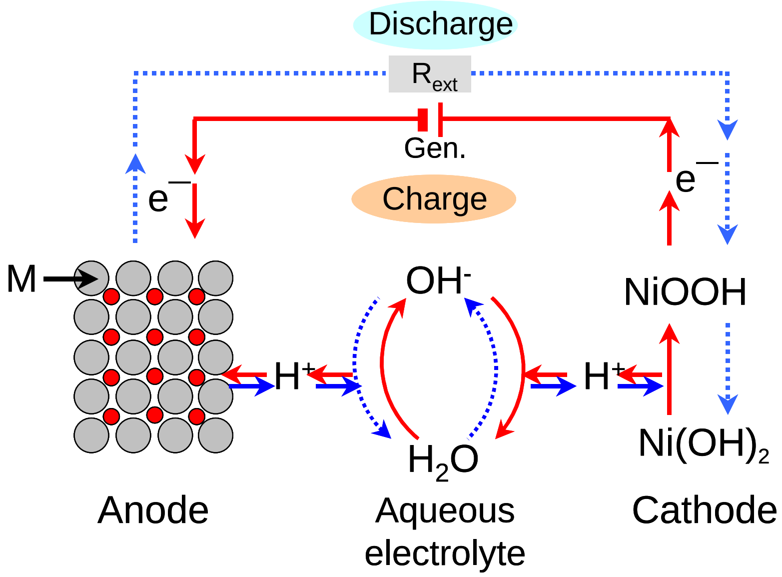


*Figure 4.3.1: Representation of Nickel Metal Hydride-based battery operating.*

### 4.3.2 Various Technologies used

Only a few anode materials are used for the Nickel metal hydride (NiMH) alkaline systems unlike lithium-ion technology where both anode and cathode materials can change. The NiMH technology is based on $Ni(OH)_2$ / NiOOH couple for the cathode and M / MH (hydrogen storage alloy) for the anode. It's one of the reason why the NiMH technology is mature today compared to the lithium based one. Another great difference is based on the electrolyte which is an aqueous one in the NiMH case.

- **Cathode type**

The only cathode type for the NiMH technology is $Ni(OH)_2$ / NiOOH couple. Nevertheless, each battery manufacturer uses a specific additives in the common aim to reduce the active material dissolution phenomenon (effect of the water redox couple). They add to $Ni(OH)_2$ active material a few amount of cobalt, zinc and/or mixed rare earth oxides, as $Yb_2O_3$ for example.

Even though the nickel hydroxide to nickel oxyhydroxide reaction is typically a one electron exchange reaction per nickel atom (cf. top of this section), it is known that the reaction is much more complex than this simple equation and in fact the theoretical upper limit for Ni(II) oxidation is about 3.5, or 1.5 electron per nickel atom due to the formation of both oxyhydroxide, namely $\beta$-NiOOH and $\gamma$-NiOOH. The challenge of battery manufacturers will be to minimize the formation of $\gamma$-NiOOH (this phase is electrochemically inert because of its non-reversible formation).
Each cathode composition is detailed in the next section.

- **Electrolyte**

Usually, the battery manufacturers use potassium hydroxide as electrolyte in their NiMH production process. Sometimes, they choose a mixture of hydroxide (KOH + NaOH and/or LiOH, in which LiOH is in small amounts). However, the standard product is a 45 % KOH solution whereas NiMH battery production needs a final 30 % solution (i.e. about approximately 4.5 g per Ah of electrolyte).
In this technology the main point remains the use of an aqueous electrolyte compared to the organic one in the lithium-based battery case. It is then easier to provide a good reliability (i.e. better than all others systems [29]), and moreover to increase the safety (inflammability of the organic electrolyte).

N.B.: The NiMH batteries operate with the same type of electrolyte used in nickel-cadmium ones.

- **Anode type**

Battery manufacturers use proprietary formulations for the anode material, the exact specifications of these hydride alloys are company secrets, but some trends can be considered.

Two hydride materials can be used to anode function for NiMH battery: alloys of $AB_5$ or $AB_2$ types. In the case of $AB_5$ alloy, A symbolizes La, Ce, Ti, a mischmetal of rare earth who is a low-cost combination and, B a transition metal (mostly nickel with added cobalt, manganese and aluminium) even when the basic formula is $TiNi_2$ for the $AB_2$ type but A also can be vanadium and, B can be zirconium with an addition of cobalt, chrome, iron and manganese.

However, even if $AB_2$ alloy presents higher hydrogen storage capacities (400 $mA.g^{-1}$ against 300 $mA.g^{-1}$ for $AB_5$ alloys) and its self-discharge rate can be decreased by modifying elements of negative alloy, the anode based on $AB_2$ alloy shows a shorter cycling life and a higher economic cost, thus, the battery manufacturers usually opt for the $AB_5$ type material instead of the $AB_2$ alloy type. For information, the usual composition of $AB_2$ hydride alloys is $(Ti_{2-x}Zr_xV_{4-y}Ni_y)_{z-1}Cr_z$ and the $AB_2$ designation is due to the Ti-Zr and Ni-V atomic fractions which are in the 1 : 2 ratio.

The most common metal hydrides used to battery applications are $AB_5$ and $AB_2$, nevertheless two other types are under development to hydrogen storage future: AB (based on ZrTi formula) and $A_2B$ alloys (based on $Ti_2Ni$ component).

In the following chapters, the SUBAT study will be focused on NiMH battery with $AB_5$ or $AB_2$ anode.
Usually during the battery charge / discharge process, the hydride phase transformation induces a high density of stresses in the material due to the coexistence of two different crystallographic phases with no identical cell volume. This phenomenon, namely "decrepitation" one, is the creation of cracks

in the alloy particle. The surface exchange between the alloy and the electrolyte increases and accelerates the aging of the anode.

- **Separator**

The separator found in the NiMH battery is usually based on polypropylene material with a thickness of about 0.13 mm. The raw fiber used in producing the separator material is manufactured in Japan. The fibers are blended and processed to produce a “wettable” surface, by the end a washing process is used to clean and finish the material.

- **Production process type**

The battery using the NiMH technology can be produced in cylindrical or in prismatic configuration (cf. an example of prismatic cell configuration on figure 4.3.2) but its composition (i.e. water container) does not allow the laminated type production process.

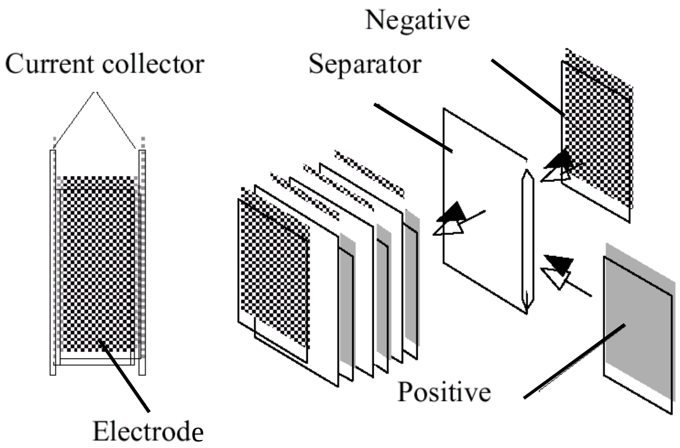


*Figure 4.3.2: Single rectangular cell scheme of a NiMH battery [30]*

- **Material substrates**

Usually, the anode grids, grids tabs and the cathode foam substrate are entirely composed of nickel.

The battery power can be affected by repeated charge-discharge cycle corresponding to an increase of internal resistance and cell internal temperature (electrochemical reactions within NiMH battery are exothermic ones).
The capacity (cycling life) of the battery can be affected by swelling of the positive active material (formation of $\gamma$-NiOOH phase leads to a large swelling of the cathode) during discharge and others effects (for example, dissolution and ageing of the active material in the aqueous medium).
Another problem of the NiMH batteries technology is the low and high temperatures decrease of performances, and the relatively high self-discharge phenomenon at room temperature (about 15 % to 25 % per month).
Another typical disadvantage of the NiMH batteries (as NiCd ones) is the memory effect.

On the contrary NiMH technology has some outstanding advantages. One of them is the rapid charge ability associated to a large specific power that allows easy hybrid applications compared to NiCd or Lead-Acid. NiMH is also more environmentally friendly than nickel-cadmium technology. The NiMH system also shows a good energy density (e.g. three times more than Advanced-Pb), reliability, rugged and safety performances.

As this technology is today near its maturity, the R&D activity is slowing down and the technical performances have reached near their best. It is then much easier in the vehicle design for car manufacturers to calculate and develop the battery pack corresponding to a given hybrid configuration.
N.B.: The charging characteristics of NiMH batteries are similar to NiCd ones, however NiMH batteries are more sensitive to overcharging phenomenon.

### 4.3.3 Battery manufacturers and corresponding data

By considering the NiMH battery state-of-the-art, it appears that all battery manufacturers had provided huge R&D efforts in order :

- to prevent the formation of $\gamma$-NiOOH phase, in particularly by increasing the oxygen overvoltage of the cathode during charge,
- to increase the $Ni(OH)_2$ active material conductivity by adding elements or compounds like cobalt, zinc, aluminium…. Indeed, cobalt or cobalt oxide powder is a key additive of the cathode because it forms a conductive coating on $Ni(OH)_2$ powder and consequently it enhances the active material utilization.
- to minimize the significantly decrease of the cathode charge efficiency at temperature over 40 °C and to increase the charge retention at high temperature by using beneficial additives like Y, Ca, Ti or Nb. For example, at 45 °C, calcium element can improve the charge acceptance of 30 %.

Many efforts have been made to improve the Cell design and battery pack design in order to implement efficient air cooling systems while a large decrease of battery volume and weight was obtained. Therefore, two version of NiMH battery have been developed as for lithium-based battery: The first one “high power” type for hybrid vehicles applications, the second one “high energy” for EV applications. Today only the “high power” version is really commercialized for the development of the new hybrids (mild and full) manufactured essentially in Japan (see Chapters C - 4 and 5).

As for the other technologies, in the following section, the specificities of each NiMH system associated to a battery manufacturer are proposed (cf. summary in Table 4.3.1).

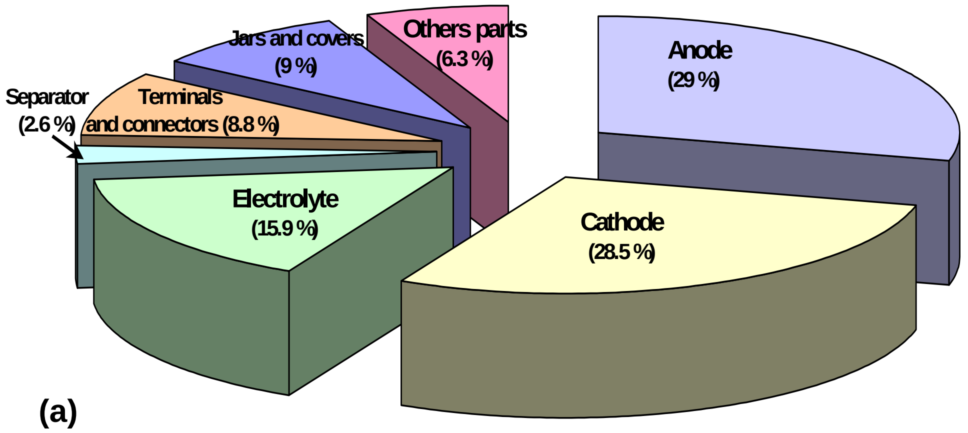
*Table 4.3.1: List of NiMH battery manufacturers and short description of each production process.*

| Group name | anode material | electrolyte | separator | cathode material | Comments |
|---|---|---|---|---|---|
| SAFT | $AB_5$: Rare earth + Ni + Co | $KOH + NaOH + H_2O$ | PP/PE | $Ni(OH)_2 + Co$ | Prismatic cell |
| Cobasys [20] | $AB_5$ or $AB_2$ | $KOH + H_2O$ | Polyolefin | $Ni(OH)_2$ | Prismatic cell |
| Panasonic | $AB_5$: $MmNi_5$ | $KOH + H_2O$ | PP | $Ni(OH)_2 + Yb_2O_3$, | Prismatic cell |
| VARTA | | | | $Ni(OH)_2$ | Prismatic cell |
| Sanyo [33] | $AB_5$ | $KOH + NaOH + LiOH + H_2O$ | Probably polyolefin separtor | $Ni(OH)_2$ | Prismatic cell |
| GS Yuasa | $AB_5 + Yb_2O_3$. $Mm(NiMnAlCo)_5$ | $KOH + H_2O$ | PE + EVOH / PP | $[Ni, Zn, Co](OH)_2 + Yb_2O_3$, $Er_2O_3$ | Prismatic cell ??? |
| | $AB_5 + Yb_2O_3$. $Mm(NiMnAlCo)_5$ | $KOH + H_2O$ | Sulfonated separtors | $Ni(OH)_2 + \alpha\text{-}Co(OH)_2) + Tm_2O_3$, $Yb_2O_3$, $Lu_2O_3$ | [32] |
| Hyundai (HMC) | $AB_2$ and $AB_5$ | $KOH + H_2O$ | Non woven polyolefin or sulfonated separtor | $Ni(OH)_2 + Co$ | Prismatic cell |

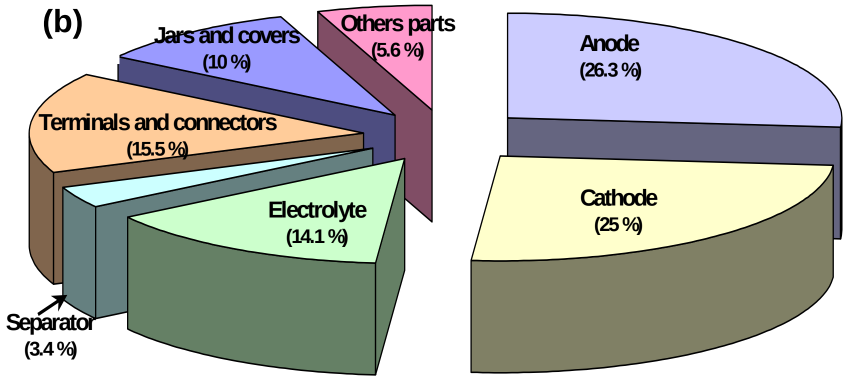
*PE = Polyethylene*
*PP = Polypropylene*
*KOH = potassium hydroxide*
*EVOH = Ethylene Vinyl Alcohol*
*NaOH = sodium hydroxide*
*LiOH = lithium hydroxide*
*Mm = Mischmetal is a naturally occurring mixture of rare earth elements and other metals (e.g. Lm, Tm)*

- **SAFT**

SAFT has developed and is manufacturing a 12 V or 24 V-100 Ah NiMH module (so providing high specific energy and energy density) for electric vehicle applications and a 12 V-34 Ah for high power applications like hybrid electric vehicle ones and power assist mild hybrids. Whatever the battery application, the same basic electrochemistry is used and only the materials ratio of the electrode is variable.
The operating temperature range indicated by the thermal management system varies between –10 °C and +45 °C for HEV battery, and between –10 °C and +45 °C in charge and –10 °C and +60 °C in discharge for EV applications. During the transport and storage, the temperature range is estimated at [–40 °C, +50 °C] and [–40 °C, +65 °C] for HEV and EV applications, respectively.
The number of cycles in deep-discharge is demonstrated at 2000 cycles for the EV (80 % DOD) and leads to more than 8 years of use for HEV application. For all applications the calendar life in service has been evaluated to more than 10 years at room temperature.



These technology is based on $Ni(OH)_2$ / KOH / $AB_5$ system, in which the $AB_5$ alloy type is composed of rare earth (i.e. A) and Nickel, Cobalt (i.e. B). The anode and the cathode are deposited on steel foil and on nickel substrate, respectively. The NiMH electrochemical cell constitution is schemed on figure 4.3.3 in which each component percentage is represented.



*<u>Figure 4.3.3</u>: NiMH electrochemical cell constitution for (a) Electric vehicle applications and (b) hybrid electric vehicle applications.*

During the cell operating various corrosion products can be formed at the surface of the alloy particle like metallic nickel, cobalt or nickel, cobalt, and rare earth hydroxides. The three mains consequences of this phenomenon are (i) a decrease of anode active material and consequently in this relative capacity; (ii) water consumption and (iii) an increase in anode charge reserve by hydrogen absorption.
In the other hand, the cathode of SAFT is made of $Ni(OH)_2$ and Cobalt (probably in cobalt hydroxide form) in the aim to increasing the electronic conductivity and reducing the active material dissolution in the aqueous electrolyte.
The electrodes performances are improved by optimization of their porosity. And, for the high power battery, the power / energy ratio becomes optimal by using ultra thin electrode technology.

For the Electric Vehicle applications, the electrolyte used by SAFT is mainly concentrated potassium hydroxide in which sodium hydroxide is added (approximately total alkaline concentration of about 5 M), whereas for the HEV applications the electrolyte is only concentrated KOH (about 4.8 M).

A description of the SAFT NiMH production process is shown on the following figure, in which all energy and material inputs/outputs are given.

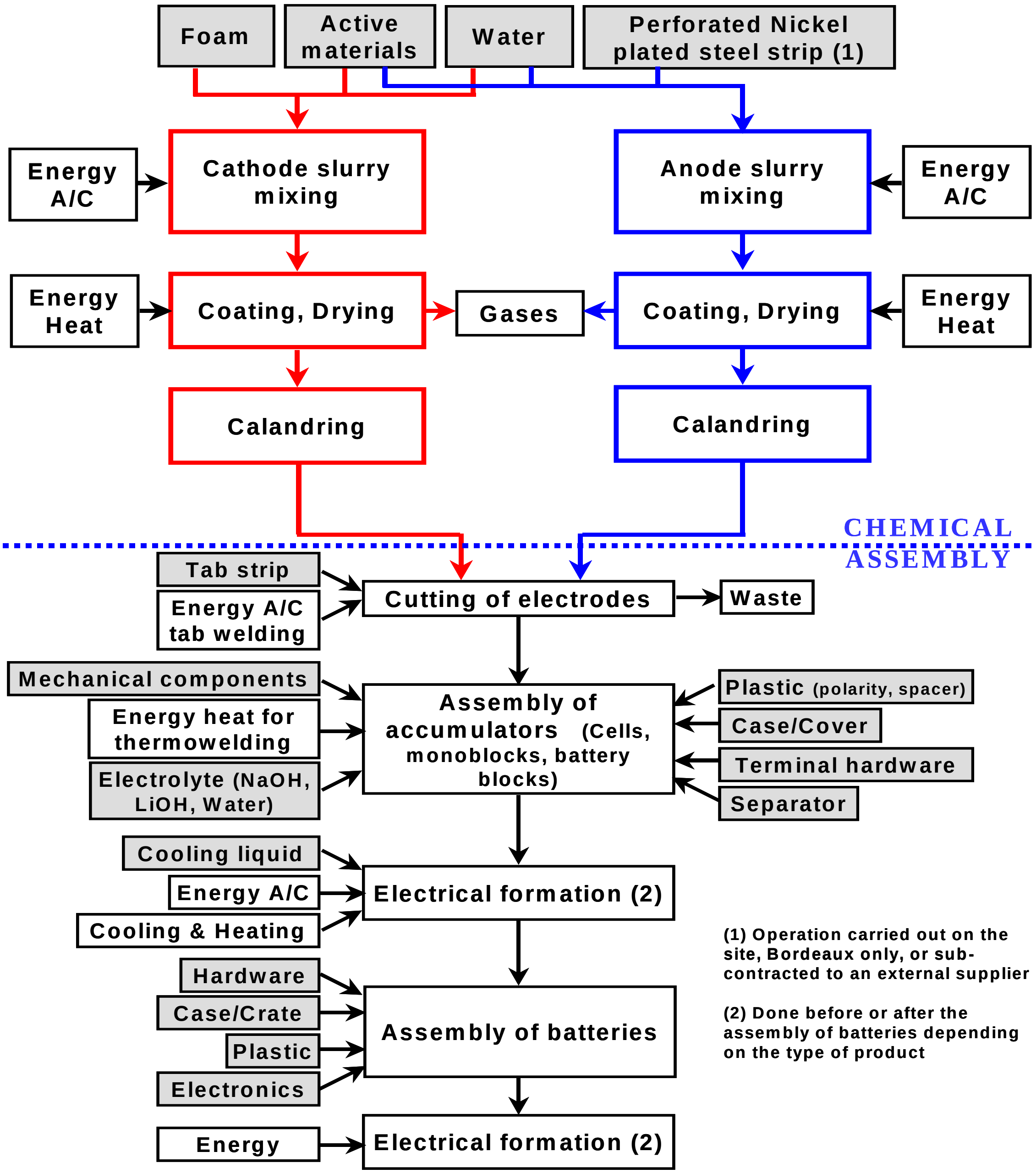


*Figure 4.3.4: Production process for Nickel-Metal-Hydride cells and batteries.*

- **Cobasys-Ovonic**

Cobasys has developed a range of advanced Nickel Metal hydride battery systems to support the expanding hybrid electric vehicle market and for stationary applications. The business target of the automotive part of their production concerns the light duty automotive / SUV field. The advanced NiMH battery is also adapted to EV applications.

The Cobasys technology is based on prismatic cell manufacturing; the battery cells are made by stacking alternate anode and cathode plates in parallel connection.

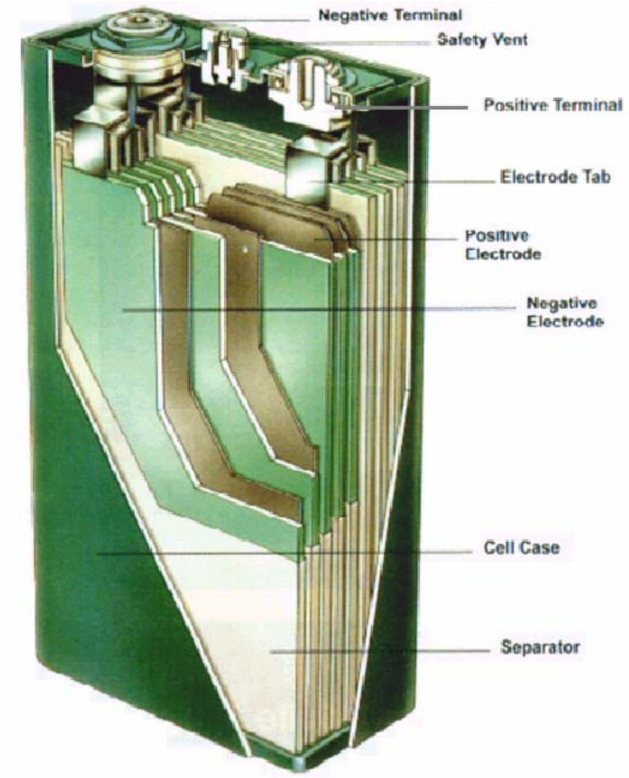


*Figure 4.3.5: Cutaway of prismatic Nickel-Metal hydride cell.*

The “positive” electrode is produced by a mechanical impregnation process. A high porosity nickel substrate, namely foam or felt, is filled with “$Ni(OH)_2$” active material in which binders and co-precipitated additives such as cobalt, zinc…are added in aim to enhance the electrochemical performances (i.e. improvement active material utilization, conductivity and cycling life).
The Nickel hydroxide active material has a high density. By the end, active material is loaded into the high porosity substrate and the material is dried, compressed to final thickness and adapted to final electrode plate. The pasted-electrode manufacturing process of the cathode allows a lower cost of production.

The “negative” electrode material is $AB_2$ (i.e. V-Ti-Zr-Ni based alloy) or $AB_5$ (composition unknown) hydride alloy type which is produced by vacuum induction melting, followed by a two steps size reduction process to lead to a metal powder. In a continuous roll to roll process, this metal powder is compacted onto an expanded metal substrate. Then, this roll compacted strip are adapted to final electrode plate with welded tab connections.

Cell assembling begins by the construction of a cell stack of alternated negative and positive plates enclosed in an electrically isolated and non-woven separator. This stack is inserted into a metal can and the electrodes tabs welded to the terminals. The cell lid is welded to the can, leak checked and KOH electrolyte added.
Finally, whatever the battery applications, Cobasys uses two types of packaging: plastic monoblock or Epoxy-coated steel. And the thermal management can be liquid cooled or air one (air cooling is also used for lower specific power).

Recently, Cobasys has developed a new advanced high power battery systems (see following figure) for Hybrids like SUV, small bus, large SUV, light truck, heavy duty equipment etc… applications, however no further information has been communicated.

*Figure 4.3.6: Nickel-Metal hydride full pack.*

### - PANASONIC/PEVE [31]

Panasonic EV Energy (i.e. PEVE JV. Panasonic-Toyota) has developed NiMH battery module for EVs applications but since 1997 they are specially working on HEV one and supplies all the hybrid vehicles production of Toyota and Honda (Prius and Civic). For example, the following figure shows the constitution of a typical NiMH battery system for HEV applications.
At the beginning of their mass production (1997), PEVE have manufactured battery packs made of cylindrical NiMH cells, since 2000 they have switched there production to prismatic cells in order to reduce the volume and increase the thermal efficiency of the cooling system of the battery pack. Since 2003, their second generation, namely the new prismatic configuration battery, is on the market (new Prius II). In this case, the module is made of six cells connected to each adjacent cell in series to make 7.2 V nominal voltage for the module.

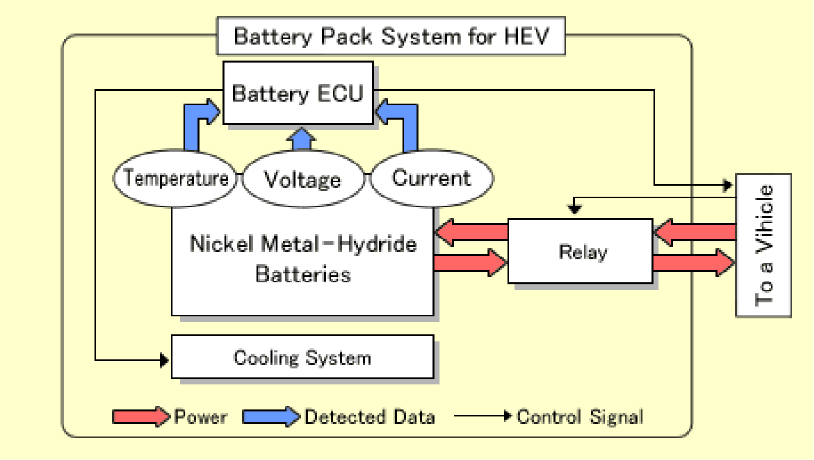


*Figure 4.3.7: Battery system for HEVs use.*

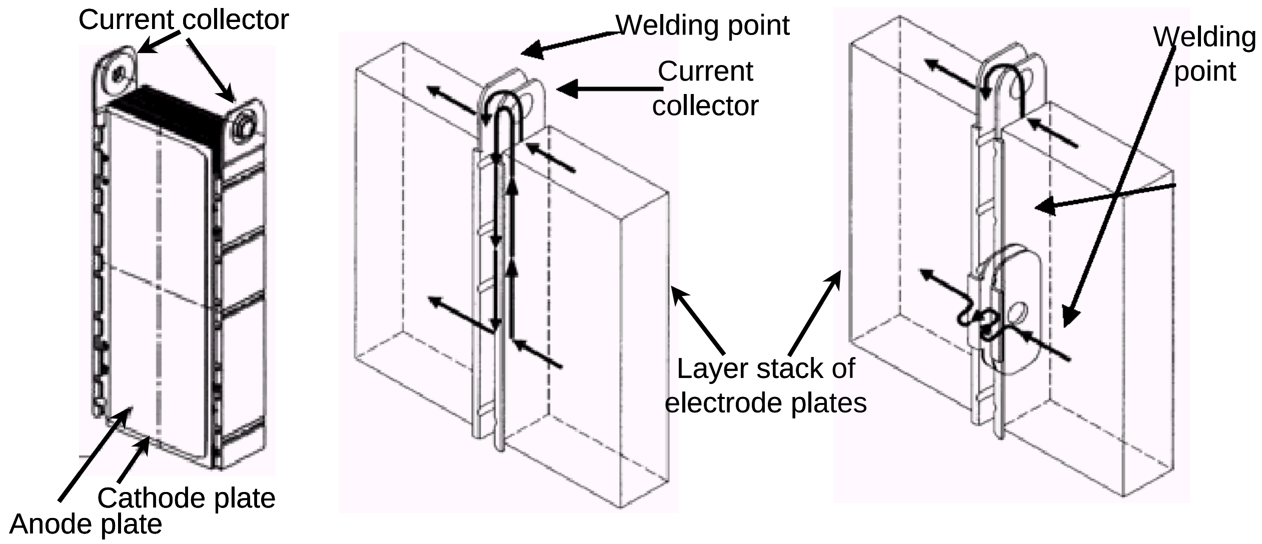
The PEVE technology is based on the classical nickel hydroxide $Ni(OH)_2$ as cathode active material. Moreover a stable discharge capacity under a wide range of temperature is an important electrochemical characteristic for the battery charge reliability. To improve the charge efficiency, yttrium oxide (i.e. $Y_2O_3$) is added to the cathode active material; and other various elements are added in $Ni(OH)_2$ active material in optimized quantities.

The anode active material is $MmNi_5$ which is a $AB_5$ type alloy. According to PEVE publications it appears that their anode material would have a new composition not yet known.
The hydrogen absorbing alloy is crushed into fine powders to increase the number of charge and discharge cycles, thereby increasing the alloy surface oxidation. Another advantage of this manufacturing process is to make small anode active material particles and to optimize the alloy composition in order to decrease the resistance.
The electrolyte used by PEVE is a concentrated potassium hydroxide solution as most of NiMH battery manufacturers. The separator is made of polypropylene (i.e. PP); and the operating temperature range is about –30 °C to +60 °C.

The cell is made of several cathode plates covered by separator, several anode plates and two current collectors. Each electrode plate is welded to each current collector vertically which make the resistance minimum. The use of the potassium hydroxide as electrolyte can induce the corrosion of terminals. This problem is solved by the development of a new type of moulded terminals (mould bus bar) by PEVE researchers.

N.B.: By thinning the cathode and anode the number of electrode has increased leading to an increased reaction area and a decreased current density.

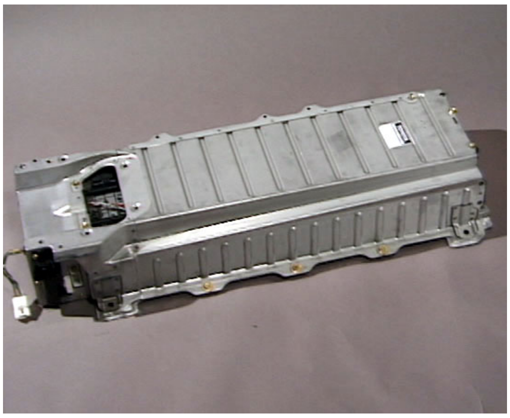
Their battery is in prismatic configuration with a rectangular module which is made of six cells combined in series. To ensure heat dissipation, the module is thin with a wide surface area. The case is made in plastic resistant to the alkaline electrolyte and ensuring electrical insulation between cells. These rectangular modules when combined into a battery pack, allow a reduced dead space associated with an efficient air cooling system.

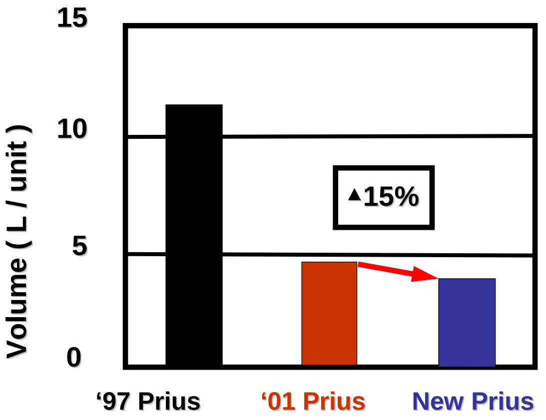


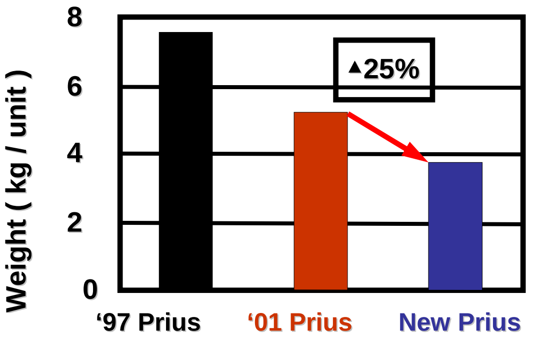
(a) Cell (b) Conventional type (c) New type

*Figure 4.3.8: (a) New battery cell and module structure of the (b) conventional battery and the (c) new battery (arrows symbolize the current path).*

This new battery pack developed for the new Prius (Prius II put on the market at the beginning of 2004) is characterized by a decrease of weight and volume compared to the old one used in the first Prius.







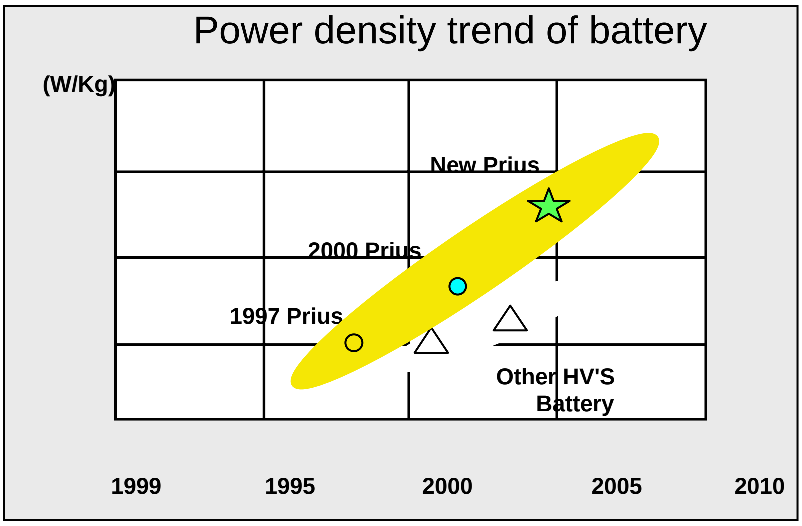


*Figure 4.3.9: New Prius NiMH battery pack and performance (Source: Toyota & PEVE).*

- **VARTA**

After a first period of research and development in 1992 VARTA was the first manufacturer to produce a NiMH battery prototype for electric vehicle. Following the failure of mass commercialization of EVs in Europe, VARTA has more recently (2004) developed three different NiMH product lines for various electric vehicle applications such as pure-EV or heavy HEV: high energy, high power and ultra-high power cells. The specific energy of these cells exceeds 80 $Wh.kg^{-1}$ (high energy ones) and a specific power of more than 1 300 $W.kg^{-1}$ (ultra high power case) can be reached.
As these developments are very recent after VARTA has joined the Johnson Control Group, no precise information's are known on the NiMH technology used.

- **GS YUASA (JSB and Yuasa)**

GS YUASA provides EV and HEV batteries based on $Ni(OH)_2$ / KOH / $AB_5$ system.
As EV and HEV batteries are used in a wide range of temperature from –20 °C to +60 °C during vehicle operation the batteries must have stable performances in this temperature range. The state-of-the-art of nickel based cathode shows that the oxygen overpotential of the electrode is lower at high temperatures because of a mutual conflict between the electrode charging and oxygen evolution. This phenomenon induces a drop of the charge acceptance. Thus, in order to limit this disadvantage cobalt hydroxide and rare earth oxides such as $Er_2O_3$ and $Yb_2O_3$ are added to the active material to increase the oxygen overpotential. By addition of zinc oxide the cathode swelling effect can be prevent. In order to clarify several problems and to suggest some solutions, a summary on a diagram form is shown on Figure 4.3.10.
The decrease of charging acceptance by the cathode material is also limited by addition of mixed rare earth oxides instead of more expensive pure rare earth oxides. YUASA uses Tm, Yb and Lu mixture, namely $Tm_2O_3$, $Yb_2O_3$ and $Lu_2O_3$, in addition to the nickel hydroxide cathode. In this case, the electronic conductivity of the nickel based electrode is improved by the formation of a coating of $\alpha$-$Co(OH)_2$ type on the $Ni(OH)_2$ surface [32].

The hydrogen storage alloy used as anode active material by GS YUASA is $AB_5$ type. They have developed a $Mm(NiMnAlCo)_5$ alloy in which a part of nickel was replaced by a part of manganese in order to increase the cell volume and to improve the alloy capacity. Within the grain boundaries of the alloy appear some layers of concentrated rare earth element such as lanthanide which can be corroded. The medium of the alkaline electrolyte can induce the corrosion of these layers and consequently some deposit such as needle of $Mm(OH)_3$ can be observed at the alloy surface. An increase of the resistance and, decrease of both specific power density and alloy capacity are then observed. The corrosion rate of the alloy is controlled by addition of a corrosion inhibitor like $Yb_2O_3$.

Like most manufacturer, GS YUASA uses a polyolefin non woven separator, and in order to prevent short-circuit a “thick” separator is used when the energy density decreases. The YUASA separator is based on polyolefin type but fibers are thinner than usual by using split micro-fibers made of polyethylene and ethylene Vinyl Alcohol (PE + EVOH) copolymers and polypropylene PP polymer compounds. This technology leads to a thin separator without decrease of energy density and short-circuit phenomena.
Another separator technology is used by this battery manufacturer; a sulfonated separator (with $SO_3$ gas and plasma process) using split micro-fiber non woven. These batteries are then showing a lower self-discharge than when polyolefin separators are used [32].

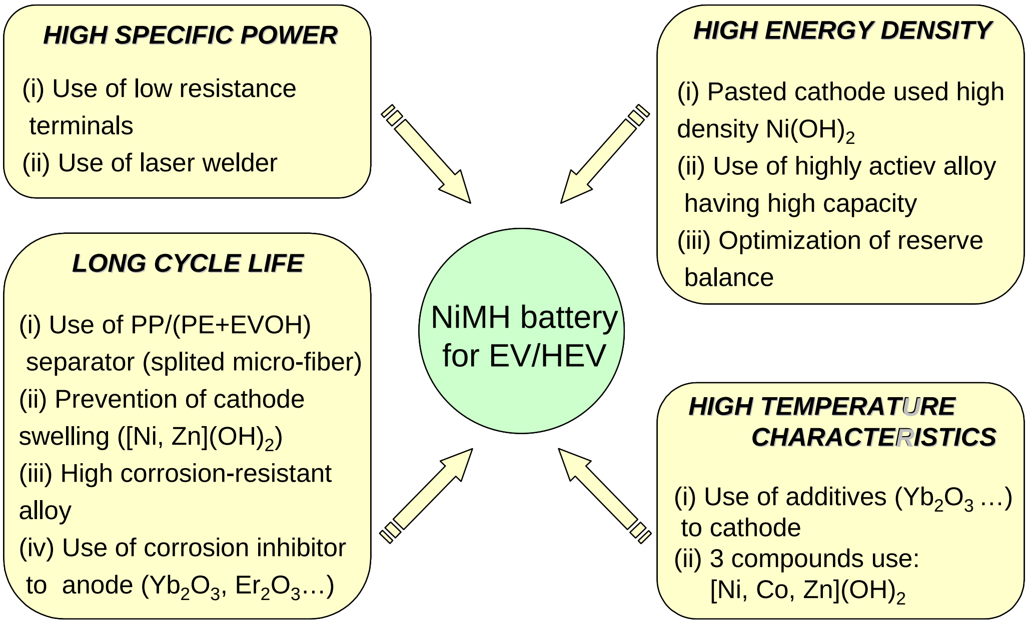


*Figure 4.3.10: Technologies applied to NiMH battery for EVs and HEVs applications by GS YUASA.*

- **SANYO**

*Figure 4.3.11: Sanyo Ford Escape Battery and HEV battery cell.*

Recently, SANYO interest has been growing in HEVs field (Sanyo is one of the three world largest portable NiMH Company), with the beginning of increasing market in the US. They have developed NiMH modules, battery holder, pack, cooling system and ECU for HEVs applications. They have recently signed an agreement with Ford for the development of a nickel metal hydride battery to be settled in the new Hybrid SUV Escape.

For the constitution of the SANYO NiMH battery, the manufacturer uses a sintered $\beta$-$Ni(OH)_2$ active material as cathode and an $AB_5$ type alloy for the anode (i.e. Mm-Ni-Co-Mn-Al hydrogen absorbing alloy). Their anode composition has been improved by using lanthane as misch-metal. The cathode resistance has been minimized using an improved anode alloy with higher oxidation resistibility.
The electrolyte used by SANYO is a mixture of some alkaline solutions composed of potassium, sodium and lithium hydroxides. The separator is probably a polyolefin one but no information available has been found.

### - <u>Hyundai Motor Co. (HMC)</u>

The cathode is made by mechanical impregnation of a paste composed of a nickel hydroxide, cobalt conductive material and binder active material mixture. This paste is laid out on a nickel foam or fiber substrate.
The alloy powder for the anode active material is obtained by crushing and grinding a various elements ingot. The anode is manufactured by compaction process of the alloy powder onto a nickel expanded metal current collector ($AB_2$ case) or onto a nickel plated punched steel (i.e. $AB_5$ case). Finally a sintered process is applied to the anode. The HMC cell is composed of a pasted cathode and a sintered anode associated to non woven polyolefin or sulfonated separator that induces a decrease of the self-discharge rate of the battery.

N.B.: The nickel expanded metal contains 99.59 % of nickel. The nickel plated steel has a surface area three times more important than the nickel expanded metal one. Finally, the nickel plated steel shows three times less electric resistance than the nickel expanded one.

* $AB_2$ case: The anode active material is made of various elements, namely V, Ti, Zr, Ni, Cr, Co and Mn in some composition with more than 5 % weight total of vanadium. However, this element is oxidized easily in alkaline electrolytic medium (namely KOH one), inducing an increase of the self-discharge of the NiMH battery system. Thus, chromium, cobalt and manganese elements (approximately 1-10 % atomic) are added to V-Ti-Zr-Ni based electrode in order to reduce the self-discharge phenomenon.

* $AB_5$ case: This type of alloy for anode active material using does not include vanadium element. In fact, the $AB_5$ anode is described by $LmNi_4Co_{0.60}Mn_{0.30}Al_{0.29}$ formula, in which Lm symbolize a La-rich misch metal (namely 80 % in this case).

### 4.3.4 Cost and Price analysis

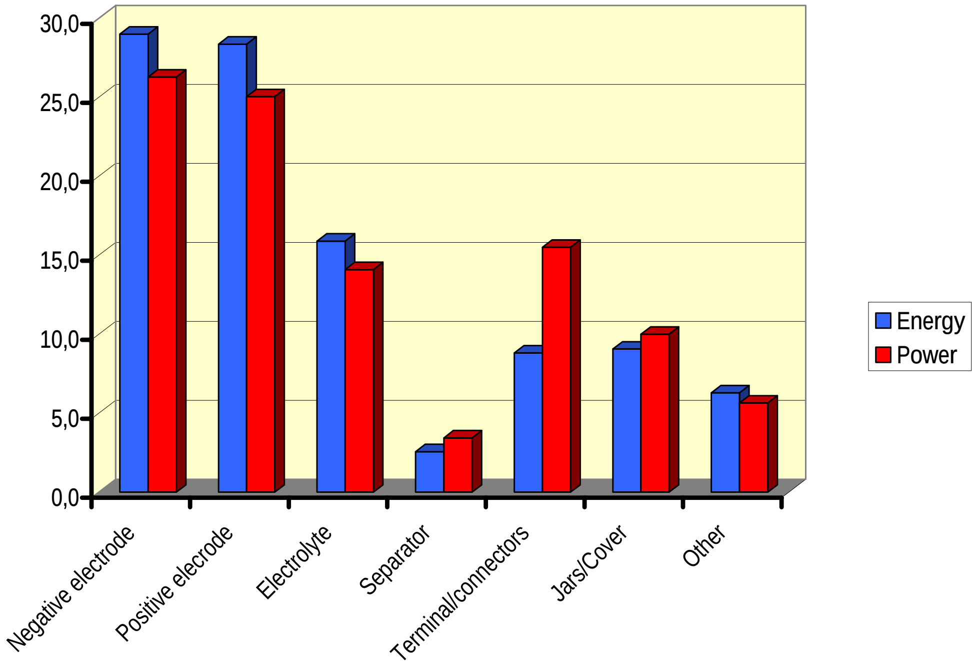
NiMH Battery is nearly a mature technology already industrialized by one Japanese Manufacturer (PEVE for Toyota and Honda) and ready to be manufactured in volume by several other manufacturers like Cobasys, Sanyo, Saft etc. Compared to lithium based technologies, the number of various electrode material, electrolyte, and separator and container type is smaller and differences between manufacturers are only at the detail level. On the other hand the scale effect on the Battery price is much lower and function of the Manufacturer. This scale effect (decrease of price vs production volume) has no influence on the cost of goods and only on the other manufacturing costs.
As for all the other Nickel based batteries (NiCd, NiZn), the NiMH cost of goods is highly function of the Nickel Market price. This Market is very volatile since 1998 and it becomes very difficult to make any long term forecast.
Our prices estimations will be made taking into account the today Nickel price and the today euro value vs dollar.
These estimations will be made in four steps:

- Module cost of goods,
- Module cost,
- Battery cost,
- Battery price.

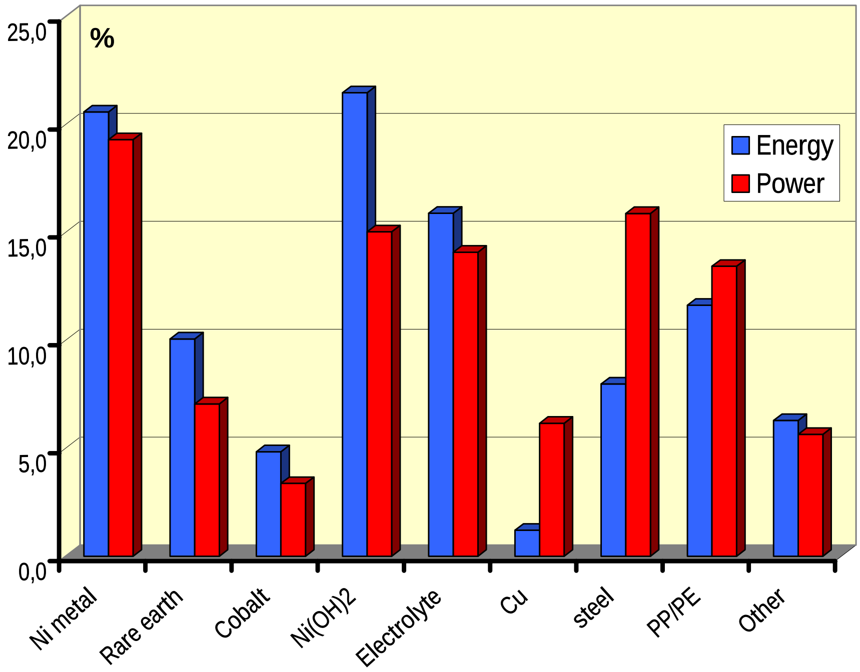
The Module specifications are chosen arbitrary according to the most used cell specifications for a given application:

- For high power modules a 7.2 V, 8 Ah, 1.22 kg, 57.6 Wh,
- For high energy modules a 12V, 100 Ah, 17.5 kg 1200 Wh module is chosen.

The Module cost of goods evaluation needs the use of the chemical composition of the cells (in weight %), as this composition changes with the Module weight, the energy and power version, and with the manufacturer, it would be necessary to make a great number of evaluation. But after some simulations made on several well known examples it appears that the composition changes have a little influence on the calculated Module cost of goods (<5%). As a minimum and a maximum price value are taken into account, only variation between energy and power versions has to be studied.
The differences in composition between the two versions of a same Battery Manufacturer are shown on figures 4.3.12 and 4.3.13.



*<u>Figure 4.3.12</u>: Comparison of the NiMH cell composition in weight % (same manufacturer) for energy and power applications.*



*<u>Figure 4.3.13</u>: Comparison of the raw materials share used in NiMH cells (same manufacturer) for energy and power applications.*

Comparisons are made in terms of type of active material and type of components of the modules. As the Power Module is smaller than the Energy Module (50 % lighter), the packaging and connector/terminal part is higher in the power Module, the active parts (electrodes) are smaller, but differences remain small (about 12 %). The impact of these differences on the cost of goods depends on the relative costs of the materials.

- **Energy modules**

A mean value of chemical composition of this type of module (three battery manufacturers and two laboratory studies) has been chosen. But these data are coming from studies or questionnaires made between 1999 and 2004. During this period, Nickel price have increased from 4.44 $/kg to about 13.5 $/kg and €/$ value from about 0.9 to 1.3. A revalue in 2004 as year of reference have been made for all these data

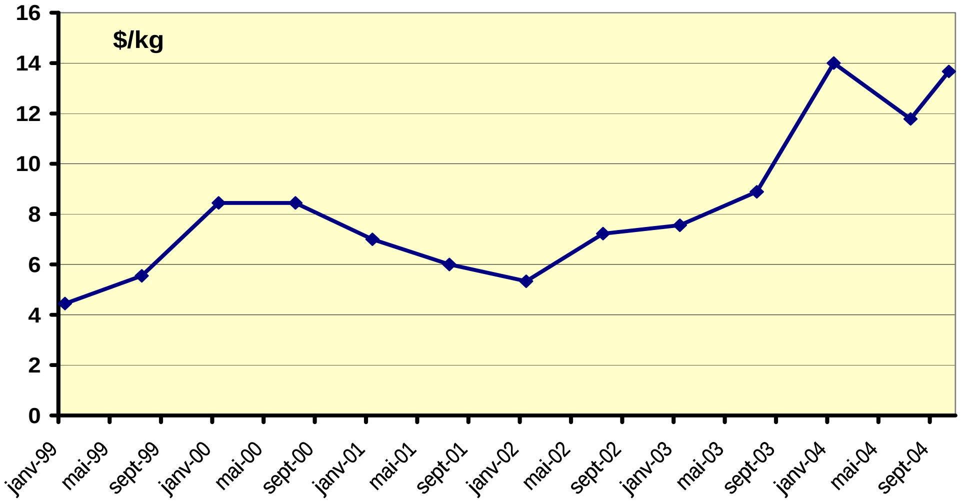


*Figure 4.3.14: Annual average Nickel price (LME Source).*

Results obtained are the following:

- Cost of goods for a NiMh Energy Module (12 V, 100 Ah, 17.5 kg 1200 Wh)
Min. value 231 €/kWh, Max value 277 €/kWh.
- Battery cost and price

For the other steps of the estimation process, hypothesis is made of a production volume of more than 100 000 modules per year (asymptotic prices). The scale effect is then negligible and all the prices are calculated in the case of large production.

For a 30 kWh battery design for BEV applications and taking into account the mean technical performances of this technology, costs calculation becomes:

| | | **Min.(€)** | **Max.(€)** |
|---|---|---|---|
| Module | Cost of goods | 277 | 330 |
| | Labour | 44 | 53 |
| | accessories | 6 | 7 |
| | TOTAL | 327 | 389 |
| Module Assembly | nbre 25 | | |
| | **TOTAL** | **8 172** | **9 735** |
| Battery | BMS(*) | 98 | 117 |
| | Mechanical | 327 | 389 |
| | Assembly labor | 74 | 88 |
| | Power devices | 654 | 779 |
| | **TOTAL** | **9 324** | **11 108** |
| | **€/kWh** | **311** | **370** |

(*) In the case of NiMH battery, the BMS can be integrated in the ECU of the vehicle

And

| | Min. (€) | Max. (€) |
|---|---|---|
| Total cost of a 30 kWh battery | 9 324 | 11 108 |
| Other Manufacturing costs | 2 797 | 3 332 |
| Overheads | 1 865 | 2 222 |
| **Total manufacturing costs** | **13 986** | **16 661** |

| | | |
|---|---|---|
| Margin | 2 797 | 3 332 |
| **Price** | **16 783** | **19 994** |
| **€/kWh** | **559** | **666** |

Comment: Today no world Battery Manufacturers more is developing NiMH batteries for Energy applications (BEV) except for light vehicles with portable type battery. It is then very difficult to compare these calculated values to real prices. As far as the actual prices are known, the values obtained are between 450 €/kWh (for Chinese battery Manufacturers) and 750 €/kWh.

**- Power Modules**

A mean value of chemical composition of this type of module (two battery manufacturers and two laboratory studies) has been chosen. The same calculation as the previous case has been made.
Results obtained are the following:
- Cost of goods for a NiMH Power Module (7.2 V, 8 Ah, 1.22 kg, 57.6 Wh)

Min. value of module 23.15 € and Max. value of Module 28.94 €; leading to Min. value of 402 €/kWh and Max. value of 502 €/kWh.

- Battery cost and price for a mild hybrid battery

For the other steps of the estimation process, hypothesis is made of a production volume of more than 100 000 modules per year (asymptotic prices). The scale effect is then negligible and all the prices are calculated in the case of large production.
For a 12 kW battery design (400 Wh) for mild hybrid applications and taking into account the mean technical performances of this technology, costs calculation becomes:

| | | Min. Cost | Max. Cost |
|---|---|---|---|
| Module | Materials | 23 | 29 |
| | Labour | 3 | 3 |
| | Cell electr. | 3 | 3 |
| | Other components | 1 | 1 |
| | **TOTAL** | **30** | **36** |
| Module Assembly | nbre 10 | | |
| | **Total** | **299** | **364** |
| Battery | BMS | 3 | 4 |
| | Mechanical | 24 | 29 |
| | Battery Ass. Labour | 4 | 4 |
| | Power devices | 36 | 44 |
| | **TOTAL** | **366** | **445** |
| | **€/kW** | **30** | **37** |

**Company Costs**

| | Min. Cost | Max. Cost |
|---|---|---|
| **Total Cost of a Mild Hybrid Battery** | **366** | **445** |
| Other Manufacturing Costs | 37 | 62 |
| Overheads | 59 | 89 |
| **Total Cost** | **461** | **596** |
| **€/kW** | **38** | **50** |

| | | |
|---|---|---|
| Margin | 20% | 20% |
| **Price** | **553** | **716** |
| **€/kW** | **46** | **60** |
| **€/kWh** | **1 382** | **1 789** |

And for a full hybrid battery (40 kW, 1.2 kWh)

| | | Min. Cost | Max. Cost |
|---|---|---|---|
| Module | Materials | 23 | 29 |
| | Labour | 4 | 4 |
| | Cell electr. | 3 | 2 |
| | Other components | 1 | 1 |
| | **TOTAL** | **31** | **36** |
| Module Assembly | nbre 28 | | |
| | **Total** | **872** | **1009** |
| Battery | BMS | 5 | 45 |
| | Mechanical | 39 | 45 |
| | Battery Ass. Labour | 19 | 22 |
| | Power devices | 30 | 34 |
| | **TOTAL** | **965** | **1156** |
| | **€/kW** | **24** | **29** |

**Company Costs**

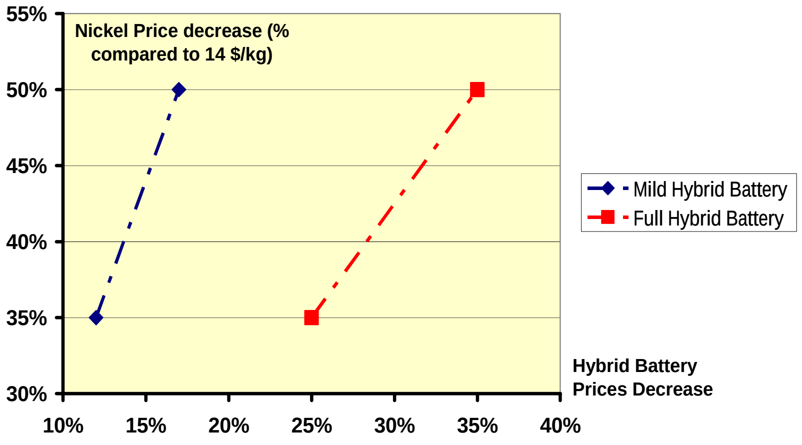
| | Min. Cost | Max. Cost |
|---|---|---|
| **Total Cost of a Full Hybrid Battery** | **965** | **1 156** |
| Other Manufacturing Costs | 116 | 139 |
| Overheads | 174 | 231 |
| **Total Cost** | **1 255** | **1 526** |
| **€/kW** | **31** | **38** |

| | | |
|---|---|---|
| Margin | 20 % | 20 % |
| **Price** | **1 506** | **1 831** |
| **€/kW** | **38** | **46** |
| **€/kWh** | **1 255** | **1 526** |

An other estimation made, based on a Nickel market price of about 9 $/kg (2002) and a ratio of 1.2 for €/$ gives the following results for the high power batteries:

- Mild Hybrid Battery (12 kW, 400 Wh) min. price 488 € (1 219 €/kWh) and max. price 542 € (1 627 €/kWh),
- Full Hybrid Battery (40 kW, 1.2 kWh) min. price 1 129 € (1 354 €/kWh) and max. price 1 406 € (1 688 €/kWh)

**Relation between Nickel Price Decrease and Hybrid Battery Prices**



*- The Chinese Manufacturers case*

It is today impossible to anticipate the prices that will be used by Chinese Manufacturers in 2012, but it seems probable that the technical performances will be of the same order compared to the other country companies and the prices will be lower for two reasons:

- A great amount of the raw material needed are coming from China (China is the main world supplier of Nickel compounds),
- Chinese manufacturing costs (as for the other industries) are much lower.

A first estimation has been made using the information obtained during a special mission made recently for SUBAT project (see appendix):

- NiMH for energy applications (BEV): a decrease of cost of about 50% seems to be possible, leading to a decrease of price of probably more (for two wheelers applications).
- NiMH for power applications (hybrids) are not really developed in China for the moment but in the case of world market development a decrease of price of about 40% can be expected,

## 4.4 Ni-Cd

### 4.4.1 Technology

The first nickel cadmium rechargeable battery has been created by W. Jungner in 1899. At this time the only direct competitor was the lead-acid battery. Both battery technologies have been progressively developed and improved during the last century. The first production manufacturer of industrial nickel cadmium batteries was formed in 1910 in Sweden. These batteries were pocket type, based on vented nickel-plated steel pockets containing “nickel” and “cadmium” active materials. At the middle of the last century, a new type of electrode appeared, namely sintered plate NiCd, it became rapidly popular. Sintered plates are made by fusing nickel powder at a temperature just below its melting point and using high pressures. Then, the plates formed are highly porous (i.e. about 80 % pore per volume).

The chemistry of the nickel electrode (i.e. cathode one) in nickel cadmium cell is the same that for NiMH cell, namely $Ni(OH)_2$ / NiOOH couple based cathode. On the other hand, the “negative” electrode (anode) is composed of cadmium hydroxide active material. The electrochemical reaction within the cadmium anode is based on a dissolution / precipitation mechanism involving the intermediate formation of a dissolved ion (a metal ion complex) which precipitates to lead to a new solid phase as cadmium during charge process.

At the positive electrode: $Ni(OH)_2 + OH^- \underset{\text{Discharge}}{\overset{\text{Charge}}{\rightleftarrows}} NiOOH + H_2O + e^-$

At the negative electrode:

$$Cd(OH)_2 + 2\ OH^- \underset{\text{Discharge}}{\overset{\text{Charge}}{\rightleftarrows}} [Cd(OH)_4]^{2-}\ ,\ [Cd(OH)_4]^{2-} + 2\ e^- \underset{\text{Discharge}}{\overset{\text{Charge}}{\rightleftarrows}} Cd + 4\ OH^-$$

Total cell reaction: $2\ Ni(OH)_2 + Cd(OH)_2 \underset{\text{Discharge}}{\overset{\text{Charge}}{\rightleftarrows}} 2\ NiOOH + 2\ H_2O + Cd$

N.B.: The nickel cadmium cells have a nominal cell voltage of about 1.2 V *versus* NHE.

On the contrary of the nickel metal hydride technology, in the nickel cadmium case, the aqueous electrolyte is not only uses as an ionic conductor but it participates to the electrode reaction. The amount of electrolyte in the cell depends on the state of charge and the porosity of the electrodes. This phenomenon has great consequences in the sealed battery case inducing a progressive lack of electrolyte.

During the dissolution / precipitation reactions, preferential crystal growth mechanisms may lead to the formation of dendrites (cadmium needles) which induce short circuits when these needles penetrate in the cell separator. A second effect of the needles growth is dangerous. During a partial discharge cycling a grain coarsening can be observed inducing a “memory effect” of the nickel cadmium battery. This phenomenon takes place when the cell is recharged before a deep discharge, and it leads to the formation of an “inactive” cadmium part which will have a low active surface area *versus* the “active” cadmium part of the electrode. The anode will contain two types of cadmium, one small grained with a high surface area and one coarsened with a low surface area. When the full capacity of the cell is needed the voltage drop at the same time that the fine grains of cadmium are used.

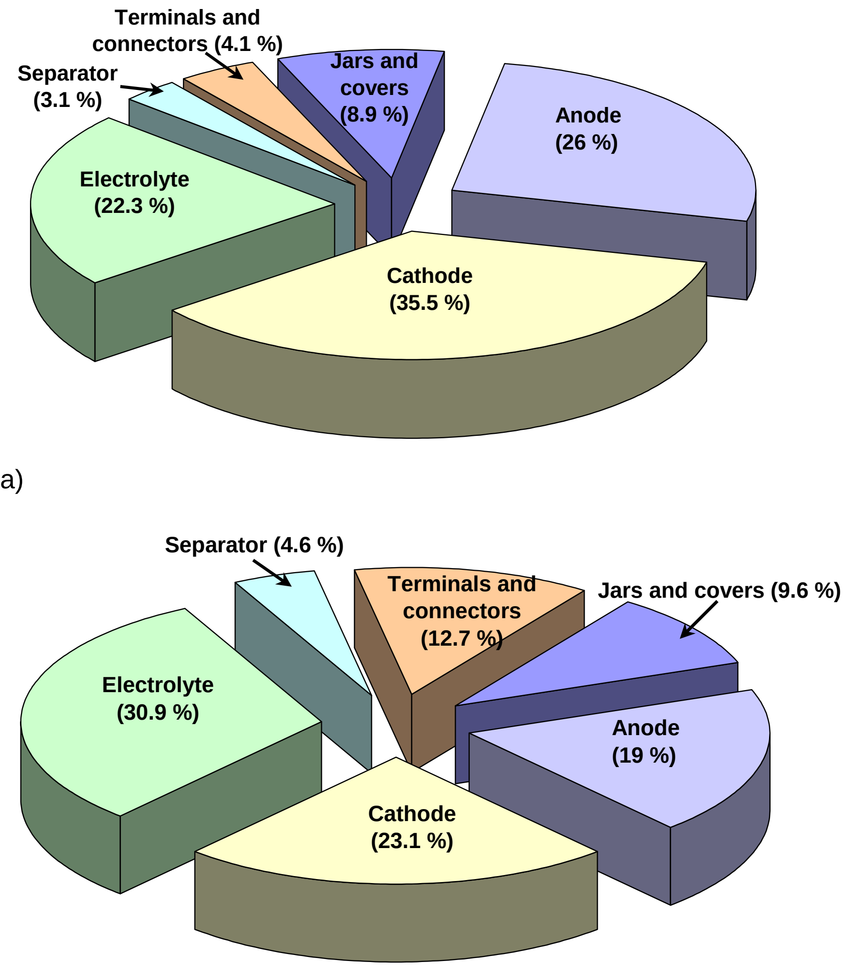
This memory effect could lead to a large decrease of the cycling life of the battery.

The basic nickel cadmium chemistry is more complex than the nickel metal hydride one and many years of development and continuous improvements have been necessary for the NiCd use.

Main disadvantages of the nickel cadmium battery are its memory effect, the water addition need (in a vented NiCd design), the environmental impact of cadmium and lower capacities than others alkaline batteries. On the other hand, the advantages of this battery technology are its very good reliability, a great cycling life if the memory effect is avoided, a great resistance to abuse tests and the possibility of the full recycling of the cadmium.

### 4.4.2 Battery manufacturer and today market

SAFT battery manufacturer is today the only one on the industrial nickel cadmium battery market for Car Manufacturers EV and HEV applications (many other battery Manufacturers are producing portable Ni-Cd rechargeable batteries used for power-tools and light vehicles applications). They have developed and are producing two ranges of nickel cadmium batteries, namely for EV and for HEV applications, both in prismatic configuration. They provide high specific energy (i.e. STM group, M for Medium power) and high specific power (i.e. STH group, H for high power) modules. Like other technologies, the EVs and HEVs electrochemical cells composition are based on the same electrochemistry. The difference only lies in the quantity of each component in the cell. The operating temperature range provided by the thermal management system evaluated to -30 °C about 35 °C for both EVs (in charge) and HEVs use. The number of cycles in deep discharge is proved at 2000 cycles at 80 % of DOD with no degradation of the initial performances, and 2500 cycles with 10 % of energy loss for EV application. In the HEV field the number of cycles in deep-discharge is demonstrated at 1400 cycles at 90 % of DOD and about 200000 cycles in partial discharge, namely 5 % of DOD, at 20 °C. However, the calendar life in service of STH NiCd series depends on cycle conditions. In floating conditions its calendar life reaches to more than 20 to 30 years.
For the STM NiCd series, the calendar life in service is about 8 years (e.g. EV cycles) when is more than 15 years in floating conditions.
As detailed previously, the NiCd battery is based on $Ni(OH)_2$ / KOH / $Cd(OH)_2$ system. Whatever the battery applications the anode is deposited on a steel foil and the cathode on a foam of nickel and then on steel substrate. The nickel cadmium electrochemical cell constitution is schemed on Figure 4.4.1 in which each component weight percentage is shown for EV and HEV applications. The details of anode, cathode and electrolyte constitution are listed in Table 4.4.1.



(a)

(b)

*<u>Figure 4.4.1</u>: NiCd electrochemical cell constitution (mass percent) for (a) Electric vehicle applications and (b) hybrid electric vehicle applications.*

*Table 4.4.1: Raw materials coming into the composition of the electrochemical cell (% per total weight).*

| **Raw materials** | **Ni** | **$Ni(OH)_2$** | **$Co(OH)_2$** | **$Cd(OH)_2$** | **KOH** | **NaOH** | **LiOH** | **Steel** | **$H_2O$** |
|---|---|---|---|---|---|---|---|---|---|
| **Cell for EV applications** | | | | | | | | | |
| Anode | 1 | 2 | / | 76.3 | | | | 20 | |
| Cathode | 36 | 42 | 4 | 2.4 | | | | 15 | |
| Electrolyte | | | | | 21.9 | 1.6 | 2.8 | | 73.7 |
| **Cell for HEV applications** | | | | | | | | | |
| Anode | 1.3 | 2 | / | 77 | | | | 20 | |
| Cathode | 37 | 43 | 1 | 2.5 | | | | 16 | |
| Electrolyte | | | | | 20.7 | 0.8 | | | 78.5 |

N.B.: The quantities of nickel metal and steel are mentioned for information, but they are not a part of active materials (only electrode substrate).

The SAFT anode is mainly made of cadmium hydroxide in which a few amount of nickel and nickel hydroxide had been added. The anode composition is approximately the same for all the battery applications (see Table 4.4.1).

*Figure 4.4.2: (a) STM for Electric vehicle applications and (b) STH for Hybrid vehicles applications.*

On the other hand the cathode is made of mainly nickel hydroxide and a few quantity of cadmium and cobalt hydroxides. Like for NiMH technology the addition of cobalt material allows to increase the electronic conductivity and to reduce the active material dissolution in the aqueous electrolyte (i.e. $Ni(OH)_2$ loss, for more information see the NiMH technology section). However, for the electric vehicle applications, SAFT put in their cathode more cobalt hydroxide than in the one for hybrid electric vehicle applications (4 % against 1 %, percent *versus* full cathode weight).

The electrolyte used by SAFT is mainly concentrated KOH in which NaOH and LiOH are added for the electric vehicle cell and only NaOH for HEV applications. The whole alkaline concentration is approximately about 7 M for the EV battery and 4 M for the HEV one.
The separator is composed of non-woven polyolefin separator (i.e. mixing of PE and PP) for all the types of battery.

SAFT provides modules in prismatic configuration, then, the electrodes are put in stack arrangement and are connected in internal hardware. Their technology lies on plastic bonded anode and in sintered cathode.

Under normal conditions using, the chemical risk lies mainly in the corrosive electrolyte nature. The battery, module and cell containers must back up the alkaline electrolyte and an eventual increase of the temperature. Then, SAFT was use two types of container material, namely steel and plastic ones. Nowadays, they provide battery in plastic container (i.e. polypropylene) in the aim to obtain lighter weight batteries inducing significant improvement in cycling capabilities. The plastic material can occasionally been used as far as a temperature of about 70 °C but beyond that 85 °C, the plastic package will go out of shape and the electrodes and/or connectors will be in short-circuit.
By the end of this section, a description of the nickel cadmium SAFT production process is shown on Figure 4.2.3, in which all energy and material inputs/outputs are noticed.

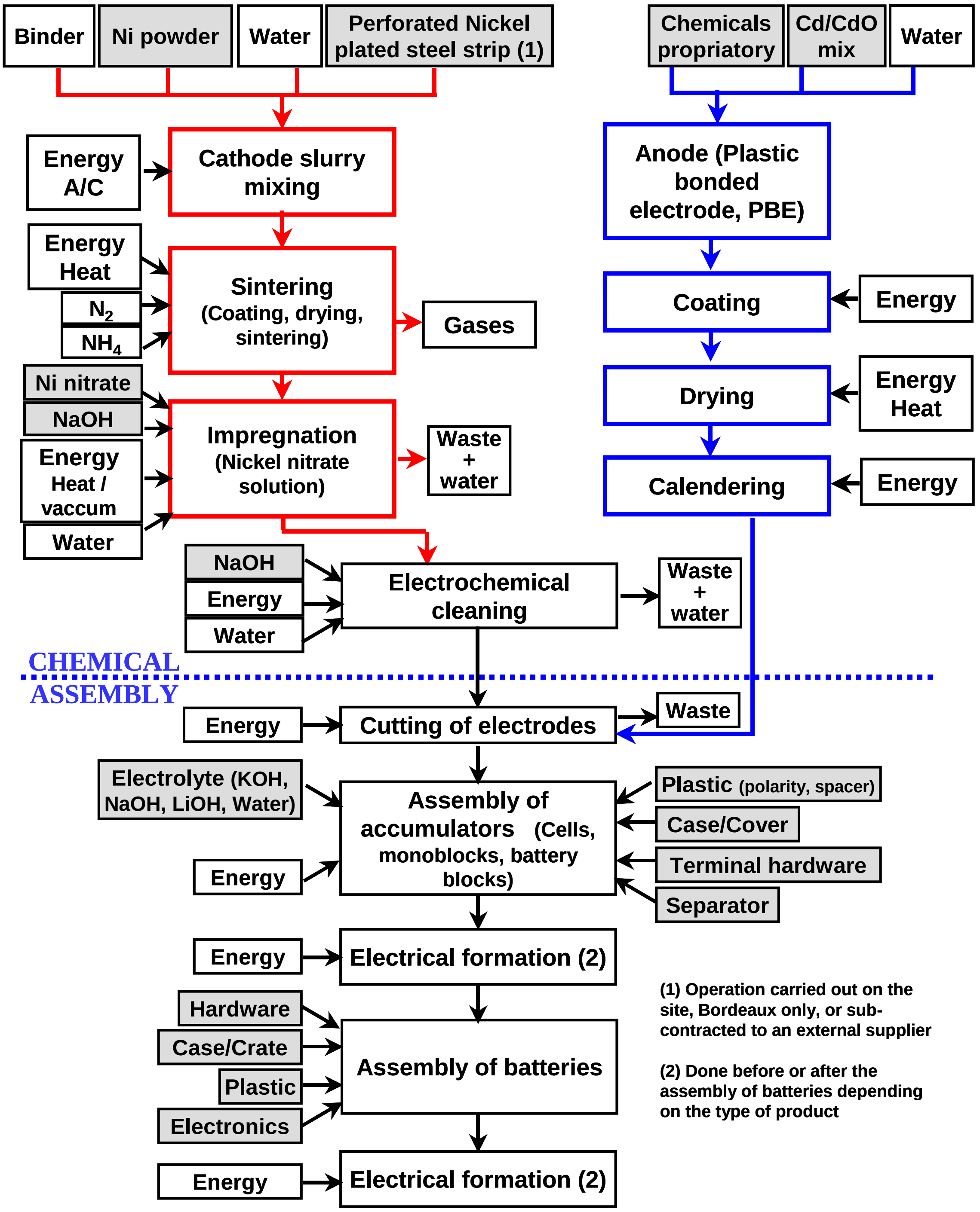


*Figure 4.4.3: Realization process for nickel cadmium cells and batteries sinter / PBE.*

### 4.4.3 Cost and price analysis

As previously mentioned SAFT Company is today the only NiCd Manufacturer in the world for vehicle “traction” applications (except for two-wheelers where portable “power-tools” NiCd can be used). It is then impossible to make a real comparative study of the cost and price of this type of battery (as for the other less common technologies, see next chapter). Information given by SAFT Company concerning the costs and prices of their NiCd batteries for EV, HEV and heavy vehicles are the following:

- **Energy type (EV STM modules or monoblocs)**

STM Module production costs

| | % |
|---|---|
| Electrodes | 54.6 |
| Separator | 8.7 |
| Module hardware | 8.6 |
| Electrolyte | 8.1 |
| Module Labour | 20 |

This cost breakdown is given for a STM5-100 module of 6 V, 100 Ah and 13.2 kg and about 630 Wh.

For a complete EV battery the cost breakdown becomes:

EV Battery system based on STM Modules

| | % |
|---|---|
| Electrodes | 44 |
| Separator | 7 |
| Module hardware | 7 |
| Electrolyte | 7 |
| Module Labour | 16 |
| Battery hardware | 14 |
| Battery Labour | 5 |

These data are showing that for NiCd batteries the cost and price calculation steps are simpler than for NiMH and Lithium based due to a simplified BMS need always integrated in the Vehicle ECU and the design of the SAFT module (with cooling system and standard connections).
Prices of this type of modules are a function of the purchase volume:

- For small quantities (less than 100 modules/year for example), the price is between 720 and 760 €/kWh,
- For large quantities (more than 100 000 modules/year), the price is in 2004 of 450 €/kWh, but as this has been kept constant since the last five years despite a constant increase of the Nickel price, it seems possible that it will be change in 2005.

For a 30 kWh EV battery and assuming a mass production (as for the other technologies), these prices lead to a battery value of about 14 700 € (with a price of 490 €/kWh).
No real decrease of price can be expected because of the Nickel price increase. No “scale effect” can be expected too, the SAFT production process is already automated since the beginning of the nineties (new plant in 1994 for EV batteries).

- **Power Type (STH cells)**

These modules have not been designed specifically for hybrid vehicles but for all “industrial” applications needing performances higher than those of “open” Lead-Acid.

On the “transport” Market, they are used today only on heavy vehicle market (Transport public hybrid busses, tramways, Trolley, hybrid trucks etc).
The constitution of a battery for this type of application is different compared to the previous case.
The cells are of 1.2 V, from 16 to 190 Ah and from 1.1 to 9.8 kg. A complete battery is then made of a number of cells assembled in complete battery pack…
The 2004 price of these cells are of 1000 €/kWh at the cell level, battery system integration has to be added. As for this type of market no scale effect can be forecast (or expected) no real decrease of price can be expected.

## 4.5 Other Battery Technologies

### 4.5.1. ZEBRA Battery - $NaNiCl_2$

#### 4.5.1.1. Technology

The beginning idea was to achieve high energy density and performances as demonstrated in sodium sulphur batteries but avoiding the safety concern which are caused by the sulphur content, and the first patent was applied in 1978. BETA Research and Development Ltd in England continued the development and was integrated into the joint venture of AEG (later Daimler) and Anglo American Corp. The jointly founded company AEG Anglo Batteries GmbH started the pilot line production of ZEBRA batteries in 1994 (acronym of Zero Emission Battery Research Activity). With the merger of Daimler and Chrysler this joint venture was finished and the ZEBRA technology was acquired in total by MES-DEA who industrialised it. Nowadays, ZEBRA batteries are only developed and manufactured by MES-DEA S.A. factory, located in Stabio, Switzerland.

The chemical reactions taken place in the ZEBRA cell are based on nickel metal (i.e. powder) and sodium salt [10z]:

$$2NaCl + Ni \rightarrow NiCl_2 + 2Na$$ (charge operating)

The cell reaction during discharge, is reversed:

$$NiCl_2 + 2Na \rightarrow Ni + 2NaCl$$ (discharge operating)

N.B.: The $NaNiCl_2$ cell have a nominal voltage of about 2.58 V *versus* NHE at 300 °C.

Because both of beta alumina and nickel chloride are solids, a second liquid electrolyte is needed to allow the sodium ions to reach the nickel chloride reaction sites from the beta alumina. The electrolyte is a composite of liquid $NaAlCl_4$ (sodium tetrachloroaluminate) which melts at 157°C and $\beta''$-$Al_2O_3$ alumina ceramic, which acts also as separator.

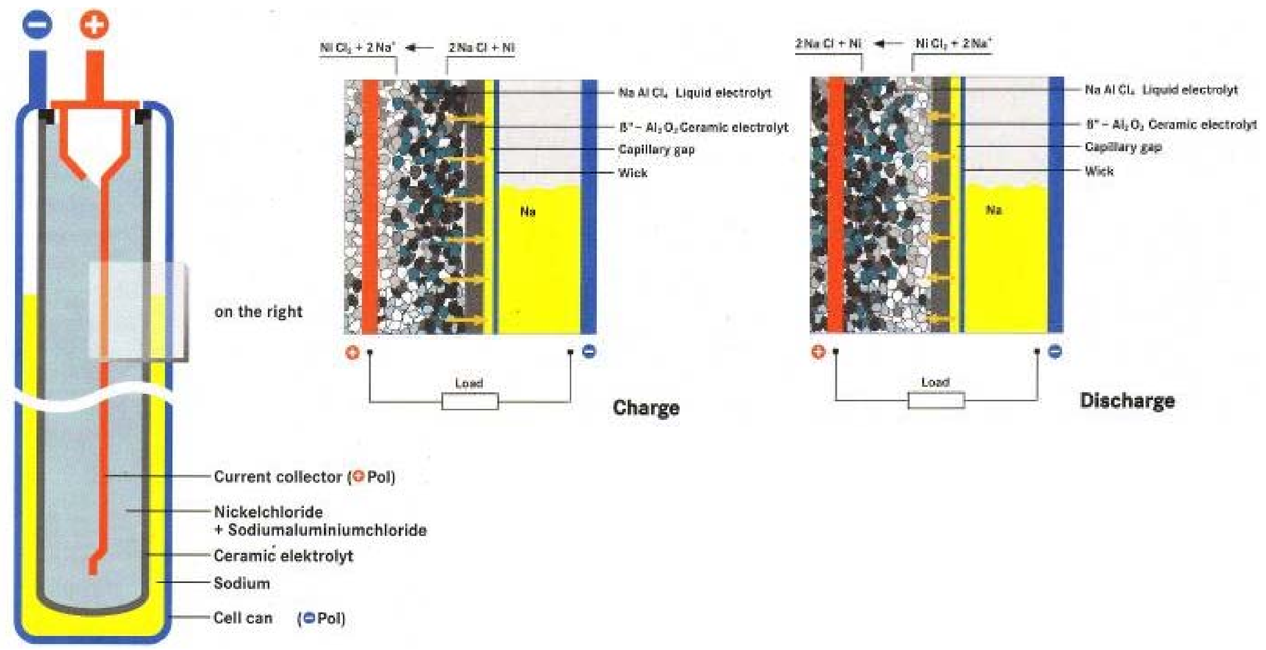


*Figure 4.5-1: ZEBRA cell description [11z].*

ZEBRA cells are produced in the discharged state. The liquid salt $NaAlCl_4$ is vacuum-impregnated into the porous nickel-salt mixture that forms the cathode. It conducts the sodium-ions between the β″-

$Al_2O_3$ ceramic surface and the reaction zone inside the cathode bulk during charge and discharge. It also provides a homogenous current distribution in the ceramic electrolyte.

The charge capacity of the ZEBRA cell is determined by the quantity of salt (NaCl) available in the cathode. More recently iron has been incorporated in the electrode to improve performance.

The absolutely maintenance-free cells are hermetically sealed by a metal/ceramic combination. The operating temperature is approximately 300 °C.

*Figure 4.5-2: Complete ZEBRA battery.*

The lowest operating temperature of the ZEBRA battery is theoretically 157 °C because, above this temperature, the liquid electrolyte is molten and the battery could carry current. In practice, the internal temperature was set to within the range of 250-350 °C. The heat is regulated by an electronically controlled cooling system.

Reliability and useful life of the battery are the most important characteristics for its use in EV. The useful life is expressed both in the number of cycles and in calendar periods. The calendar period is about 13 years demonstrated. The thermal insulation is stable for more than 15 years.

The ZEBRA battery is robust and fault tolerant. A current of sodium ions is maintained which protects the electrolyte ceramic against fracture by excess voltage. The reaction products (aluminium and common salt) lead to a cell short circuit, are not corrosive and, even at high temperatures, have an insignificant vapour pressure [13z], all of which justifies the categorisation of the ZEBRA battery as extremely safe. In serious accident situations, the whole battery could be mechanically destroyed. To this end, safety test programmes were run in which a fully charged battery, operational at 300 °C, was dropped on to a vertically erected crash barrier with a final velocity of 50 $km.h^{-1}$. The barrier penetrated the battery by about 30 cm destroying the cells in the penetration zone (Fig.II.5).

The whole of the stored energy was converted to heat which raised the temperature inside the battery to approximately 700 °C. The effective thermal insulation kept the outer surface of the battery considerably less hot. Thus, the ZEBRA battery did pass all these tests because it has several barrier safety concept: barrier by the chemistry (for a heavy mechanical damage of the battery the brittle ceramic breaks whereas the cell case made out of steel is deformed and most likely remains closed and, the liquid electrolyte reacts with the liquid sodium to form salt and aluminium) and, a barrier by the thermal enclosure (the thermal insulation material of the battery box is made out of foamed $SiO_2$ which is stable for above 1000 ◦C).

ZEBRA batteries have been used in a lot of test on EV. MES-DEA has converted a Renault Twingo and a Mercedes VITO van with one and two Z5 Zebra battery, respectively, in the aim to make tests such as overcharge, overheating, resistance after failure and freeze thaw testing. A Z21 type ZEBRA battery has been also tested on Smart cars. The battery fits across the vehicle and under the floor pan leaving the vehicle interior virtually standard. The vehicle has a top speed limited to 100 $km.h^{-1}$ and a range of approximately 100 km under normal urban driving conditions.

#### 4.5.1.2. Cost and Price analysis

As for NiCd Saft Battery no comparative study is possible while only one manufacturer is producing this type of Battery. But MES-DEA (ZEBRA Battery Company) has realized a detailed study of the costs and prices of their battery at the end of 2002 and it is possible to analyse the data and results given.

## ZEBRA Battery

**Cell cost of goods**

| | | MES-DEA data | | Subat data | |
|---|---|---|---|---|---|
| | **kg/cell** | **$/kg** | **$/cell** | **€/kg** | **€/cell** |
| Nickel | 0,15 | 11,6 | 1,74 | 19,99 | 3,00 |
| Iron | 0,14 | 3,36 | 0,47 | 3,40 | 0,48 |
| Copper | 0,03 | 2 | 0,06 | 3,20 | 0,10 |
| Halide salts | 0,22 | 0,77 | 0,17 | 0,70 | 0,15 |
| Beta-Alumina (Boehmite) | 0,14 | 2,38 | 0,33 | 2,58 | 0,36 |
| **TOTAL** | **0,68** | | **2,77** | | **4,09** |

*Comments:*

*. As for all other Nickel based Battery the Nickel used is of Battery grade and in different type of shape (sheet, powder, wire etc.) in that case price is higher than "normal" Nickel but related to the Nickel Market price.*

*. A value of 1,25 has been taken for €/$*

*. 30% of the Beta-Alumina crucible produced are not usable.*

And

| **21 kWh Battery case cost of goods** | MES-DEA data | | | Subat data | |
|---|---|---|---|---|---|
| | kg/bat | $/kg | $/bat | €/kg | €/bat |
| Stainless steel | 18 | 3,2 | 57,6 | 3,8 | 68,0 |
| Steel (cooling system) | 7,5 | 1,5 | 11,3 | 1,8 | 13,3 |
| Thermal isolation | 7,5 | 12,5 | 93,8 | 11,0 | 82,5 |
| Miscellenious | 4 | 9,0 | 36,0 | 7,9 | 31,7 |
| **TOTAL** | **37** | | **198,6** | | **195,4** |

| 21 kWh Battery Manufacturing costs | **MES-DEA** | **SUBAT** |
|---|---|---|
| | **$/bat** | **€/bat** |
| Battery production costs | 1125 | 1661 |
| Energy | 36 | 35 |
| Case cost of goods | 199 | 195 |
| Case Labour | 179 | 186 |
| BMS | 300 | 250 |
| **TOTAL** | **1 838** | **2 327** |
| **€/kWh** | **88** | **111** |

| | **MES-DEA $** | **SUBAT €** |
|---|---|---|
| Total cost of a 21 kWh battery | 1 838 | 2 327 |
| Other Manufacturing costs | 643 | 931 |
| Overheads | 459 | 698 |
| **Total manufacturing costs** | **2 941** | **3 955** |

| | | |
|---|---|---|
| Margin | 588 | 791 |
| **Price** | **3 529** | **4 746** |
| **€/kWh** | **168** | **226** |

Results of the MES-DEA column are based on MES-DEA data but estimated using our method. Results of MES-DEA were of 72.63 $ for battery production costs.
Results of these estimations show that in mass production ZEBRA Battery could be one of the cheapest (compared to Lithium based and NiMH), but the process used (high temperature process for beta-alumina separator) is completely different compared to a classical battery production process and it becomes difficult to estimate the manufacturing and company costs (depreciation, labour, maintenance and overheads). These results have also to be compared with the prices announced by MES-DEA in 2005 of about 450 €/kWh.

## 4.5.2 Ni-Zn Battery

### 4.5.2.1 Technology

The nickel-zinc battery dates back to 1901 when a Russian patent was deposited by Michaelowski. Further work was performed in the 1930's on the nickel-zinc battery which is an aqueous alkaline rechargeable system. In the sixties' the will of the replacement of the silver-zinc battery as a better cycling life in the military applications induced the development of the nickel-zinc technology. In the second time, the oil crisis implied an increase of the electric vehicle interest in the world and main effort have been undertaken to improve the nickel-zinc system.
This system is based on the nickel hydroxide / nickel oxyhydroxide electrode as the cathode and on the zinc / zinc oxide electrode as the anode. Indeed, the same "nickel" electrode and alkaline electrolyte are already used in the NiCd and in the NiMH technologies.

At the cathode: $$\mathrm{Ni(OH)_2 + OH^-} \underset{\text{Discharge}}{\overset{\text{Charge}}{\rightleftarrows}} \mathrm{NiOOH + H_2O + e^-}$$

At the anode: $$\mathrm{Zn(OH)_2 + 2e^-} \underset{\text{Discharge}}{\overset{\text{Charge}}{\rightleftarrows}} \mathrm{Zn + 2OH^-}$$

Total cell reaction: $$\mathrm{2Ni(OH)_2 + Zn(OH)_2} \underset{\text{Discharge}}{\overset{\text{Charge}}{\rightleftarrows}} \mathrm{2NiOOH + Zn + 2H_2O}$$

Actually, the electrochemistry of zinc hydroxide in alkaline solution is quite complex thus, the reaction previously proposed within to the anode is largely simplified.
When the nickel-zinc battery is overcharged (-discharge), oxygen is produced at the nickel electrode (-zinc one) and hydrogen is produced at the zinc electrode (-nickel one). Thus, during the overcharge, the oxygen may recombine with the metallic zinc directly at the zinc electrode.

N.B.: The nickel-zinc cell have a nominal voltage of about 1.6 V *versus* NHE (whereas in the nickel-cadmium and in the nickel-metal hydride system the nominal voltage is about 1.2 V *versus* NHE). The nickel-zinc battery has a theoretical specific energy of about 334 $\mathrm{Wh.kg^{-1}}$ nevertheless, the practical specific energy is only about 70 $\mathrm{Wh.kg^{-1}}$.

The main disadvantage of the NiZn technology is its low cycling life due to the dissolution of the zinc hydroxide in the alkaline electrolyte solution. In spite of good results of the zinc electrode stabilization and thus the decrease of its solubility in the electrolyte the cycling life of the nickel-zinc battery remains about of 500-700 cycles.

The advantages of the Nickel-Zinc battery are a high specific energy density, a good deep cycle capability, an abundant low cost materials and an environmentally friendly chemistry, namely these batteries are called "Green" batteries.
The nickel-zinc battery is appropriate for a number of commercial applications, namely electrics scooters and bicycles, electric garden equipments and marine applications.

*Table II.2: List of Nickel-Zinc battery manufacturers and concise description of each production process*

| Group name | Anode material | Electrolyte | Separator | Cathode material | Comments |
|---|---|---|---|---|---|
| Evercel | $Zn(OH)_2$ + $Ca(OH)_2$ + PTFE | KOH (20 % w) | PP film (Celgard$^{®}$ type) | $Ni(OH)_2$ + PTFE + graphite (as collector) | Prismatic cell |
| Evionyx | $Zn(OH)_2$ | Probably KOH | Probably polyolefin | $Ni(OH)_2$ | Unknown |
| SCPS | $Zn(OH)_2$ + additive + conductor ceramic particles + plasticizer components | KOH | Probably polyolefin | $Ni(OH)_2$ + potential additive | Prismatic cell R&D stage, no production. By the end of 2004, pre-production line is available |

* Evercel

Nowadays, Evercel is the leader industry in nickel-zinc technology. This manufacturer was formed in 1999 by an industry experts group in Ni-Zn battery technology, and to increase their development and their production, Evercel and Three Circles Battery Corporation Ltd (Xiamen, China) formed a joint venture. As the beginning of 2003, Evercel has purchased the remaining interest in the joint venture, inducing a wholly owned foreign entity existence, namely Evercel-Xiamen. Their activity is focused on high energy battery products, meant to marine trolling motors, EV and scooters.

The operating temperature range has been evaluated from –10 °C to 50 °C in normal load ranges and performance levels. They use standard types of nickel electrodes in their Ni-Zn system. These electrodes can be prepared according to different methods, namely sintered or nonsintered preparation.

*Sintered nickel electrode:* The electrode substrate is a nickel based compound, forming an electrode structure which the porosity is about 80 to 84 %. The most common process of the introduction of the $Ni(OH)_2$ active material in the electrode structure is by chemical impregnation. The porous substrate is alternately dipped in a bath of nickel-nitrate and potassium hydroxide led to the chemical precipitation of $Ni(OH)_2$ in the electrode structure. This process is relatively expensive and a high nickel content is used which 60 % is inactive material. A second process of deposition can be used, namely cathodic or electrochemical deposition. The main advantage of this technology is that the complete deposition takes place in a single step, resulting in electrodes with better performances.

*Nonsintered nickel electrode*: In the first case, the nickel hydroxide electrode can be pasted mechanically into a porous nickel substrate, namely nickel foam or nonwoven nickel fiber. In a second case, the $Ni(OH)_2$ active material is blended with a PTFE binder and then rolled-bonded into a graphite composite porous structure, inducing a plastic-bonded electrode type, that is the technology chose by Evercel.

*Zinc electrode*: Like the nickel electrode, the zinc electrode contains a mechanical support (i.e. current collector), namely copper compound one (plated, foil, wire mesh etc…). They are manufactured in their discharge state (i.e. zinc oxide). Some metallic zinc can be added to the electrode to offset the initial high resistance. Nevertheless, zinc has the tendency towards dissolution in the alkaline electrolyte, inducing the formation of some solvated complex ions. The species involve in zinc oxides and hydroxides. In fact, only 60 % of the active material is used. In the aim to improve zinc electrode cycling life, some substitutes are added as calcium, lead, indium, tin or antimony based compounds, and the best results are obtained by about 25 % (weight) calcium addition. An associated phenomenon is zinc dendrite formation and if the zinc surface is not uniform the risk of short-circuit increases. Evercel' zinc electrodes are also manufactured by the plastic-bonded method (similar to the nickel electrode one described above). The zinc oxide dry powder, PTFE binder and other additives are blended with organic solvent and the mixture undergoes a calendaring process.

* Evionyx

Evionyx has especially developed a "Revolutionary Power Cell™" (i.e. RPC device) based on metal-fuel anode in the aim to operate in Metal-air battery (see in the following section). They have produced an "electric/hybrid" prototype car outfitted with the combination of both high-power nickel-zinc batteries and high-energy zinc-air fuel cells. The nickel-zinc battery does not constitute their main activity then no precise information's are known on the Ni-Zn technology used.

* SCPS (Société de Conseil et de Prospective Scientifique)

In 1998 SCPS had kicked off a R&D program to develop a new zinc electrode, namely without the well-known problems linked to the zinc dissolution/instability. Nowadays, they remain at the R&D stage and they have not production capacity but only pre-production step.

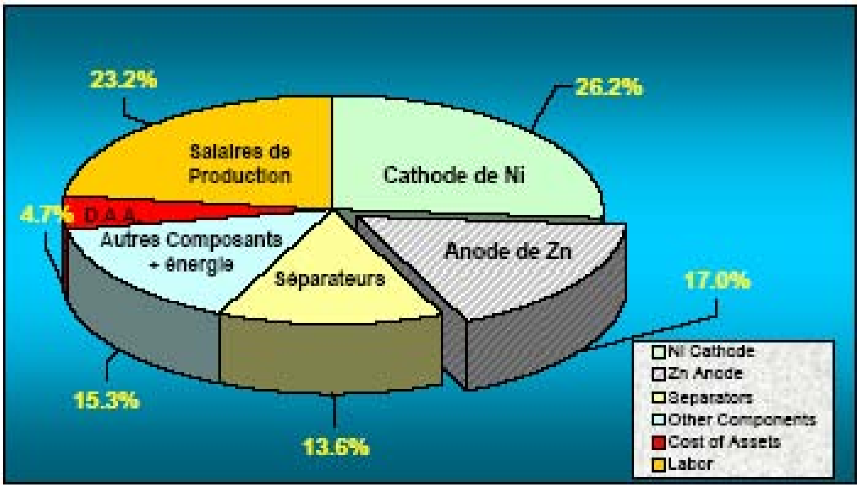
*Zinc electrode:* the anode is formed mainly by zinc oxide in which specific additives and conductor particles of ceramic are added. The addition of the particles of ceramic allows a micro-network formation within the active material in the aim to improve its conductivity. Then, the specific additives promote the retention of the zincates in the anode (these being responsible for the dendrite formation), inducing a best cycling life. The key point of the SCPS technology is the using of a special copper foam as electrode collector. The active material is introduced as a plasticized paste form within the copper pores.
SCPS manufacturer has registered some patents for the active material composition, for the copper foam process and for the specific conductor ceramic.

*Nickel electrode and separator:* nowadays, no precise information's are known on the nickel electrode nature and on the separator type.

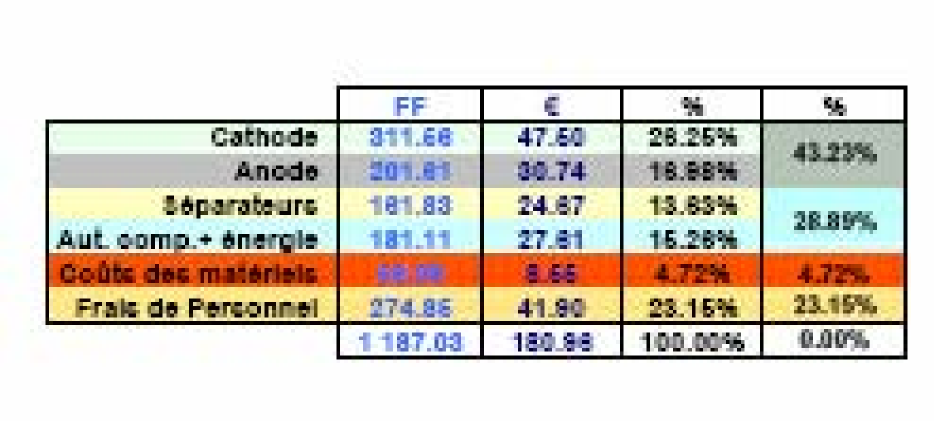
The assembly of the battery is made in opening configuration, implying some regular addition of water to compensate the electrolyte loss. Thus, these batteries are not free-maintenance ones.
Actually, SCPS manufacturer is at the R&D stage and it is not in production step, but by the end of 2004, a pilot line would be available.

### 4.5.2.2 Cost and Price analysis

As seen in the previous paragraph, the Ni-Zn battery is comparable to Ni-Cd one when cost and price analysis is concerned (same type of module, comparable electrodes, same type of electrolyte and probably comparable production process). No really reliable data are available in order to realize a valuable estimation of the price of these batteries (little production for Evercell and Evionyx and R&D stage for SCPS). But SCPS has very recently published a full set of data concerning the potential production costs of Ni-Zn battery with very surprising results.



SCPS Data: Costs distribution of Ni-Zn battery

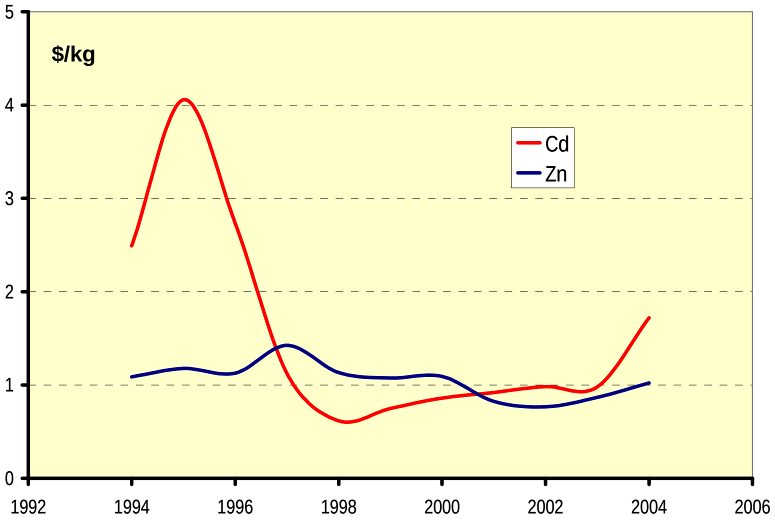


| | FF | € | % | % |
|---|---|---|---|---|
| Cathode | 311.58 | 47.50 | 26.25% | 43.23% |
| Anode | 201.61 | 30.74 | 16.99% | |
| Séparateurs | 161.83 | 24.67 | 13.63% | 28.89% |
| Aut. comp.+ énergie | 181.11 | 27.61 | 15.26% | |
| Coûts des matériels | [illegible] | 8.66 | 4.72% | 4.72% |
| Frais de Personnel | 274.86 | 41.90 | 23.15% | 23.15% |
| | 1 187.03 | 180.96 | 100.00% | 0.00% |

In an other publication made at the same time they announced a potential price in mass production of about 210 €/kWh. A comparison of cost of goods, cost of production, cost of manufacturing and corresponding price can be made with the well known NiCd Battery.

The constitution of the Ni-Zn battery can be considered as similar to NiCd except for the anode of Zinc. Price comparison between Cadmium and Zinc (see following diagram) shows that since 2000, Zinc and Cadmium are at similar prices around 1$/kg

It seems then impossible to find such a great difference between NiZn and NiCd prices.



### 4.5.3 Zn-Air Battery

#### 4.5.3.1 Technology

Zinc-air “batteries” are constituted with a metallic zinc and an oxygen electrodes in an alkaline electrolyte, generally concentrated KOH.

The half-cell reactions during discharge may be written:

*Cathode* $O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$

*Anode* $Zn + 4OH^- \rightarrow Zn(OH)_4^{2-} + 2e^-$

$Zn(OH)_4^{2-} \rightarrow ZnO + 2OH^- + H_2O$

*Overall reaction*: $2Zn + O_2 \rightarrow 2ZnO$

The theoretic specific energy density is 1350 $Wh.kg^{-1}$ whereas the practical one is about 200 $Wh.kg^{-1}$. High power requires an appropriate catalyst on the electrodes, impregnated with transition metal oxides. The overall capacity is determined from the anodic capacity because the electrode is continuously fed by oxygen from the air.

According to the advantages of this technology are safety; high energy density; moderate cost and environmental compatibility. The disadvantages are self discharge for high zinc corrosion (more than 6% per month, because of zinc relative stability in alkaline electrolyte); slow kinetics depending on ion diffusion and charge exchange at the interface; vehicle autonomy; the system behaviour is highly dependent on the temperature. The power is strongly decreasing with the temperature and the capacity is decreasing over 60 °C for the zinc oxidation. The carbon dioxide of air precipitates solid $ZnCO_3$ crystals on cathode with degradation of catalytic activity and decreases the capacity because oxygen diffusion, clogging the cathode pores.

Different zinc-air systems has been developed from different manufacturer: Electric Fuel Ltd from USA and Israel, Powerzinc Electric Inc. from USA (HQ) and Shanghai (R&D and plant) and Evionyx from USA (HQ And R&D) and Taiwan (R&D and plant).

*Table II.3: List of Zinc-air battery manufacturers and concise description of each production process*

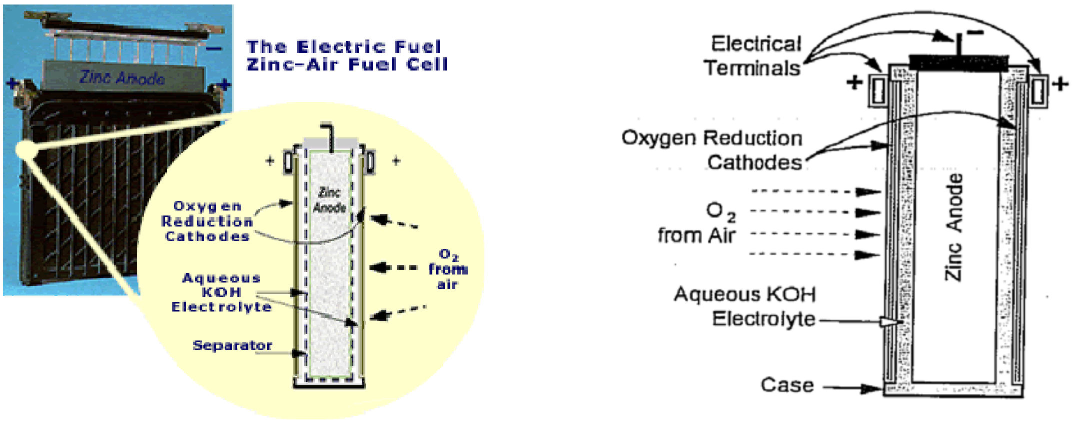
| Group name | Anode material | Electrolyte | Separator | Cathode material | Comments |
|---|---|---|---|---|---|
| Arotech & Electric fuel Ltd | Zn | KOH | Hydrophobic membrane | $O_2$ (air) + porous carbon black (support) + PTFE + metal grid (collector) | *Cylindrical cell* |
| Evionyx | Zn (MetFuel™) | Membrion™ + probably KOH | / | $O_2$ (air, O-Cat™) + carbon support + nickel collector | *Cylindrical cell R&D* |
| Powerzinc | Zn | KOH | | $O_2$ (air) | Prismatic cell |

*** Arotech & Electric fuel Ltd (EFL)**

The most known of Zn-air manufacturer is Electric Fuel Ltd (EFL) because of its intensive efforts in the development of a complete system for EV applications, including battery, refuelling station and regeneration plant (exhausted anodes).

The EFL zinc-air battery is mechanically recharged, substituting the exhausted zinc with fresh anodes. The spent zinc anodes are electrochemically recharged in a regeneration plant. Mechanical recharge is better than electrical recharge because has not problem of zinc dendritic growing.

EFL's zinc-air cell includes a zinc anode in a potassium hydroxide electrolyte (KOH). The anode is partially withdrawn from the plastic case of the cell.



(a) (b)

*Figure 4.5-3: (a) Electric Fuel Ltd (EFL) zinc air cell and (b) EFL cell scheme*

The cathode is an oxygen reduction membrane. During discharge, the zinc is converted in zinc oxide. Electrodes are multistage on a porous carbon base, an air diffuser and hydrophobic membrane. Metal grids act as positive conductors.
Withdrawal of the anode is a part of the regeneration process: spent anodes have the zinc oxide remove from the current collector at the regeneration plant.

*Air circuit*
The air-diffusion electrode most commonly used consist of a thin, porous structure of catalyzed carbon black and polytetrafluoroethylene (PTFE). The carbon provides a conductive substrate for the catalyst, and the PTFE provides a porous hydrophobic network for the diffusion of reactant air. This combination of two solid phase, the conducting carbon phase and hydrophobic PTFE phase, when fabricated into an appropriate porous structure, provides a stable three-phase boundary (i.e.: solid-liquid-gas) and successful operation of air diffusion electrode. The structure and the electrocatalytic activity of the active layer are the most critical factors in determining whether the performance of an air-diffusion electrode is optimal.
The catalysts used are non-noble metals and environmental friendly materials. In addition, these electrodes can perform reasonably well at very low temperature, down to -40°C.

*Refuelling station*
In the refuelling station, two types of operations are possible:

1. Complete batteries substitution. For this operation the spent batteries are carried out with the tray and transported to the regeneration plant.
2. Zinc anodes substitution. For this operation an anodes substitution machine is needed. This device perform the substitution of the exhausted zinc anodes with fresh anodes and it is the most important element of the refuelling station.

The anodes substitution machine is a robot able to execute the following list of operations:

- Exhausted zinc electrodes extraction from battery;
- Electrode placing in transportation container;
- Fresh zinc electrodes extraction from regeneration plant container;
- Fresh zinc electrodes placing in the battery.

All this operation must be performed in less than 20 minutes.

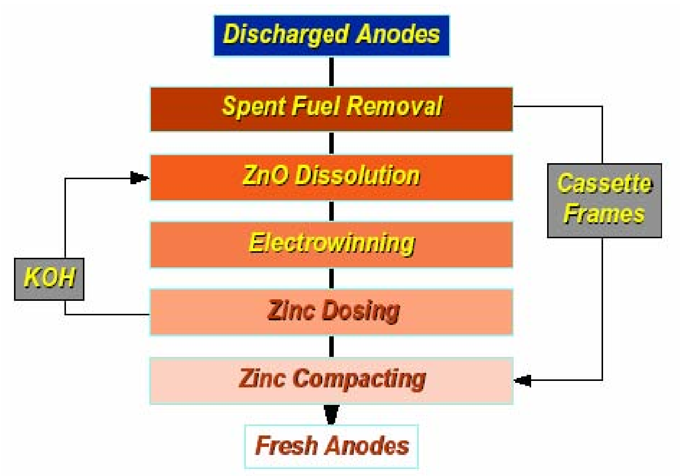


*Figure 4.5-4: schematic of regeneration process*

*Zinc regeneration process (Figure 4.5-4 )*
It is a centralized plant where spent zinc electrodes are electrically recharged (electrowinning). The metal zinc is sent to a solution unity fed with an alkaline solution. This solution with an high content of zincates is sent to a storage tank and to the electrolytic cell.
The regeneration process can be summarized as in the following:

- Spent fuel removal: exhausted electrode material (ZnO) removal from current collector;
- ZnO dissolution: zinc oxide dissolution in a KOH aqueous solution;

- Electrowinning: dendritic zinc electrodeposition from the solution obtained from oxide dissolution;
- Zinc dosing: preparation of the right zinc quantity needed from electrodes;
- Zinc compacting: the zinc is pressed on the current collector.

The zinc slurry is periodically extracted and sent to an homogenization tank.
The regenerated anodes are fitted in bags and ready for the battery recharge. The alkaline solution, with a low content of zincates, after the pressed operation, is send back at the storage tank. The whole operation is produced a very low environmental impact, due to non-toxic materials used.

*EDISON zinc anodes regeneration plant*
The system was conceived by Electric Fuel Ltd. (EFL) and co-developed by Edison Co.
A complete flow chart of the regeneration process is shown on Figure 4.5-5.

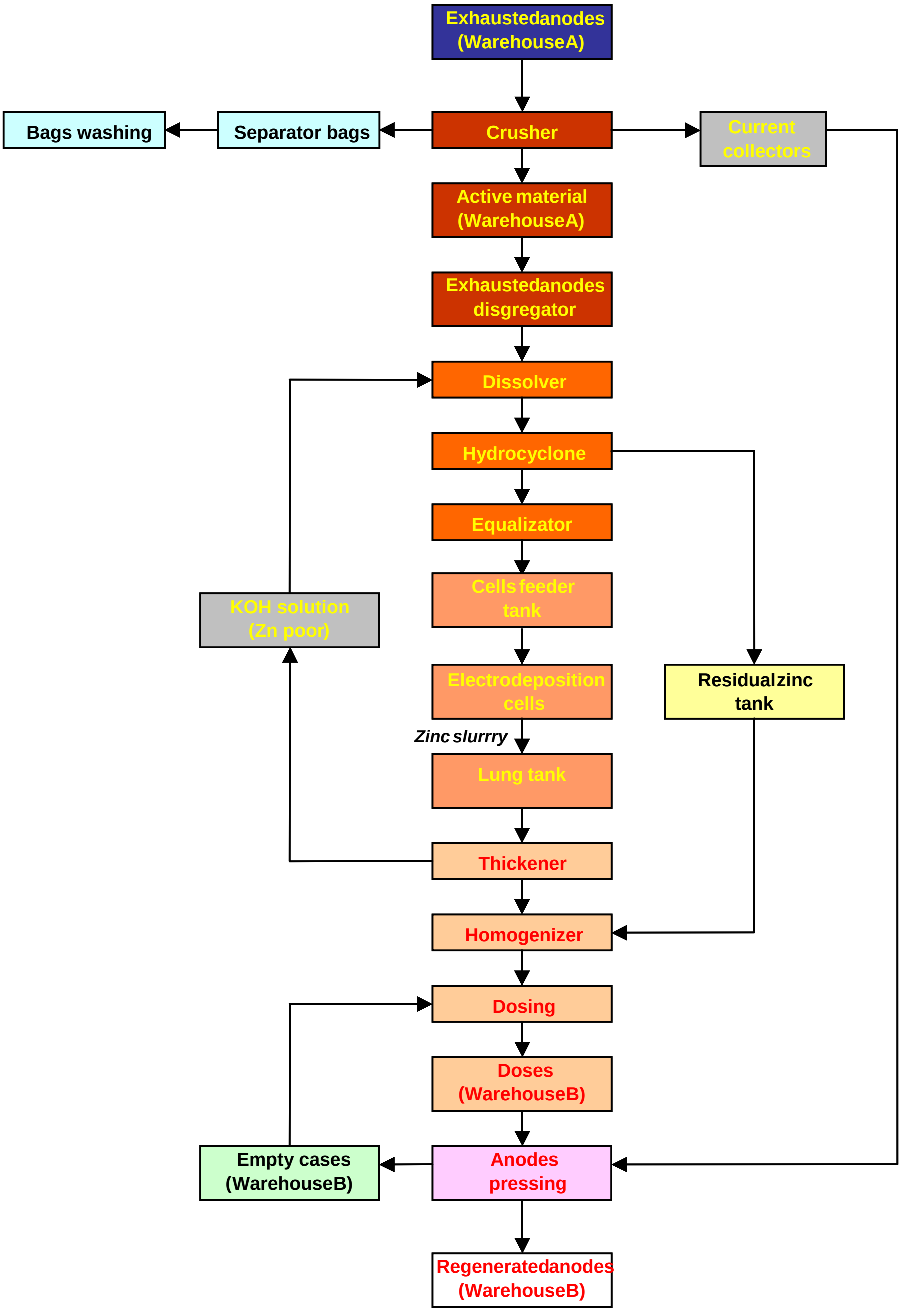


*Figure 4.5-5: Schematic of the regeneration process.*

*Zinc electrodes regeneration plant*

Processing of spent anodes begins with them removal from the module with the separator sleeve attached. The electrolyte is then drained out of the modules, conditioned by filtering and $CO_2$ absorption and stored to await use in a regenerated module.

The sleeves are removed from the anodes, washed in KOH solution and transferred to the anode forming machine to be installed in a newly regenerated anode.

The spent anode materials (approximately 80% ZnO, 20% Zn) are removed from the current collectors. The current collectors are inspected and transferred for use in new anodes formation.

The anode material is dissolved in KOH solution to form a zincate rich solution. The conditioned zincate/zinc solution is fed into trains of electrowinning cells.

The output zinc slurry is conditioned and used to form new anodes on the current collectors and then replaced in the batteries. Figure II.9 shows a flow sheet of the regeneration process .

The regeneration plant efficiency can be improved adopting a (Zn + ZnO) saturated solution and a tape dispenser for a quickly pressing.

*Zinc air battery development*

Heating problems limit battery power. The zinc-air battery efficiency can be improved bu developing a more functional cooling system. There are to ways: liquid cooling system, very effective but very complicated because causes problem with valves and gaskets maintenance; forced air cooling system, less effective but easier.

The second issue is the necessity to adopt a new air filter to improve cathode efficiency.

* Evionyx

Evionyx manufactures zinc-air batteries for scooters, golf carts, lawnmowers and electric/hybrid vehicles applications. They have especially developed a "Revolutionary Power Cell™" (i.e. RPC device) based on metal-fuel anode in order to operating in Metal-air battery (see in the following section). The RPC consists of three proprietary electrochemical components developed by this manufacturer: MetFuel™ (as zinc anode for example), O-cat™ and membrion™. The O-Cat is a cathode, namely air diffusion electrode, based on catalytic carbon (so non-precious metal catalyst) that is capable to convert oxygen from the air into hydroxyl ions. The active material of the cathode is deposited on nickel substrate. The membrion is used to electrolyte solid state, under membrane form, with a good hydroxyl ion conductivity at room temperature.

Indeed, this solid state electrolyte is also used as a separator membrane which prevents the growth of metal dendrites during the charge phenomenon.

* Powerzinc Electric, Inc

The founders of Powerzinc Electric began the research and the development of the zinc air technology in 1995 and in order to commercialise their technology they established Powerzinc Electric Inc in 1999 (USA) and in 2000 (China). The renewable zinc-air battery is used to electric buses, vehicles, motorcycles, scooters, bicycles and stationary applications. Primary cells are also developed, for non-exhaustive military applications. Nowadays, the Powerzinc market is only Asian one (i.e. Taiwan and China). The principle of the Powerzinc technology is shown on Figure 4.5-6.

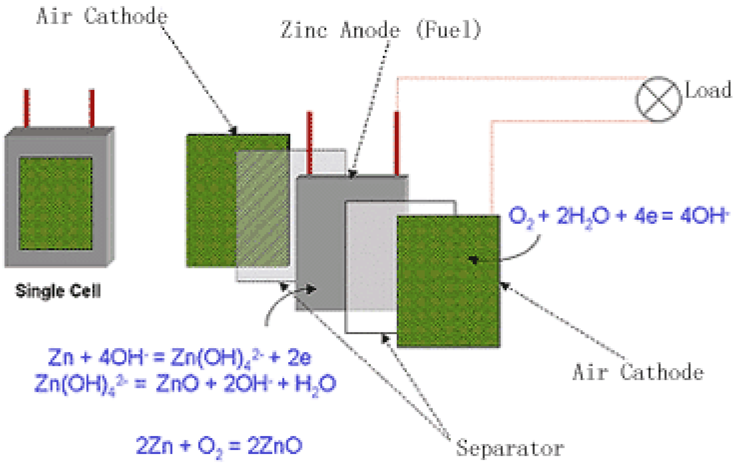


Figure 4.5-6: Zinc-air cell scheme of Powerzinc electric manufacturer.

The cathode is an air electrode, namely a permeable membrane, whom has the ability to convert atmospheric oxygen into hydroxyl ions (i.e. $OH^-$). This ion will be carried away by the electrolyte in order to reach the anode. The anode used by this manufacturer is a special zinc powder which the specific surface area is very high (about 1.5 $m^2.g^{-1}$ against 0.02 $m^2.g^{-1}$ in the conventional case), inducing the generation of high power and high energy.

Fuel regeneration:
The battery operating induces the transformation of the metal zinc into zinc oxide, this process being non reversible electrochemically. So, this technology needs refuel plants who the principle is shown on Figure II.11. The zinc electrode is disassembled to the zinc-air complete battery, then it is regenerated for their repacking and so it is available for their using in a new battery.

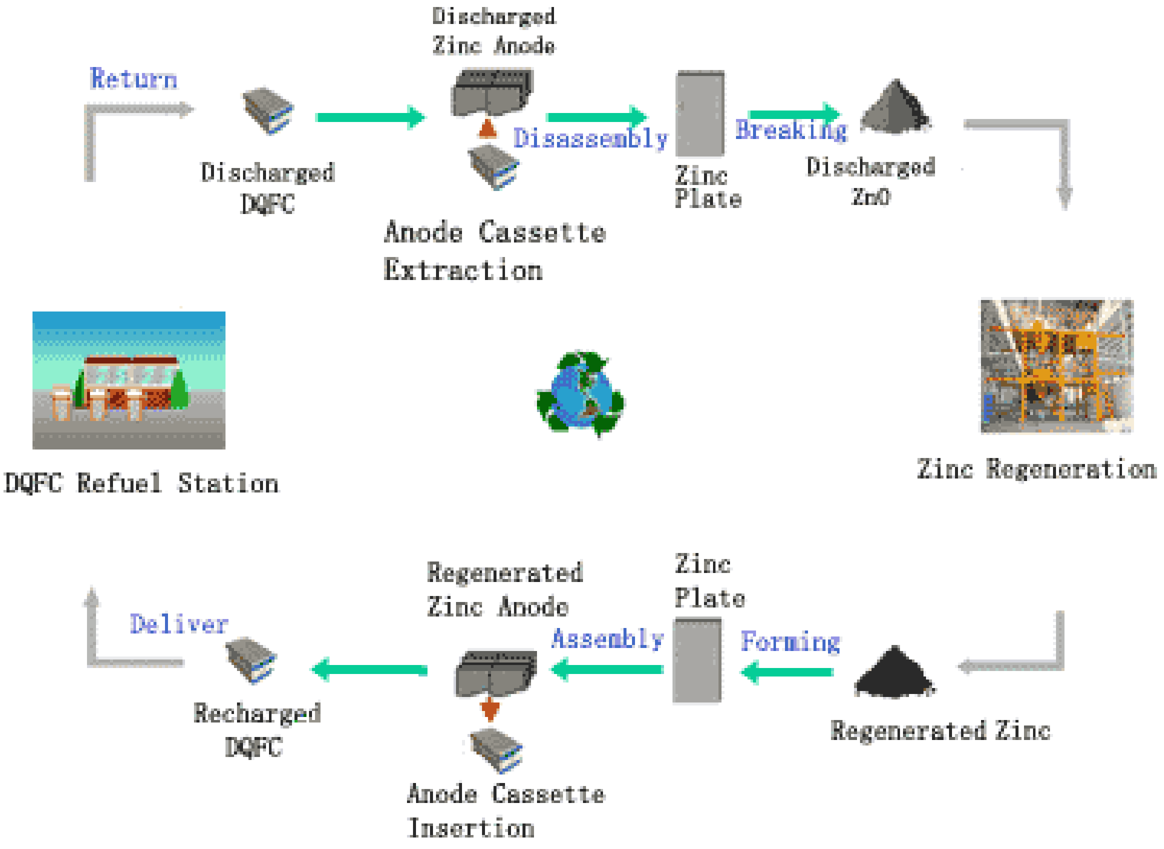


Figure 4.5-7: Integrated Refuel plant

### 4.5.3.2 Cost and Price analysis

The zinc-air battery is not a commercial product yet. Due to this fact, data on the production process of the batteries are not available. At the same time Zn-Air Battery is not really a Battery comparable with the others but rather a Fuel Cell. It becomes then very difficult to make a comparison with the other battery technologies (part of the Zn-Air price will be expressed in terms of depreciation of the recycling plant). Some information can be found in order to evaluate the investments needed to begin the commercialization of batteries.

The following table summarizes the overall costs of the zinc-air system, with a comparison between the actual costs and a cost projection for long-term commercial production.

*Zinc-air system costs summary.*

| *Type of manufacturing costs* | | *Actual cost* | *Long-term (commercial production) estimation*[1] |
|---|---|---|---|
| *Cell* | *Zinc* | 1 $/kg | 0,4 ÷ 0,6 $/kg |
| *Module* | | 10000 $ | 1700 $ |
| *Battery*[2] | | 200000 $ | 30600 $ |
| *Refuelling process* | | Depends on frequency | 270 ÷ 400 $/cycle |
| *Refuelling plant* | | 1000000 $ | |
| *Battery exchange system* | | 400000 $ | |

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[1] It is planned to deliver 3 bus at each transit agency who partecipate at the program in 2007 and 10 ÷ 20 from 2008.

[2] A bus battery is composed by 18 modules

## 4.6 Summary of micro-economic results and short LCC analysis

The results are shown in two cases, in the first one prices are calculated in 2005 in a mass production hypothesis (more than 100 000 modules or batteries per year). In this case the potential decrease of raw material prices is not taken into account.
The second case shows the prices estimation in 2012 (in € 2004) taking into account the potential price decrease of raw material.

### 4.6.1 2005 prices estimation and LCC Analysis

| | | Pb | NiCd | NiMH | Zebra | Li-Ion | |
|---|---|---|---|---|---|---|---|
| EV (30 kWh) | weight (kg) | 850 | 550 | 430 | 270 | 270 | |
| | Min. | 3 480 | 14 700 | 16 770 | 13 500 | 20 988 | [ (2004) € ] |
| | | 116 | 490 | 559 | 450 | 700 | €/kWh |
| | Max. | 4 530 | 21 600 | 19 980 | 15 000 | 25 801 | [ (2004) € ] |
| | | 151 | 720 | 666 | 500 | 860 | €/kWh |
| mild HEV (0,4 kWh, 12 kW) | weight (kg) | 66 | | 15 | | 7 | |
| | Min. | 142 | | 553 | | 527 | [ (2004) € ] |
| | | 12 | | 46 | | 44 | €/kW |
| | Max. | 185 | | 716 | | 626 | [ (2004) € ] |
| | | 15 | | 60 | | 52 | €/kW |
| full HEV (1,2 kWh, 40 kW) | weight (kg) | 111 | 75 | 38 | | 27 | |
| | Min. | 472 | 2 080 | 1 506 | | 2 277 | [ (2004) € ] |
| | | 12 | 52 | 38 | | 57 | €/kW |
| | Max. | 616 | 2 160 | 1 831 | | 2 701 | [ (2004) € ] |
| | | 15 | 54 | 46 | | 68 | €/kW |

The full hybrid Lead-Acid Battery has been estimated, but its weight and volume are not suitable for a full hybrid design.

*Figure 4.6-1 Estimated price of a 30 kWh Battery for BEV in 2005 (mass production)*

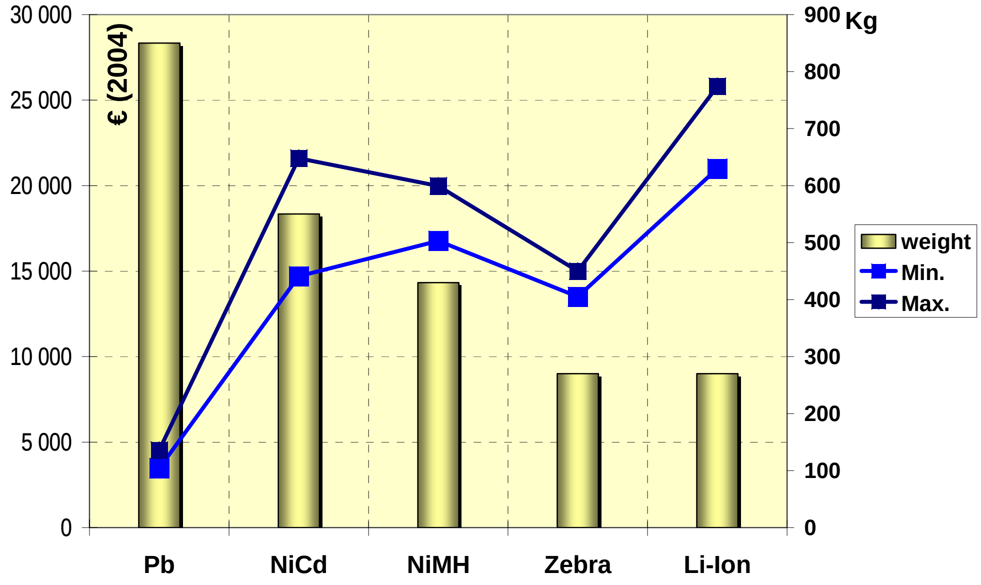


*Figure 4.6-2 Estimated prices of a Full Hybrid Battery of 40 kW and 1.200 Wh (2005,mass production)*

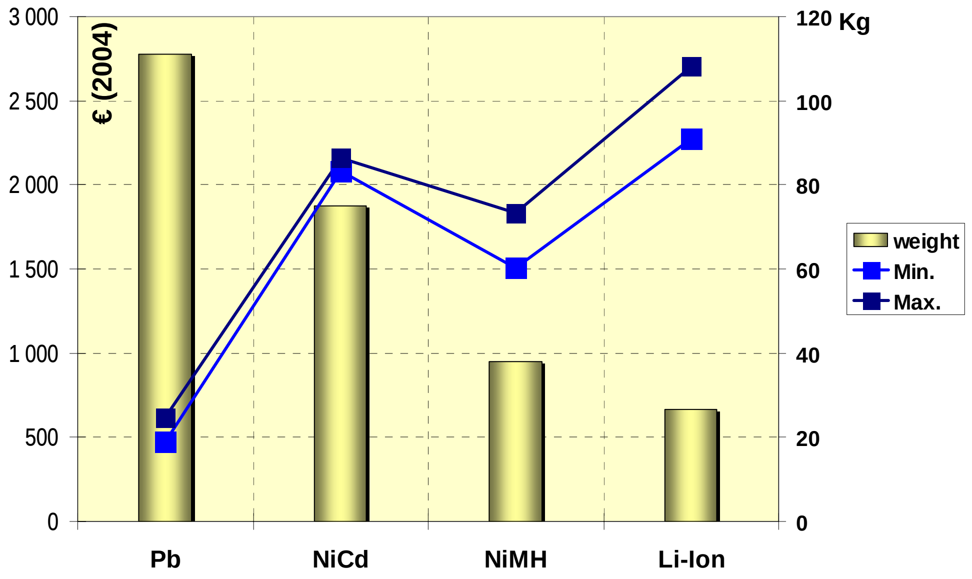
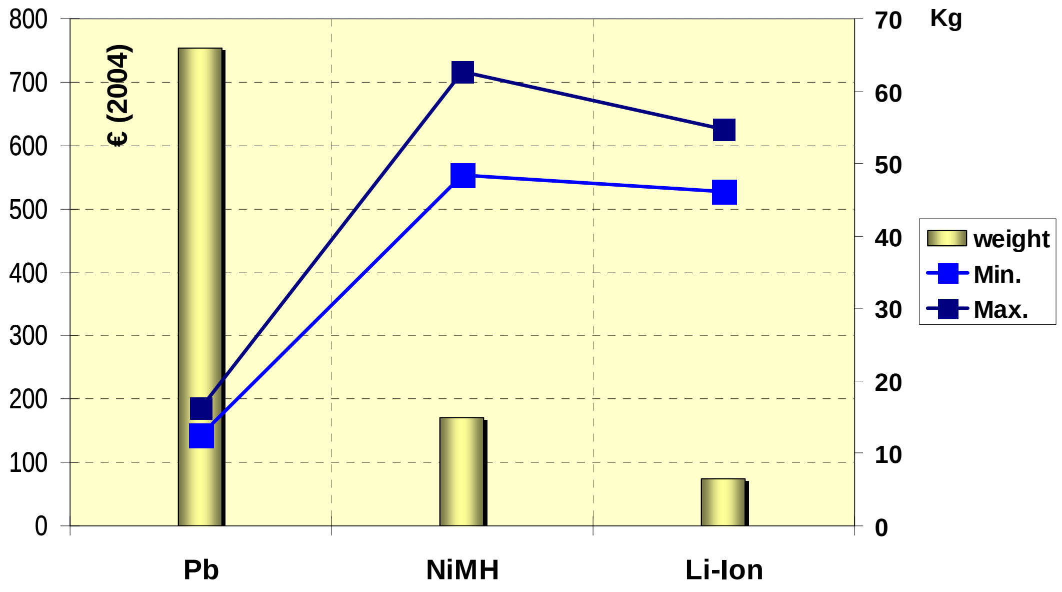


*Figure 4.6-3 Estimated prices of a Mild Hybrid Battery of 12 kW and 400 Wh (2005, mass production)*



The Battery LCC analysis has been made using cycle life data corresponding to the mean values of the best reliable performances known today. They are given in number of battery packs needed for a given vehicle with a standard useful life of 8 years.

Number of battery packs needed for 10 years vehicle life

| Battery Technology | BEV | Mild HEV | Full HEV |
|---|---|---|---|
| Lead-Acid | 5 | 6 | x |
| NiCd | 2 | x | ? |
| NiMH | 2 | 1 | 1 |
| Li-Ion | 2 | 1 | 1 |
| Zebra | 2 | x | x |

*Life Cycle Cost results in 2005 for the three types of vehicles (in red the lowest price value)*

| | BEV (30 kWh) | | Mild Hybrid | | Full Hybrid | |
|---|---|---|---|---|---|---|
| | **min.** | **max.** | **min.** | **max.** | **min.** | **max.** |
| Pb | 17 400 | 22 650 | 852 | 1 110 | 2 832 | 3 696 |
| NiCd | 29 400 | 43 200 | | | | |
| NiMH | 33 540 | 39 960 | 553 | 716 | 1 506 | 1 831 |
| Zebra | 27 000 | 30 000 | | | | |
| Li-Ion | 41 976 | 51 602 | 527 | 626 | 2 277 | 2 701 |

### 4.6.2 2012 prices estimation and LCC analysis

| | | **Pb** | **NiCd** | **NiMH** | **Zebra** | **Li-Ion** | |
|---|---|---|---|---|---|---|---|
| **EV (30 kWh)** | **weight (kg)** | 850 | 550 | 430 | 270 | 270 | |
| | **Min.** | 4 594 | 14 700 | 16 770 | 6 360 | 10 800 | [ € (2004) ] |
| | | 153 | 490 | 559 | 212 | 360 | €/kWh |
| | **Max.** | 5 980 | 21 600 | 19 980 | 7 500 | 14 310 | [ € (2004) ] |
| | | 199 | 720 | 666 | 250 | 477 | €/kWh |
| **mild HEV (0,4 kWh, 12 kW)** | **weight (kg)** | 66 | 23 | 15 | | 7 | |
| | **Min.** | 187 | 624 | 553 | | 268 | [ € (2004) ] |
| | | 16 | 52 | 46 | | 22 | €/kW |
| | **Max.** | 244 | 648 | 716 | | 367 | [ € (2004) ] |
| | | 20 | 54 | 60 | | 31 | €/kW |
| **full HEV (1,2 kWh, 40 kW)** | **weight (kg)** | 111 | 75 | 38 | | 27 | |
| | **Min.** | 544 | 2 080 | 1 506 | | 1 184 | [ € (2004) ] |
| | | 14 | 52 | 38 | | 30 | €/kW |
| | **Max.** | 708 | 2 160 | 1 831 | | 1 619 | [ € (2004) ] |
| | | 18 | 54 | 46 | | 40 | €/kW |

The hatched zones are for battery types not convenient for the given application : Full hybrid Lead-Acid battery is too heavy, Zebra power battery type does not exist, NiCd power type battery is not planned to be used for hybrid passenger cars.

*Estimated prices of a 30 kWh Battery for BEV (mass production, 2012 estimated prices in € 2004)*

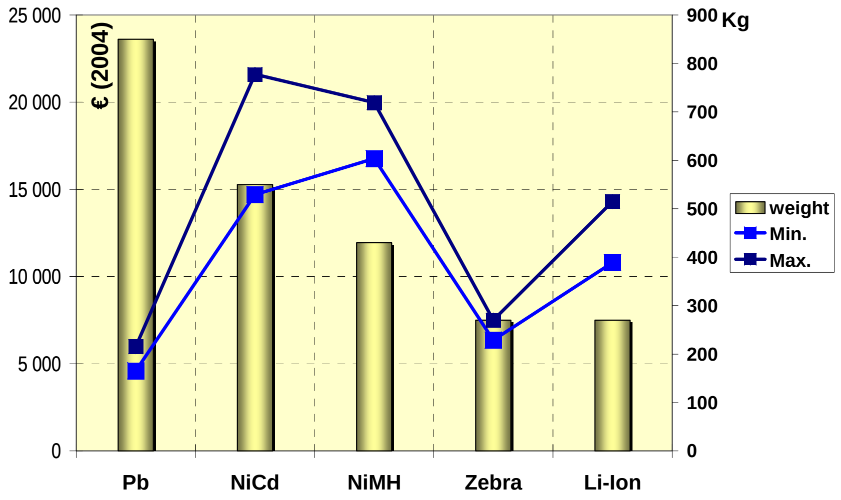


*Figure 4.6-4 Estimated prices of a Full Hybrid Battery of 40 kW and 1.200 Wh (mass production, 2012 estimated prices in 2004 €)*

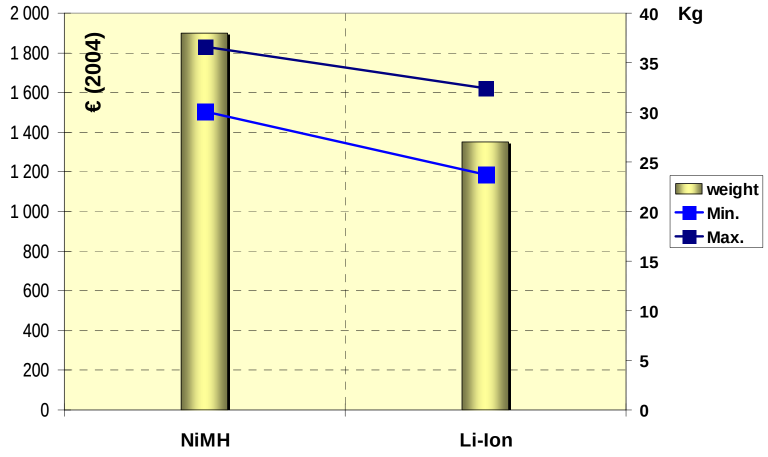


*Figure 4.6-5 Estimated prices of a Mild Hybrid Battery of 12 kW and 400 Wh (mass production, 2012 estimated prices in € 2004)*

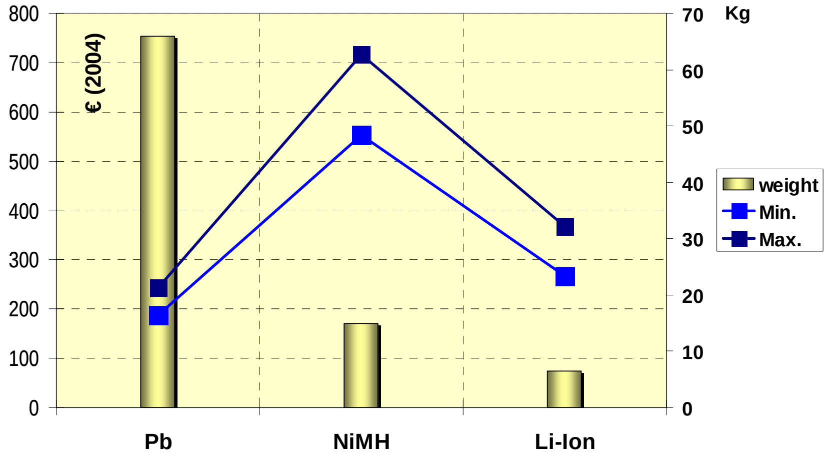


*Figure 4.6-6 Life Cycle Cost results in 20012 for the three types of vehicles (in red the lowest price value)*

| | BEV (30 kWh) | | Mild Hybrid | | Full Hybrid | |
|---|---|---|---|---|---|---|
| | min. | max. | min. | max. | min. | max. |
| Pb | 22 968 | 29 900 | 1 122 | 1 464 | 0 | 0 |
| NiCd | 29 400 | 43 200 | | | | |
| NiMH | 33 540 | 39 960 | 553 | 716 | 1 506 | 1 831 |
| Zebra | 12 720 | 15 000 | | | | |
| Li-Ion | 21 600 | 28 620 | 268 | 367 | 1 184 | 1 619 |

# C – “Traction Battery” Market Study

# 1. Map of Battery Suppliers

Using the global SUBAT Battery Manufacturers database, the WP3 “map of battery suppliers” takes into account more economical criteria such as ownership of the company existing Joint Ventures etc, R&D centres location and decision making organization, available commercial products and development ability in order to make a “classification” of the Companies. This approach will give a better representation of industrial groups able to play a leading role on the future battery market for transport industry. Three main criteria will be used:

- Financial capacity in order to assume R&D and industrial development,
- Scientific and Technical background in the field of battery new technologies,
- Links with automotive industry for future commercial developments.

As the market and the company types are often different between the different types of batteries for traction applications, this map will be organized by battery technologies and two main types of companies (major: have already products to sale, often a market, a real R&D activity and financial development capacities; others: have prototypes products with interesting performances, often patents, some R&D activities but either insufficient financial means or industrial capacities and links with automotive industry).

## 1.1 Ni-Cd & NiMH batteries

Unlike Lead-Acid batteries Ni-Cd and NiMH can be used in automotive applications under two product categories depending on the fabrication process used, the size of the modules and the packaging type: battery assembly of cells coming from portable applications (power tools for example), battery made of modules of industrial type. For high energy or power applications (EV, heavy hybrid or electric vehicles and part of full hybrids) only industrial types of batteries are used, but for smaller battery size (light vehicles as bikes and scooters and part of mild and full hybrids) portable type is very often the best choice.

As far as only road transportation industry applications are concerned there is only one company in the world that produces and commercializes specific Ni-Cd rechargeable batteries for automotive applications. Only a few of them are now concerned by the production or development of NiMH batteries after several years of intense R&D activities all over the world.
These two technologies have reached their maturity and very little progress has to be expected in the next few years (only for NiMH).

### 1.1.1 NiCd

(For more detailed information on NiCd battery types and market see B – 4.4)
Except for light vehicles (E-bike, electric scooters and three wheelers), NiCd batteries used for automotive applications are all of industrial type. For heavy vehicles (bus, trucks and railway applications) it’s very important to avoid confusion between standby batteries that are today very often used (railway) and traction batteries more rarely used (buses, tramway).

- *Passenger Cars (PC) and Light Duty Vehicles (LDV) Market*

Essentially the big car manufacturers are concerned by this market segment. In this case NiCd batteries are no more used for the HEV (Hybrid Electric Vehicle) applications. They are still used only in Europe for BEV production and the only battery manufacturer is SAFT with its STM type battery. These batteries are specific for EV and have needed the development of an automated production equipment in Bordeaux (France).
Saft production capability already installed is for more than 5000 Electric Vehicle per year that means approximately 60 MWh. Real production was about 1000 batteries per year the three past years with a decrease of 20% per year. As an EV battery capacity is between 12 and 15 kWh (depending on the Vehicle) that means about 13 MWh and 259 tons per year for a total sales about 6 M€.

| Known Name | Company and subsidiaries | Country | Other names | Products (automotive market) | comments |
|---|---|---|---|---|---|
| Saft | SAFT | HQ in France<br>R&D France and USA<br>Plants in Europe and USA | | Ni-Cd for EVs<br>Ni-Cd for heavy Vehicles<br>Ni-Cd for light Vehicles<br>Ni-MH for EV, Hybrids, 42 V, heavy Vehicles and light Vehicles | |
| Ovonic | Cobasys (JV Chevron Texaco & ECD Ovonic) | USA, HQ in Troy, Michigan<br>Plant in Springboro, Ohio | Texaco Ovonic Battery System | Ni-MH for EV, Hybrids, 42 V, heavy Vehicles and light Vehicles | |
| **Panasonic (PEVE)**<br>**Panasonic EV Energy Co., Ltd.** | **Subsidiary of Matsushita Electric Industrial Co., Ltd** | **Japan, HQ in Kosai, Shizuoka** | | **Ni-MH for Hybrids (full and mild), largest world manufacturer of NiMH batteries for hybrids (Toyota and Honda HEV)** | **JV between Matsushita and Toyota** |
| **Sanyo** | **Sanyo Electric Co. Ltd** | **Japan, HQ in Osaka, R&D in Kobe** | | **NiMH for Hybrids (full and mild), Ford Escape Hybrid** | **largest world battery manufacturer for portable applications** |
| Varta AG | Johnson Controls | Plants and R&D in Germany, HQ in USA (Johnson Controls) | | NiMH for EV and Hybrids essentially Heavy vehicles | Seem to be late compared to the other Companies |

Note: (The two major Companies are in bold)
In 2004 only PEVE and Sanyo (beginning at the end of the year) are producing HEV battery packs for industrial production vehicles (Toyota Prius, Honda Civic and some others for PEVE, Ford Escape for Sanyo). All the others are at the prototype stage (in terms of production capacity) and seem to be late to become competitive on this growing market. Saft and Varta are looking for niche markets in the field of heavy and military vehicles (Europe and USA) when Ovonic is now essentially involved in stationary applications (telecom).

This production constitutes 0.64% of the total NiCd battery market in € (portable market included) and 2.2% in weight of battery.
Despite the low production volume compared to the expectations and thanks to the fully automated manufacturing process, Saft has preserved the low cost and prices corresponding to the initial expected volumes (450 €/kWh).

- *Heavy Hybrid or Electric Vehicles*

NiCd batteries are sometimes used in this type of applications but only for Hybrid Vehicle type. The battery configuration is then the "power" one (different from BEV one). This market is small and related with specific experimental projects. In this case NiCd is directly in competition with Lead-Acid or NiMH and its higher price (1000€/kWh) or lower performances are not in favour of a market increase.
Saft is the only European Manufacturer of specific batteries for this type of applications (STH batteries) and have sold about 500 kWh in 2003, corresponding to 500 k€ and about 15 tons of battery.
Some other Manufacturers of Industrial NiCd batteries (in Europe, China and Japan) are using non specific battery types in hybrid projects but quantity remained very small.

- *Light Vehicles (e-bikes, scooters and three wheelers)*

Depending on their weight these types of vehicle are equipped with portable battery types or modules of BEV type when they are available. For e-bikes (important market in Asia) portable batteries cells are always used and the suppliers are nearly the same as for power-tools (see chap. III.4 and III.3). For heavier vehicles NiCd is often used in Europe (portable types or BEV type) because modules are available from SAFT production. In the other countries Lead-Acid or NiMH are more often used (since 2000).

### 1.1.2 NiMH

As for NiCd (and Lithium based) the NiMH batteries can be developed into several versions depending on energy or power demand, that's to say depending on HEV or BEV applications purpose. After a short period (1996-2000) of the energy version development used in several BEV fleets experimentation, the power version has been developed intensively as an answer to the growth of hybrid passenger car market led by Toyota. Some of these power NiMH batteries are coming from the portable technology world, others are of industrial type depending on the size of battery pack that means of the electric energy/power demand of the vehicle power train configuration.

- *Passenger Cars (PC) and Light Duty Vehicles (LDV) Market*

Today 99% of the industrial NiMH production for automotive applications is manufactured by only one Japanese Company (Panasonic EV Energy Co.) result of a joint venture between a large portable Battery Manufacturer (Panasonic, Matsushita Electric Industrial Co., Ltd) and Toyota, the leading car manufacturer for hybrid vehicles development.
In 2003 Panasonic EV Energy Co. has produced about 140 000 kWh corresponding to 3 500 tons of battery and 132 Million $. That means an estimated value of about 2.5 million of modules (7.2V) using the Prius battery specifications. In 2004 PEVE supplies Toyota and Honda the only two car manufacturers commercializing hybrid vehicles in the world.
At the end of 2004, Sanyo (Japanese first world manufacturer of portable batteries) will come on the market with the beginning of Ford Escape hybrid commercialization.
Taking into account the planned sales of all the car manufacturers that have products or projects on the hybrid vehicle market for 2005, the HEV NiMH battery market could become the following:

- PEVE: 80% of the global market, about 260 Million $ for approximately 300 000 kWh and 6 500 tons of battery all produced in Japan in a new plant built in 2003.
- Sanyo: 20% of the global market, about 50 Million $ for approximately 50 000 kWh and 1 250 tons of battery.

All the other battery manufacturers able to produce NiMH batteries for automotive applications seem to have withdrawn from this specific competition.

- *Heavy Hybrid or Electric Vehicles*

As previously noticed, Saft and Varta Johnson Controls (Cobasys seems to be very active on the stationary market with for example telecom applications, on the opposite the automotive market seems to be of less activity) have no real opportunity to go into the HEV Market for the following reasons:

- Such Industrial development needs agreements between the Battery Manufacturer and the HEV Manufacturer. Today all the HEV Manufacturers are Japanese (Toyota and Honda) and agreements have been signed with Japanese Battery Manufacturers,
- There is no real HEV Market in Europe,
- After four years of intense R&D works with the corresponding Car Manufacturers (PEVE & Sanyo), the battery performances obtained are higher (in power 1 400W/kg) than these of the other Companies.

Nevertheless in order to develop their knowhow and pilot plants Saft and Varta become very active on several Niche Markets of great future like:

- Hybrid urban and suburban buses in substitute of Lead-Acid with higher performances (about 10 to 20 projects per year in Europe),
- Utility vehicles
- Military Vehicles for special applications.

- *Light Vehicles (e-bikes, scooters and three wheelers)*

As for Ni-Cd batteries these types of vehicle are most often equipped with portable battery types. For e-bikes (important market in Asia) NiMH cells of portable type are always used and the suppliers are nearly the same as for power-tools (see chap. III.4 and III.3). The market trends are the same as power-tools with a progressive decrease of NIMH against Lithium based assuming that NiCd is still the first type used for this market segment.

## 1.2 Lithium based

Unlike NiCd and NiMH batteries, Lithium based ones are today in development technologies. This industrial situation is characterized by the following elements:

- Several types of Lithium based battery technologies are developed depending on the companies involved (Li-Ion, Li-Ion-Polymer, Li-Metal-Polymer etc),
- Three main manufacturing processes are in competition,
- About 20 known Battery Manufacturers are developing an intense R&D activity in this field,
- Many Consortium, joint Venture or round-up of Companies take place in order to increase the R&D financial capacity,
- All the main Companies are at the pilot plant stage with restricted production capacity,
- Some needed performances (essentially related to security) are still unproven,
- As these batteries are now in low volume production, today costs are not significant of what they could be in mass production,
- For power-tools (biggest battery cells) on the portable Market, Lithium based batteries are still at the beginning.

The Map of Lithium based battery suppliers is then based on the following Company characteristics:

- Pilot production capacity of prototypes for automotive applications with known performances,
- Financial capacity in order to provide high level R&D and industrial development,
- Scientific and Technical background in the field of Lithium battery,
- Links with automotive industry for future commercial developments.

| Known Name | Company and subsidiaries | Country | Other names | Products (automotive market) | comments |
|---|---|---|---|---|---|
| Toyota | Toyota Motor Co | HQ, R&D and plants in Japan | | Li-Ion prismatic with LiNiCoAl cathode | First industrial manufacturing plant for Vitz |
| Saft | SAFT | HQ in France<br>R&D France and USA<br>Plants in Europe and USA | | Li-Ion power for hybrid<br>Li-Ion mild for hybrid<br>Li-Ion energy for EV | Plants in pilot stage in USA and France |
| Hitachi Vehicle Energy, Ltd | Joint Venture between:<br>Hitachi Ltd (36.7%)<br>Shin-Kobe Electric Machinery Co. Ltd (43.7%)<br>Hitachi Maxell Ltd (19.6%) | HQ Ibaraki Japan<br>R&D and Plants in Japan (Shin-Kobe) | | Li-Ion batteries for automotive applications<br>Prismatic and cylindrical cells.<br>Cathode $LiMn_2O_4$ based | Start July 2004<br>Agreement with Nissan and Yamaha |
| Panasonic (PEVE)<br>Panasonic EV Energy Co., Ltd. | Subsidiary of Matsushita Electric Industrial Co., Ltd | Japan, HQ in Kosai, Shizuoka | | Li-Ion for EV (other version ?)<br>$LiMn_2O_4$ based | JV between Matsushita and Toyota |
| GS Yuasa Corporation | Joint holding Company between :<br>Japan Storage Battery<br>Yuasa Corporation | HQ, R&D, plants in Japan | GS battery | Li-Ion for EV<br>Li-Ion for HEV<br>Cylindrical and prismatic cells, LiCoNiMn and $LiMn_2O_4$ cathodes | Laminate ? |
| LG (1) | LG Group<br>Subsidiary LG Chem with CPI (100% LG) | HQ, R&D and plants in south Korea<br>Compact Power Inc. in Colorado USA | CPI | Li-Ion-Polymer; cylindrical, prismatic and laminated | For automotive industry specific laminated battery are developed. Consortium (see note 1) |
| NEC Lamilion Energy Co. | Joint Venture between NEC Co. and Fuji Heavy Industry (Subaru) | HQ, R&D and plants in Japan | | Li-Ion-Polymer laminated LiMn204 | Created in 2003 |
| BYD | BYD Company Ltd<br>Subsidiary : BYD Auto Co. (previously Qinchuan automobile company) | HQ, R&D and plants in China | | Lithium based for BEV and HEV<br>Project in BEV development with subsidiary BYD auto (forecast 100 000 bev/year in 2006?) | 2nd world battery manufacturer for portable applications, 1st for NiCd portable batteries |
| Sanyo | Sanyo Electric Co. Ltd | Japan, HQ in Osaka, R&D in Kobe | | Lithium based (projects for auto. appli.) : Li-Ion, Li-Ion-polymer cylindrical, prismatic and laminated | first world battery manufacturer for portable applications (NiMH and Lithium) |
| Valence | Valence Technology Inc. | HQ in Austin, Texas USA, R&D in Nevada, USA, Plants (for portable) in Ireland | | Phosphate based Saphion Li-Ion polymer technology (cylindrical and prismatic).<br>Portable, telecom and automotive applications | 12V battery for automotive applications |

| Known Name | Company and subsidiaries | Country | Other names | Products (automotive market) | comments |
|---|---|---|---|---|---|
| GAIA | GAIA Akkumulatoren GmbH Lithium Technology Co. (merger of the 2 companies in 2002) | LTC in PA, USA.<br>GAIA Germany | | Li-Ion-Polymer with specific production process. Cylindrical and prismatic. Specific 42V and HEV products. | Involved in freedom car program. |
| B&K | Shenzhen B&K Technology Inc. | HQ, R&D and Plants in China | | high performance li-ion batteries, polymer li-ion batteries, and large size batteries for automobile and high power applications. | Li-Ion battery for BEV |
| Samsung SDI (1) | Samsung SDI Co. | HQ, R&D and plants in Korea | | Li-Ion, Li-Ion-polymer, cylindrical, prismatic and laminated. Specific development for HEV | One of the biggest world Company for Lithium portable applications. Consortium (see note 1) |
| SKC (2) | SK Group<br>Subsiadiary SKC Co. (2) | HQ in Korea, R&D and Plants in Korea and New Jersey USA | | Li-Ion-Polymer and laminated. Specific development for BEV and HEV | Consortium (2) |
| Varta AG | Johnson Controls | Plants and R&D in Germany, HQ in USA (Johnson Controls) | | Li-Ion for EV and Hybrids | Results of development on the automotive market are not known. |
| Tianjin Lantian High Tech. Power Sources Joint Stock Co | Tianjin Lantian Power Sources Co. Ltd subsidiary of China Electronics Group Corporation. | Plants, R&D and HQ in China (Tianjin) associated with nat. laboratory: Tianjin Institute of Power Sources (Institute n°18) | | Li-Ion for EV and HEV (other battery products for stat applications) | Two wheelers applications and R&D on BEV with 863 program |
| Wanxiang Power Battery Co. Ltd | Subsidiary of WanXiang Group. Wanxiang Electric Vehicle Center Co. | Plants, R&D and HQ in Hangzhou (China) | | Li-Ion for EV, BEV and heavy vehicles.<br>Li-Ion-polymer with Mn cathode. | Several Electric cars and buses have been developed within the 863 program |
| Aucma New Power Tech. Co Ltd | Subsidiary of Qingdao AUCMA Group. | Plants, R&D and HQ in Qingdao China. | | Li-Ion batteries for EV and HEV (Cobalt based) | Focus on two wheelers applications R&D on BEV with 863 program |
| Xingheng Phylion Battery Co. Ltd. | Subsidiary of the Chinese national Institute of Physics from the Chinese Scientific Academy. | Plants, R&D and HQ in Beijing (China) | | Li-Ion for HEV applications (high power for PAC HEV) | PAC HEV applications within the 863 program with Tongji University |
| Thundersky | Thunder Sky Battery Ltd | HQ, R&D and plants in China | | Solid Sate Cr-F-Li Battery (?) for EV and HEV applications | More than 200 EV equipped. No cooperation with automakers. |

| Known Name | Company and subsidiaries | Country | Other names | Products (automotive market) | comments |
|---|---|---|---|---|---|
| Avestor | Avestor Co.<br>Subsidiary of Hydroquebec and Keer McGee | HQ, R&D and Plants in Quebec, Canada. | | Li-Metal-Polymer (LMP) for stationary applications | Automotive market seems to have been withdrawn for the moment. |
| Batscap | Batscap<br>Subsidiary of Bolloré Technology Group and EDF. | HQ in Paris France, R&D and Plants in Quimper, France. | | Li-Metal-Polymer (LMP) for stationary applications and BEV, HEV | EV project with Matra auto "Blue car" |

Note : *In gray major companies*

*1 : LG Chem, SamsungSDI, Hyundai Motor (Korean automaker), and others have recently built a Korean Consortium in order to develop a specific BEV Li-Ion-Polymer battery of 20 kWh and other Li-Ion-Polymer products for automotive industry.*

*2 : Ssangyong Motor Co. (Korean automaker specialized in SUV and trucks), SKC and Nexcon Technology (electronic company manufacturing different types of BMS and ECU) have recently built an other Korean Consortium in order to develop a specific BEV Li-Ion-Polymer battery of 30 kWh and other Li-Ion-Polymer products for automotive industry.*

## 1.3 Other new technologies

- *Na-NiCl*

| Known Name | Company and subsidiaries | Country | Other names | Products (automotive market) | comments |
|---|---|---|---|---|---|
| ZEBRA | MES-DEA SA | HQ and plant in Switzerland<br>R&D in Switzerland and England | | Na-NiCl batteries for EV | Several EV prototypes in Europe and US |

- *Zn-Air*

| Known Name | Company and subsidiaries | Country | Other names | Products (automotive market) | comments |
|---|---|---|---|---|---|
| Arotech<br>& Electric fuel | Arotech Co. subsidiary<br>Electric Fuel Company | HQ, R&D and plant in USA and Israel | | Zn-Air for EV in fleets. Military applications and heavy vehicles | Fleets experimentations |
| Evionyx | Reveo Inc. subsidiary eVionyx Inc. | HQ and R&D in USA, R&D and plant in Taiwan | | Zn-Air and Zn-Air, Ni-Zn hybrid systems for EV applications (scooters, military vehicles and EV prototypes) | Production of 1000 cells per day |
| Powerzinc | Powerzinc Electric Inc.<br>Subsidiary Powerzinc Electric Shangai | HQ in USA, R&D and Plant in Shangai | | Zn-Air batteries for light vehicles and heavy vehicles in fleets | All automotive applications in China |

- *Ni-Zn*

| Known Name | Company and subsidiaries | Country | Other names | Products (automotive market) | comments |
|---|---|---|---|---|---|
| Evercel | Evercel Inc. and Xiamen Three Circles ERC Battery Co. | HQ in USA, R&D and plant in China | | Ni-Zn batteries for light vehicles applications and golf cart | In very difficult financial condition |
| Evionyx | Reveo Inc. subsidiary eVionyx Inc. | HQ and R&D in USA, R&D and plant in Taiwan | | Zn-Air and Zn-Air, Ni-Zn hybrid systems for EV applications (scooters, military vehicles and EV prototypes) | Production of 1000 cells per day |
| SCPS | SCPS | HQ R&D in France | | New techno. of Ni-Zn for EV applications | R&D stage no production capacity |

For several reasons these batteries are not very often considered by the car makers as potential substitute of the today commercialized technologies. But the technical and industrial development state is very different following the technology chosen depending on the specific technical performances of each type of battery.

- Na-NiCl : this battery (well known under the name ZEBRA) is manufactured by only one Company in the world in Switzerland. The production is of industrial type with a potential production capacity of 110 000 cells/year and a real one of about 30 000 (could be increased to more than 5 million of cells in case of Market demand). Today these batteries are not HEV convenient (low specific power) and only used in BEV applications (light and heavy vehicles). About 2000 20 kWh batteries have been sold during the eight past years for experimentation with passenger cars and buses or utility vehicles in Europe. ZEBRA battery is a “hot” battery (about 300°C) and then not really suitable for private vehicles but only for fleets or utility vehicles (see chap. II.4.e)
- Zn-Air: with an operating principle very different compared with all the others batteries, Zn-Air could be considered as a fuel cell where Zn is the fuel material. Zn-Air is not a rechargeable battery but a refuelable one by changing the Zn electrode. Then this type of system is only usable for fleets or utility vehicles and needs a specific refuel station. For these reasons it cannot considered as a competitor on the Automotive Market but only for some “niche” markets (heavy vehicles, utilities and military vehicles). Three small Companies are manufacturing this type of system with pilot production capacities (and it seems that the Asian Market (Taiwan, China etc) is a better market target than all the others.
- Ni-Zn: eVionyx seems to be the only Company able to develop an industrial production capacity and the Market is very low leading Evercel towards high financial difficulties. SCPS in Europe (France) has developed a new type of Zn electrode and try to manufacture its products. It seems that the only “niche” market is for e-bike or scooters applications in Asian countries.

Redox technologies have not been studied because of a development stage incompatible with a real marketing activity.

# 2. Automotive Industry Markets

## 2.1 Type of vehicles and related markets

*(Sources: OICA, ACEA, ANFAC, CCFA)*

The products of the Automotive Industry are classified in a great number of types and Market segments but in the context of SUBAT study only a few of them are interesting. The essential factor is the power train type and its power; the type of use or type of customer have no importance. In fact, many types (or market segments) are gathered when battery choice criteria are the same.

- Passenger Cars and Light Duty Vehicles (VP or PV and LDV)

  This first type contains all types of passenger cars (compact, midsize, luxury etc) whether they are private or not, and all the light duty vehicles that are using the same power trains (weight < 2.5 t to 3.5 t following the various regulations all over the world).
- Heavy Duty Vehicles (HV or HDV)

  In the SUBAT context, this category contains trucks (>3.5 t), heavy utility vehicles, buses and coaches and military vehicles.
- Light vehicles (LV)

  This type contains all the light vehicles like bikes, all the motorcycles, golf kart and quads and others three or two-wheelers.

The first type described (VP) makes 94% of the world vehicle production number of the first two categories. Taking into account that more than 60 millions of vehicles have been built in 2003, battery choice for these types of vehicles could have a huge importance on the Battery Industry Market

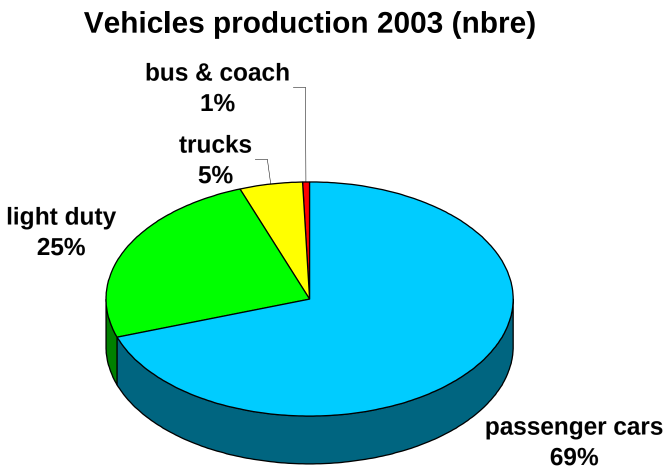


*Figure 2.1-1 Vehicles production 2003 by type of vehicles*

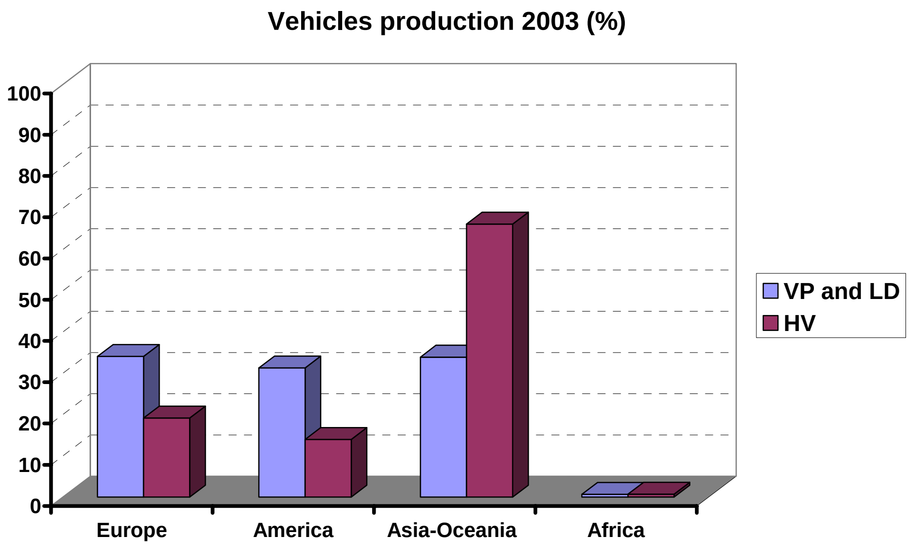


*Figure 2.1-2 Vehicles production 2003 by country*

## 2.2 Today world passenger cars market

*(Sources : PSA, Renault, Valeo, JCI, Audi, Toyota, Honda, GM, Ford, CARB, ADEME, AVERE, JARI, IEA, ANL, EPRI, JAMA)*

The passenger car market represents 73% (or more depending on the category chosen for pick-up and light trucks made in US) of the total VP type. In such conditions and for industrial reasons, the light duty vehicle market follows very often the same characteristics than the previous one.
This market mainly driven by customer expectations and habits is divided in three or four geographical parts depending whether the new Chinese market is considered as a new one or not.

- ***European Market (market size about 17 million units)***

Characterized by small cars, small engines, high price fuel and recent diesel engine development allowing high fuel economy and GHG (GreenHouseGas) emission reduction.

This market is mainly driven by fuel economy and vehicle price that can be summarized by (in term of electric power increase possibility of the vehicle):

- Increasing part of diesel engine (more than 60% of new vehicles sold in 2004 in France),
- Rise of direct injection gasoline engine,
- Downsizing of engine (or power increase for the same size),
- Stop and start function introduction,
- Gear shifting optimization (see also comfort),

In a second level the comfort increase:

- More electronic comfort functions (audio, video, GPS, automation etc)
- For high-end vehicles torque smoothing, automatic gear shifting, e-heating, electric boost etc)

European or countries regulations and directives are also important:

- Euro IV (2008) and Euro V (2010-2012) for local pollution (diesel)
- 2008: 140g of GHG by km commitments, and 2012: 120g/km.

Image is not today a strong driver but has to be clarified:

- Increasing market of SUV and other types of fashion vehicles
- Environmental friendliness

This market is also characterized by very low margin of the car manufacturers (<2,5%).
These characteristics have consequences on European EV and HEV market trends:

- EV could have a “niche” market if price, range and comfort are convenient (see III.4).
- Diesel Engine will continue at high rate but Hybrid version for gasoline will gradually and slowly appear,
- Hybrid version for diesel beginning by soft hybrids will appear too and will be considered as optimal for consumption reduction (Hybrid version for diesel are technically more difficult to design than the equivalent for gasoline engine).

It seems that European Market couldn’t be the leading market for automotive battery in the next future (before 2012) in the SUBAT field of interest, but the first significant soft hybrid market could be in Europe.

- ***US & Canadian Markets (market size about 18 million units)***

Characterized by large cars, large engines, low fuel price and specific local regulations with a great competition between US car manufacturers and Japanese one.
This market is mainly driven by the comfort increase with electric power growth as a consequence:

- Electronic developments (X by wire)
- New electric functions (Electric AC compressor, Electric power steering etc)
- Specific hybrid functions: 110 V for power-tools, creeping, launch assist, torque smoothing etc,

Image is still a strong driver:

- High power
- SUV market strong development, passenger “trucks” etc,
- Environmental friendliness influence is unclear

Influence of regulations are not clear:

- Specific regulations by countries or states,
- Mainly driven by local pollution problems,
- Specific situation of California (CARB, California Air Resource Board, pressure upon low consumption vehicles, 10% of low consumption in 2008)

Fuel Economy is not a real driver for the customer and little diesel engines will be more acceptable but still not to the European level.

This market is also characterized by greater margin of the car manufacturers than the European one.
These characteristics have consequences on North America EV and HEV market trends:

- Gasoline engine will continue to prevail,
- Hybrid version will be gradually introduced, lead by Japanese car Manufacturers but not based on a global fuel consumption decrease purpose (large engine with high power boosted by electric motors, full hybrid type).

- ***Japanese and related Markets (market size about 13 million units)***

Characterized by small engines in midsize cars and strong incentives toward fuel economy and GHG reduction:
This market is mainly driven by fuel economy and increase of comfort but on the contrary of European Market Diesel Engines development will not be the solution:
Fuel economy and GHG emission reduction:

- No diesel
- Hybrid functions introduction (Stop&Go, downsizing of gasoline engine)

More comfort:

- Air conditioning and electronic devices compatibility with stop&go,
- Electronic developments (X by wire)
- New electric functions (Electric AC compressor, Electric power steering etc).

Regulations:

- Strong incentives for consumption reduction and emission reduction as local pollution reduction,

Image:

- Environmental friendliness could help the full hybrid market.

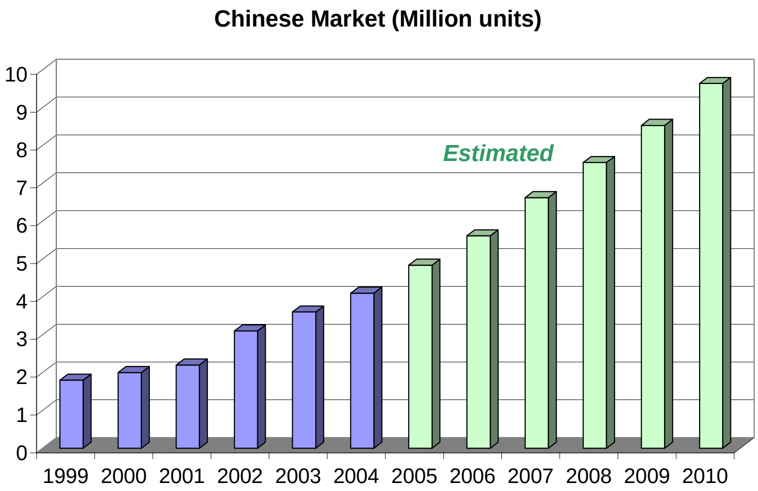
This market is also characterized by low margin of the car manufacturers but a little higher than the European one.

These characteristics have consequences on Japanese EV and HEV market trends:

- Gasoline engine supremacy will drive the hybrid market,
- The Diesel engine success in Europe is still under review, only because mild hybrid diesel is a potential low cost solution,
- Full hybrid market will gradually increase driven by fuel economy and environmental friendliness as Japanese Car Manufacturers are leading.

### - *Chinese Market*

*Figure 2.2-1 Chinese Passenger cars Market*



As the Chinese market is a new one it is not as well known as the others and market forecast is very difficult. From a size of about 4 million vehicles in 2003 with an increasing rate of 8 to 10% per year, it could become the third world market in 2008 with about 10 million vehicles per year. This market is characterized by a very high margin of the car manufacturers (near 20%).
As far as it is possible to have reliable information's concerning the Chinese market trends, it will be mainly driven by fuel consumption reduction and related regulations, it is also possible that local pollution in the large cities becomes an important factor.

As China import today more than 50% of its oil consumption and assuming that these oil importations have increased of more than 40% in 2003, it becomes of strategic importance to monitor the fuel consumption for the Chinese authorities. In such condition regulations and incentives could become the main driven factor toward a substantial increase of “clean vehicle” market, and then a global growth of the automotive battery market.

## 2.3 Today world other vehicles markets

- *Heavy vehicles*

There are three main categories of heavy vehicles in the SUBAT field of interest (with electric traction batteries):

- Buses and coaches: Electric and Hybrid urban and suburban busses and coaches,
- Hybrid or Electric Utility Vehicles
- Military Vehicles for special applications.

For all these types of vehicle a global world study of the market is not convenient. As the Vehicle Manufacturers and the markets are much smaller, the development and commercialization of heavy vehicles generally occurred taking the opportunity of specific projects.

The military vehicles market (at prototype stage today) is very different of all the others because of the very high cost of each vehicle and then the relative low price of the batteries even of advanced technology.

- *Light vehicles*

This type of vehicles is made of two main categories where battery common choice is different.

- E-bikes where batteries are coming from portable production (power-tools cells) except for a part of Chinese Market where Lead-Acid has been used for years but decrease rapidly,
- Scooters and non road vehicles like golf karts where most often Lead-Acid batteries are used.

E-bike market is a very important market only in Asian countries except in Italy where more than 140 000 e-bikes have been sold the past few years. As the manufacturers are very numerous and often very small companies located in China, Japan, Taiwan etc, it becomes very difficult to describe the market and to gather reliable data concerning the production volume. Taking into account the number of cells sold for this type of applications and assuming that part of the market (the Chinese one) is equipped with lead-acid batteries, it seems that more than 15 millions of e-bikes are sold per year in 2003.

Electric scooter market is not very developed today (more in Asian countries than in Europe and negligible in US) but an increase could appear with the use and cost decrease of new battery technologies like Li-Ion in the next few years.

Non-road vehicles like golf karts are part of well known market including little handling vehicles, airport vehicles etc. Only low price Lead-Acid batteries are used for this type of vehicles and the influence of this market on the new battery technologies market seems to be negligible.

# 3. Electric and Hybrid Vehicles definition and related battery Characteristics

Since 1997 and the first coming onto the market of commercial hybrid vehicle (Prius I by Toyota), Electric and Hybrid Electric Vehicles definition and properties are various. As the related battery characteristics and technologies are different whether the electric motor power is high or not, it becomes necessary to describe all types of vehicles.

A classification can be made following the electric motor power and the battery corresponding energy need. All these new electrical technologies are introduced in order to reduce the fuel consumption and $CO_2$ emission while still improving drive-ability and comfort.

- Hybrid Electric Vehicles (HEV)

They can be classified in 5 main categories according to the new electric functions available compared to a conventional ICE vehicle:

- **Category 1** often called micro-hybrid or µ-hybrid. This category can also be considered as a conventional ICE vehicle with an electric option (Japanese Manufacturers point of view). The new electrical function is called stop&start, the ICE stop when the vehicle stops and starts automatically when the driver accelerates. Only a reversible starter alternator is necessary with a power of about 2 kW. The corresponding battery energy need is of about 500 Wh and in most cases (according to comfort improvement options) the battery voltage is 14 V. In this case traditional Lead-Acid batteries are always chosen today for cost reason but when the electricity consumption increase (in urban area for example) appears some problems of reliability (decreasing reliability of Lead-Acid with deep cycles). This function leads to a fuel economy of about 8 % on an urban cycle and 0 % on a highway cycle.
- **Category 2** often called soft hybrid. Stop&Start function becomes Stop&Go with the possibility of electrical launch assistance. In same case regenerative braking can be used following the specific power of the battery pack used. The electric motor power is about of 4 to 5 kW and the corresponding battery energy need of 500 Wh (battery specific power must be high in case of regenerative braking). The battery voltage is 14 V or 42 V according to comfort options and motor power. Lead-Acid batteries are most often used, but according to the battery cost and performances new technologies like NiMH or Li-Ion begin to be used. This category leads to a fuel economy of about 15 % on urban cycle and 2 to 8 % (in case of regenerative braking or not).
- **Category 3** often called mild hybrid. Several new electric functions can be developed in this category but they can be summarized by “electric power assist”:
  - Stop and Go (launch assist)
  - Regenerative braking
  - Automated manual gear box control
  - ICE optimizing
  - Torque assistance or torque assistance with ICE downsizing.

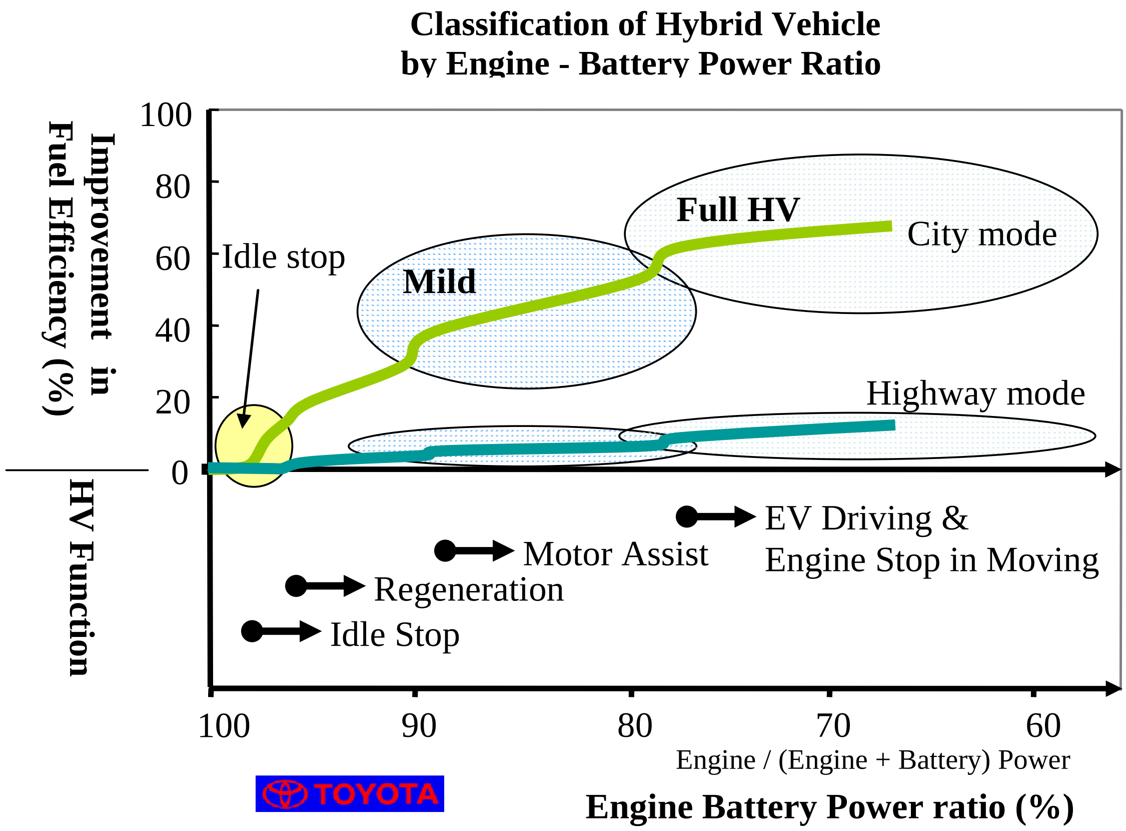


*Figure 3-1 Classification of Hybrids Vehicles by Toyota*

The electric motor power is a function of the options chosen but most often between 10 to 20 kW and the corresponding battery energy need is about 800 Wh. In this case the specific power of the battery technology is the most important factor. The battery voltage is sometimes of 42 V for the lower motor power choice and most often high voltage (> 100 V). For 42 V battery pack the battery technology choice can be Advanced Lead-Acid or NiMH following the type of hybrid functions and the Industrial agreements between car manufacturer and battery supplier. For High voltage battery pack the choice is NiMH today nearly for all car manufacturers.

Fuel economy is strongly related with the hybrid function chosen but a mean value of 28 % during city driving and 6 to 8 % on highway can be given.

- **Category 4** called Full Hybrid or Strong Hybrid. It's a mild hybrid where the electric motor can drive the vehicle by itself but with a low battery energy leading to a low range of 1 to 2 km in ZEV mode (ZEV= Zero Emission Vehicle= electric drive without ICE started). The electric motor power increases to about 50 kW (function of car weight) and the battery energy is between 1.5 to 2.5 kWh. In this case as for mild hybrid a high battery power is more important than the energy value. The battery voltage is always high and very often over 200 V. Today the battery type choice is NiMH for all car manufacturers. This type of hybrid leads to a fuel economy of about 35 to 40 % on a city cycle and about 10% on highway.
- **Category 5** called Dual Mode or Full Hybrid with ZEV. It's a full hybrid with an increasing ability to drive the vehicle in all electric mode (more than 5 km and reaching the range of a pure BEV of about 100 km). To types of dual mode can be built :
  - Non plug-in hybrid, where the batteries are charged only by the ICE of the vehicle,
  - Plug-in hybrid where the batteries can be charged on a plug.

As for full hybrid the electric motor power is about 50 kW but the battery energy increases to values between 5 kWh to 15 kWh following the ZEV range. The battery is always of high voltage. As no industrial Dual Mode hybrid have been built and sold today by any car manufacturer in the world, there is no major battery choice. The battery performances needed are near those for a pure BEV or a serial hybrid and the battery choice will be similar.

The fuel economy can't be evaluated compared with a classical ICE vehicle consumption

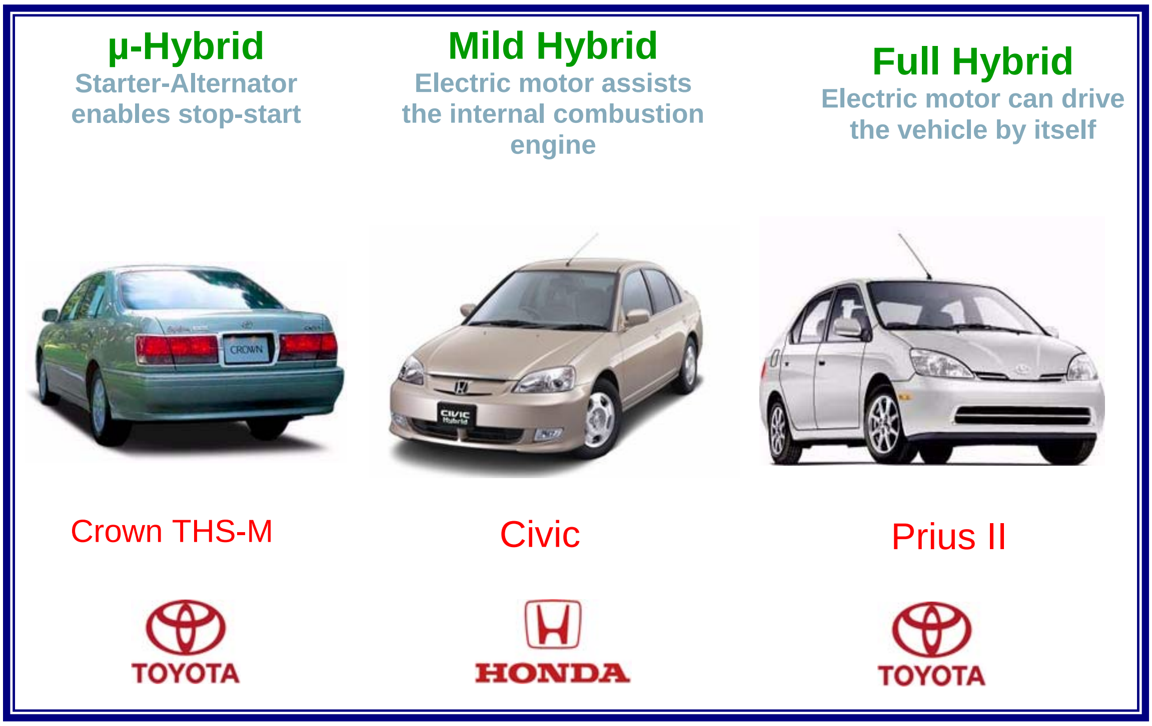


*Figure 3-2 Example of three different types of Hybrid Vehicles*

All these types of hybrids can be used either for passenger vehicles (VP type) or heavy vehicles, but these power train configurations are not very convenient for light vehicles.

- Battery Electric Vehicle and Serial Hybrids

These types of vehicles are always electric driving (ZEV mode) but a ICE can be added in order to increase the range.
The main characteristics are:

- **Battery Electric Vehicle (BEV),** for VP the electric motor power is about 40 to more than 60 kW following the vehicle weight (can be more than 100 kW for heavy vehicles and less than 800 W for light one) and the corresponding battery energy is between 12 to 30 kWh following the battery technology used and the range needed. In this case the specific energy of the battery technology becomes the most important factor. As the battery weight can’t increase over about 15 to 20 % of the total vehicle weight the range obtained is a function of the battery specific energy. Today advanced Lead-Acid, NiCd and NiMH have been used (Li-Ion and Na-NiCl for some prototypes) but the corresponding market remains small because of too low specific energy. New technologies like Lithium based are not ready for industrial stage and price is still too high (see chapter III-5 & 6).
- **Serial Hybrids,** used since many years in the railway industry this type of vehicle is a BEV where an ICE and an electric generator have been added. This category is very often called BEV with range extender for passenger cars. The engine is often of 2 to 3 kW and the increased range is of about 50 %. In some case (often for heavy vehicles) the Internal Combustion Engine is of higher power and the range can be doubled. The battery choices are the same than for BEV but often the corresponding battery weight (and energy) is a little lower.

# 4. Today BEV and HEV markets

*(sources: AVERE, JARI, ADEME, IEA, Audi, Toyota, Honda)*

## 4.1 Battery Electric Vehicles Market

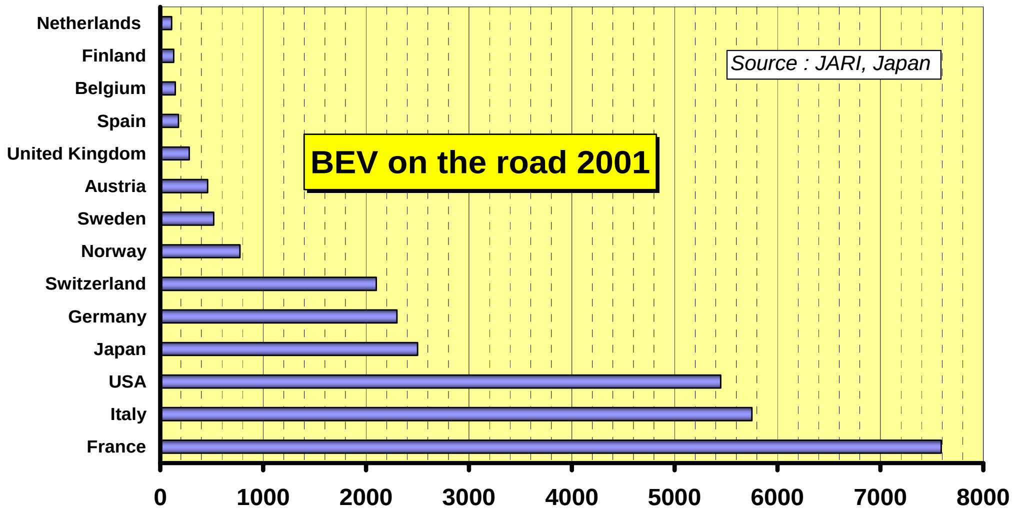


*Figure 4.1-1 Battery Electric Vehicle on the road in the world in 2001*

- **Passenger cars and light duty vehicles**

As shown on the previous diagram describing the Electric Vehicle world market for passenger cars in 2001 and the past ten years history of sales in France the EV market has not increased in volume as it was expected in 1992.
It can't be considered by a car manufacturer as a real existing market.
About 70 % of these Electric Vehicles are today equipped with Ni-Cd batteries, all in Europe. In USA and Japan advanced lead-Acid and NiMH (energy type) have been used following the design period (before 1998, a large majority of US BEV were equipped with advanced Lead-Acid) and only prototypes have been built using new technologies (like Li-Ion and Na-NiCl) of battery.

*(Sources: ADEME)*

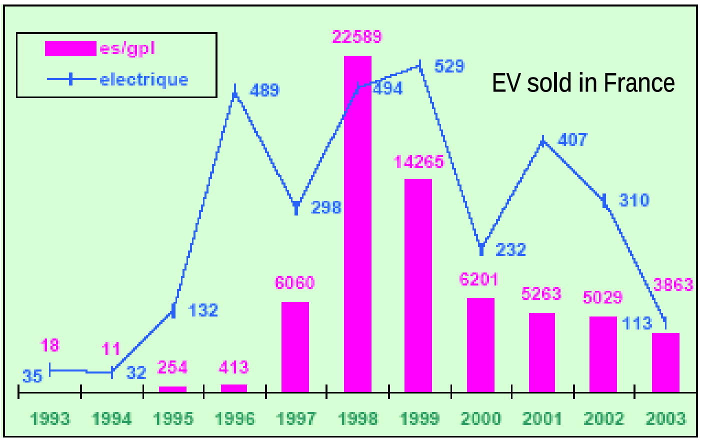


*Figure 4.1-2 Battery Electric Vehicles sold in France*

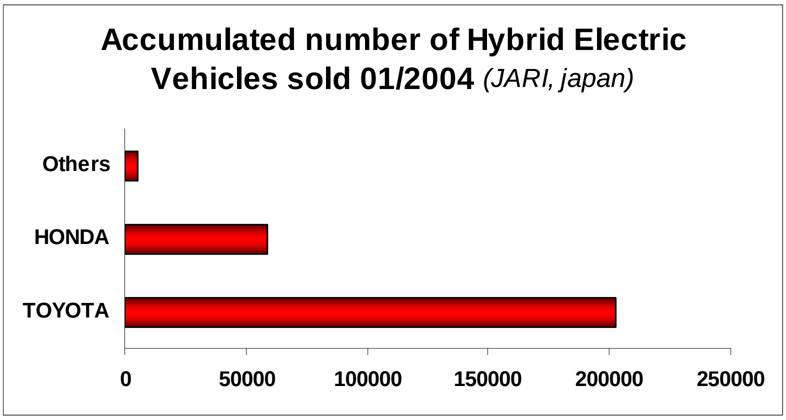
In 2003 (and beginning of 2004) sales have dramatically decrease in Europe and it seems that they will be less than 50 VP for 2004 in France . At the same time potential customers (fleets operators) have more and more difficulties to purchase any Electric Vehicle from any European Automaker (like PSA and Renault).

This unfortunate situation is the consequence of several factors:

- The potential market is too small for such companies the production capacity is now very small and the commercial action very poor (low margin),
- The Electric Vehicles sold are only light duty vehicle types for fleets operators
- The phase out of Ni-Cd battery (European ELV Directive) is considered by many operators and car manufacturers as the end of this EV generation.

Some new projects seem to appear (in Europe and Asia) based on new technologies for power train and batteries but the possible emergence of this new generation depends on the price and maturity of these new technologies.

## 4.2 Hybrid Electric Vehicles Market

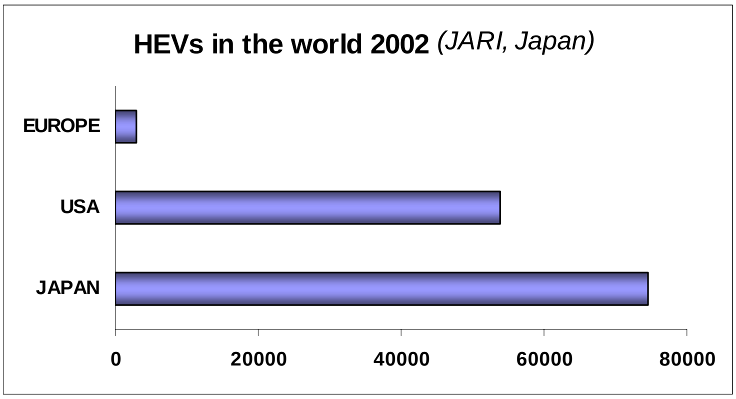


In USA and Japan the BEV market has never really started because of the lack (and type) of customer demand and with the recent hybrid market growth the probability of an increasing market is very low. As neighbourhood electric vehicles (non-road vehicles like golf karts, NEV) are classified in light duty or passenger vehicles in the US, it becomes very difficult to estimate the real number of EV. It seems that over 18 564 EV in 2002, more than 12 000 were NEV. Nearly all these little vehicles are equipped with Lead-Acid batteries.

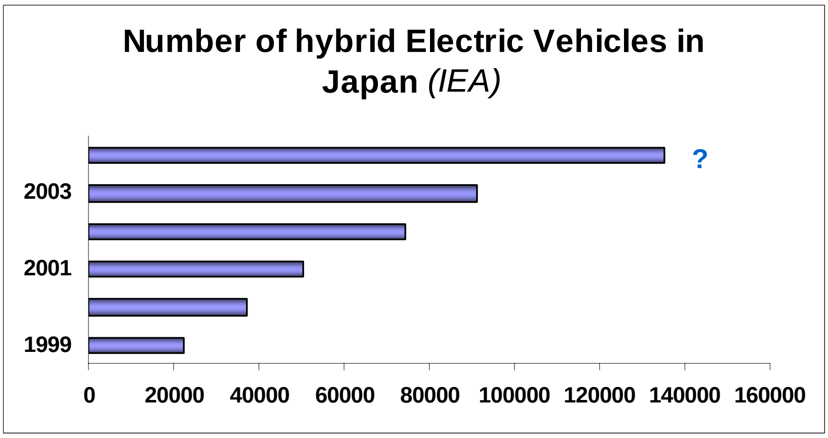
On the opposite the Hybrid Electric Vehicle market started in 1997 with the first Prius of Toyota and seems to grow regularly as shown in the next diagrams.

As shown previously in this report, SUBAT is concerned by Hybrids with electric traction ability (often called full hybrids). This type of hybrid is today the only one on the market but it will change during 2004. HEV today market is characterised by the following points:

- All commercial vehicles are coming from Japanese Car Manufacturers with a leading one :Toyota,
- The market is very different between Europe, North America and Japan, related with the characteristics of the ICE markets for each area
- All these vehicles are equipped with NiMH batteries because of the technical performances (power density) of this technology, the reduced size of the battery pack compared to the one used in a BEV (cost), and the technology maturity,
- Several new HEV from other Car Manufacturers will appear in 2004 and 2005 (from US and Japanese Manufacturers, more than 14 known projects),
- The European Industry is not really involved in full Hybrid developments (clean diesel strategy),
- Sales of the new Toyota Prius II and Honda IMA for beginning of 2004 exceed all the expectations in Japan and USA (see diagram) and more than 250 000 hybrid vehicles sales are planed for 2005,
- US Car Manufacturers sales forecast are very optimistic on SUV market for 2005,
- Japanese Car Manufacturers anticipate a world market of several millions of vehicles in 2012

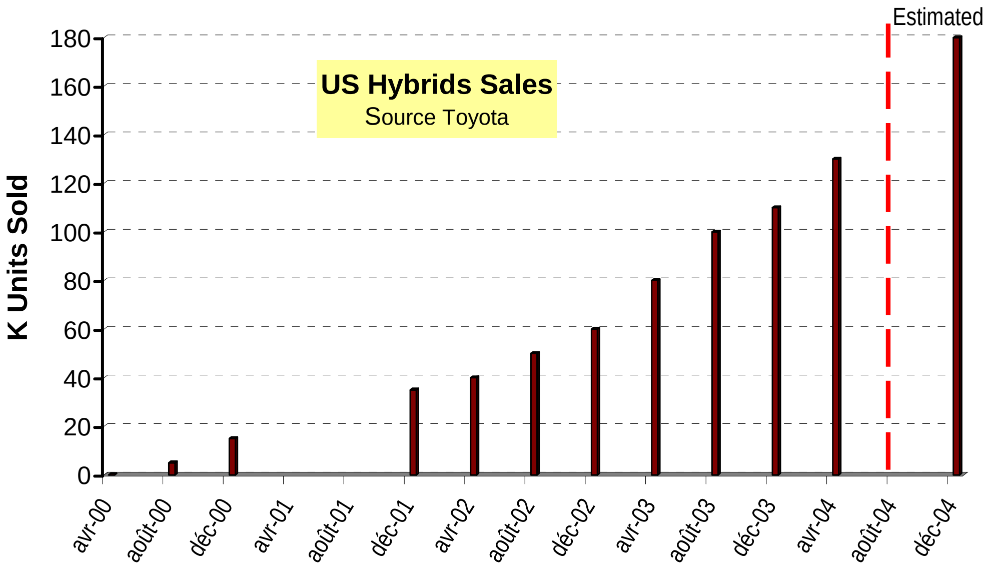


**HEVs in the world 2002** *(JARI, Japan)*



**Number of hybrid Electric Vehicles in Japan** *(IEA)*

All these points are showing that new technologies of batteries development will first depend on this particular market. A detailed study of the development hypothesis becomes necessary and will be made in the next chapters.



### 4.3 Heavy vehicles

Many projects of electric buses and coaches and utility vehicles have been developed in Europe, USA and Japan since 1992. In 2002 there were more than 1 100 electric heavy duty vehicles in USA and about the same number for Europe and Japan.
Most of these vehicles are Lead-Acid batteries equipped for two main reasons:

- The battery pack size and weight are much larger than for a passenger car and the battery cost becomes often too high with other technologies,
- The vehicle weight is much higher and the battery specific energy can become of less importance than for VP's.

But since the end of the 90's in order to obtain higher range, specific EV NiCd batteries from Saft have been used in Europe.

### 4.4 Light vehicles

It seems that the Chinese Market (larger one) exceed 5 millions of e-bike per year (or more?) and increases quickly since three or four years. Prices are very low (under 300 € per bike) and low price Lead-Acid batteries are still very often used (about 50%) despite their low specific energy very penalizing for such light vehicles. Since the beginning of the great development of Chinese portable battery industry in 1995, the use of NiCd and NiMH portable cells increases rapidly. These batteries are the most often used in other Asian countries and the increase of e-bike market lead to a 6% market in volume of the whole NiCd portable market (about 60 million $ market). Since one or two years portable Li-Ion cells are appearing as for power-tools and future developments seem to be very important (see chapter 7).

## 5. Battery choice: Today Car Manufacturers point of view

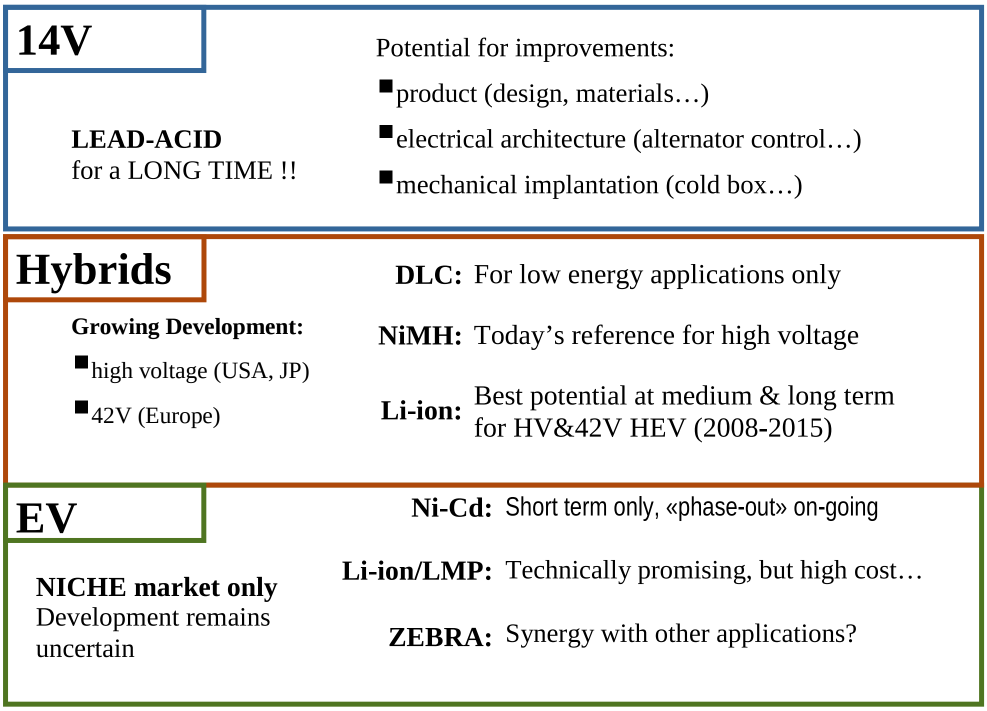
*(Based on PSA, Renault, GM, Toyota, Honda, Nissan, Ford, Audi, Valeo, Delphi, JCI, Hyundai point of view)*

The Car Manufacturers point of view concerning the battery type choice for a given hybrid or electric vehicle can be summarized by the two following diagrams drawn up by the Renault specialists. This point of view was previously very different whether the Companies were from USA, Europe or Japan, but after several years of battery and vehicle development the differences remaining are small.

For BEV all car manufacturers agree that the most promising technology is lithium based battery. But improvements are needed before any vehicle industrial developments like:

- Cost reduction to a reasonable level,
- Security improvements (abuse tolerance tests).

Part of these R&D activities will be developed for HEV but the high power Lithium based battery version is not exactly comparable to the energy version one (see Li-Ion chapter). A great majority of car manufacturers and battery specialists are expecting a competitive Lithium battery between 2007 and 2010. Na-NiCl battery technology is also of some interest but the use is restricted to fleets because of its high operating temperature.



**14V**

**LEAD-ACID**
for a LONG TIME !!

Potential for improvements:

- product (design, materials…)
- electrical architecture (alternator control…)
- mechanical implantation (cold box…)

**Hybrids**

**Growing Development:**

- high voltage (USA, JP)
- 42V (Europe)

**DLC:** For low energy applications only

**NiMH:** Today's reference for high voltage

**Li-ion:** Best potential at medium & long term for HV&42V HEV (2008-2015)

**EV**

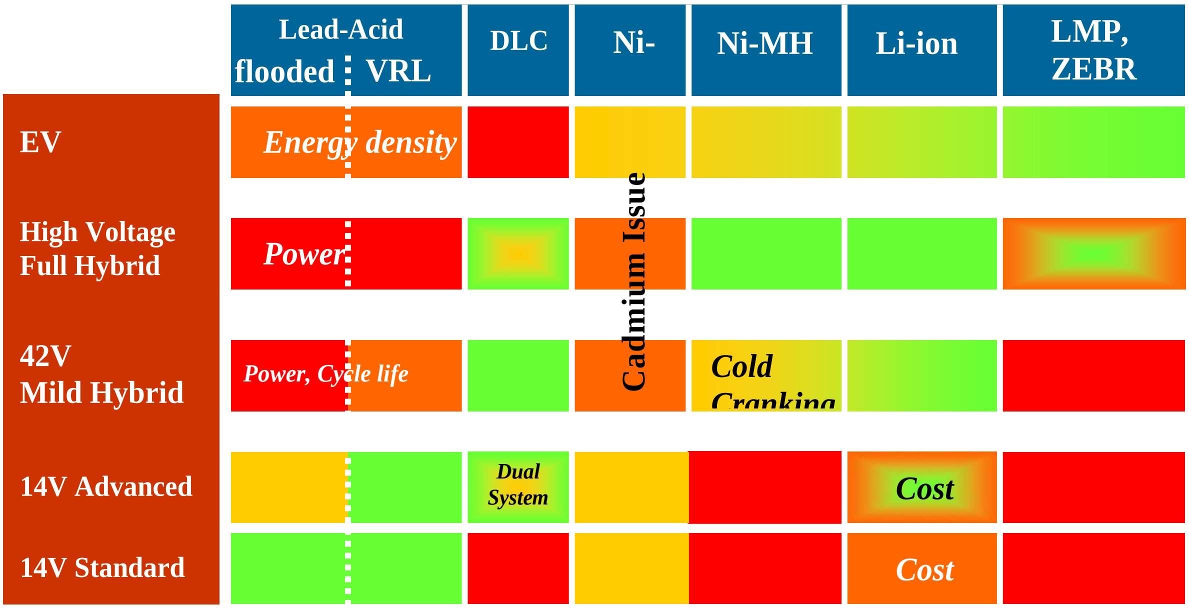
**NICHE market only**
Development remains uncertain

**Ni-Cd:** Short term only, «phase-out» on-going

**Li-ion/LMP:** Technically promising, but high cost…

**ZEBRA:** Synergy with other applications?

## Technologies vs Applications (Renault point of view)



|  | Lead-Acid flooded | Lead-Acid VRL | DLC | Ni- | Ni-MH | Li-ion | LMP, ZEBR |
|---|---|---|---|---|---|---|---|
| **EV** | 🟧 *Energy density* | 🟧 | 🟥 | 🟨 | 🟨 | 🟨🟩 | 🟩 |
| **High Voltage Full Hybrid** | 🟥 *Power* | 🟥 | 🟩🟨 | 🟧 Cadmium Issue | 🟩 | 🟩 | 🟧🟩 |
| **42V Mild Hybrid** | 🟥 *Power, Cycle life* | 🟧 | 🟩 | 🟧 | 🟨 *Cold Cranking* | 🟩 | 🟥 |
| **14V Advanced** | 🟨 | 🟩 | 🟩 *Dual System* | 🟨 | 🟥 | 🟧🟩 *Cost* | 🟥 |
| **14V Standard** | 🟩 | 🟩 | 🟥 | 🟨 | 🟥 | 🟧 *Cost* | 🟥 |

NiMH batteries have been used for EV in USA and Japan but the forecast of this technology (only for BEV) seems to be poor and nobody works any more on the energy version for future BEV developments. The increase of specific energy between Lead-Acid and NiMH is not sufficient compared to the increase of price. Despite the phasing-out of European specific EV Ni-Cd technology, these batteries are the only solution for short term BEV development (Lead-Acid can also be used but with a lower specific energy).

As the hybrid market is growing quickly all the Car Manufacturers are paying attention to the battery performances progress and Market development. The today battery choice is a function of hybrid type and local car market trends.

Nearly all Companies agree with Renault for micro and soft hybrids (14 V battery) with a leading position of Lead-Acid (advanced or not following the number of “electric” options) mainly for cost reason. Some recent projects (Saft, Toyota, Cobasys etc) are looking for new solutions with NiMH or Li-Ion 14 V batteries. These projects are mainly developed for future taking into account the poor cycle life properties of Lead-Acid (Life Cycle Cost) and the hypothesis of a phasing out of lead for environmental impact reason (see Getting the Lead out report, Clean car Campaign, USA, 2003).

Point of views are more complicated for mild hybrid batteries following the fact that this specific market seems to have very different trends in Asia and USA than in Europe. Many specialists are thinking that mild hybrid (42 V) have short term forecast only in Europe. Advanced Lead-Acid seems to be the best candidate (cost) but its low specific power and cycle life in such operating conditions seem to be a problem for the battery manufacturers. Further R&D activities have to be developed by the Lead-Acid specialists.

US Manufacturers are also advanced Lead-Acid supporter for 42 V mild hybrids. But the Japanese Manufacturers have a more mixed position with a frequent use of NiMH battery (pack made very often with portable cells) despite the quick decrease of NiMH properties at low temperature.

All Manufacturers agree that for this type of hybrids as for BEV Li-Ion technology is probably the best choice for mid and long term (decreasing price).

For all high voltage batteries hybrids (mild or full) NiMH is still the best choice for some years (and perhaps more). PEVE and Sanyo are highly leading on this market (see map of battery suppliers) but further developments can be expected from other battery Manufacturers.

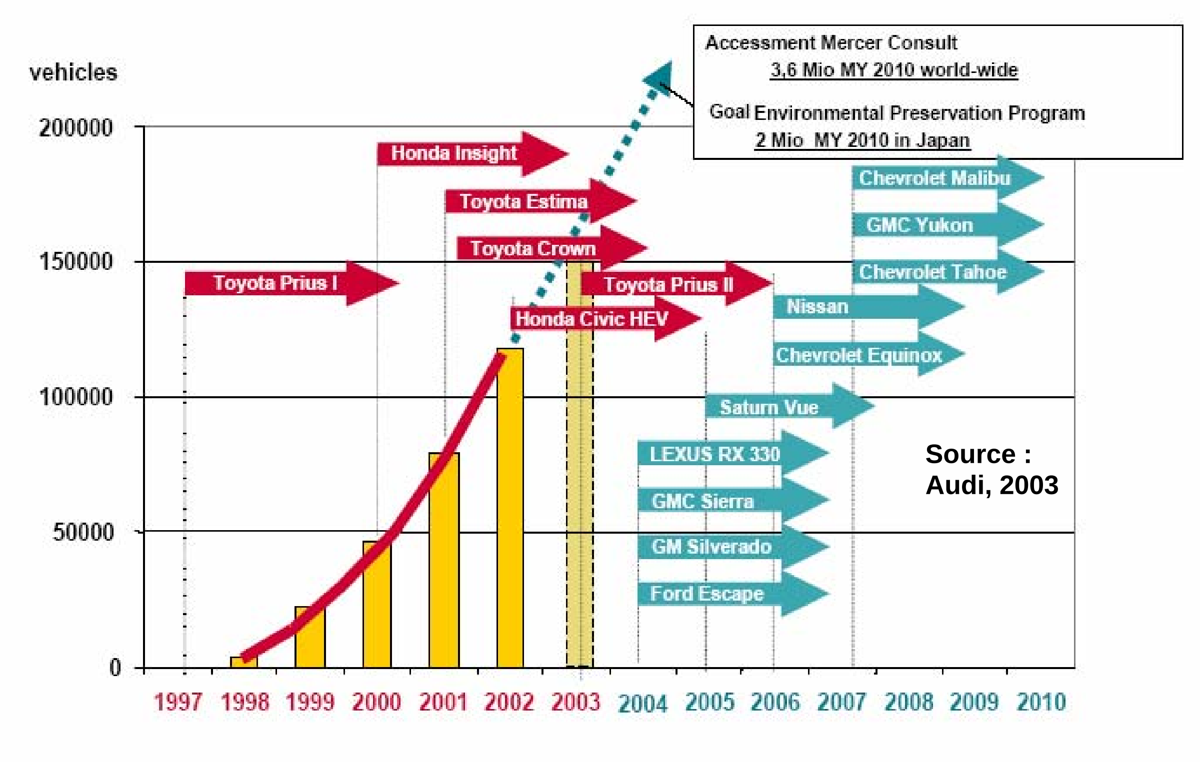
For dual mode hybrids (plug in or not) the today situation is the same as for BEV and serial hybrids, except for dual mode hybrids with small battery packs where NiMH can be used. As today no dual mode hybrids are planed to be built (and have been built already) car Manufacturers choice are not well known (or not really made).

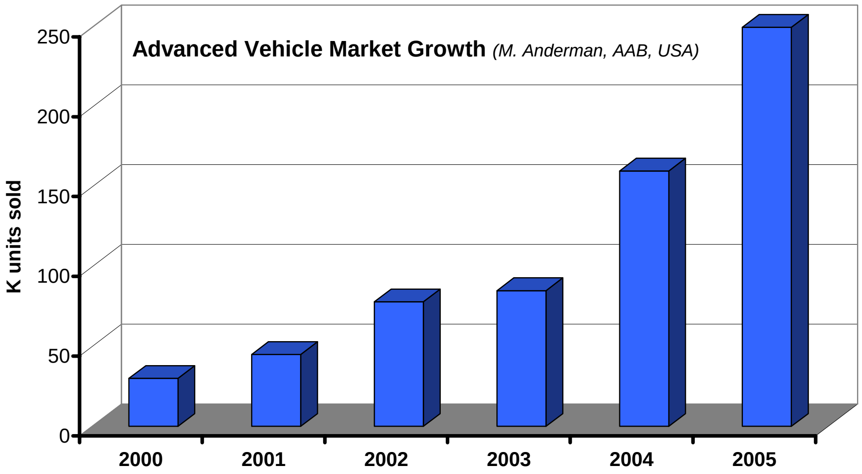
# 6. Battery Market as a result of BEV and HEV market trends

As far as in SUBAT study only the Battery Market for automotive application is concerned (traction batteries), the future battery market trends are closely related with the forecast of HEV and BEV markets (VP market).
Many studies have been made by Car Manufacturers and other specialists since 2002 concerning these markets but the results are not always comparable because the types of vehicle considered are not identical. For some studies µ-hybrids (and sometimes soft hybrids) are considered as ICE vehicles with electric options and not included in the hybrid types (or advanced vehicles) for others all types are considered. BEV vehicles market trends are so that even if it's difficult to know if they are considered or not the results are not affected.

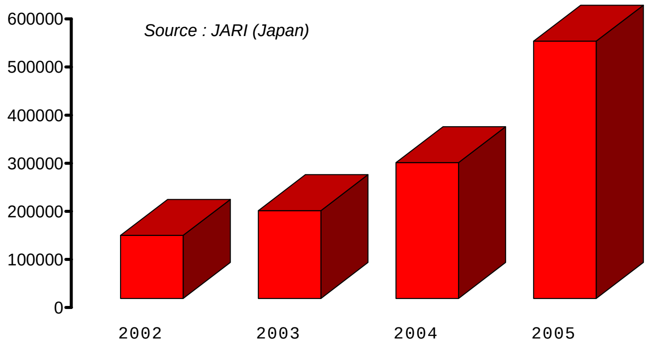
## 6.1 Short term results (2004 & 2005)

*(Sources : M. Anderman USA, Audi (Mercer consult study in 2003) Europe and USA, JARI Japan and data coming from Toyota, Honda, Nissan, Ford, GM and PSA).*



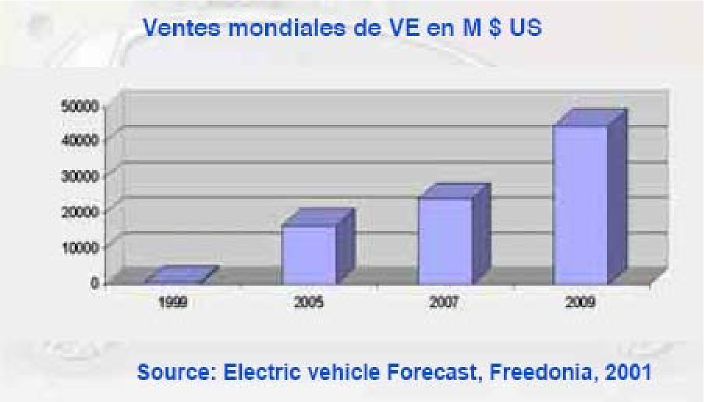


**HEVs in the world (trends)**



If all data known are taken into account as new vehicles commercialization, production capacities planned by every Car Manufacturers, 2004 first half sales data and the results of previous studies, the following conclusions can be highlighted:

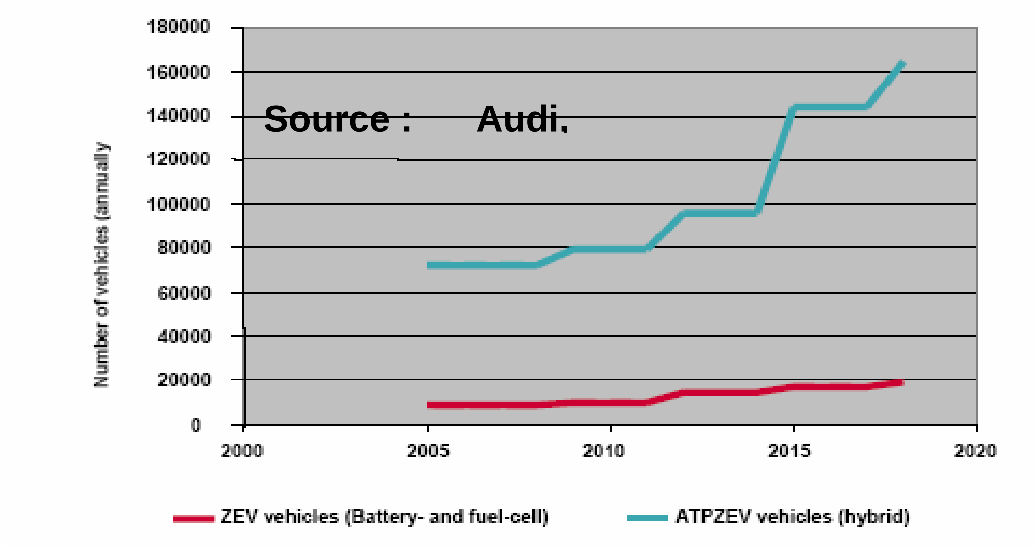
- About 210 000 hybrid vehicles will be commercialized in 2005, less than 35 000 in Europe (90% of µ-hybrid or soft hybrid), more than 100 000 in USA (full hybrid and mild hybrid) and about 80 000 in Japan if the Car Manufacturers expectations are used.
- These expectation values are closed to the recent study results: Anderman 240 000 units/year in 2005, JARI about 210 000 units/year, the older studies were more optimistic as Mercer Consult (300 000) but if the schedule of vehicles commercialization is studied, it's only a one year too early estimation.
- About 180 000 of these hybrids are NiMH batteries equipped (major part by PEVE, the other by Sanyo)
- All the European hybrids are Lead-Acid or Advanced Lead-Acid batteries equipped
- Part of the full hybrids are SUV types (about 50 000) and the Car Manufacturers strategy has changed for the US market from "ecological vehicles" hybrids are becoming "turbo charger" (increase of power, ICE downsizing),
- More than 80% of planned vehicles are coming from Japanese Manufacturers, but the µ-hybrid and soft hybrid production will be mainly from European Manufacturers.



Ventes mondiales de VE en M $ US

Source: Electric vehicle Forecast, Freedonia, 2001

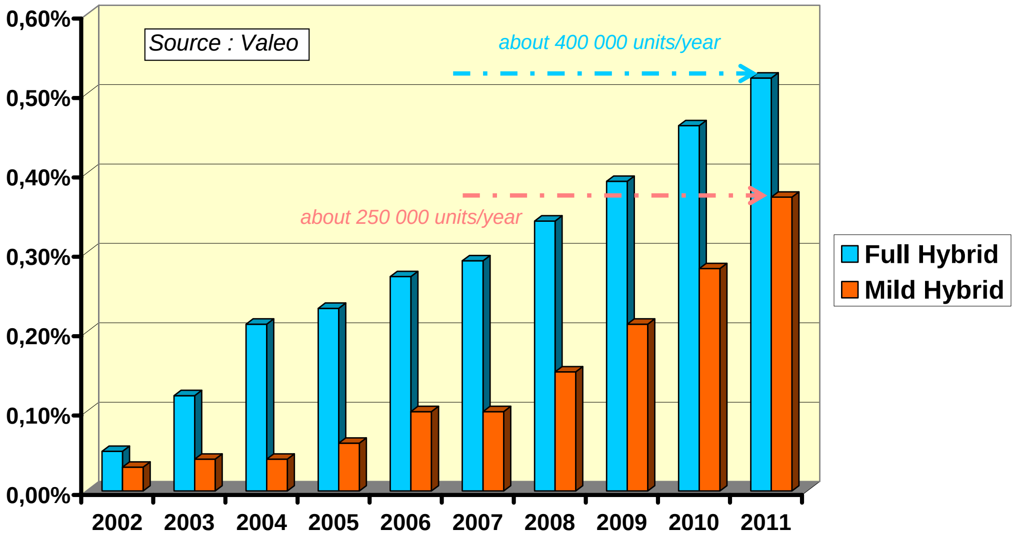
BEV Market trends are not very optimistic and much lower than the results of 2001 to 2002 studies. From a forecast of about 100 000 units/year in 2001 it seems that no significant new production will appears in Europe, USA and Japan in 2004 and 2005. But new projects are in development (for the years after 2006 to 2010) based on new battery technology use (Lithium and Na-NiCl) in China, Japan and in Europe. These projects are waiting for price decrease of the new batteries anticipated from the HEV market growth.



Source : Audi.

The main projects are coming from China with a goal of more than 200 000 vehicles per year in 2006-2007 (Lithium based batteries), but these projects could be delated.

**Hybrid Architectures penetration (% of world market in volume)**



## 6.2 Long term results (2012)

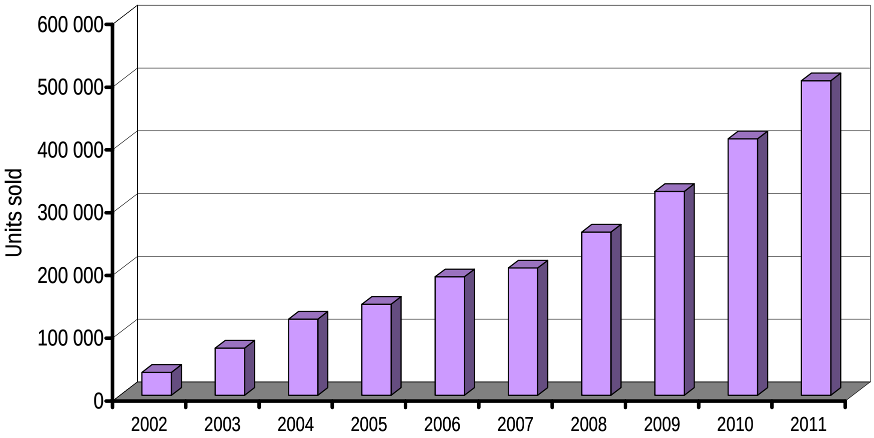
Results of the different studies have to be compared taking into account the date of the study, the type of vehicle and the countries concerned. It’s also important to take notice of the known goals of some local or national authorities in term of “clean vehicles”.

Million units

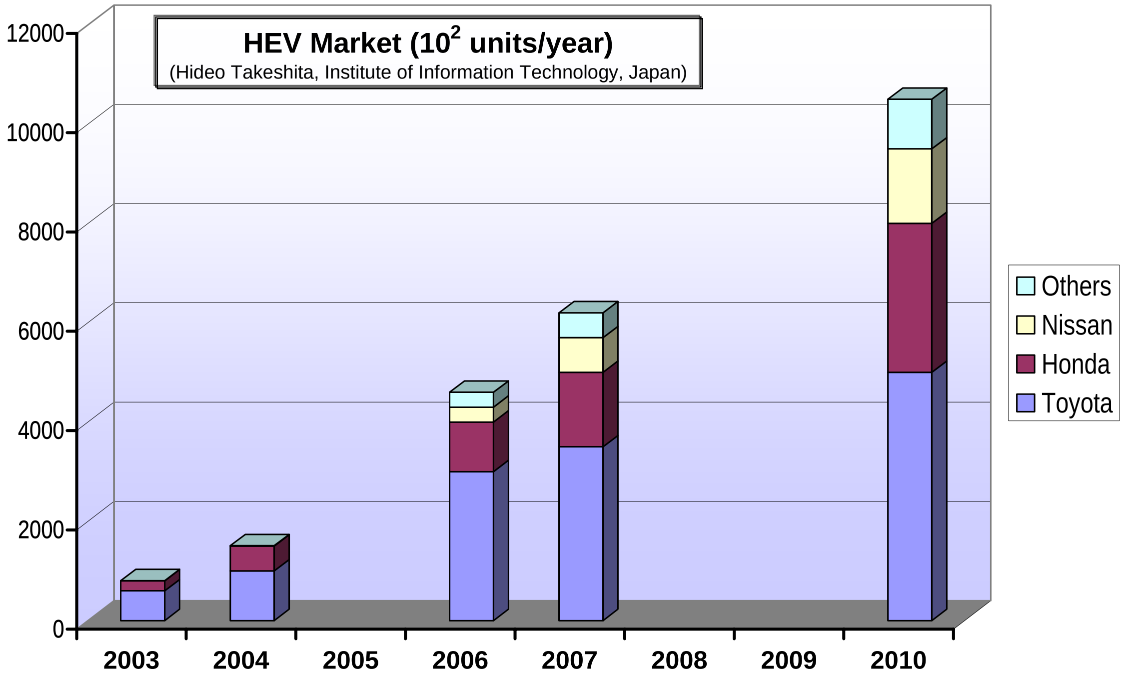
| study | Country of Author | date | Full &mild HEV | µ-soft HEV | BEV | comments |
|---|---|---|---|---|---|---|
| Valeo | France | 2004 | 0.4 | 0.25 | ? | (original source not known) |
| Audi | Germany | 2002 | 0,08 | ? | 0.01 | (information source but not the study author) |
| Mercer | USA | 2001 | 2 | 1.6 | ? | |
| Takeshita | Japan | 2004 | 1.05 | ? | 0.1 | (HEV global) |
| Freedonia | USA | 2001 | ? | ? | 0.36 | |
| VES MTP | USA | 2003 | 0.4 | ? | ? | |
| Chinese goals | China | 2003 | ? | ? | 0.5 | (estimated) |
| CARB goals | USA | 2004 | 1.2 | ? | 0.1 | |
| Japanese environmental program | Japan | 2003 | 2 | ? | 0.1 | (HEV global) |

**Advanced Vehicle Market forecast**

Source : VES MTP Oct. 10th, 2003

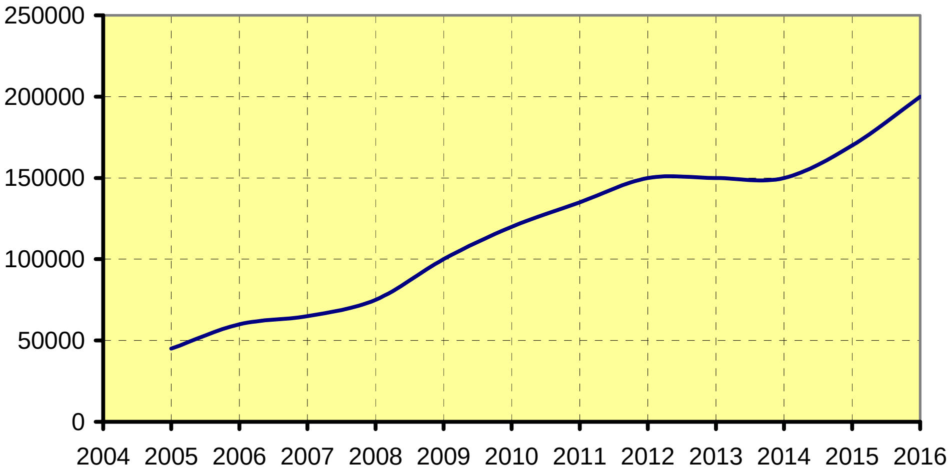


All the studies made before 2003 (except Mercer very optimistic study of 2001 where a quick increase of 42 V vehicle market was planned) are showing results under 0.4 million of HEV all types. As the Japanese and US Markets have increased much higher than these results (0.21 million in 2005 i.e. more than twice the forecast value) it seems that the more recent studies results are nearer of what can really happen.
In this case the Takeshita forecasts seem to be the best (these values have been estimated after meetings with all Japanese Cars Manufacturers).


**HEV Market ($10^2$ units/year)**

(Hideo Takeshita, Institute of Information Technology, Japan)

**Plugin HEV in USA (CARB expectation)**
**with annual sales of all HEV : 1,8 million in 2015**

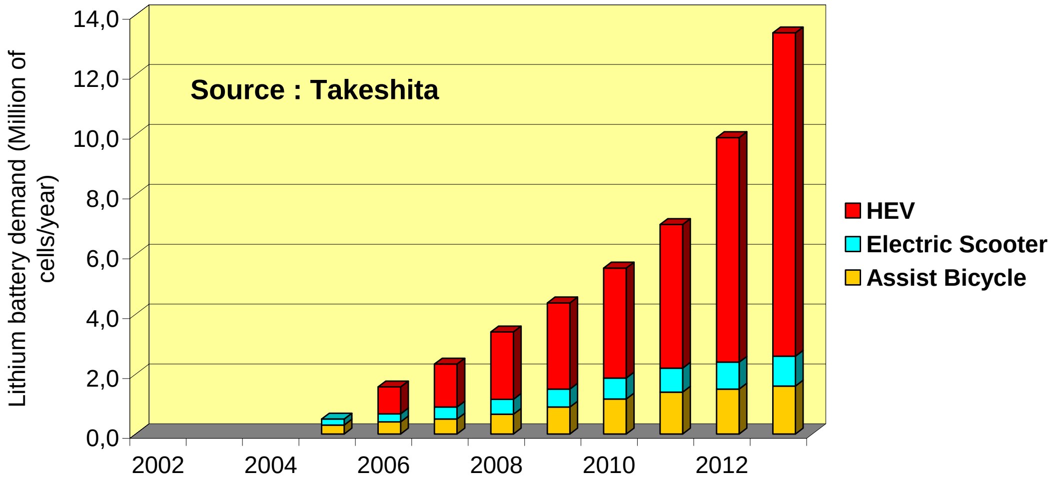


CARB goals (California Air Resource Board) are consistent with Takeshita values but as shown on the previous diagram, CARB expects a dual mode hybrid growth (called plug in HEV or PHEV) to 200 000 units/year, hypothesis not taken into account in the Japanese studies.

In term of battery market the consequences are based on several points:

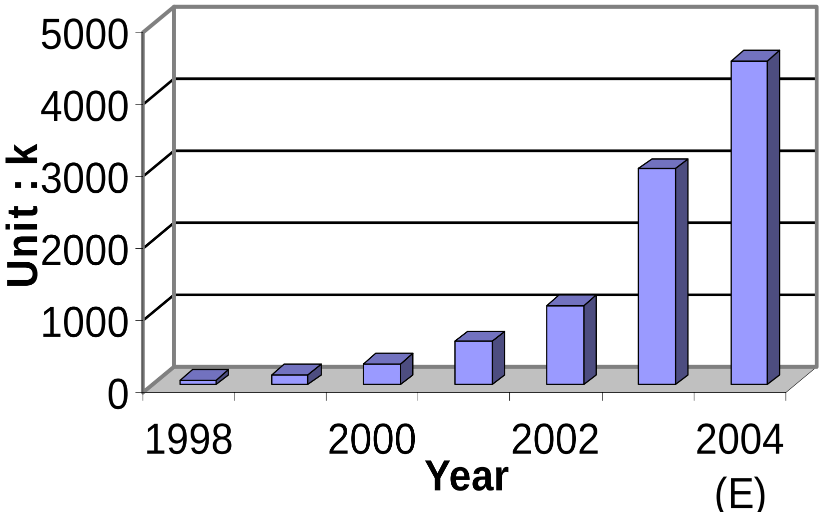
- In 2010 part of HEV batteries will be of Lithium based type (see diagram) and 500 000 Lithium HEV/year creates 10% of material consumption of portable Lithium,
- It seems to be difficult for a battery manufacturer to take place on the market without a close agreement with a car manufacturer,
- Japanese and other Asian countries car manufacturers will lead the HEV market,
- The competition is nearly already finished concerning NiMH battery for HEV,
- The hypothesis of dual mode and BEV growth to reasonable values (0.3 to 0,5 million units with the Chinese market) will change the market of Lithium based batteries (portable and automotive applications). One BEV battery is nearly ten times higher in material consumption compared to HEV. 0.3 million BEV and about 1 million HEV creates more than 60% of material consumption of portable Lithium.

**Long term demand forecast for automotive Lithium based batteries**



Source : Takeshita

**e-bike : Booming of niche production accelerated by China market (e.g. ByD forecasts)**



For the light vehicles market (e-bikes and scooters) a Chinese portable battery Manufacturers (BYD) agree with the Takeshita forecasts. They anticipate a quick growth of the Lithium based batteries use starting in 2004, with more than 2 million of cells only for this type of application.

# 7. Synthesis of Portable Battery Market development (1990-2004) and Trends

*(Source: Hideo TAKESHITA, Institute of Information Technology, Ltd, Tokyo, 2004 and Avicenne Development, Paris, 2004))*

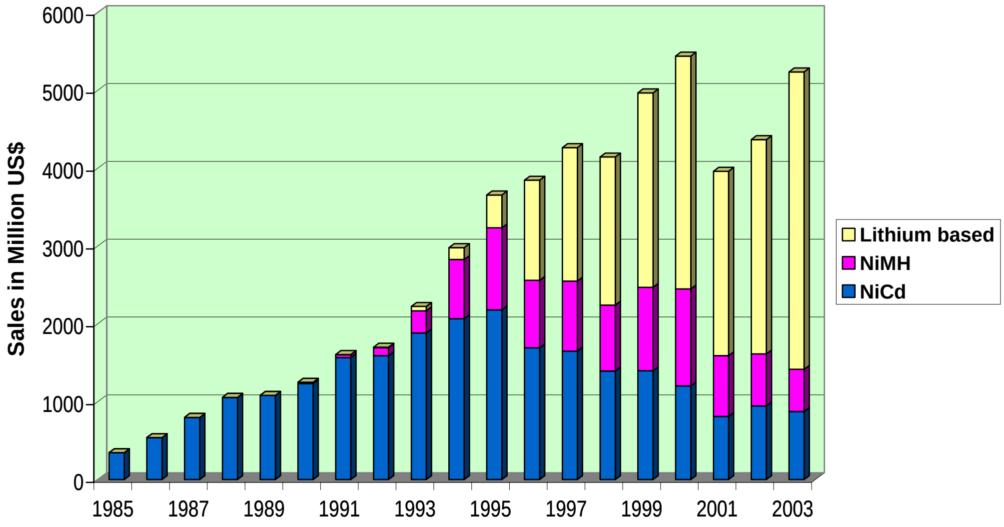
A detailed comparison of the secondary battery (rechargeable batteries) market development for portable applications (phone, computers, electronic devices etc) with the automotive one for the same electrochemical technologies is of great interest for several reasons:

- Secondary portable battery market is a recent one (started between 1982 and 1984) but about 20 years older than the corresponding automotive one (except SLI traditional Lead-Acid market),
- Used electrochemical technologies are the same,
- This market is characterized by a continuous switch of one technology to a new one for a given application depending on the R&D activities and results,
- Market growth is fast (20%/year) and function of battery increasing performances and new application designing,
- Parts of the factors that are driving the Manufacturers choice for a battery technology suitable for a given product are the same on the two markets (often not in the same order like energy density, specific power, cycle ability, price, reliability etc). Market development of portable secondary batteries could give some valuable information's concerning the future of the automotive one.
- Many major Companies that are leading the portable market are as well involved on the automotive one.

## 7.1 Secondary battery market overview (portable applications)

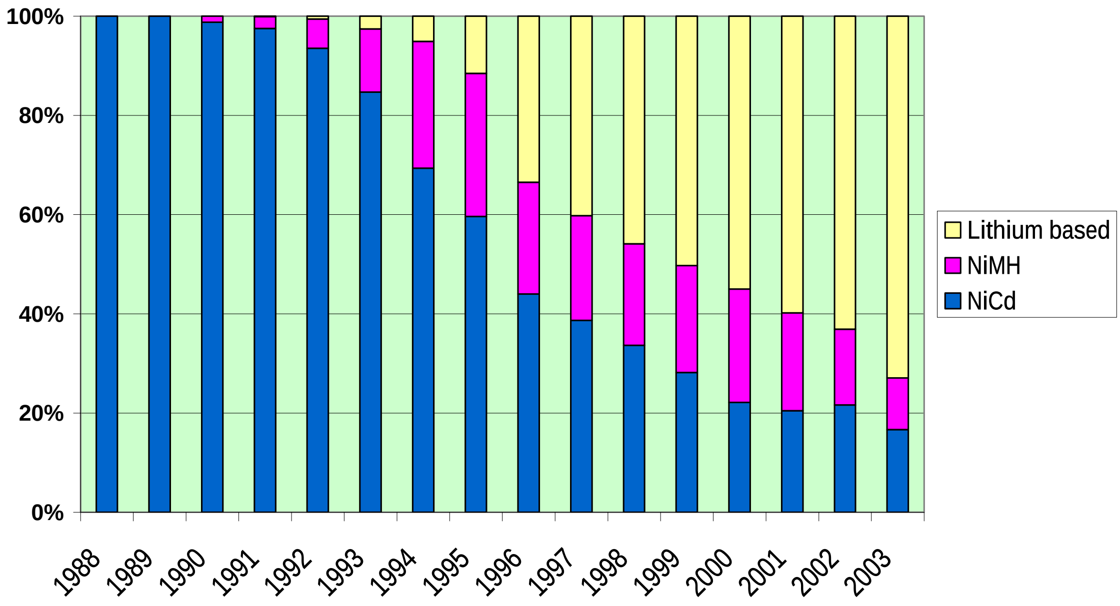
The total rechargeable portable battery market size is about 5 237 Million $ with a 20% growth per year.

**World rechargeable portable battery market**



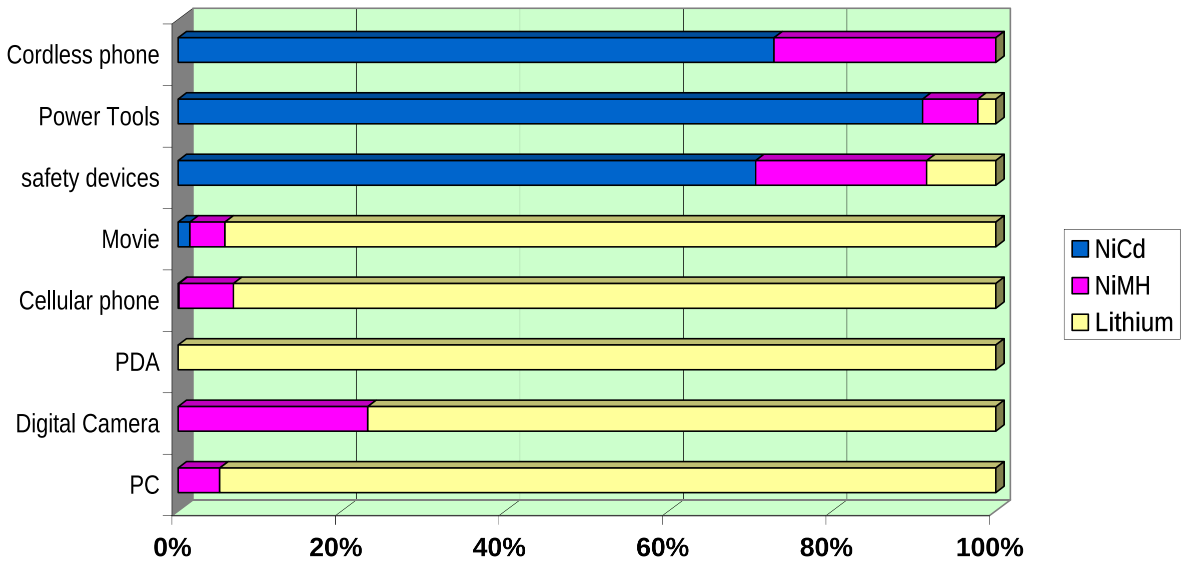
As shown on the two next diagrams, after a continuous growth of NiCd between 1985 and 1995 at the beginning of the market, it began to decrease in volume replaced by NiMH and Lithium based. NiMH appears in 1990, only two years before the first Lithium based secondary batteries.

**World rechargeable portable battery market (in volume)**

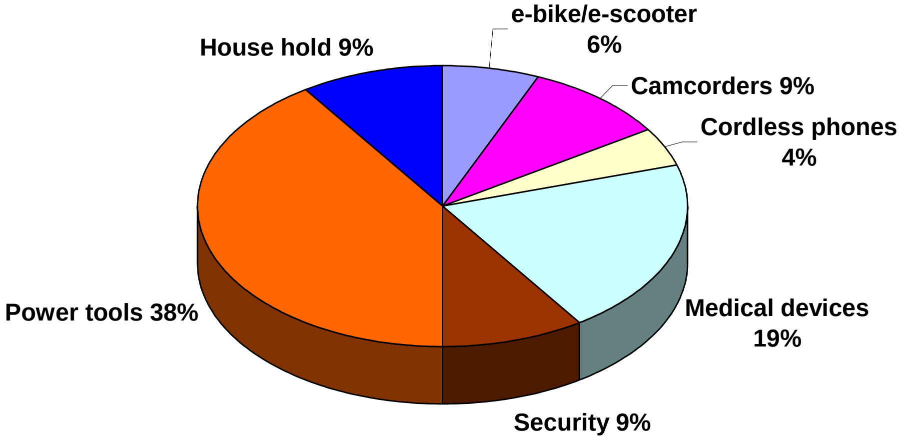


NiMH market reaches about 20% in volume after five years (1994) and then is stabilized up to 2001. A constant decrease of NiMH appears from 2002. Simultaneously Lithium based market shows a constant increase starting in 1993 and reaching about 70% in volume of the total portable secondary batteries in 2003.

**Type of battery vs application in 2003**



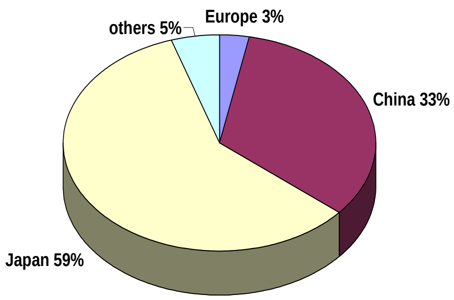
These market changes are different whether high energy and low power applications (electronic like PC, Cellular etc) are concerned or high power one like power-tools. In the first type of application Lithium based batteries shares more than 90% of the market in 2004 and probably about 100% in 2005. Up to 2002 no Lithium based rechargeable batteries were used in power-tools (high power large battery packs) applications where NiCd was dominating. But Lithium based are now adopted for some of this type of applications. As profit of cell suppliers come mainly from Lithium based business and of less importance NiCd, it seems that Lithium based will continue to increase in power-tools applications (light vehicles like e-bike uses the same batteries). For the same reasons NiMH will continue to decrease.



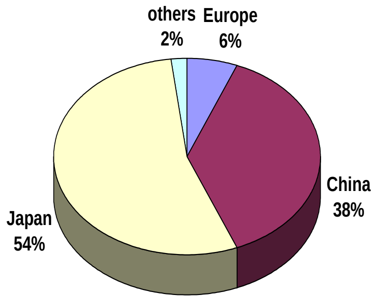
**Portable Ni-Cd Market 2003**
**1 140 Million of cells, 960 M$**

## 7.2 Map of portable battery suppliers

Except the case of NiCd where Europe (Saft) takes a little place, for all the other technologies Asian suppliers (Japan, China and Korea) are completely dominated the market. Only two European Companies (Saft and Varta-JCI) are in the twenty largest companies of the world and the first ten are from Asian countries.

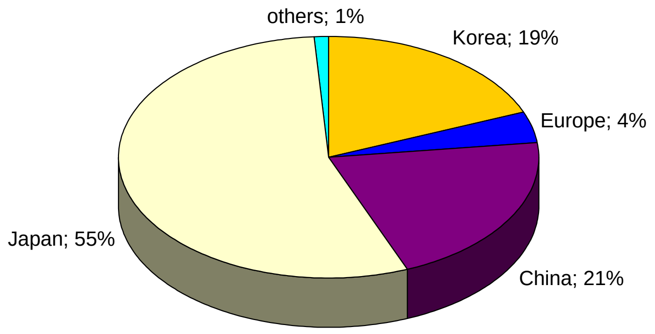


NiMH suppliers HQ location (% volume in US $)



NiCd suppliers HQ location (% volume in US$)

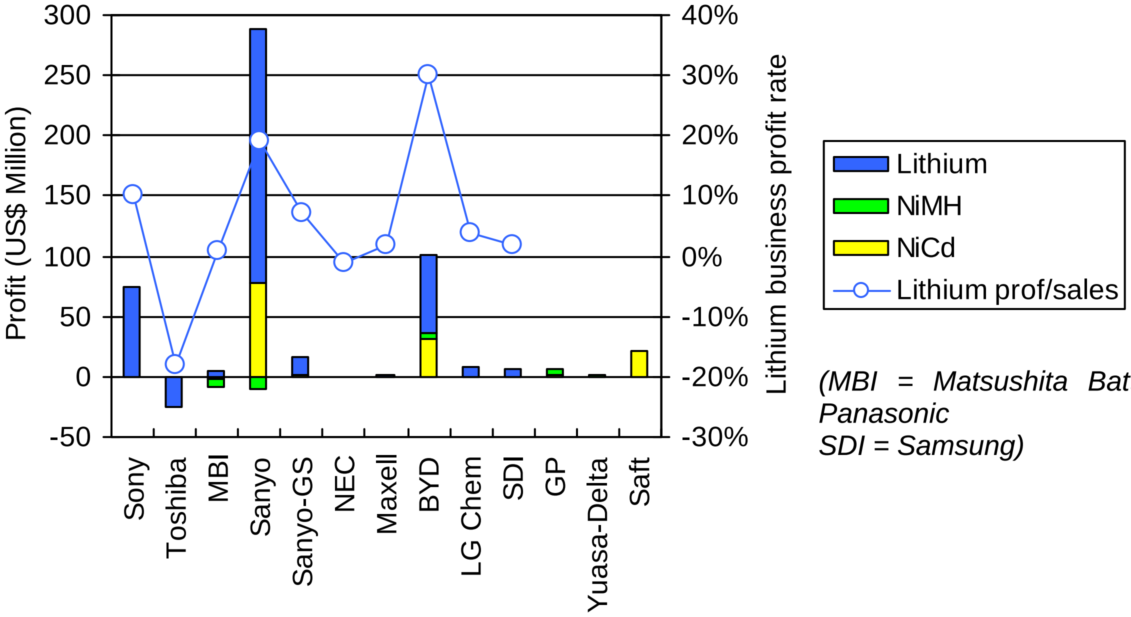
**Lithium based suppliers HQ location (% volume in US $)**



Up to 2000, Japan was leading for all technologies with more than 80% of the market. Since then China and Korea are increasing their market share year after year to reach about 45% for the Lithium based technologies in 2004. The largest Chinese Company (BYD) just behind Sanyo, becomes the second largest company of the world. It is for Lithium based technologies where the competition is the hardest that Korean Companies are appearing with LG the largest one.
The USA activity is nearly insignificant on this market.

As for breaking out on the automotive market the financial, technical and industrial abilities of the Companies are needed at the same time, the following diagram shows that only a few of these coming from portable battery industry are able to play a leading role.

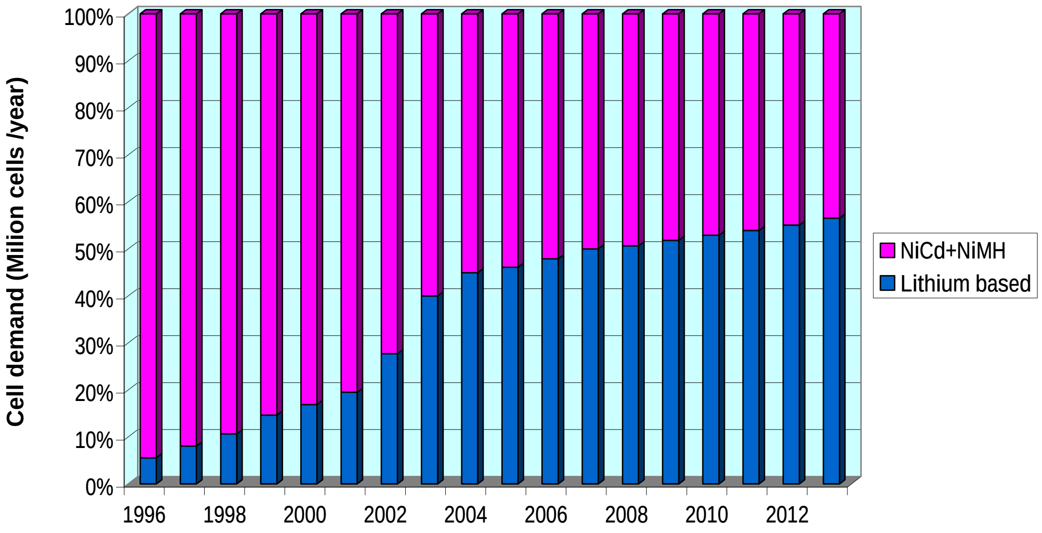
Compared to the automotive market map of suppliers (for lithium based technologies), all these leading companies are known for their significant R&D activities. Leading Companies on the automotive Market that are not known on the portable market (like PEVE for example) are very often the result of a joint venture between a Car Manufacturer and a well known Company of the portable market.



*(MBI = Matsushita Battery = Panasonic
SDI = Samsung)*

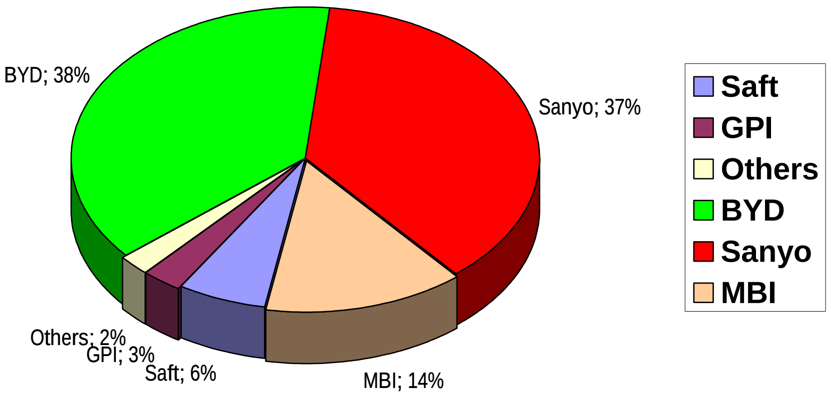
Long term (2012) demand forecast for portable secondary batteries expressed in Cell demand per year shows a continuous increase of Lithium based batteries against NiCd and NiMH. But this increase of about 10% in 2004 becomes smaller up to 2005 (2 to 5%) and concerned mainly the “power” market (electronic, audio, video, game etc).

**Long term demand forecast for portable rechargeable battery**



### 7.2.1 NiCd market

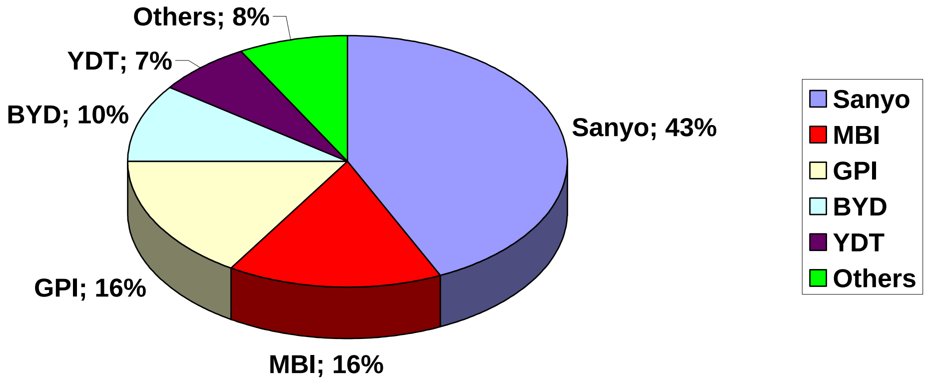
**NiCd Supplier volume share in portable battery (2003)**



Sanyo (world first company on the portable market) leads but BYD (China) is nearly at the same level. Only Saft appears as non Asian Company.

### 7.2.2 NiMH market

**NiMH supplier volume share in portable battery (2003)**

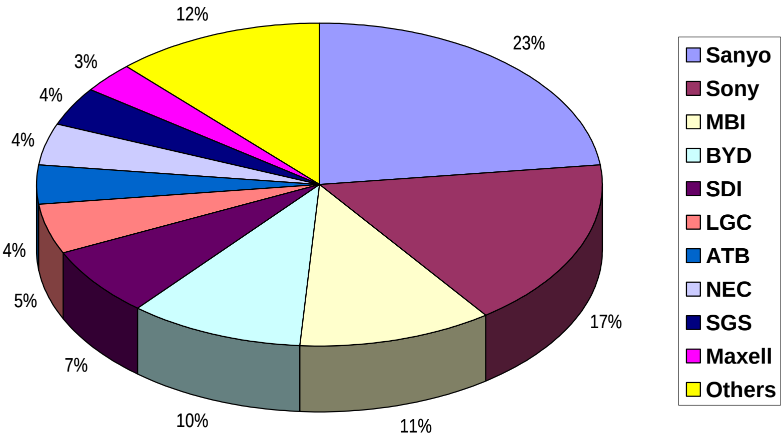


### 7.2.3 *Lithium based technologies market*

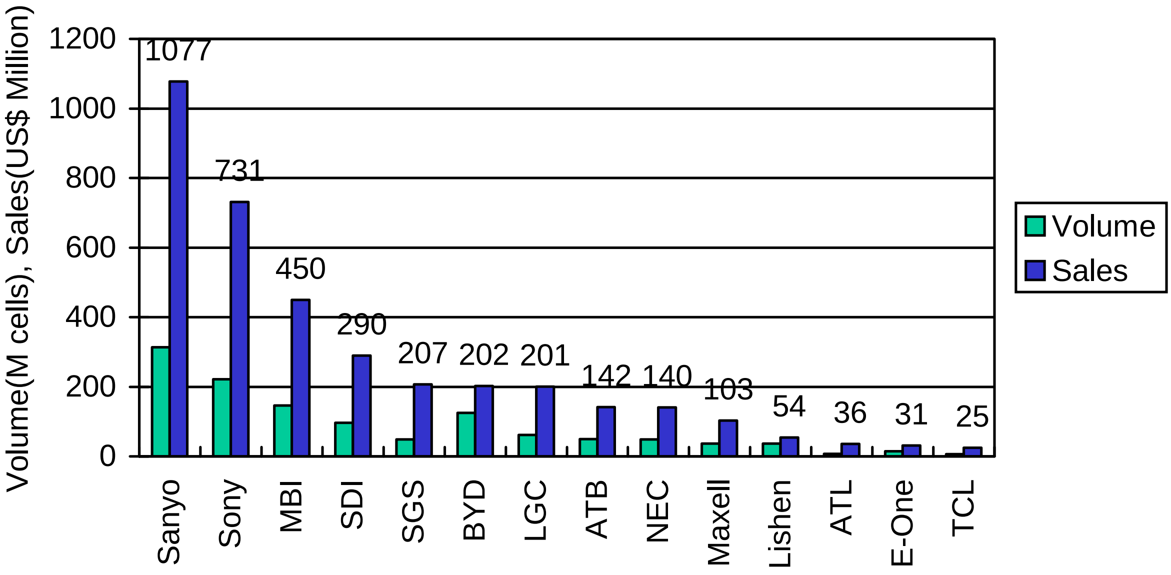
The Lithium based technology market is more complicated for two basic reasons:

- As for the same technology on the automotive market several technologies are in competition and some of them are just coming from the R&D field (many cathode materials are used, several electrolytes in liquid or polymer state and industrial process could be for cylindrical, prismatic or laminated cells),
- Suppliers are more numerous and the real competition has just started in 2003.

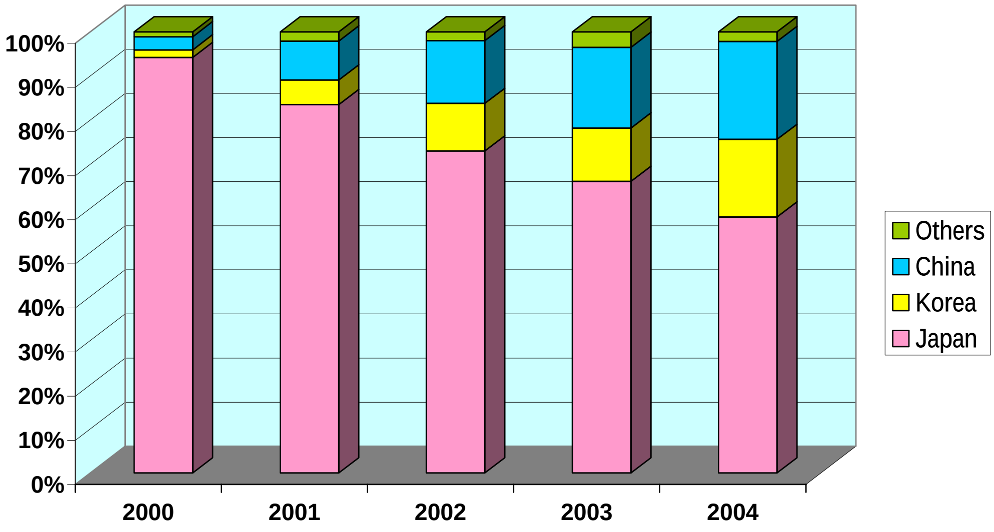
**Lithium based supplier volume share in portable battery (2003)**



Four Companies are leading with more than 60% of the market in volume. Three of them are from Japan the other one Korean, but several other large Companies are appearing from China (BYD, Lishen etc) and Korea (LGChem, Maxell etc).



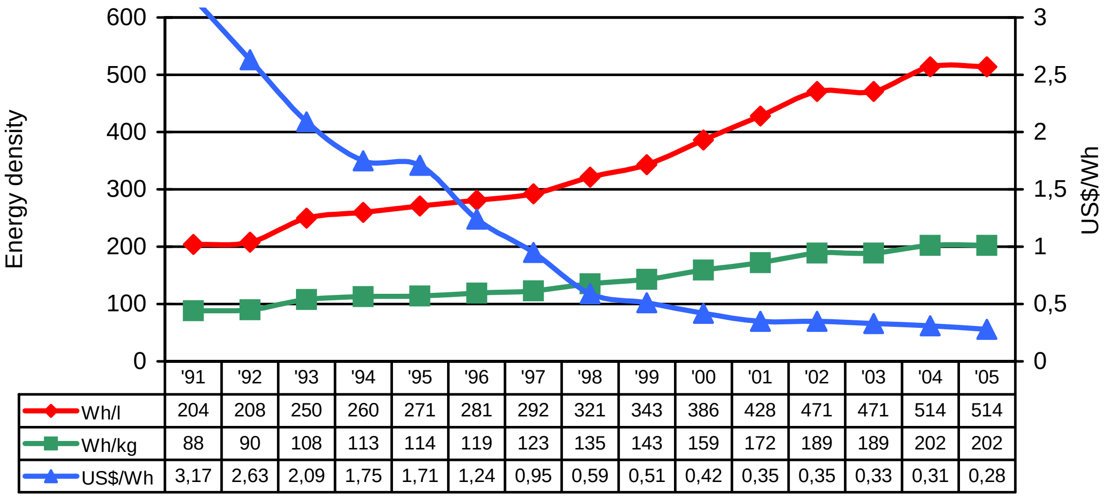
**Lithium based battery shipment volume (in cells) by HQ location**



Since 2003 the lithium based shipment is growing faster than the demand (49% against 19%) and the competition becomes harder. It seems that the high level demand growth will be slower in 2005 and small or new Companies will have difficulties.

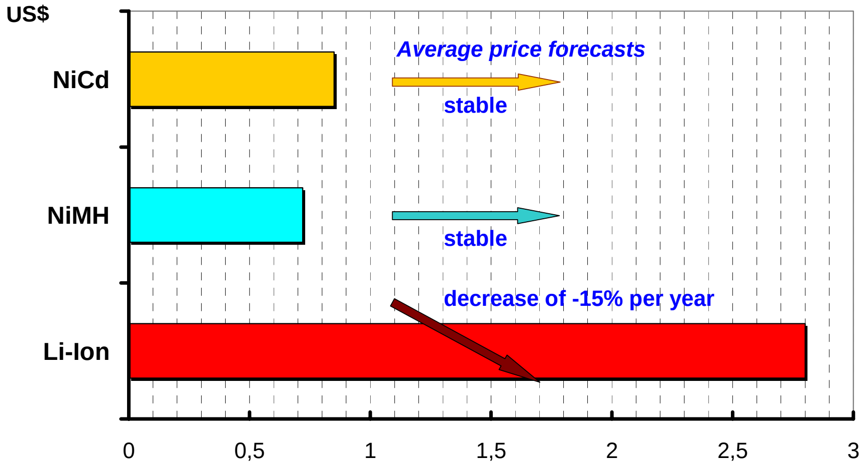
One of the major aspect of this competition and market growth is the decrease of price of lithium based cells coming with an increase of performances in energy density. This reduction is based on several factors:

- Chinese low labour cost and cheap local cathode material supply but with a good reliability,
- New fabrication processes like laminate that reduces the manufacturing cost
- New cheaper cathode material (Ni or Mn type) that avoid Co-type use and rise of Co prices, new type of cathode development (Fe type) demanded for automotive industry and large size cell,
- Scale effect for the largest Company and tough competition,
- Cost of separator and electrolyte and new technologies implementation for polymer electrolyte and new type of separator.

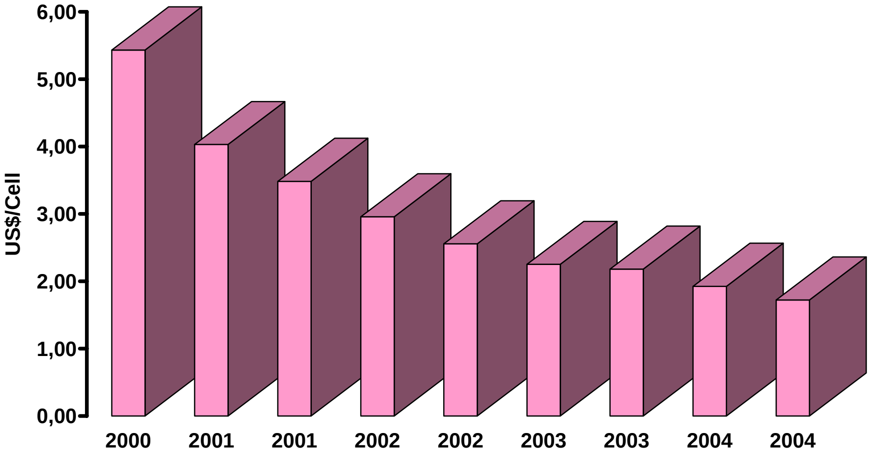


| | '91 | '92 | '93 | '94 | '95 | '96 | '97 | '98 | '99 | '00 | '01 | '02 | '03 | '04 | '05 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Wh/l | 204 | 208 | 250 | 260 | 271 | 281 | 292 | 321 | 343 | 386 | 428 | 471 | 471 | 514 | 514 |
| Wh/kg | 88 | 90 | 108 | 113 | 114 | 119 | 123 | 135 | 143 | 159 | 172 | 189 | 189 | 202 | 202 |
| US$/Wh | 3,17 | 2,63 | 2,09 | 1,75 | 1,71 | 1,24 | 0,95 | 0,59 | 0,51 | 0,42 | 0,35 | 0,35 | 0,33 | 0,31 | 0,28 |

**Average price per cell in 2003 (US$) (Portable Market)**



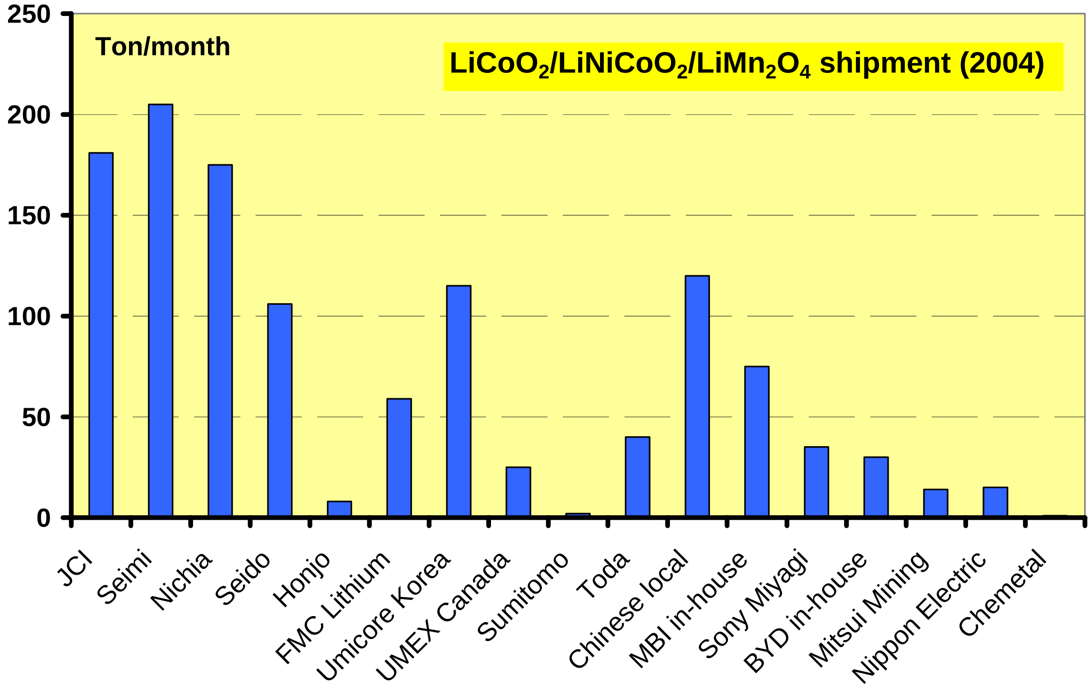
**Lithium based cell bare: cell price decrease**



As all these factors are exactly the same in the case of Lithium based batteries for automotive applications, it seems very interesting to detail some aspects of the problem.

Despite an increase of Cobalt price, prices of cells have decreased from 6 to about 2 US $ in four years mainly because the Chinese “in-house” production increase.

But for the next years, it seems that the cathode material price will rise (perhaps by 25%) and the R&D activity with the purpose of changing the cathode material becomes very important.



It is then possible that the development of lithium based HEV batteries expected in the long run results in a decreasing price of portable lithium because:

- Material used in Lithium based automotive batteries should be similar one to portable,
- 500 000 hybrid vehicles/year creates 10% of material consumption of portable lithium
- Special material and technologies for automotive Lithium can be developed but only if they are cheaper.

# 8. Scenarios to 2012

The purpose of this study has been described in the SUBAT contract form as an assessment of the European battery industry on the global market illustrated by the *building of several scenarios on the possible emergence of these new battery technologies by 2012 and the consequences study for the European Industry.*

The today market growth of Hybrids Electric Vehicles shows that if this emergence takes place it can only come from this phenomenon. As all these vehicles must use in most cases new battery technologies (Lead-Acid could be convenient only for mild hybrid vehicles) the Hybrid market growth hypothesis will be followed by a corresponding battery market growth. If the scale factor is sufficient to induce a significant price decrease of batteries a new development of the BEV market becomes possible (in Europe and Japan).

The building of SUBAT scenarios consists in studying the hypothesis of HEV market growth to 2012 and the main factors that have an influence on it. Then hypothesis could be made on the market growth of new battery technologies following these scenarios.

## 8.1 Main factors

These factors can be classified as following:

- Collective factors
    - Local pollution and related regulations (NOx, CO etc)
    - Global pollution (GreenHouse Gas) and related policy and regulations
    - Oil market (price, reserve, production, consumption etc)
- Individual factors
    - Decrease in consumption of the vehicle
    - Price of the vehicle
    - Maintenance cost and reliability
    - City traffic regulations
    - Public subsidy
    - Comfort increase and noise reduction
    - Green attitude and sense of civic responsibility
- Policy factors
    - GreenHouse Gas world policy (Kyoto agreement and evolution)
    - Local pollution policies and evolution
    - National Energy policies
    - Energy consumption in developing countries
    - Commercial policy of oil production countries
    - Public transport policies
- Technical and economical factors
    - Increase of new technologies battery performances and decrease of cost
    - Schedule of PAC development and commercialisation
    - Increase of power electronics and electric power train performances associated with a decrease of cost

## 8.2 Study of the main factors

Some of these factors (as oil market, GHG effect, local pollution effect etc) must be studied regardless of the others. The purpose is to build up individual scenarios using studies made by expert in this field. By association of these hypothesis in a logical way it becomes possible to build up SUBAT scenarios for "clean vehicles" market development (Europe, North America, Japan and China) and then for battery market development.

### 8.2.1 Oil Market Evolution

All the studies of Oil Market evolution (reserve, production, world consumption and price) made before 2004 in order to forecast the oil price variation between 2003 and 2010 are leading to results that can be compared to 2004/2005 real prices. All these studies are leading to a mean oil price value in 2005 of about 20 to 25 $/bl and in 2012 of 30$/bl. Compared to the three first 2005 months mean value of about 55 $/bl. It becomes then impossible to use these data and reliable forecast are impossible. In our case the question is not really the oil price evolution between today and 2012 but its influence on the purchasing behaviour of the car manufacturer customers. Recently several studies have been made regarding this question in Noth America, in Europe and Japan. All the results are similar; the fuel price is not the main factor. The purchasing behaviour of the customers seems to be modified by the fuel price only for very high values (not really known and function of the today country fuel price), it is only the car using behaviour that is modified (reduced mileage made by year). This factor could not be taken then as a main one for the development of advanced vehicles market.

### 8.2.2 Local pollution and related regulations and policies

The local pollution problems (NOx, CO, HC and Particulate) in the large cities all over the world have reached a so high level that many countries have published regulations concerning the vehicle emissions. But, in relation with the mean type of vehicle sold on each market, these regulations are very different depending on the country. A global comparison between Europe, Japan and USA can be seen on the following diagram (NOx and PM).
It seems that no clear regulations or incentives are available today in China.

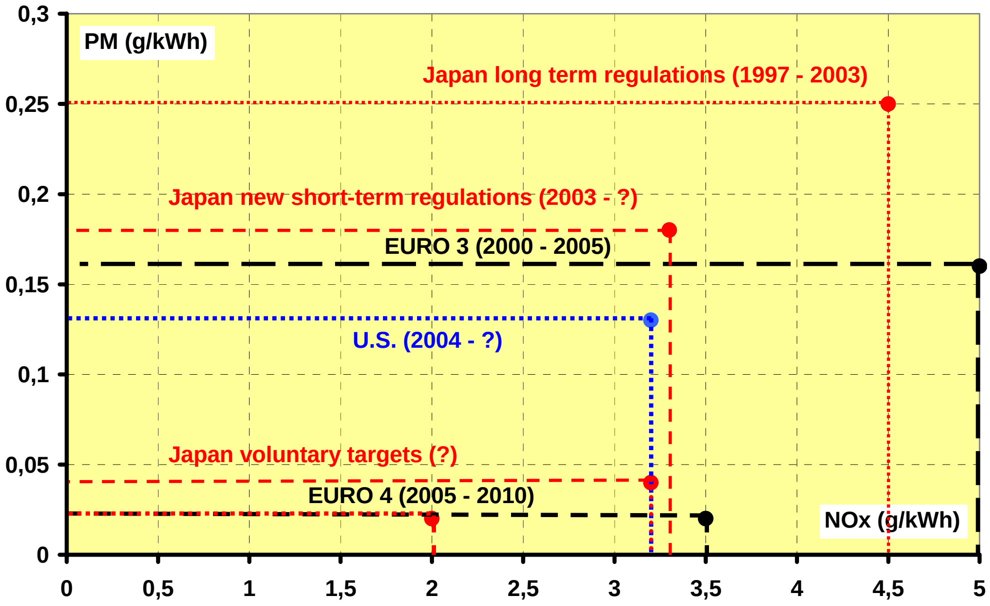


*Figure 2.2-1 Emission standards and regulations in EU, Japan and USA for PM and NOx.*

The US targets are less stringent than the European and Japanese one, in relation with the fact that the US cars are of larger size with large engines, high weight and high oil consumption. Japanese regulations (or targets) are of the same order but consequences on the advanced vehicle market and battery market could be different.
In Europe with the large development of “eco-diesel” engines and the ambitious targets concerning the reduction of fuel consumption associated with the market demand concerning the increase of comfort and power, the situation culd become very favourable to hybrids development and then for the traction battery market in 2012. The values of emissions chosen by the European Union for the EURO V standards (2010-2012) are not known yet. They will be of major importance especially concerning the PM value (Particulate Matter). If this value decreases in Euro V compared to Euro IV it could become very difficult to reach for diesel engines without complexe and expensive aftertreatments creating simultaneously an increase of fuel consumption ($CO_2$ emission). The increase of electric hybridation level could be then the only short term solution.
For Japanese market where diesel engines are not used at the same level than in Europe, and taking into account the fact that hybridation of gasoline engine is easier and costless than for diesel engine, it seems the ambitious targets shown in the previous figure could create an increase of advanced

vehicule market. As Japanese car makers are leaders on this market it could induce a high level of growth of Asian traction battery market.

It is very difficult to make any relation between local pollution regulations and advanced vehicle market in the USA for two main reasons:

- Regulations (or incentives and commitments) are different depending on the US state concerned (California has an historical leading role in this field),
- The US policy is much more made of Commitments and fiscal incentives than of regulations concerning a level of emission.

But, taking into account the published studies and incentives of the last 3 years (for example by California Air Ressource Board), it becomes clear that the pressure of the authorities will increase gradually in order to avoid any uncontrolled increase of local pollution.

On the other hand, the Chinese case is very interesting because probably comparable to what could be the situation for more than three billion of people in 2012 (China and India).

Since 1997 the number of passenger cars sold in China has increased of about 10% each year. The local pollution level in the man Chinese cities is very high, with 7 Chinese cities listed among the top 10 of the worst pollution in the world. At the same time in 2010 auto emission will be the double of the 2004 pollution level. As only a little amount of Chinese cars are coming today from Chinese car Manufacturers (less than 20%), it seems that new regulations or incentives from Chinese Government couldn't be very efficient. But under the pressure of increasing oil consumption (see next paragraph) and perhaps stimulated by the 2008 Olympic Games organization, it becomes possible that the Chinese Government decide to take very hard regulations leading to an increasing development of advanced clean vehicles of all types.

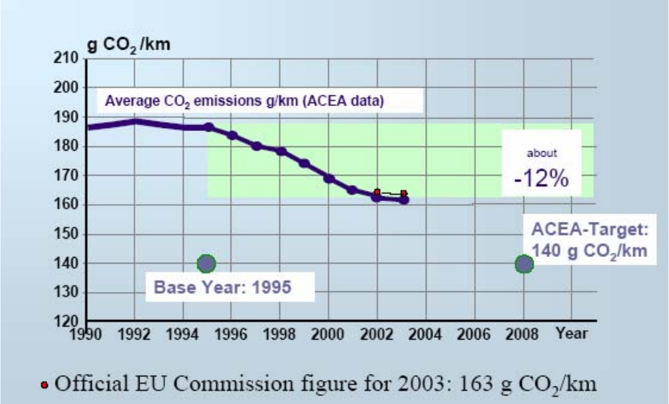
### 8.2.3 Global pollution (GreenHouse Gas emission GHG)

GHG emission by the transport activities (passengers, goods and all type of transport systems) is between 25% and 50% of the total GHG emission of a country depending on many factors and continuously increasing for many years.

As GHG emissions are directly related to fuel consumption in the case of ICE vehicles, countries without oil resources are more concerned by GHG emission than the others. Simultaneously the sense of civic responsibility concerning the temperature growth is very different depending on the country and its level of development.

European countries, Japan and Korea have a very dynamic policy in agreement with the Kyoto protocole. For transport, this fact is often translated into governmental incentives. But on the contrary of local pollution no regulation has been published yet.

The European Union GHG reduction strategy for passenger cars (and duty vehicles) can be summarized by the following figure.



The most important short and mid term action is the Car Manufacturers Commitment signed by ACEA (European Automobile Manufacturers Association), JAMA (Japan Automobile Manufacturers Association) and KAMA (Korean Automoble Manufacturers Association). This commitment is an agreement between all these car manufacturers in order to reach an average $CO_2$ emission of new cars of 140 g/km in 2008 and 120 g/km in 2012 (starting with a mean value of about 160 g/km in 2004 for all these countries).

At the same time the customer comfort and safety demand will increase leading to an increase of power and weight (this effect can be seen on the following diagram for the two last points 2002-2003 where the decrease of emission is nearly null). It seems then very difficult to reach the 2012 target without developing the hybrids vehicle market for all type of vehicle.

The mean value of consumption and $CO_2$ emission of new cars in the USA are higher than in all the other countries all over the world (about 248 g $CO_2$/km). As the comfort, size, safety and power increases continuously (SUV, Trucks etc) on the US market without any restriction coming from the fuel price and despite many actions developed on advanced combustion engines, the decrease of GHG emission seems to be very difficult to reach in the USA. Following the California Air Ressource Board short and mid term commitments have been published and can be summarized by a 20% reduction of new cars GHG emission in 2012 (190 to 195 g CO2/km) and 30% in 2016.

It seems that only two ways could be used to reach such targets taking into account the US customers habits:

- An increasing rate of new eco-diesel engine cars (50% diesel cars proportion lead to about 10% decrease of fuel consumption),
- The development of hybrid vehicle market especially for the largest types of vehicule (SUV trucks etc). This development has already started based on the Toyota Prius II in 2004-2005 and seems to be able to grow in 2005-2006 with more than 8 types of hybrids (3 SUV).

The most important problem of Chinese authorities concerning the transport GHG emissions is not really related with earth temperature increase but with Chinese oil consumption. More of 60% of Chinese oil consumption in 2004 is coming from outside with an increase of 12% to 15% each year, the economical pressure could become very high on the Chinese government. Since 1999 many R&D national programs have been launched concerning sustainable mobility especially for the development of EV and HEV industry (see SUBAT China study trip report). China is also one of the main world producer of raw material for advanced battery technologies and has developed in 6 years one of the largest portable battery industry in the world.

The Chinese industrial organization as the political management traditions are so different from ours that it becomes very difficult to forecast the way that could be used in the next few years in order to keep this problem under control. The hypothesis of very stringent regulations promoting zero emission vehicles (or very low emission vehicles) could be one of the chosen solutions as far as this solution could promote the Chinese industry at the same time.

#### 8.2.4 Other factors

All the other factors are less important except the price (or costs) problems related with the increasing level of complexity of advanced vehicles and the size and cost of the battery.

## 8.3 Scenarios

As seen in the previous chapter the consequences of these factors on the vehicle market can be studied only considering four different markets: Europe, Japan, America and China. For each market two or three scenarios will be studied leading to a minimum, a maximum and a mean value of advanced vehicles sold for each type of vehicle and then a minimum and maximum value of traction batteries produced.

### 8.3.1 European Market

Market of about 17 million of vehicles in 2004, this market is mainly driven by three factors: the European Union laws and regulations concerning the local pollution (Euro IV and Euro V), fuel economy and CO2 emission incentives and price of vehicles. It is also characterised by small vehicles with small engines and a high amount of new type of eco-diesel engines.

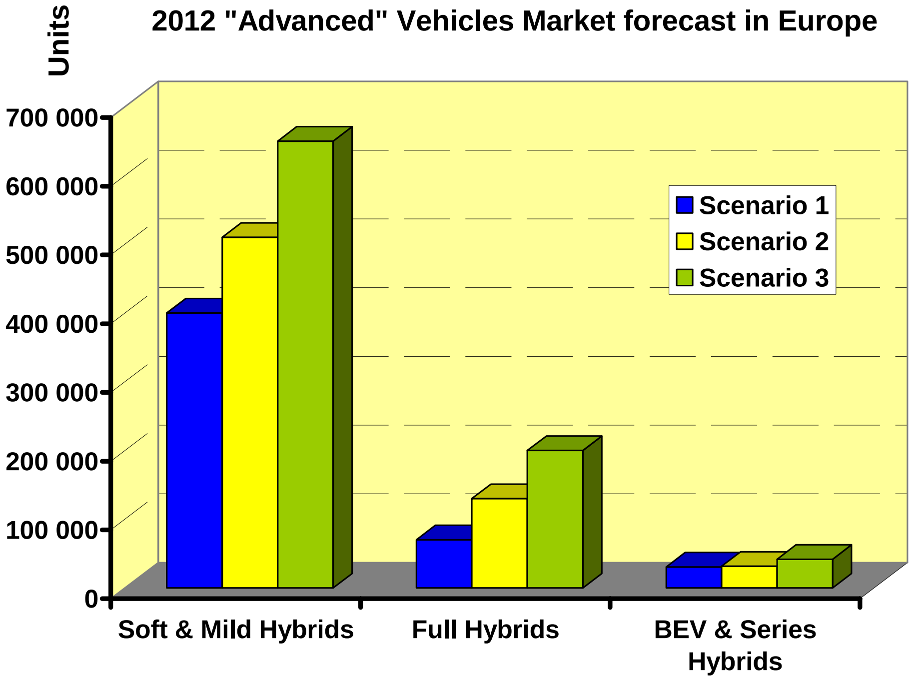
Results of the complete analysis can be summarized by the following tables, figures and conclusions:

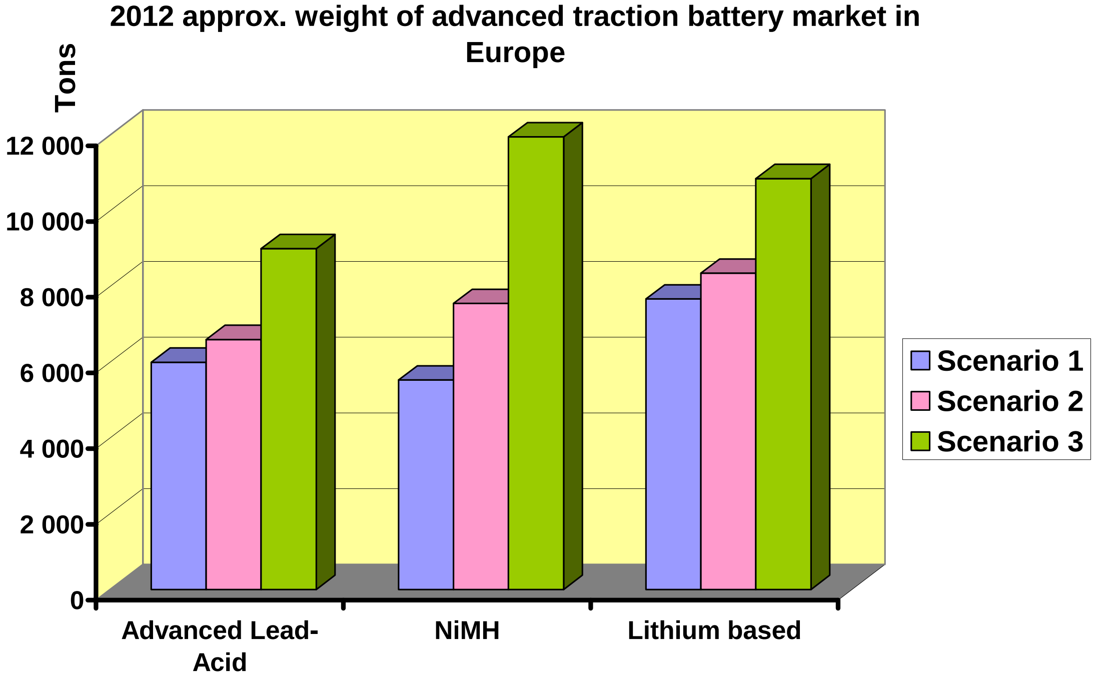
| | | | | | |
|---|---|---|---|---|---|
| **Scenario 1** | **Hypothesis** | High fuel price (between 35 and 45 $/bl), Euro V and Euro IV of the same order concerning PM, nothing new concerning GHG emissions, slow decrease of battery prices, good results for advanced combustion engines and new type of fuels. | | | |
| | **Type of vehicle*** | **nbre** | **Type of battery** | **approx. weight of battery (kg)** | **total by type (kg)** |
| **400 000** | Soft Hybrid | 200 000 | Lead-Acid (12 V) | 2 400 000 | |
| | Mild Hybrid | 60 000 | Lead-Acid (42 V) | 3 600 000 | 6 000 000 |
| | | 130 000 | NiMH | 3 250 000 | |
| | | 10 000 | Lithium | 170 000 | |
| **70 000** | Full hybrid | 60 000 | NiMH | 2 280 000 | 5 530 000 |
| | | 10 000 | Lithium | 280 000 | |
| **30 500** | BEV and Series Hybrid | 30 000 | Lithium | 7 500 000 | 7 670 000 |
| | | 500 | Others | 150 000 | |
| **Scenario 2** | **Hypothesis** | High fuel price (between 35 and 45 $/bl), Euro V and Euro IV of the same order concerning PM, large decrease of battery advanced technology prices, high pressure concerning GHG emissions. | | | |
| | **Type of vehicle*** | **nbre** | **Type of battery** | **approx. weight of battery (kg)** | **total by type (kg)** |
| **510 000** | Soft Hybrid | 250 000 | Lead-Acid (12 V) | 3 000 000 | |
| | Mild Hybrid | 60 000 | Lead-Acid (42 V) | 3 600 000 | 6 600 000 |
| | | 150 000 | NiMH | 3 750 000 | |
| | | 50 000 | Lithium | 850 000 | |
| **130 000** | Full hybrid | 100 000 | NiMH | 3 800 000 | 7 550 000 |
| | | 30 000 | Lithium | 840 000 | |
| **31 500** | BEV and Series Hybrid | 30 000 | Lithium | 7 500 000 | 8 350 000 |
| | | 1 500 | Others | 450 000 | |
| **Scenario 3** | **Hypothesis** | Very high fuel price (between 55 and 75 $/bl), Euro V more stringent than Euro IV concerning PM , large decrease of battery advanced technology prices, high pressure concerning GHG emissions. | | | |
| | **Type of vehicle*** | **nbre** | **Type of battery** | **approx. weight of battery (kg)** | **total by type (kg)** |
| **650 000** | Soft Hybrid | 250 000 | Lead-Acid (12 V) | 3 000 000 | |
| | Mild Hybrid | 100 000 | Lead-Acid (42 V) | 6 000 000 | 9 000 000 |
| | | 250 000 | NiMH | 6 250 000 | |
| | | 50 000 | Lithium | 850 000 | |
| **200 000** | Full hybrid | 150 000 | NiMH | 5 700 000 | 11 950 000 |
| | | 50 000 | Lithium | 1 400 000 | |
| **41 500** | BEV and Series Hybrid | 40 000 | Lithium | 10 000 000 | 10 850 000 |
| | | 1 500 | Others | 450 000 | |

* *Soft Hybrids = 2 to 5 kW of electric traction power with stop and go, Mild Hybrids = 6 to 12 kW electric traction power with stop and go, launch assit and power assist, reg. braking.*

A complete analysis of all the data made for several scenarios of development leads to the following conclusions:

- Advanced vehicle market will start and increase to a value between 3 and 8% of the total passenger car market (500 000 to 1.4 millions of vehicles) in 2012 depending on the scenario chosen,
- Mild hybrid type will prevail, probably equipped with a 42V battery pack of about 0.2 to 0.4 kWh and 9 to 12 kW (10s) leading to a battery weight between 1 800 to 4 000 t.
- Competition will prevail between advanced lead-acid, NiMH and Lithium based,
- Ratio will depend on relative cost for Lead-Acid and NiMH and of cost and safety for Lithium based.
- Market seems to be to small by itself to induce a world increase of the new technology battery market,
- BEV market will remain a niche market (between 30 000 to 100 000 vehicles/year) using probably mainly lithium based batteries.





### 8.3.2 Japanese Market

Market of about 13 millions of vehicles in 2004 (with Korea), this market is mainly driven by fuel economy, increase of comfort and vehicle price. It is also characterized by a great majority of small gasoline engines, midsize cars and strong incentives towards fuel economy and $CO_2$ emission reduction (a mean value of 25% in ten years). Laws and regulations for local pollution are less important (but standard values are comparable to European one) in relation with the type of fuel used.
Results of the complete analysis can be summarized by the following tables, figures and conclusions:

| **Scenario 1** | **Minimum** | | | | |
|---|---|---|---|---|---|
| | **Type of vehicle*** | **nbre** | **Type of battery** | **approx. weight of battery (kg)** | **total by type (kg)** |
| **250 000** | Soft Hybrid | 60 000 | Lead-Acid (12 V) | 720 000 | |
| | Mild Hybrid | 0 | Lead-Acid (42 V) | 0 | 720 000 |
| | | 70 000 | NiMH | 1 750 000 | |
| | | 120 000 | Lithium | 2 040 000 | |
| **350 000** | Full hybrid | 250 000 | NiMH | 9 500 000 | 11 250 000 |
| | | 100 000 | Lithium | 2 800 000 | |
| **10 000** | BEV and Series Hybrid | 10 000 | Lithium | 2 500 000 | 7 340 000 |
| | | 0 | Others | 0 | 0 |
| **Scenario 2** | **Maximum** | | | | |
| | **Type of vehicle*** | **nbre** | **Type of battery** | **approx. weight of battery (kg)** | **total by type (kg)** |
| **450 000** | Soft Hybrid | 90 000 | Lead-Acid (12 V) | 1 080 000 | |
| | Mild Hybrid | 0 | Lead-Acid (42 V) | 0 | 1 080 000 |
| | | 200 000 | NiMH | 5 000 000 | |
| | | 160 000 | Lithium | 2 720 000 | |
| **550 000** | Full hybrid | 400 000 | NiMH | 15 200 000 | 20 200 000 |
| | | 150 000 | Lithium | 4 200 000 | |
| **31 000** | BEV and Series Hybrid | 30 000 | Lithium | 7 500 000 | 14 420 000 |
| | | 1 000 | Others | 300 000 | 300 000 |

A complete analysis of all the data made for several scenarios of development leads to the following conclusions:

- Advanced vehicle market has started in 2004 and will increase to a value between 5 and 10% of the total passenger car market (perhaps more) leading to values between 650 000 and 1.5 million of vehicles/year in 2012. But as this market is also driven by the US market these values can be higher if the US Car Manufacturers are not able to compete on this market,
- Full hybrid type will prevail equipped with high voltage batteries but probably all types of mild and full hybrids will be produced.
- Competition will prevail between NiMH and Lithium based batteries probably manufactured in China under (or not) Japanese licence (8 000 to about 30 000 t of batteries) and in the case of success of current lithium based development projects (cost and safety) lithium based have probably the best future,
- This market is enough to induce a mass production market for the new battery technologies concerned (in this case the consumption of active material is greater than the portable battery market),
- BEV market will remain very low and it seems to be too early to forecast any development of FC vehicle market.

### 8.3.3 The North American Market

Market of about 18 million of vehicles in 2004, this market is mainly driven by comfort and vehicle performances and for a part by incentives of several administrations (California and other states). It is also characterized by large cars (SUV, trucks etc), large gasoline engines and low fuel price. It becomes possible that very stringent regulations appear before 2012 concerning the local pollution, but no reliable forecast can be done.

Results of the complete analysis can be summarized by the following tables, figures and conclusions:

| **Scenario 1** | **Minimum** | | | | |
|---|---|---|---|---|---|
| | **Type of vehicle*** | **nbre** | **Type of battery** | **approx. weight of battery (kg)** | **total by type (kg)** |
| **200 000** | Soft Hybrid | 60 000 | Lead-Acid (12 V) | 720 000 | |
| | Mild Hybrid | 60 000 | Lead-Acid (42 V) | 3 600 000 | 4 320 000 |
| | | 80 000 | NiMH | 2 000 000 | |
| | | 0 | Lithium | 0 | |
| **510 000** | Full hybrid | 450 000 | NiMH | 17 100 000 | 19 100 000 |
| | | 60 000 | Lithium | 1 680 000 | |
| **1 000** | BEV and Series Hybrid | 0 | Lithium | 0 | 1 680 000 |
| | | 1 000 | Others | 300 000 | 300 000 |

| **Scenario 2** | **Maximum** | | | | |
|---|---|---|---|---|---|
| | **Type of vehicle*** | **nbre** | **Type of battery** | **approx. weight of battery (kg)** | **total by type (kg)** |
| **400 000** | Soft Hybrid | 80 000 | Lead-Acid (12 V) | 960 000 | |
| | Mild Hybrid | 100 000 | Lead-Acid (42 V) | 6 000 000 | 6 960 000 |
| | | 220 000 | NiMH | 5 500 000 | |
| | | | Lithium | 0 | |
| **800 000** | Full hybrid | 640 000 | NiMH | 24 320 000 | 29 820 000 |
| | | 160 000 | Lithium | 4 480 000 | |
| **11 000** | BEV and Series Hybrid | 10 000 | Lithium | 2 500 000 | 6 980 000 |
| | | 1 000 | Others | 300 000 | 300 000 |

A complete analysis of all the data made for several scenarios of development leads to the following conclusions:

- The advanced vehicle market has started in 2004 and will increase driven more by the increase of comfort and performances without any increase of consumption than other reasons. It will probably reach values between 4 and 8% of the total passenger car market (700 000 to 1.5 million of vehicles/year),
- On the opposite of European Market large or powered hybrid vehicles will prevail probably of all types depending on the market segment,
- Part of this production will come from Asia (Japan, Korea and perhaps China) and it seems that nearly all the corresponding battery packs will come from Asia too,
- Competition will prevail between Lead-Acid (for the smaller part), NiMH and Lithium based,
- This battery market can be considered as comparable to the Japanese one (manufacturers, volume and consequences),
- There is no reason to have any change of the BEV market that now nearly does not exist.

### 8.3.4 The Chinese Market

This Market is a new one, from about 4 million of vehicles in 2003 and with a yearly increase of more than 12%, it becomes possible to reach a size of more than 8 million of vehicles/year in 2012. As a new one, it is not so well known than the others and it becomes difficult to make reliable forecast. But some of the main characteristics can be described and consequences can be analysed assuming several different scenarios

Results of the complete analysis can be summarized by the following tables, figures and conclusions:

| **Scenario 1 Minimum** | | | | | |
|---|---|---|---|---|---|
| | **Type of vehicle*** | **nbre** | **Type of battery** | **approx. weight of battery (kg)** | **total by type (kg)** |
| **50 000** | Soft Hybrid | 20 000 | Lead-Acid (12 V) | 240 000 | |
| | Mild Hybrid | 30 000 | Lead-Acid (42 V) | 1 800 000 | 2 040 000 |
| | | 0 | NiMH | 0 | |
| | | 0 | Lithium | 0 | |
| **150 000** | Full hybrid | 60 000 | NiMH | 2 280 000 | 2 280 000 |
| | | 90 000 | Lithium | 2 520 000 | |
| **80 000** | BEV and Series Hybrid | 80 000 | Lithium | 20 000 000 | 22 520 000 |
| | | 0 | Others | 0 | 0 |

| **Scenario 2 Maximum** | | | | | |
|---|---|---|---|---|---|
| | **Type of vehicle*** | **nbre** | **Type of battery** | **approx. weight of battery (kg)** | **total by type (kg)** |
| **200 000** | Soft Hybrid | 60 000 | Lead-Acid (12 V) | 720 000 | |
| | Mild Hybrid | 40 000 | Lead-Acid (42 V) | 2 400 000 | 3 120 000 |
| | | 100 000 | NiMH | 2 500 000 | |
| | | 0 | Lithium | 0 | |
| **350 000** | Full hybrid | 200 000 | NiMH | 7 600 000 | 10 100 000 |
| | | 150 000 | Lithium | 4 200 000 | |
| **201 000** | BEV and Series Hybrid | 200 000 | Lithium | 50 000 000 | 54 200 000 |
| | | 1 000 | Others | 300 000 | 300 000 |

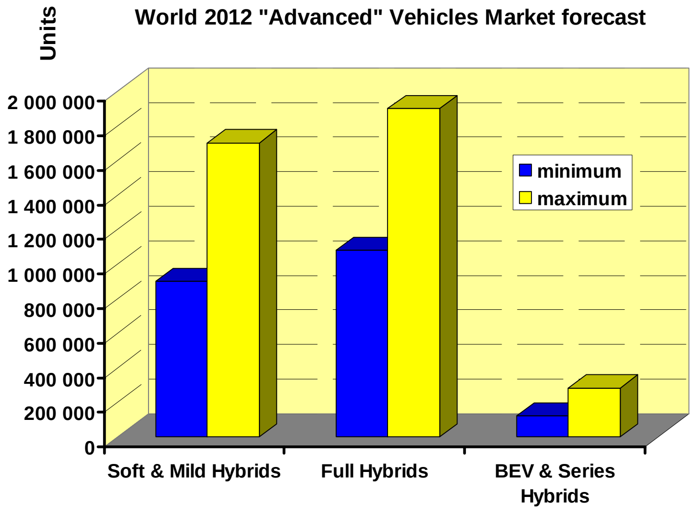
This market will be mainly driven by fuel economy and governmental policy and hypothesis of a rapid growth of ultra-low-emission vehicles can be done for the following reasons:

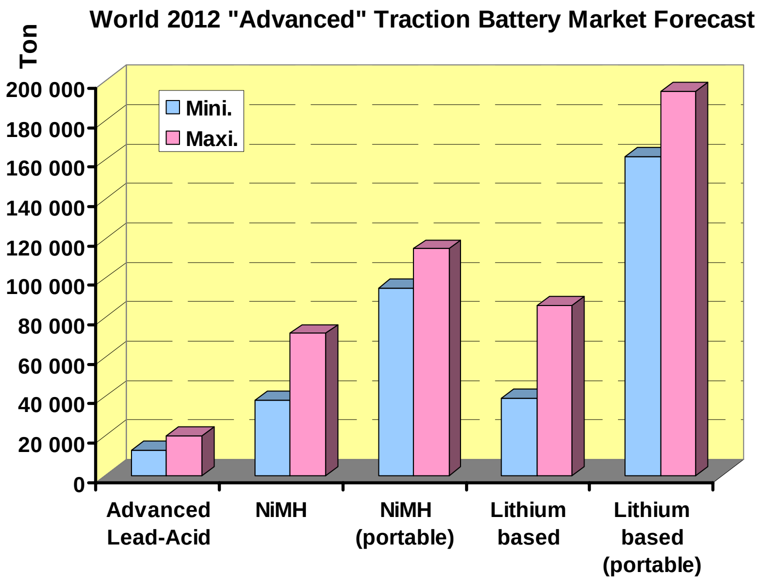
- Chinese oil consumption increases very rapidly (about 30% per year) even though more than 50% is imported today,
- Local pollution has dramatically increased the last few years in all the main Chinese towns,
- China is one of the main world producer of active material for NiMH and Lithium based batteries,
- Development of advanced vehicle market could be a way to improve the development of Chinese car industry,
- On the opposite of all the other markets, Chinese authorities can have a direct impact on the vehicle market changes.

Consequences on the advanced vehicle market could be the following:

- Development of low prices little hybrids of all types, advanced electric vehicles and US type hybrids at the same time,
- Development of the electric two wheelers market (very important in China),
- Development of the hybrid and electric bus market.

In all cases the Chinese traction battery market will increase based on an internal production and consumption. This increase could have a consequence on the other markets (European and US) with an important decrease of the battery prices (NiMH, Lithium based).




World 2012 "Advanced" Traction Battery Market Forecast
Ton
200 000
180 000
160 000
140 000
120 000
100 000
80 000
60 000
40 000
20 000
0
Mini.
Maxi.
Advanced Lead-Acid
NiMH
NiMH (portable)
Lithium based
Lithium based (portable)

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# G – SUBAT Study Trip to China Report

# 1. Participants and agenda

## 1.1. Participants

The SUBAT delegation was composed of four participants :

| | | |
|---|---|---|
| - Claude ADES | CEREVEH | (France) |
| - Sandrine MEYER | Université Libre de Bruxelles | (Belgium) |
| - Julien MATHEYS | Vrije Universiteit Brussel | (Belgium) |
| - Carmine MIULLI | Università di Pisa | (Italy). |

The mission has been organized by AVERE Europe in collaboration with the Electric Vehicle department of the Chinese Electrotechnical Society. Professeur Liqing SUN (Ass. Professor of the School of Mechanic and Vehicle Technology of the Beijing Institute of Technology & Vice Secretary General of the Special Committee of Electric Vehicle, China Electrotechnical Society) accompanied the SUBAT delegation and handled most of the practical aspects during the trip.

## 1.2. Time Schedule of the mission

- 12/12/2004
    - Arrival in Beijing
    - China North Vehicle Research Institute, North Automotive
    - Quality Supervision & Inspection Institute & Appraisal Test

- 13/12/2004 :
    - Citic Guona MGL New Material Technology Institute ; Citic Guona Mengguli Power Science & Technology Co., Ltd
    - National Development Center of High-Tech Green Material, Beijing Institute of Technology Department of Automotive Engineering, State Key Laboratory of Automotive Safety & Energy, Tsinghua University, Beijing
    - Chinese Electrotechnical Sociéty (informal meeting)

- 14/12/2004 :
    - China Automotive Technology & Research Center (CATARC), Electric Vehicle Research Center (Tianjin)
    - Tianjin Institute of Power Sources, Tianjin Lantian Hi-Tech Power Sources Joint-Stock Co. Ltd

- 15/12/2004 :
    - Zibo Angel Electric Vehicle Co. Ltd
    - AUCMA New Power Technology Co Ltd (Qindao)

- 16/12/2004 : .
    - Wanxiang Group Power Battery Co Ltd, Wanxiang Group EV development Center (Hangzhou)

- 17/12/2004 : .
    - Tongji University (Shanghai)
    - BYD Company Limited

- 18/12/2004 : .
    - CC. Chan (Honarary Professor at the Hong-Kong University et Honorary Director of the International Research Center for Electric Vehicles)
    - Thunder sky Green Power Source Co Ltd (Shenzhen)

## 2. The 863 program

The 863 program is a long term program based on consecutive 5-year terms. This program was launched in 1986 with the aim to promote research and development in China. During the 2001-2005 period, almost 170 M€ were allocated to the new theme concerning clean vehicles. The goal is mainly to solve the major problems regarding transportation in China (energy supply, pollution, strong reliance on foreign manufacturers) before the 2008 Olympics in Beijing.
More specifically, this plan contains the key project « Electric Automobile » which is mainly devoted to hybrid electric vehicles, fuel cell vehicles and battery electric vehicles.

Most of the visited labs and companies strongly depend on the development of the 863 program. As a consequence, their activities have often been launched very recently (the eldest one are from 1999).

## 3. The private-public distinction

In China, the distinction between university laboratories and their private « spin-offs » is often quite vague, regarding the activities as well as regarding the employees.
This can probably be explained by the fact that most companies (even when they're listed on the stock-market) are government owned. Additionally the government strongly encourages universities to create associated companies, generally with public funding.

## 4. Global policy

In general, the R&D concerning traction batteries seems to be essentially focussed on batteries for pure electric vehicles. These R&D activities are mostly based on the electric bike market (this market is actually dominated by the lead-acid technology, mainly for reasons of a lower initial investment when buying the batteries)[3]. The only hybrid applications observed during the trip (Tongji University in Shanghai) were coupled to a fuel cell.

Regarding the technology, lithium seems to be the subject of most attention. Nevertheless, the NiMH and NiCd technology are taken into account too. Concerning NiMH, the cell size varies between 500g and 1kg at most, while the casing is always prismatic and plastic.

Concerning the lithium batteries, the research seems to be heading towards both the lithium-ion and the lithium polymer batteries, including the most recent cathodes based on lithiated iron phosphate.
Regarding the sizes of the lithium batteries, the offer is diversified and spreads from 50g to over 3kg. While, as far as packaging is concerned both steel and plastic prismatic casings are present, while the cylindrical casing (aluminium) is present too, but to a smaller extent.
During testing, great attention is given to the security issues linked to the use of lithium batteries.

It looks like all of the observed elements are derived from the portable devices market.

## 5. Regarding the visited labs

### 5.1. Testing Laboratories

Two of the three officially designated laboratories (Beijing and Tianjin, see agenda) were visited by the SUBAT delegation.

Both laboratories are very well-equipped with recent testing material (for example : 12 Digatron power type test banks, 10 cycling banks, etc.). However, none of the visited labs seems to dispose of test banks for complete batteries (complete battery including BMS and charger).

---

[3] Lithium batteries for example have a longer life time than the lead-acid ones, but the extra cost when buying them forms a serious impediment. An electric bike equipped with lead-acid batteries appears to cost +/- 200 € in China (+/- 3.5 kg of batteries with an autonomy of 45-50 km), while a lithium equipped version would cost twice as much.

On the other hand, the safety conditions to perform these tests (smoke evacuation problems for the fire testing, some compounds used during the nail test are non-conform to the European legislation, etc.) as well as the way the batteries are mounted (for example: no thermal conditioning, rudimentary BMS without any individual control of the elements, etc.) leave quite a lot to be desired,.

### 5.2. Research laboratories

No applied electrochemistry lab has been visited, as the Chinese organizer stressed the laboratories dedicated to the systems and to the vehicles (amongst other Bibendum Challenge 2004 in Beijing).

Except for CATARC (Tianjin), the university laboratories are mostly quite small and dispose of limited resources. However, the skills and competence of the personnel are comparable to the skills and competences of personnel in Europe.

CATARC works directly with several battery manufacturers (for example: Tianjin Lantian Hi-Tech Power Sources Joint-Stock Co. Ltd) and takes advantage of a joint-venture between Toyota and « Tianjin Auto ». The ultimate goal of the centre being the development of electric vehicles using Chinese compounds only. Additionally, these vehicles would probably be industrialized by the Chinese manufacturer in cooperation with the 863 program from 2008 or 2010 on.

## 6. Regarding the visited companies

A general characteristic seems to be the gigantism of the facilities (plants, premises) compared to the relatively low degree of activity (the production of lithium or NiMH traction batteries cannot yet be regarded as a real industrial activity) and compared to the available production tools.

The strategic behaviour of the companies, including the more important groups, such as BYD, AUCMA or Wanxiang, is still strongly dependent on the government's political decisions and on the developing strategies of the 863 program (cf. grants).

### 6.1. The start ups

The production level of car batteries of these companies is difficult to evaluate, but seems quite marginal.
Sometimes, like in the Zibo Angel company, a production line exists, but seems to be dedicated to two-wheeler applications (NiMH and NiCd).

#### 6.1.1. Citic Guona Mengguli Power Science & Technology (MGL)

MGL seems to be mainly focussing on the production of mineral powders dedicated to parts for electric, electronic and battery industry. More recently, the company started producing lithiated oxides. Since 2001, the company develops lithium batteries (all lithium technologies).

The produced cathodes are from the Li(CoO), Li(CoNiO) or Li(MnO) type, but research seems to be devoted to the « lithiated iron phosphate » type cathodes.

Prismatic battery prototypes in a flexible casing (100 to 400 Ah ; 115 Wh/kg for the elements), probably produced by simultaneous laminating of the electrodes and of the electrolyte (polymer), are equipping two electric buses and a van for the 863 program, as well as an electric bike (8Ah) and an electric scooter.
The batteries show poor performances for lighting applications (lamps) as the capacity drops 30% at 300 cycles. The main concern seems to be the thermal behaviour of the batteries (20% losses at -15°C ; identical discharge curves at 40°C and 60°C).

#### 6.1.2. Zibo Angel Electric Vehicle (1999 ; initial investment: 5 M€)

Zibo produces prismatic NiCd batteries with open as well as closed fritted electrodes. More recently, they started the production of NiMH batteries using prismatic elements in stainless steel casings (cf. pilot NiMH production for the 863 program).
The production chain seems to include a production line for electrodes as well as a packaging line.
Production capacity is said to reach 5 million Ah (aviation and military sales) and it's claimed, this capacity could be doubled.
The finishing of the 4 types of batteries (12, 25, 60 and 110 Ah ; 340 to 2800 g) is excellent and 1400 cycles can be performed in electric vehicle applications.

The market aimed at in the second place is the electric bike market as a more stringent regulation towards lead-acid batteries (90% of the actual e-bike market) is expected.

These batteries should be sold at about 300 €/kWh, which is three times the price of the lead-acid batteries, but which is still 20 to 40% cheaper than the European or American equivalent.

### 6.1.3. **Thundersky** (1998)

This company has provided several electric vehicle batteries to European companies, but its reputation amongst the Chinese scientists remains inconstant.
The diffusion of information concerning the (impressive) spectrum of products (cells, modules, packs and electric vehicles) is important but, little information is released concerning the performances or the production of the batteries.

Released information is often contradictory and the visit of the factory was limited to the visit of an empty plant (due to imminent moving) and to a stock pile of ready-to-sell batteries. The predicted turn-over of the new high capacity plant (end of 2005) would be over 400 M€.
Currently, the production is restricted to the commitments taken in the framework of the 863 program and this production is performed in a rented factory, according to the ordered products.

As opposite to previous communications, Thundersky certifies it produces Li-Ion polymer batteries and Li-Ion batteries with a solid electrolyte based on Li(MnO) type cathodes. According to the performances of the Leitian EV3, calculations would yield a specific energy of about 144 Wh/kg and a specific power of 40 to 120 kW/kg (constant/pulsed).
According to Thundersky, the cycle life of the batteries could reach 1000 to 2000 DOD80 cycles.

Production cost would be approximately 100 $/kWh (in China) and the sales price would be fluctuating between 200 and 280 $/kWh in Europe and in the USA.

## 6.2. Companies consolidating previous (existing) activities

Tianjin Lantian Hi-Tech Power Sources Joint-Stock is a part of a complex group based principally in Tianjin. The main activity of this group is the production of batteries of all types (it seems, this would be the biggest industrial battery producer in China, and the Joint-Stock would have been created in 1998 to focus on the electric and hybrid electric vehicle market).
The company provides CATARC with lithium batteries and signed a joint venture with the Chinese car manufacturer Wuhan.
Prismatic and cylindrical cells of diverse capacities are produced, but mostly these capacities are quite high (BEV 50 Ah ; HEV 8 Ah ; 112 Wh/kg ; 271 Wh/l). These cells are based on a Li(CoO) cathode / and a classic liquid electrolyte. Today, the research is mainly focussing on new cathode materials.

The new production line is based on spiralling machines bought in Japan and in the USA, but the local machines remain quite outdated.
Right now, 10 batteries (250 kg including BMS) are produced each year mainly for the 863 program. In 2004, roughly 200 EV have been sold in China, while 1000 units are expected to be sold in 2008. A production capacity of 10 millions cells per year will be reached in 2006.

Since recently, attention has been paid to hybrids, with following performances: 850 W/kg, 80 Wh/kg, 15 C 10 s and 50 A in charge below 50% SOC (9 Ah cell).

While the safety tests are quite severe (amongst others usage at 65°C), but the cycle life is relatively limited (600 cycles 100%DOD).

The size of the testing centre and the resources of the Tianjin Institute of Power Sources, are comparable to its European equivalents. It appears this centre is the largest one on this subject.

## 6.3. Departments or subsidiaries of large groups

### 6.3.1. **AUCMA New Power Technology** (Qingdao ; first household appliances and electricity components manufacturer; turn-over 2004 : 3000 million RMB (+/- 300million €) ; 8.000 employees ; 20 subsidiaries)

The traction battery subsidiary has been created in 2000 under the encouragement of the government and in the framework of the lithium-ion batteries aspect of the 863 program.
Since 2003, AUCMA produces lithium-ion batteries (40 million cells/year) for cellular phone applications (amongst others Nokia or Motorola). One production line is dedicated to « stacks » (anodes, separators, cathodes) and a second one is dedicated to the assembly of the elements and to packaging. Most of the operations are performed by hand. Only the fritting of the electrodes is performed using semi-automatic ovens. Additionally, the company disposes of a testing laboratory and a quality control laboratory (reproducibility problems?).

An automated production line should be installed next year to double the production capacity.

The development of the cells began with the Li(CoO) technology with liquid electrolyte (15 Ah ; 286 Wh/l and 117 Wh/kg), and then evolved to the Li(MnO) technology. However, this included serious problems regarding cycle life at high temperatures (12 Ah ; 230 Wh/l ; 80 Wh/kg). It appears the BMS on has got no thermal balance and that the cycle life performances of the elements would be low (300 cycles at 100%DOD).
In the end, the choice has been to focus on a lithiated iron cathode with a polymeric electrolyte (195 Wh/l ; 60 Wh/kg). It seems this last technology shows excellent cycle life performances.

According to a market study performed by AUCMA, the price of the lithium batteries should drop to 250-300 €/kWh to enable it to breakthrough the electric bike market (depending on the applied exchange rate).

### 6.3.2. **Wanxiang Group Power Battery** (Hangzhou ; largest Chinese automobile OEM manufacturer, 31000 employees)

The group diversified heavily and created, a subsidiary, Wanxiang Electric Vehicle Centre in the framework of the 863 program, in 1999 and its subsubsidiary Wanxiang Power Batteries Co., Ltd. in 2000. The last one develops Li(MnO) type lithium-ion polymer batteries from different sizes (12 Ah, 60 Ah up to 120 Ah, 3,8 kg). The packaging is partially made of rigid plastics and partially made of metal.

Wanxiang also develops electric motors, BMS electronics as well as the centralized BMS of the pack (not cooled).

Three buses (2 electric and 1 hybrid) as well as 6 personal vehicles (based on Mazda models ; 50 kW) were developed for the 863 program. The battery (290 kg ; 37 kWh ; 127 Wh/kg) does not work on the basis of modules but on the basis of individual cells. The battery is partially located under the hood (natural air cooling) and partially in the trunk (no cooling) of the car. The BMS is centralized and does not include any cell electronics or thermal control unit. The battery can withstand temperatures up to 65°C.
Anyhow, most of the batteries tested in the company's laboratories were cellular phone type batteries.

### 6.3.3. **BYD Company Limited** (Shenzhen ; one of the most important portable Li-ion, NiCd and NiMH batteries manufacturers; over 35.000 employees)

BYD was created in 1995 and diversified in 1999. In 2001, the 863 program raised its interest in traction batteries and BYD bought a « government owned » Chinese car manufacturer (Xi'an Auto) in 2003.

Various electric and hybrid vehicle concepts have been developed. These are based on the LiCoO type lithium-ion batteries (cell at 200 Ah), including a high autonomy (400 kg of batteries), a concept car and a small hybrid car (100 kg of batteries, 296 V).
A cycle life of 1000 cycles at 80%DOD is claimed.
The BMS is produced on-site and it seems it includes a complementary electronic cell equilibrating system. The cooling is performed using air circulation.

BYD aims at a production of 200.000 vehicles in 2008. However, the company has no clear sight regarding the development of the electric vehicle market in China. Also, BYD confirms that the e-bike market is promising, but estimates the prices should drop, should they want to enter that market.

## 7. Environmental issues

Various national emissions standards concerning air and water emissions exist in China. However, environmental aspects are far from being the main concern of the visited companies. Additionally, the compliance with the environmental regulations does not appear to be an issue when developing the activities.

During the discussions with the visited companies, no environmental data concerning the fabrication of batteries or their components could be provided at all. It seems the companies do not even possess such kind of data.

A swift visual analysis of the installations we visited did not result in the discovery of extended air or water pollution control systems.

Additionally, the separation of industrial and residential areas is virtually inexistent as the production facilities are sometimes located in urban areas and as the employees and their families often live in residential buildings on the same site as the production plant.

Concerning energy consumption, no data were available neither, but as has been told before, the installations are often quite ancient, and as a consequence, we can assume that the energy efficiencies are most probably lower than in more recent/modern plants.

Finally, as has been said in the paragraphs concerning the testing laboratories, the safety conditions (amongst others regarding smoke evacuation) most often don't match any occidental standards and thus tend to be very poor.

## 8. Conclusions

The 863 program is the essential trigger to the development of the traction batteries business in China. Originally, the attention was set on the NiMH batteries, but quite soon, (all types of) lithium batteries seemed to be preferred.
Up to now, the performances of the batteries are average, but optimization seems plausible.
Laboratories are well-equipped, employ skilled personnel and collaborate closely with companies.
As far as commercialization is concerned, the main goal is the electric bike market (very important in China), followed by the power type portable applications.
The industrial activity is somewhat presents a slight « delay » compared to the EU or the USA and can be described as a little more ancient. But, the start of this industrial activity is quite recent (+/- 2000) and is expected to develop quite rapidly in the next few years as the mass production costs are estimated to be 20 to 30 % lower than the mass production costs in Japan, the USA or Europe.
Finally, from an environmental point of view, and from a workers safety point of view, numerous optimizations should be implemented should the production and testing be performed in a way that's comparable or even acceptable when using European standards. Next to the low employment cost in China, this « environmental indulgence » might play a role in the decision of a corporation, when it comes to choosing a place to invest in the building of new facilities or extension of existing ones.

APPENDIX IV

# WP5 Annex
# Subat Overall Assessement

MKA_DLAB_v16.dlab
Report generated on18/04/2005 14:02:43

- Author: Joeri Van Mierlo
- Date Created: 18/02/2005 10:31:40
- Date Modified: 18/02/2005 10:33:58
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- Walking Weights
- Stability Intervals

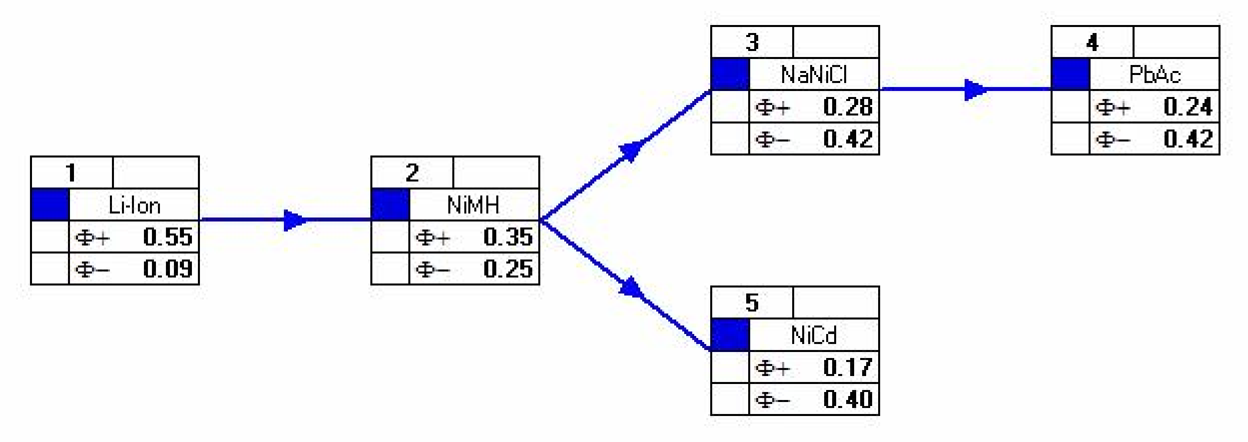
## Scores for scenario

| | Energy Density | Power Density | Cycles | Energy efficiency | LCA | Cost | Maturity | userfriendly |
|---|---|---|---|---|---|---|---|---|
| PbAc | -0.9688 | -0.2500 | -1.0000 | 0.0833 | -0.4038 | 0.4644 | 0.3125 | 0.2500 |
| NiCd | -0.4792 | -0.5000 | 0.3281 | -0.7292 | -0.4606 | -0.2683 | 0.3125 | 0.2500 |
| NiMH | -0.0521 | 0.5670 | 0.3281 | -0.7708 | 0.1682 | -0.1170 | -0.0625 | 0.2500 |
| Li-Ion | 0.6585 | 0.9330 | 0.1719 | 0.9792 | 0.6935 | 0.1280 | -0.3125 | 0.2500 |
| NaNiCl | 0.8415 | -0.7500 | 0.1719 | 0.4375 | 0.0027 | -0.2070 | -0.2500 | -1.0000 |

Rankings for scenario

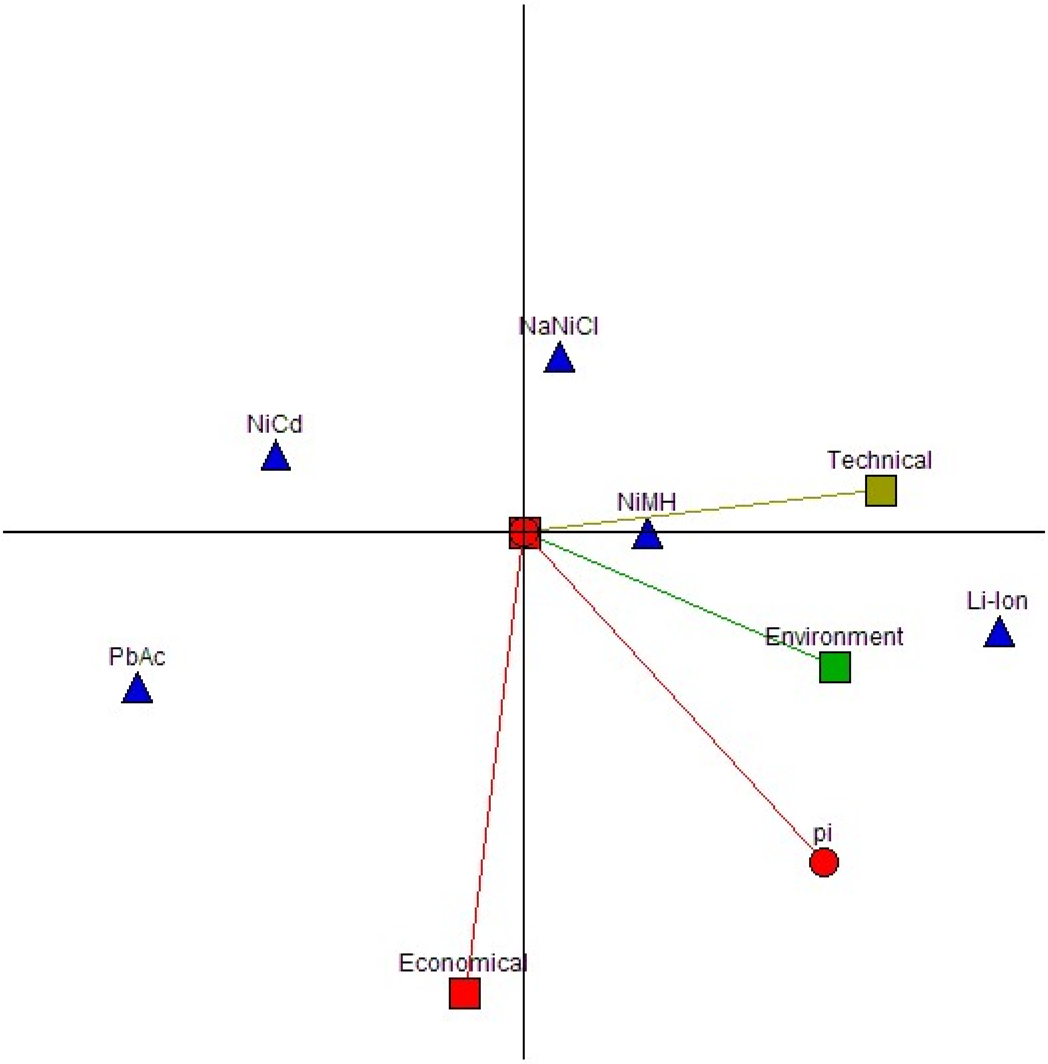
| | Phi Plus | Phi Minus | Phi Net | Ranking |
|---|---:|---:|---:|---:|
| PbAc | 0.2437 | 0.4237 | -0.1800 | 4 |
| NiCd | 0.1681 | 0.4001 | -0.2320 | 5 |
| NiMH | 0.3477 | 0.2467 | 0.1009 | 2 |
| Li-Ion | 0.5460 | 0.0902 | 0.4558 | 1 |
| NaNiCl | 0.2752 | 0.4199 | -0.1447 | 3 |

Partial Ranking (PROMETHEE I)

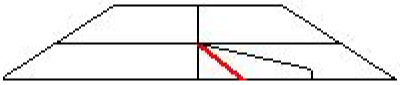


Complete Ranking (PROMETHEE II)

GAIA Planes

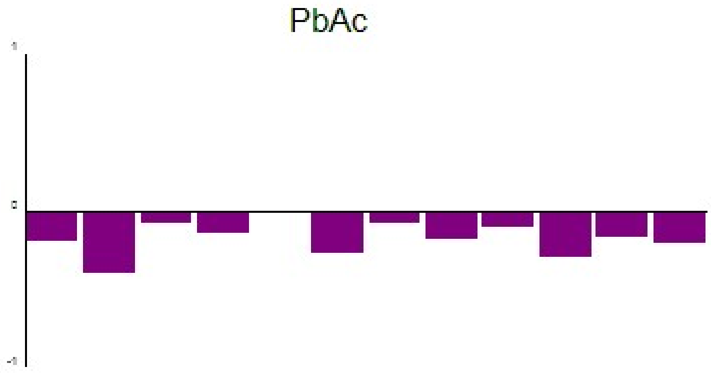


Decision Stick

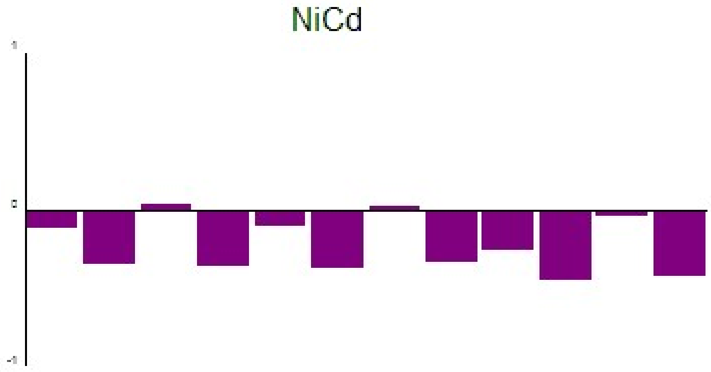


Actions Profiles

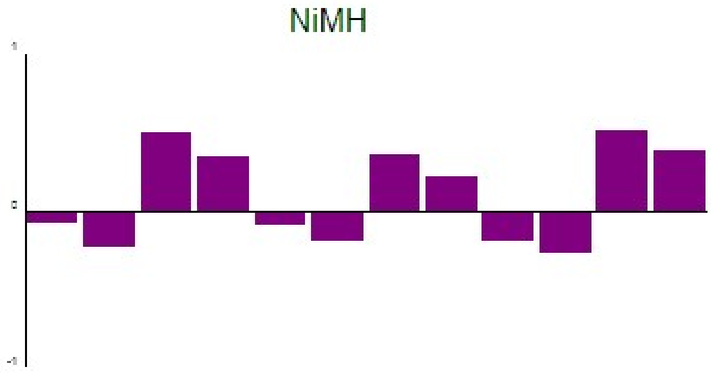
Action : PbAc



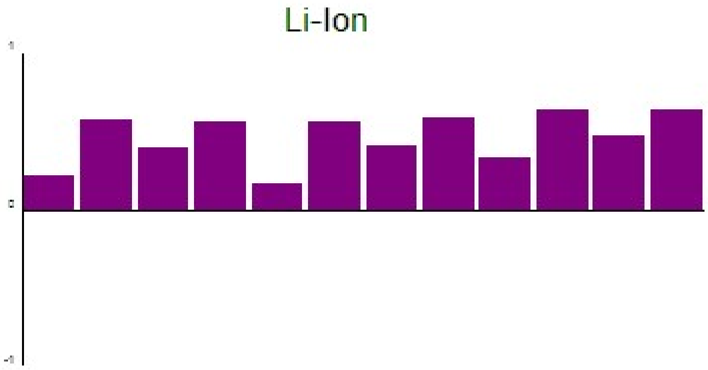
Action : NiCd



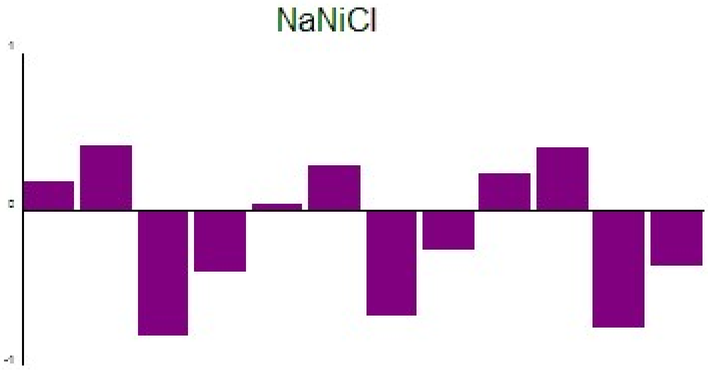
Action : NiMH



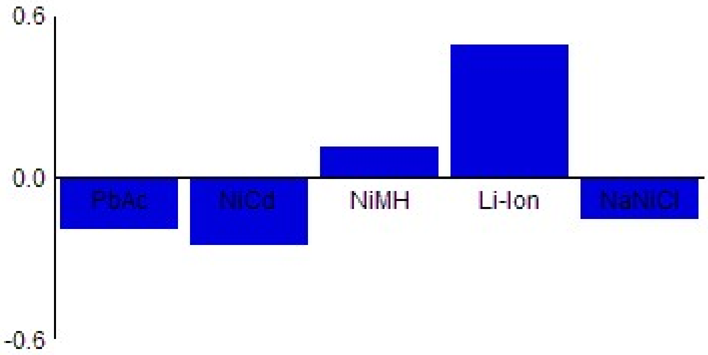
Action : Li-Ion

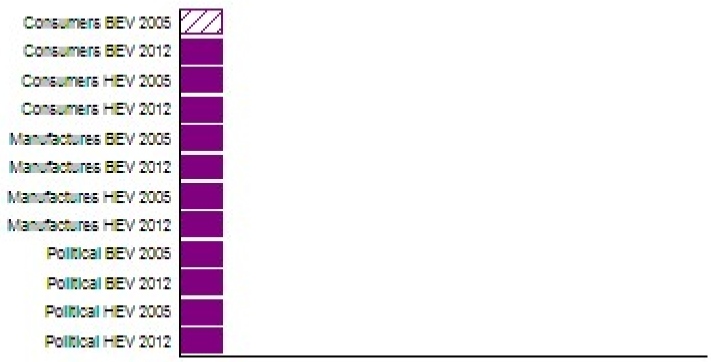


Action : NaNiCl



Walking Weights





Stability Intervals for scenario
Level=5

| | Absolute values | | | Relative values (%) | | |
|---|---|---|---|---|---|---|
| | Weight | Min | Max | Weight | Min | Max |
| Consumers BEV 2005 | 1.0000 | 0.0000 | 9.1725 | 8.33% | 0.00% | 45.47% |
| Consumers BEV 2012 | 1.0000 | 0.4738 | 5.6596 | 8.33% | 4.13% | 33.97% |
| Consumers HEV 2005 | 1.0000 | 0.0000 | 1.5839 | 8.33% | 0.00% | 12.59% |
| Consumers HEV 2012 | 1.0000 | 0.0000 | 2.6603 | 8.33% | 0.00% | 19.47% |
| Manufactures BEV 2005 | 1.0000 | 0.0000 | 24.0778 | 8.33% | 0.00% | 68.64% |
| Manufactures BEV 2012 | 1.0000 | 0.2310 | 7.3088 | 8.33% | 2.06% | 39.92% |
| Manufactures HEV 2005 | 1.0000 | 0.0000 | 1.7070 | 8.33% | 0.00% | 13.43% |
| Manufactures HEV 2012 | 1.0000 | 0.0000 | 6.3368 | 8.33% | 0.00% | 36.55% |
| Political BEV 2005 | 1.0000 | 0.0000 | 7.9759 | 8.33% | 0.00% | 42.03% |
| Political BEV 2012 | 1.0000 | 0.3844 | 5.4940 | 8.33% | 3.38% | 33.31% |
| Political HEV 2005 | 1.0000 | 0.0000 | 1.7366 | 8.33% | 0.00% | 13.63% |
| Political HEV 2012 | 1.0000 | 0.0000 | 3.9630 | 8.33% | 0.00% | 26.49% |

Scenario: Consumers BEV 2005

- Short Name: Con BEV 05
- Description:
- Color: 5
- Symbol: 9
- Category: Scenarios
- Enabled: Yes

Evaluations Preferences Results

Evaluations for scenario *Consumers BEV 2005*

| | Energy Density | Power Density | Cycles | Energy efficiency | LCA | Cost | Maturity | userfriendly |
|---|---|---|---|---|---|---|---|---|
| PbAc | 40 | 250 | 500.0 | 83 | 503 | 10085 | 100 | 100 |
| NiCd | 60 | 200 | 1350.0 | 73 | 544 | 17355 | 100 | 100 |
| NiMH | 70 | 350 | 1350.0 | 70 | 491 | 20254 | 60 | 100 |
| Li-Ion | 125 | 400 | 1000.0 | 90 | 278 | 25338 | 60 | 100 |
| NaNiCl | 125 | 200 | 1000.0 | 86 | 234 | 17109 | 80 | 60 |

Back to scenario *Consumers BEV 2005*

Preferences for scenario *Consumers BEV 2005*

| | Energy Density | Power Density | Cycles | Energy efficiency | LC |
|---|---|---|---|---|---|
| Function Type | 4 | 4 | 4 | 4 | |
| Minimized | False | False | False | False | Tr |
| P | 25 | 25 | 50 | 5 | |
| Q | 5 | 5 | 10 | 2 | |
| S | 1.17647058823529 | 5.55555555555556E-02 | 0.117647058823529 | 1 | 0.322580645161 |
| Unit | Wh/kg | W/kg | # | % | EcoPoi |
| Scale | (Numerical) | (Numerical) | (Numerical) | (Numerical) | (Numeric |
| Weight | 30 | 5 | 15 | 0 | |

Back to scenario *Consumers BEV 2005*

Results for scenario *Consumers BEV 2005*

- Rankings
- Scores
- PROMETHEE I
- PROMETHEE II
- GAIA Planes
- Actions Profiles
- Walking Weights
- Stability Intervals

Back to scenario *Consumers BEV 2005*

Scores for scenario *Consumers BEV 2005*

| | Energy Density | Power Density | Cycles | Energy efficiency | LCA | Cost | Maturity | userfriendly |
|---|---|---|---|---|---|---|---|---|
| PbAc | -1.0000 | 0.0000 | -1.0000 | 0.1667 | -0.4561 | 0.8579 | 0.7500 | 0.2500 |
| NiCd | -0.3958 | -0.7500 | 0.5625 | -0.7083 | -0.4908 | -0.0865 | 0.7500 | 0.2500 |
| NiMH | -0.1042 | 0.6339 | 0.5625 | -0.7917 | -0.4448 | -0.2495 | -0.7500 | 0.2500 |
| Li-Ion | 0.7500 | 0.8661 | -0.0625 | 0.9583 | 0.6417 | -0.4504 | -0.7500 | 0.2500 |
| NaNiCl | 0.7500 | -0.7500 | -0.0625 | 0.3750 | 0.7500 | -0.0715 | 0.0000 | -1.0000 |

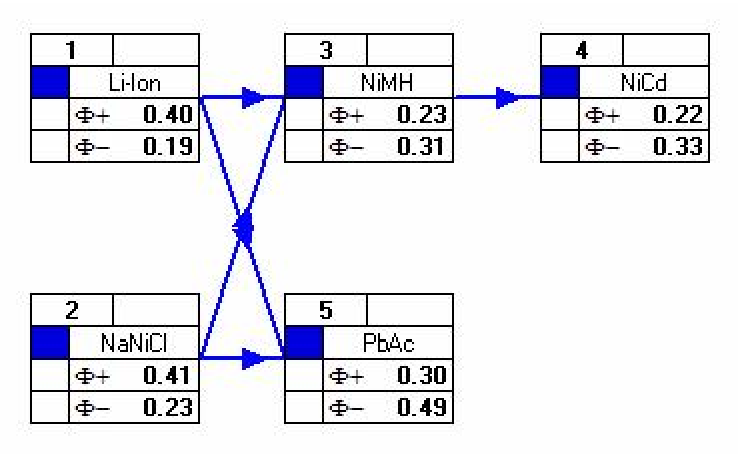
Back to results of scenario *Consumers BEV 2005*

Rankings for scenario *Consumers BEV 2005*

| | Phi Plus | Phi Minus | Phi Net | Ranking |
|---|---|---|---|---|
| PbAc | 0.2999 | 0.4924 | -0.1925 | 5 |
| NiCd | 0.2179 | 0.3340 | -0.1161 | 4 |
| NiMH | 0.2311 | 0.3107 | -0.0796 | 3 |
| Li-Ion | 0.3993 | 0.1909 | 0.2084 | 1 |
| NaNiCl | 0.4076 | 0.2278 | 0.1797 | 2 |

Back to results of scenario *Consumers BEV 2005*

Partial Ranking (PROMETHEE I)

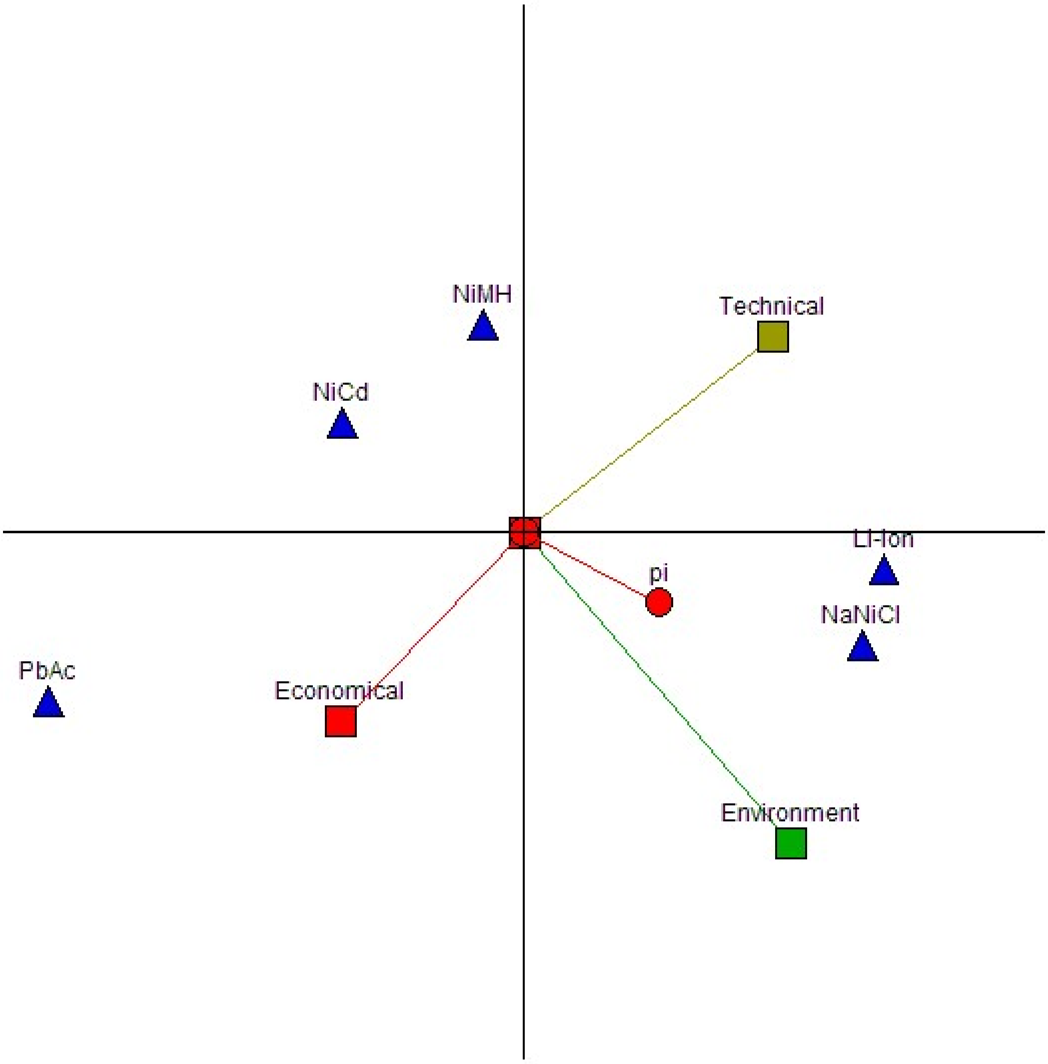


Back to results of scenario *Consumers BEV 2005*

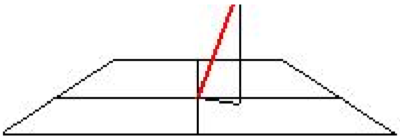
Complete Ranking (PROMETHEE II)

Back to results of scenario *Consumers BEV 2005*

GAIA Planes



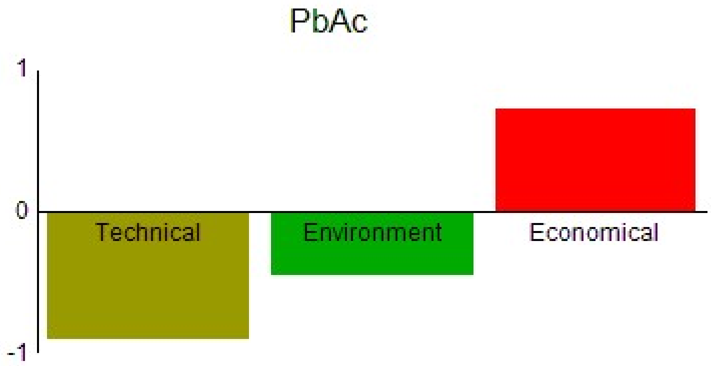
Decision Stick



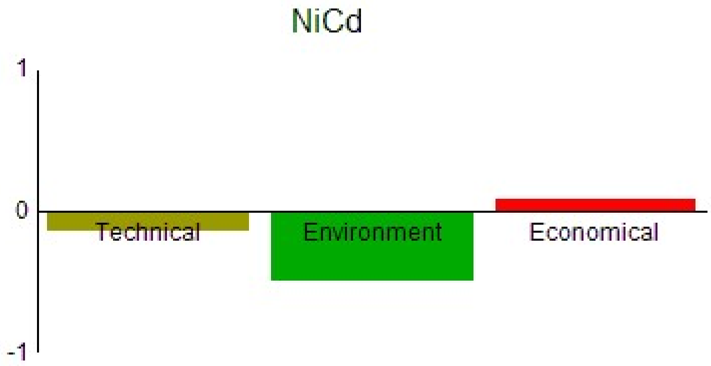
Back to results of scenario *Consumers BEV 2005*

Actions Profiles

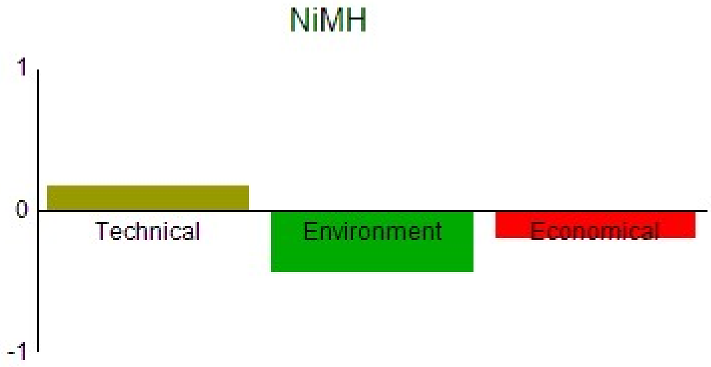
Action : PbAc



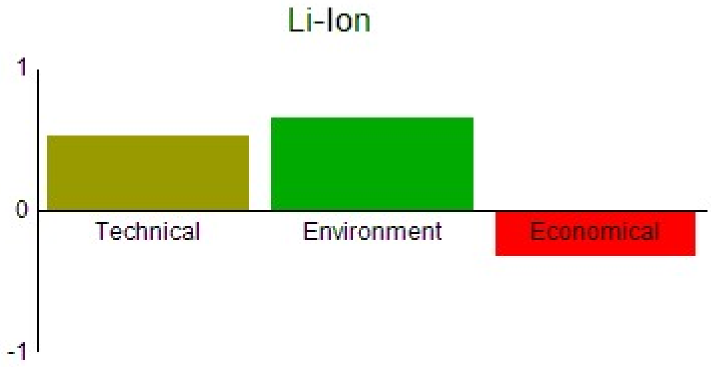
Action : NiCd



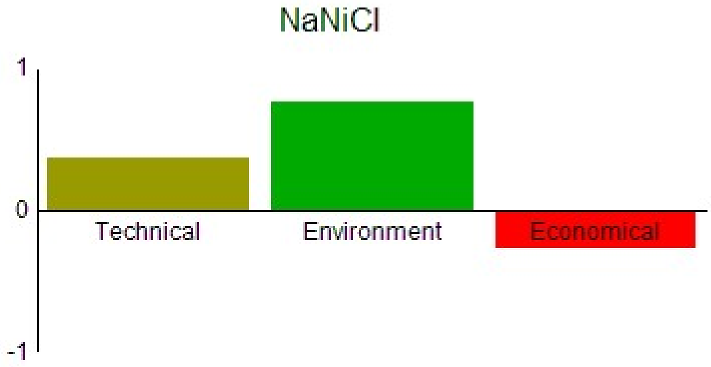
Action : NiMH



Action : Li-Ion

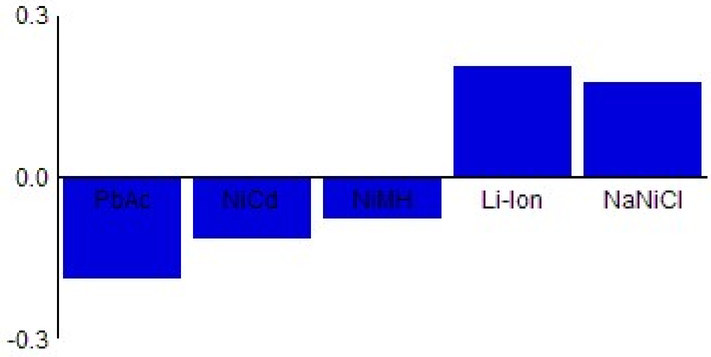


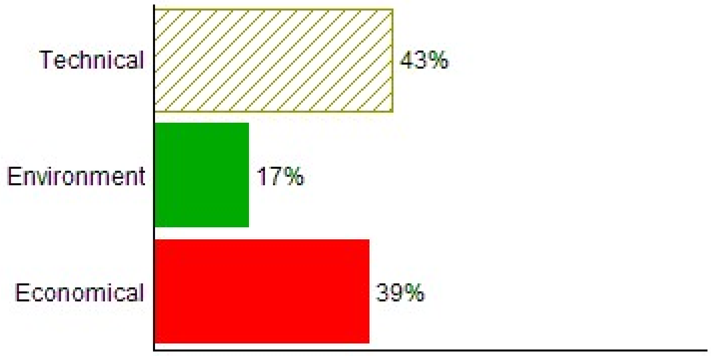
Action : NaNiCl



Back to results of scenario *Consumers BEV 2005*

Walking Weights





Back to results of scenario *Consumers BEV 2005*

Stability Intervals for scenario *Consumers BEV 2005*
Level=5

| | Absolute values | | | Relative values (%) | | |
|---|---|---|---|---|---|---|
| | Weight | Min | Max | Weight | Min | Max |
| Energy Density | 30.0000 | 38.3819 | -1.0000 | 26.09% | 37.13% | 100.00% |
| Power Density | 5.0000 | 0.0000 | 17.5809 | 4.35% | 0.00% | 11.52% |
| Cycles | 15.0000 | 0.0000 | 9.0117 | 13.04% | 0.00% | 5.85% |
| Energy efficiency | 0.0000 | 0.0000 | 13.8487 | 0.00% | 0.00% | 8.72% |
| LCA | 20.0000 | 0.0000 | 50.4629 | 17.39% | 0.00% | 34.69% |
| Cost | 30.0000 | 0.0000 | 58.9552 | 26.09% | 0.00% | 45.72% |
| Maturity | 5.0000 | 0.0000 | 6.7511 | 4.35% | 0.00% | 6.98% |
| userfriendly | 10.0000 | 0.0000 | 0.0000 | 8.70% | 0.00% | 0.00% |

Back to results of scenario *Consumers BEV 2005*

Scenario: Consumers BEV 2012

- Short Name: Con BEV 12
- Description:
- Color: 5
- Symbol: 9
- Category: Scenarios
- Enabled: Yes

Evaluations Preferences Results

Evaluations for scenario *Consumers BEV 2012*

| | Energy Density | Power Density | Cycles | Energy efficiency | LCA | Cost | Maturity | userfriendly |
|---|---|---|---|---|---|---|---|---|
| PbAc | 40 | 250 | 1000.0 | 85 | 331 | 6432 | 100 | 100 |
| NiCd | 60 | 200 | 2000.0 | 75 | 427 | 11286 | 100 | 100 |
| NiMH | 70 | 350 | 2000.0 | 75 | 364 | 12684 | 100 | 100 |
| Li-Ion | 150 | 400 | 2000.0 | 95 | 122 | 4504 | 100 | 100 |
| NaNiCl | 150 | 200 | 2000.0 | 90 | 129 | 4059 | 100 | 60 |

Back to scenario *Consumers BEV 2012*

Preferences for scenario *Consumers BEV 2012*

| | Energy Density | Power Density | Cycles | Energy efficiency | LCA | Cost | Maturity | userfriendly |
|---|---|---|---|---|---|---|---|---|
| Function Type | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Minimized | False | False | False | False | True | True | False | False |
| P | 25 | 25 | 50 | 5 | 50 | 50 | 20 | 20 |
| Q | 5 | 5 | 10 | 2 | 20 | 20 | 10 | 10 |
| S | 1.17647058823529 | 5.55555555555556E-02 | 0.117647058823529 | 1 | 0.32258064516129 | 5.17812758906379E-03 | 1 | 0 |
| Unit | Wh/kg | W/kg | # | % | EcoPoints | EUR | % | |
| Scale | (Numerical) | (Numerical) | (Numerical) | (Numerical) | (Numerical) | (Numerical) | (Numerical) | (Numerical) |
| Weight | 30 | 5 | 15 | 0 | 20 | 30 | 5 | 10 |

Back to scenario *Consumers BEV 2012*

Results for scenario *Consumers BEV 2012*

- Rankings
- Scores
- PROMETHEE I
- PROMETHEE II
- GAIA Planes
- Actions Profiles
- Walking Weights
- Stability Intervals

Back to scenario *Consumers BEV 2012*

Scores for scenario *Consumers BEV 2012*

| | Energy Density | Power Density | Cycles | Energy efficiency | LCA | Cost | Maturity | userfriendly |
|---|---|---|---|---|---|---|---|---|
| PbAc | -1.0000 | 0.0000 | -1.0000 | 0.0000 | -0.4793 | 0.2119 | 0.0000 | 0.2500 |
| NiCd | -0.3958 | -0.7500 | 0.2500 | -0.7500 | -0.5207 | -0.6917 | 0.0000 | 0.2500 |
| NiMH | -0.1042 | 0.6339 | 0.2500 | -0.7500 | -0.5000 | -0.7441 | 0.0000 | 0.2500 |
| Li-Ion | 0.7500 | 0.8661 | 0.2500 | 1.0000 | 0.7500 | 0.5831 | 0.0000 | 0.2500 |
| NaNiCl | 0.7500 | -0.7500 | 0.2500 | 0.5000 | 0.7500 | 0.6408 | 0.0000 | -1.0000 |

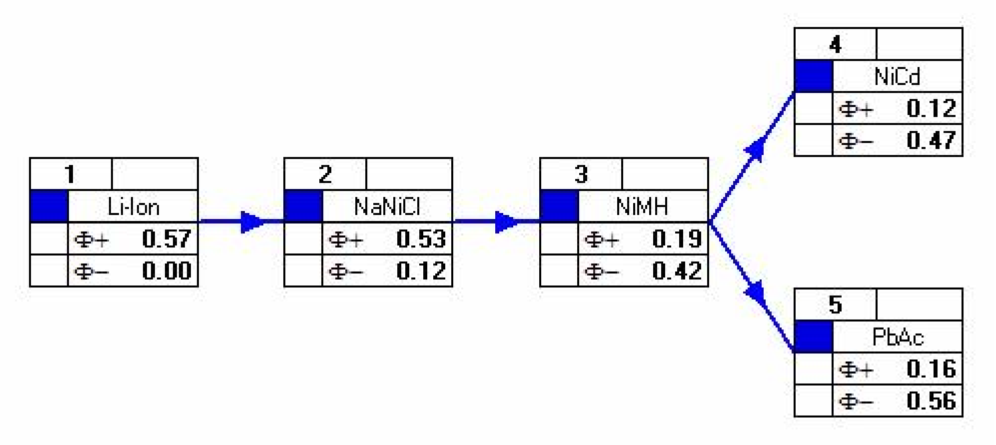
Back to results of scenario *Consumers BEV 2012*

Rankings for scenario *Consumers BEV 2012*

| | Phi Plus | Phi Minus | Phi Net | Ranking |
|---|---|---|---|---|
| PbAc | 0.1608 | 0.5584 | -0.3976 | 5 |
| NiCd | 0.1196 | 0.4721 | -0.3525 | 4 |
| NiMH | 0.1902 | 0.4165 | -0.2263 | 3 |
| Li-Ion | 0.5702 | 0.0000 | 0.5702 | 1 |
| NaNiCl | 0.5259 | 0.1196 | 0.4063 | 2 |

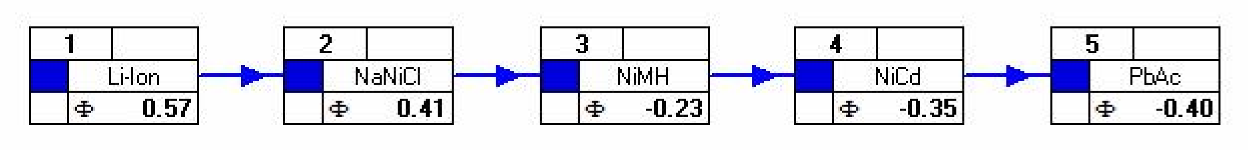
Back to results of scenario *Consumers BEV 2012*

Partial Ranking (PROMETHEE I)



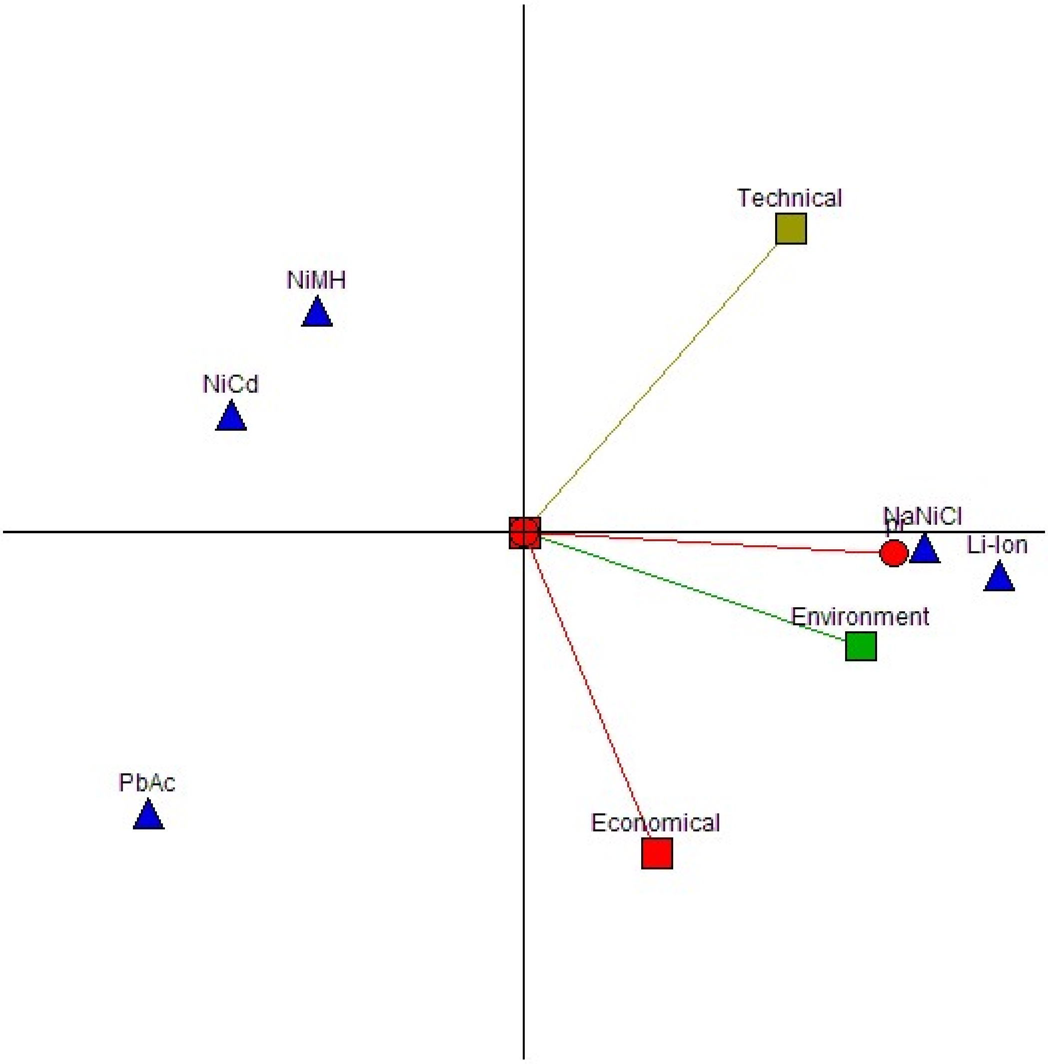
Back to results of scenario *Consumers BEV 2012*

Complete Ranking (PROMETHEE II)

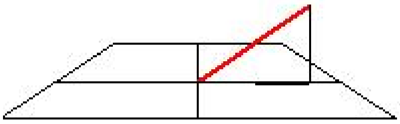


Back to results of scenario *Consumers BEV 2012*

GAIA Planes



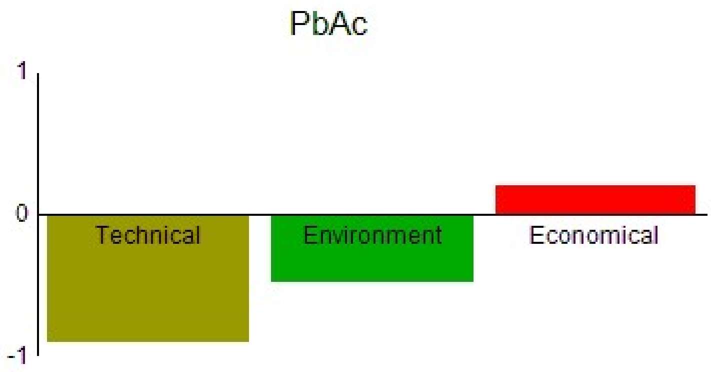
Decision Stick



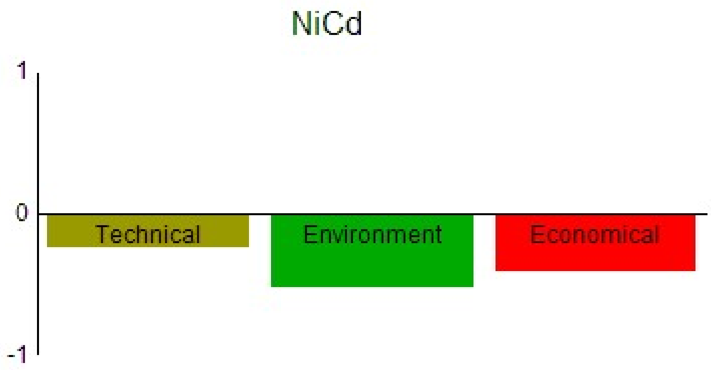
Back to results of scenario *Consumers BEV 2012*

Actions Profiles

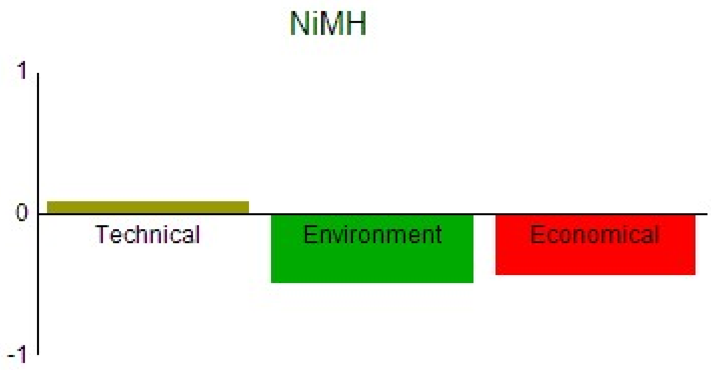
Action : PbAc



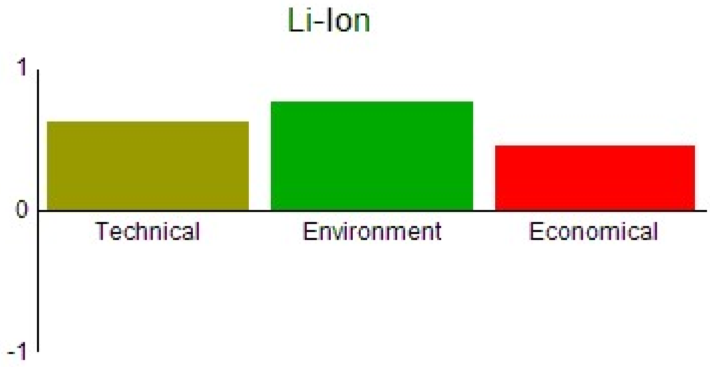
Action : NiCd



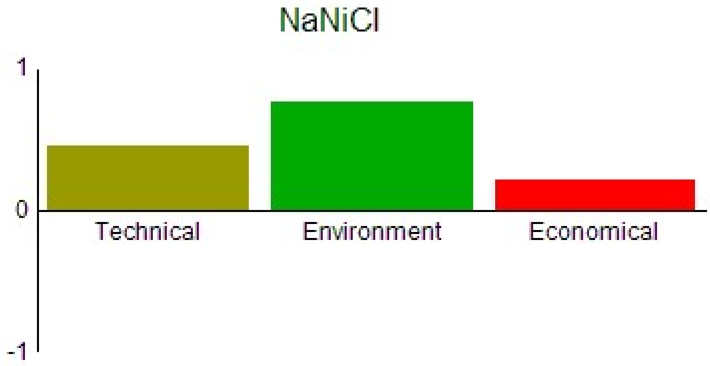
Action : NiMH



Action : Li-Ion

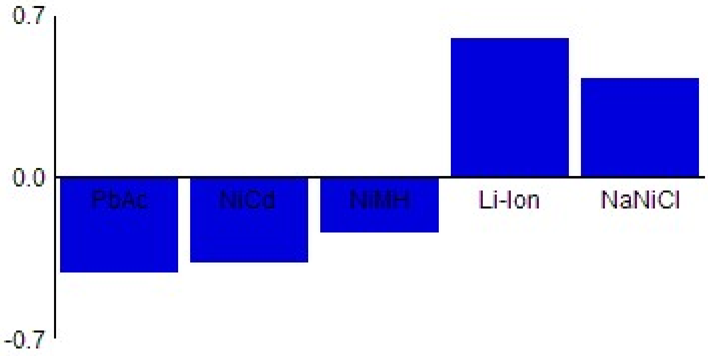


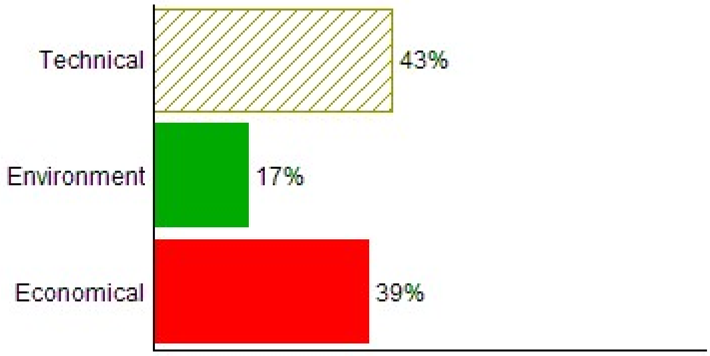
Action : NaNiCl



Back to results of scenario *Consumers BEV 2012*

Walking Weights





Back to results of scenario *Consumers BEV 2012*

Stability Intervals for scenario *Consumers BEV 2012*
Level=5

| | Absolute values | | | Relative values (%) | | |
|---|---|---|---|---|---|---|
| | Weight | Min | Max | Weight | Min | Max |
| Energy Density | 30.0000 | 42.1697 | -1.0000 | 26.09% | 39.35% | 100.00% |
| Power Density | 5.0000 | 0.0000 | 17.5809 | 4.35% | 0.00% | 11.52% |
| Cycles | 15.0000 | 0.0000 | 9.0117 | 13.04% | 0.00% | 5.85% |
| Energy efficiency | 0.0000 | 0.0000 | 13.8487 | 0.00% | 0.00% | 8.72% |
| LCA | 20.0000 | 0.0000 | 145.3830 | 17.39% | 0.00% | 60.48% |
| Cost | 30.0000 | 0.0000 | 53.6109 | 26.09% | 0.00% | 43.37% |
| Maturity | 5.0000 | 0.0000 | 6.7511 | 4.35% | 0.00% | 6.98% |
| userfriendly | 10.0000 | 0.0000 | 0.0000 | 8.70% | 0.00% | 0.00% |

Back to results of scenario *Consumers BEV 2012*

Scenario: Consumers HEV 2005

- Short Name: Con HEV 05
- Description:
- Color: 5
- Symbol: 9
- Category: Scenarios
- Enabled: Yes

Evaluations Preferences Results

Evaluations for scenario *Consumers HEV 2005*

| | Energy Density | Power Density | Cycles | Energy efficiency | LCA | Cost | Maturity | userfriendly |
|---|---|---|---|---|---|---|---|---|
| PbAc | 25 | 350 | 1.0 | 83 | 14 | 432 | 100 | 100 |
| NiCd | 30 | 500 | 3.0 | 73 | 10 | 624 | 100 | 100 |
| NiMH | 55 | 1500 | 3.0 | 70 | 3 | 456 | 100 | 100 |
| Li-Ion | 70 | 2000 | 3.0 | 90 | 4 | 684 | 50 | 100 |
| NaNiCl | 125 | 200 | 3.0 | 86 | 23 | 2976 | 0 | 60 |

Back to scenario *Consumers HEV 2005*

Preferences for scenario *Consumers HEV 2005*

| | Energy Density | Power Density | Cycles | Energy efficiency | LCA | Cost | Maturity | userfriendly |
|---|---|---|---|---|---|---|---|---|
| Function Type | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Minimized | False | False | False | False | True | True | False | False |
| P | 25 | 25 | 50 | 5 | 50 | 50 | 20 | 20 |
| Q | 5 | 5 | 10 | 2 | 20 | 20 | 10 | 10 |
| S | 1.17647058823529 | 5.55555555555556E-02 | 0.117647058823529 | 1 | 0.32258064516129 | 5.17812758906379E-03 | 1 | 0 |
| Unit | Wh/kg | W/kg | # | % | EcoPoints | EUR | % | |
| Scale | (Numerical) | (Numerical) | (Numerical) | (Numerical) | (Numerical) | (Numerical) | (Numerical) | (Numerical) |
| Weight | 5 | 20 | 5 | 0 | 20 | 30 | 5 | 10 |

Back to scenario *Consumers HEV 2005*

Results for scenario *Consumers HEV 2005*

- Rankings
- Scores
- PROMETHEE I
- PROMETHEE II
- GAIA Planes
- Actions Profiles
- Walking Weights
- Stability Intervals

Back to scenario *Consumers HEV 2005*

Scores for scenario *Consumers HEV 2005*

| | Energy Density | Power Density | Cycles | Energy efficiency | LCA | Cost | Maturity | userfriendly |
|---|---|---|---|---|---|---|---|---|
| PbAc | -0.9375 | -0.5000 | -1.0000 | 0.1667 | -0.3936 | 0.4801 | 0.5000 | 0.2500 |
| NiCd | -0.5625 | 0.0000 | 0.2500 | -0.7083 | -0.1945 | 0.1026 | 0.5000 | 0.2500 |
| NiMH | 0.0000 | 0.5000 | 0.2500 | -0.7917 | 0.8645 | 0.4188 | 0.5000 | 0.2500 |
| Li-Ion | 0.5000 | 1.0000 | 0.2500 | 0.9583 | 0.6355 | -0.0015 | -0.5000 | 0.2500 |
| NaNiCl | 1.0000 | -1.0000 | 0.2500 | 0.3750 | -0.9118 | -1.0000 | -1.0000 | -1.0000 |

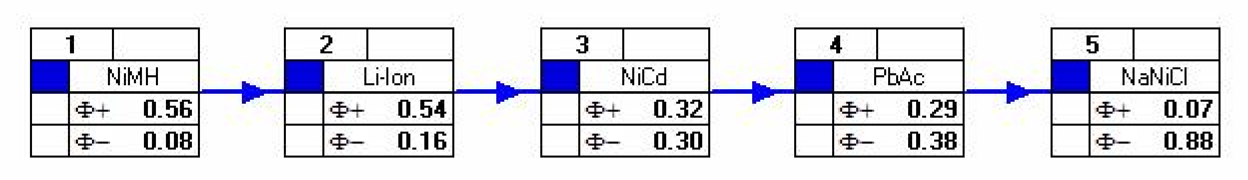
Back to results of scenario *Consumers HEV 2005*

Rankings for scenario *Consumers HEV 2005*

| | Phi Plus | Phi Minus | Phi Net | Ranking |
|---|---|---|---|---|
| PbAc | 0.2909 | 0.3768 | -0.0859 | 4 |
| NiCd | 0.3242 | 0.2966 | 0.0276 | 3 |
| NiMH | 0.5642 | 0.0789 | 0.4853 | 1 |
| Li-Ion | 0.5395 | 0.1561 | 0.3833 | 2 |
| NaNiCl | 0.0658 | 0.8762 | -0.8104 | 5 |

Back to results of scenario *Consumers HEV 2005*

Partial Ranking (PROMETHEE I)

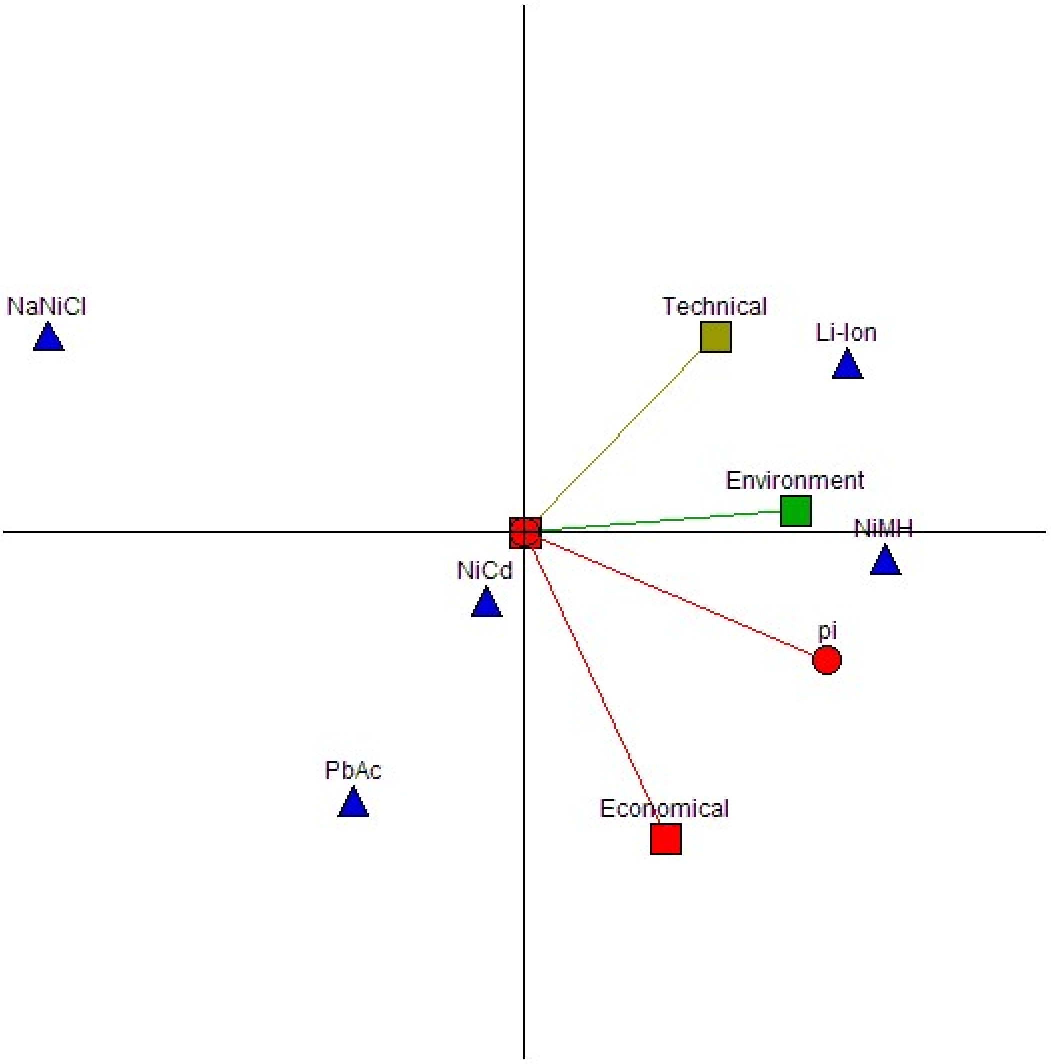


Back to results of scenario *Consumers HEV 2005*

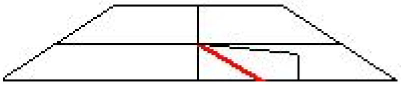
Complete Ranking (PROMETHEE II)

Back to results of scenario *Consumers HEV 2005*

GAIA Planes



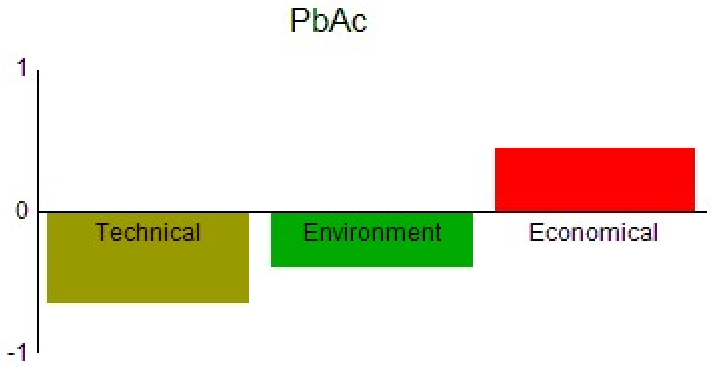
Decision Stick



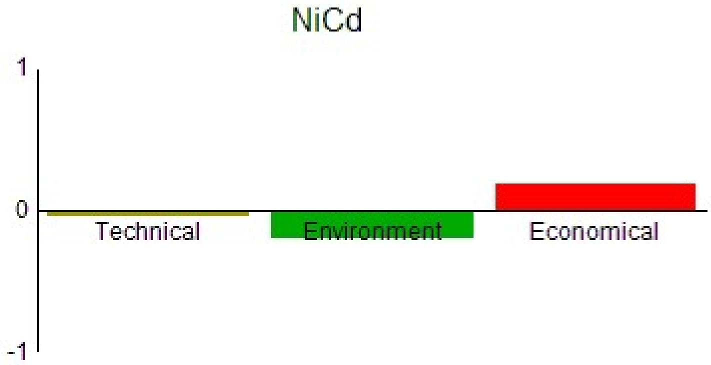
Back to results of scenario *Consumers HEV 2005*

Actions Profiles

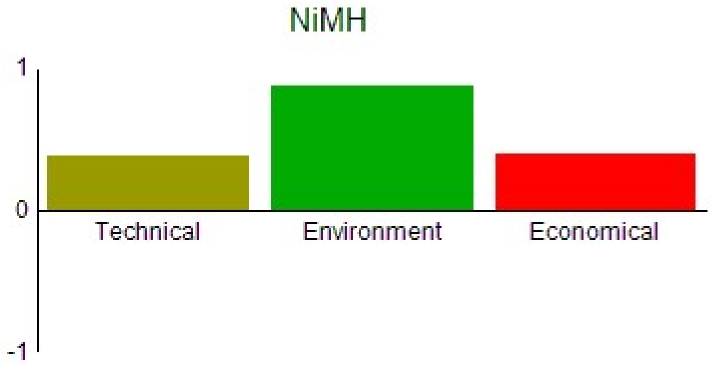
Action : PbAc



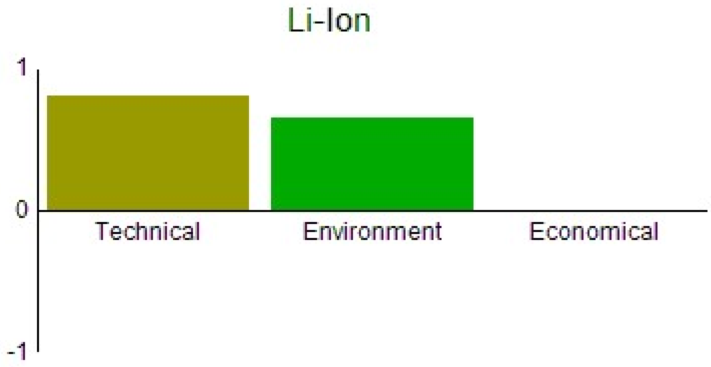
Action : NiCd



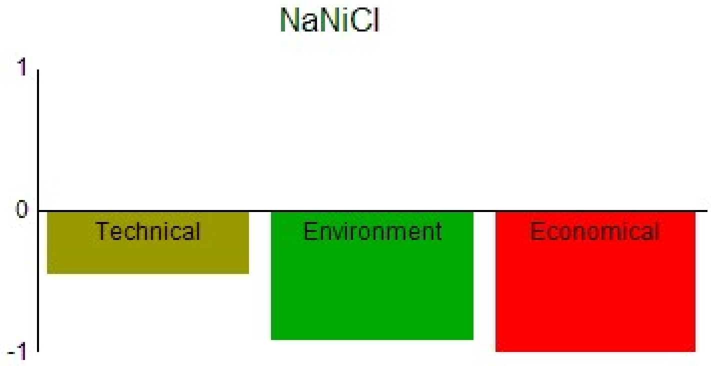
Action : NiMH



Action : Li-Ion

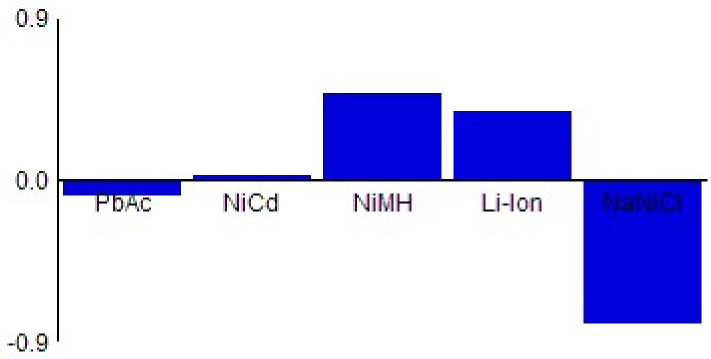


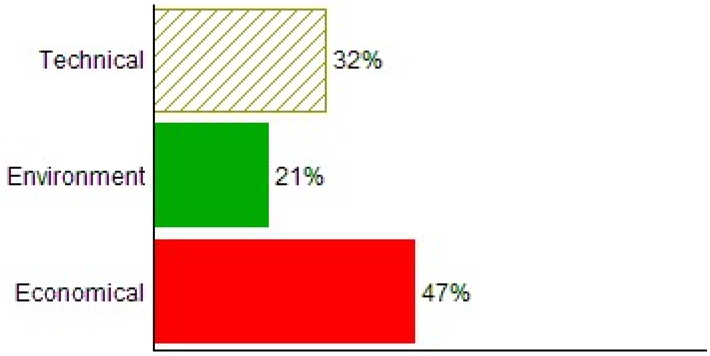
Action : NaNiCl



Back to results of scenario *Consumers HEV 2005*

Walking Weights





Back to results of scenario *Consumers HEV 2005*

Stability Intervals for scenario *Consumers HEV 2005*
Level=5

| | Absolute values | | | Relative values (%) | | |
|---|---|---|---|---|---|---|
| | Weight | Min | Max | Weight | Min | Max |
| Energy Density | 5.0000 | 12.1552 | 53.2494 | 5.26% | 15.75% | 45.03% |
| Power Density | 20.0000 | 0.0000 | 17.5809 | 21.05% | 0.00% | 11.52% |
| Cycles | 5.0000 | 0.0000 | 9.0117 | 5.26% | 0.00% | 5.85% |
| Energy efficiency | 0.0000 | 0.0000 | 13.8487 | 0.00% | 0.00% | 8.72% |
| LCA | 20.0000 | 0.0000 | -1.0000 | 21.05% | 0.00% | 100.00% |
| Cost | 30.0000 | 20.2427 | 87.8359 | 31.58% | 28.82% | 63.72% |
| Maturity | 5.0000 | 0.0000 | 6.7511 | 5.26% | 0.00% | 6.98% |
| userfriendly | 10.0000 | 0.0000 | 0.0000 | 10.53% | 0.00% | 0.00% |

Back to results of scenario *Consumers HEV 2005*

Scenario: Consumers HEV 2012

- Short Name: Con HEV 12
- Description:
- Color: 5
- Symbol: 9
- Category: Scenarios
- Enabled: Yes

Evaluations Preferences Results

Evaluations for scenario *Consumers HEV 2012*

| | Energy Density | Power Density | Cycles | Energy efficiency | LCA | Cost | Maturity | userfriendly |
|---|---|---|---|---|---|---|---|---|
| PbAc | 25 | 600 | 1.5 | 85 | 5 | 384 | 100 | 100 |
| NiCd | 30 | 600 | 3.0 | 75 | 9 | 624 | 100 | 100 |
| NiMH | 55 | 2500 | 3.0 | 75 | 2 | 456 | 100 | 100 |
| Li-Ion | 70 | 4000 | 3.0 | 95 | 2 | 360 | 100 | 100 |
| NaNiCl | 80 | 600 | 3.0 | 90 | 8 | 624 | 100 | 60 |

Back to scenario *Consumers HEV 2012*

Preferences for scenario *Consumers HEV 2012*

| | Energy Density | Power Density | Cycles | Energy efficiency | LCA | Cost | Maturity | userfriendly |
|---|---|---|---|---|---|---|---|---|
| Function Type | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Minimized | False | False | False | False | True | True | False | False |
| P | 25 | 25 | 50 | 5 | 50 | 50 | 20 | 20 |
| Q | 5 | 5 | 10 | 2 | 20 | 20 | 10 | 10 |
| S | 1.17647058823529 | 5.55555555555556E-02 | 0.117647058823529 | 1 | 0.32258064516129 | 5.17812758906379E-03 | 1 | 0 |
| Unit | Wh/kg | W/kg | # | % | EcoPoints | EUR | % | |
| Scale | (Numerical) | (Numerical) | (Numerical) | (Numerical) | (Numerical) | (Numerical) | (Numerical) | (Numerical) |
| Weight | 5 | 20 | 5 | 0 | 20 | 30 | 5 | 10 |

Back to scenario *Consumers HEV 2012*

Results for scenario *Consumers HEV 2012*

- Rankings
- Scores
- PROMETHEE I
- PROMETHEE II
- GAIA Planes
- Actions Profiles
- Walking Weights
- Stability Intervals

Back to scenario *Consumers HEV 2012*

Scores for scenario *Consumers HEV 2012*

| | Energy Density | Power Density | Cycles | Energy efficiency | LCA | Cost | Maturity | userfriendly |
|---|---|---|---|---|---|---|---|---|
| PbAc | -0.9375 | -0.5000 | -1.0000 | 0.0000 | -0.2863 | 0.3077 | 0.0000 | 0.2500 |
| NiCd | -0.5625 | -0.5000 | 0.2500 | -0.7500 | -0.6364 | -0.3974 | 0.0000 | 0.2500 |
| NiMH | 0.0000 | 0.5000 | 0.2500 | -0.7500 | 0.7532 | 0.1066 | 0.0000 | 0.2500 |
| Li-Ion | 0.6339 | 1.0000 | 0.2500 | 1.0000 | 0.7468 | 0.3806 | 0.0000 | 0.2500 |
| NaNiCl | 0.8661 | -0.5000 | 0.2500 | 0.5000 | -0.5773 | -0.3974 | 0.0000 | -1.0000 |

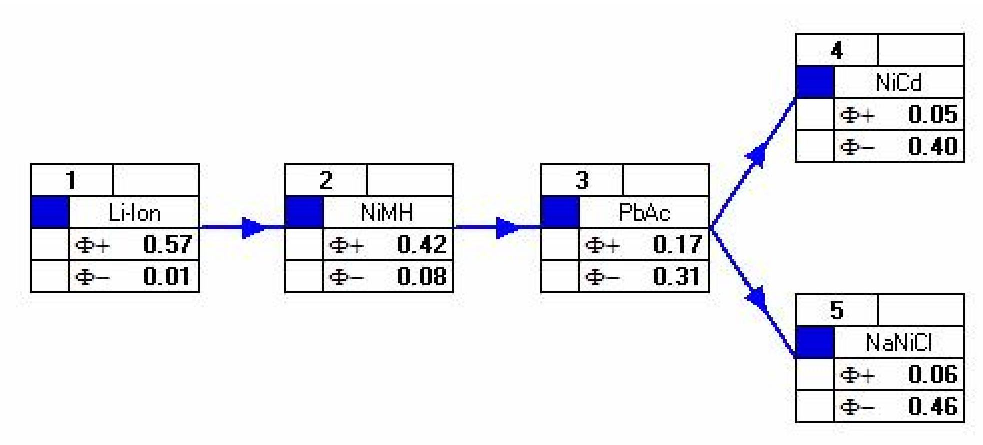
Back to results of scenario *Consumers HEV 2012*

Rankings for scenario *Consumers HEV 2012*

| | Phi Plus | Phi Minus | Phi Net | Ranking |
|---|---|---|---|---|
| PbAc | 0.1685 | 0.3125 | -0.1440 | 3 |
| NiCd | 0.0493 | 0.4042 | -0.3549 | 4 |
| NiMH | 0.4187 | 0.0817 | 0.3370 | 2 |
| Li-Ion | 0.5675 | 0.0068 | 0.5608 | 1 |
| NaNiCl | 0.0587 | 0.4576 | -0.3988 | 5 |

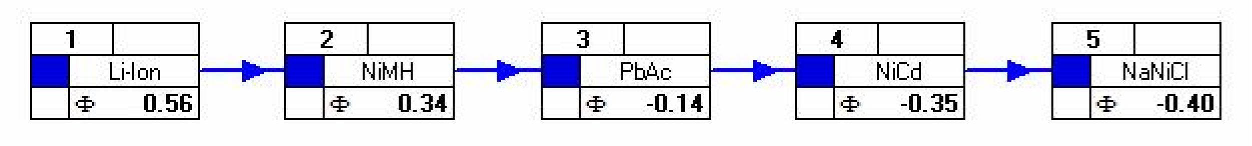
Back to results of scenario *Consumers HEV 2012*

Partial Ranking (PROMETHEE I)



Back to results of scenario *Consumers HEV 2012*

Complete Ranking (PROMETHEE II)



1 Li-Ion Φ 0.56

2 NiMH Φ 0.34

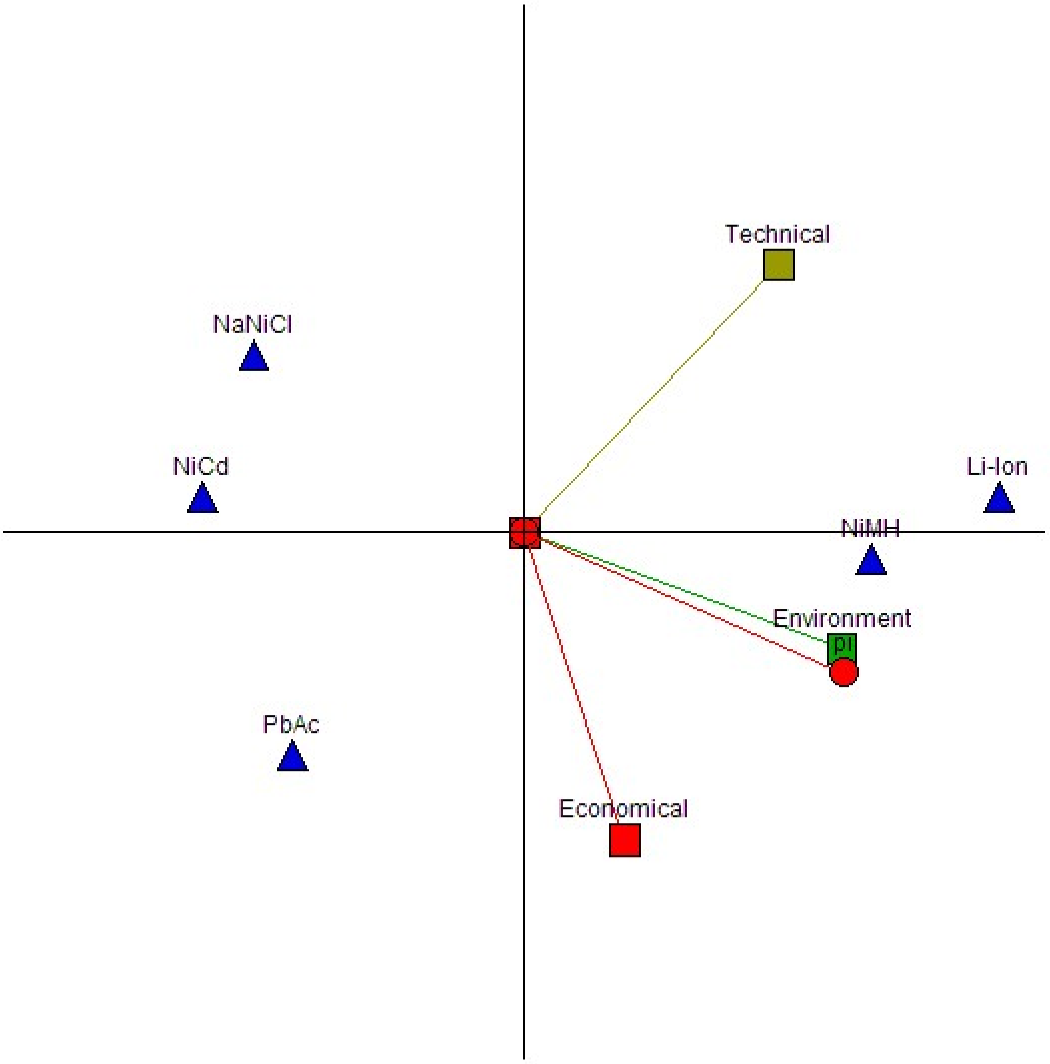
3 PbAc Φ -0.14

4 NiCd Φ -0.35

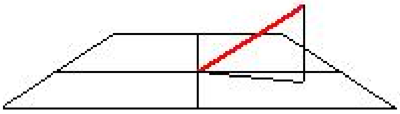
5 NaNiCl Φ -0.40

Back to results of scenario *Consumers HEV 2012*

GAIA Planes



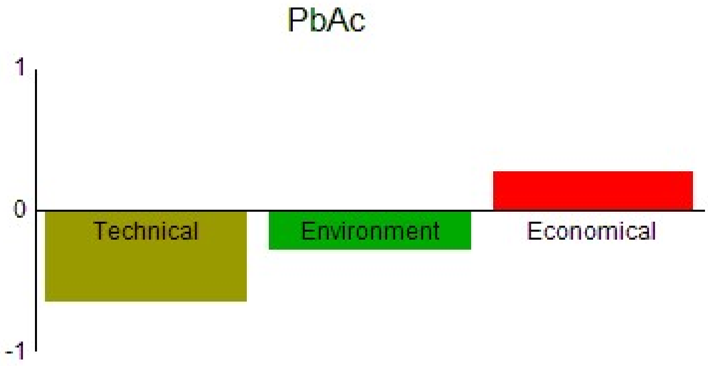
Decision Stick



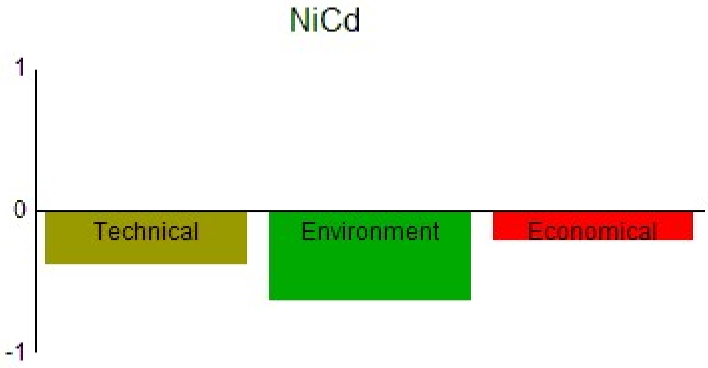
Back to results of scenario *Consumers HEV 2012*

Actions Profiles

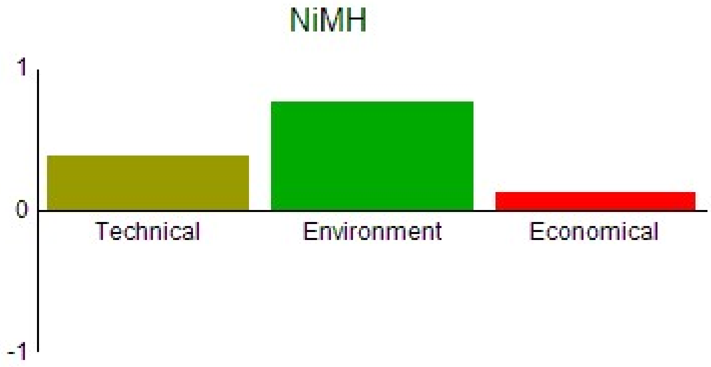
Action : PbAc



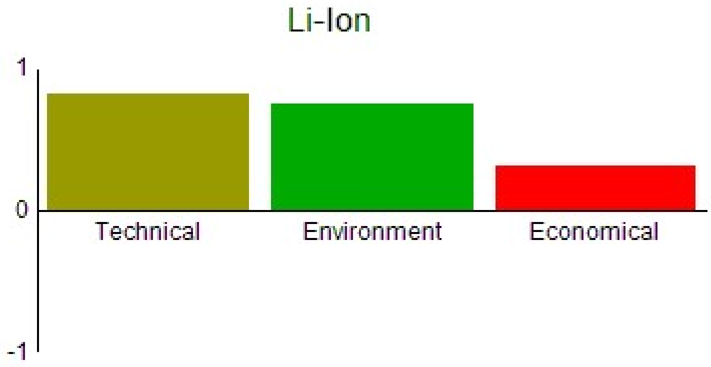
Action : NiCd



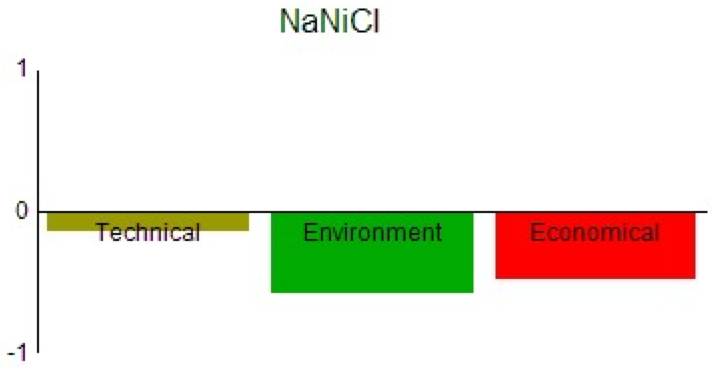
Action : NiMH



Action : Li-Ion

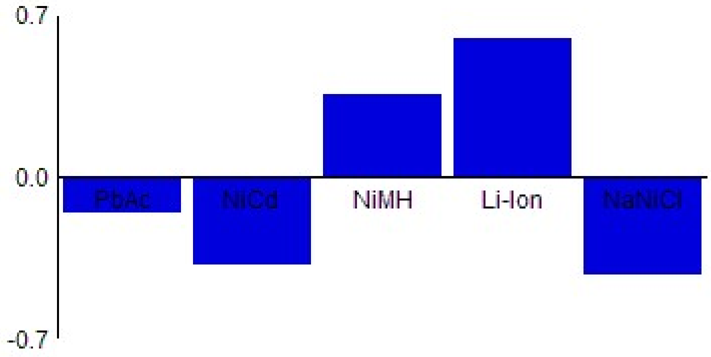


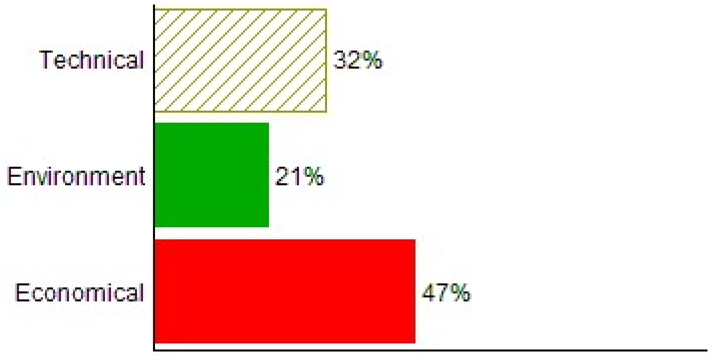
Action : NaNiCl



Back to results of scenario *Consumers HEV 2012*

Walking Weights





Back to results of scenario *Consumers HEV 2012*

Stability Intervals for scenario *Consumers HEV 2012*
Level=5

| | Absolute values | | | Relative values (%) | | |
|---|---|---|---|---|---|---|
| | Weight | Min | Max | Weight | Min | Max |
| Energy Density | 5.0000 | 0.0000 | 47.5377 | 5.26% | 0.00% | 42.24% |
| Power Density | 20.0000 | 0.0000 | 17.5809 | 21.05% | 0.00% | 11.52% |
| Cycles | 5.0000 | 0.0000 | 9.0117 | 5.26% | 0.00% | 5.85% |
| Energy efficiency | 0.0000 | 0.0000 | 13.8487 | 0.00% | 0.00% | 8.72% |
| LCA | 20.0000 | 0.0000 | 90.6834 | 21.05% | 0.00% | 54.73% |
| Cost | 30.0000 | 29.9677 | 385.8858 | 31.58% | 37.47% | 88.53% |
| Maturity | 5.0000 | 0.0000 | 6.7511 | 5.26% | 0.00% | 6.98% |
| userfriendly | 10.0000 | 0.0000 | 0.0000 | 10.53% | 0.00% | 0.00% |

Back to results of scenario *Consumers HEV 2012*

Scenario: Manufactures BEV 2005

- Short Name: Man BEV 05
- Description:
- Color: 5
- Symbol: 9
- Category: Scenarios
- Enabled: Yes

Evaluations Preferences Results

Evaluations for scenario *Manufactures BEV 2005*

| | Energy Density | Power Density | Cycles | Energy efficiency | LCA | Cost | Maturity | userfriendly |
|---|---|---|---|---|---|---|---|---|
| PbAc | 40 | 250 | 500.0 | 83 | 503 | 10085 | 100 | 100 |
| NiCd | 60 | 200 | 1350.0 | 73 | 544 | 17355 | 100 | 100 |
| NiMH | 70 | 350 | 1350.0 | 70 | 491 | 20254 | 60 | 100 |
| Li-Ion | 125 | 400 | 1000.0 | 90 | 278 | 25338 | 60 | 100 |
| NaNiCl | 125 | 200 | 1000.0 | 86 | 234 | 17109 | 80 | 60 |

Back to scenario *Manufactures BEV 2005*

Preferences for scenario *Manufactures BEV 2005*

| | Energy Density | Power Density | Cycles | Energy efficiency | LCA | Cost | Maturity | userfriendly |
|---|---|---|---|---|---|---|---|---|
| Function Type | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Minimized | False | False | False | False | True | True | False | False |
| P | 25 | 25 | 50 | 5 | 50 | 50 | 20 | 20 |
| Q | 5 | 5 | 10 | 2 | 20 | 20 | 10 | 10 |
| S | 1.17647058823529 | 5.55555555555556E-02 | 0.117647058823529 | 1 | 0.32258064516129 | 5.17812758906379E-03 | 1 | 0 |
| Unit | Wh/kg | W/kg | # | % | EcoPoints | EUR | % | |
| Scale | (Numerical) | (Numerical) | (Numerical) | (Numerical) | (Numerical) | (Numerical) | (Numerical) | (Numerical) |
| Weight | 25 | 10 | 10 | 5 | 5 | 30 | 10 | 10 |

Back to scenario *Manufactures BEV 2005*

Results for scenario *Manufactures BEV 2005*

- Rankings
- Scores
- PROMETHEE I
- PROMETHEE II
- GAIA Planes
- Actions Profiles
- Walking Weights
- Stability Intervals

Back to scenario *Manufactures BEV 2005*

Scores for scenario *Manufactures BEV 2005*

| | Energy Density | Power Density | Cycles | Energy efficiency | LCA | Cost | Maturity | userfriendly |
|---|---|---|---|---|---|---|---|---|
| PbAc | -1.0000 | 0.0000 | -1.0000 | 0.1667 | -0.4561 | 0.8579 | 0.7500 | 0.2500 |
| NiCd | -0.3958 | -0.7500 | 0.5625 | -0.7083 | -0.4908 | -0.0865 | 0.7500 | 0.2500 |
| NiMH | -0.1042 | 0.6339 | 0.5625 | -0.7917 | -0.4448 | -0.2495 | -0.7500 | 0.2500 |
| Li-Ion | 0.7500 | 0.8661 | -0.0625 | 0.9583 | 0.6417 | -0.4504 | -0.7500 | 0.2500 |
| NaNiCl | 0.7500 | -0.7500 | -0.0625 | 0.3750 | 0.7500 | -0.0715 | 0.0000 | -1.0000 |

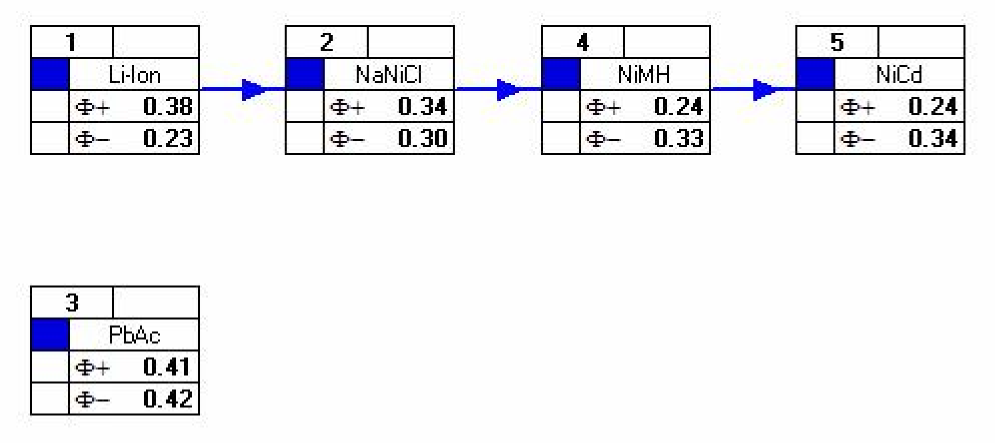
Back to results of scenario *Manufactures BEV 2005*

Rankings for scenario *Manufactures BEV 2005*

| | Phi Plus | Phi Minus | Phi Net | Ranking |
|---|---|---|---|---|
| PbAc | 0.4118 | 0.4185 | -0.0068 | 3 |
| NiCd | 0.2377 | 0.3364 | -0.0987 | 5 |
| NiMH | 0.2432 | 0.3318 | -0.0886 | 4 |
| Li-Ion | 0.3849 | 0.2299 | 0.1550 | 1 |
| NaNiCl | 0.3432 | 0.3041 | 0.0391 | 2 |

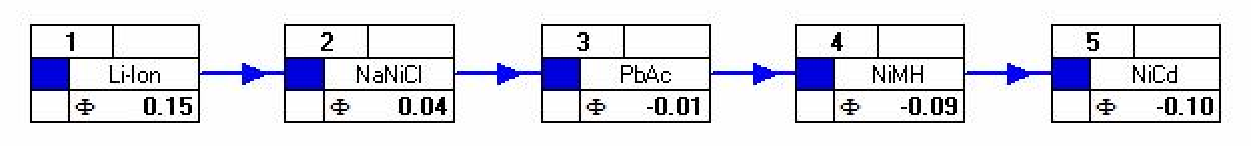
Back to results of scenario *Manufactures BEV 2005*

Partial Ranking (PROMETHEE I)



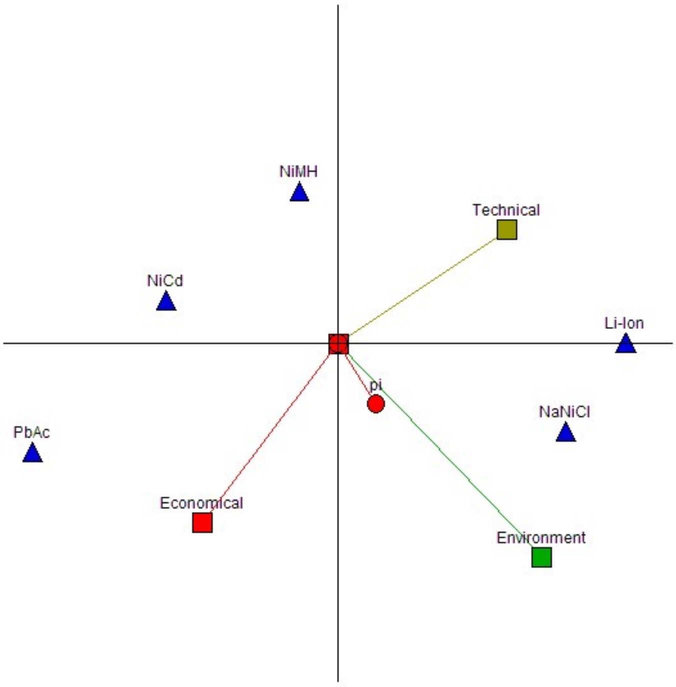
Back to results of scenario *Manufactures BEV 2005*

Complete Ranking (PROMETHEE II)

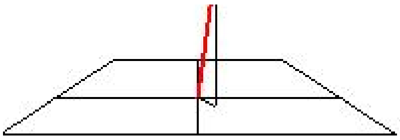


Back to results of scenario *Manufactures BEV 2005*

GAIA Planes



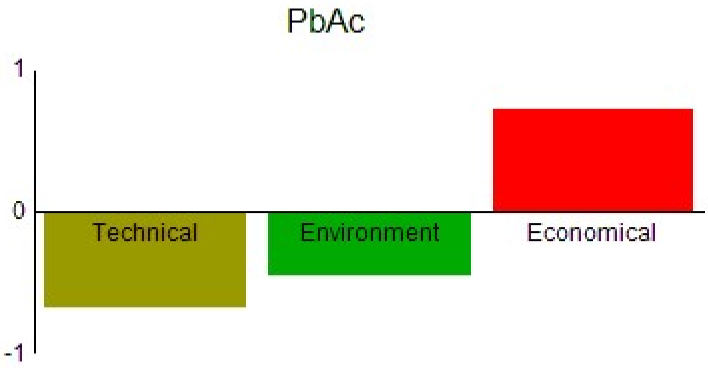
Decision Stick



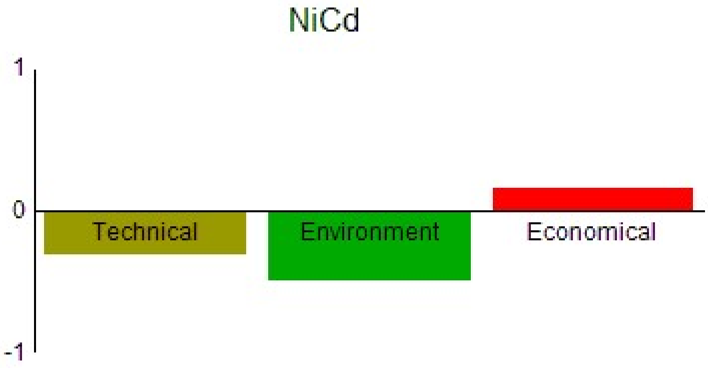
Back to results of scenario *Manufactures BEV 2005*

Actions Profiles

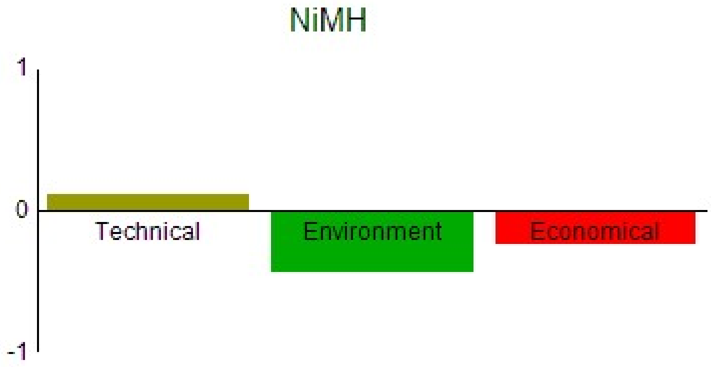
Action : PbAc



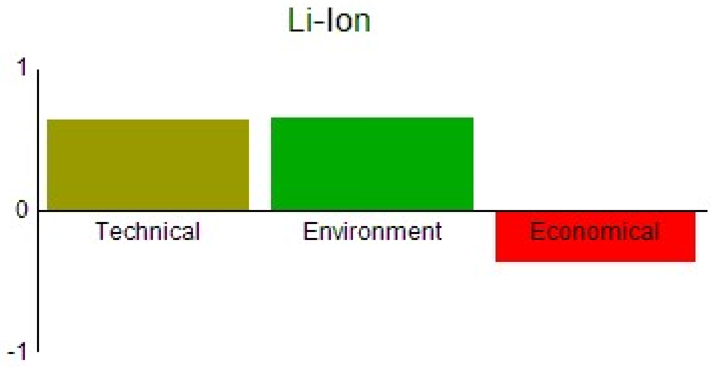
Action : NiCd



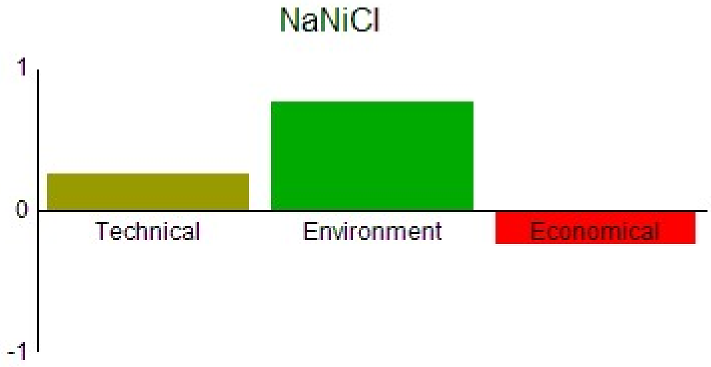
Action : NiMH



Action : Li-Ion

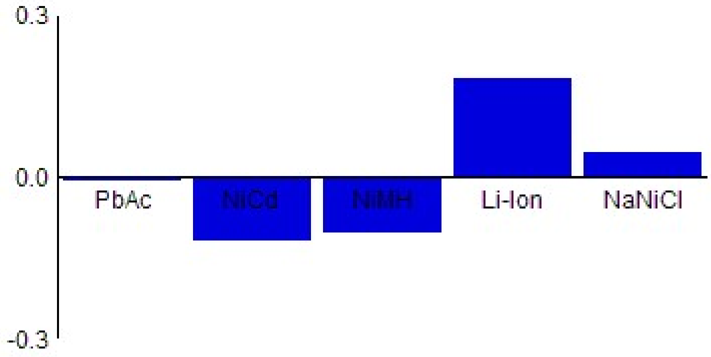


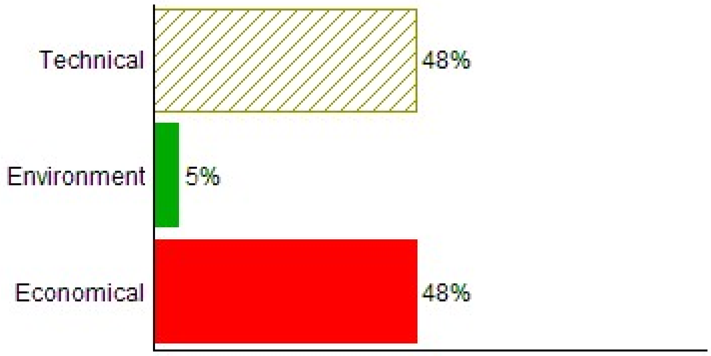
Action : NaNiCl



Back to results of scenario *Manufactures BEV 2005*

Walking Weights





Back to results of scenario *Manufactures BEV 2005*

Stability Intervals for scenario *Manufactures BEV 2005*
Level=5

| | Absolute values | | | Relative values (%) | | |
|---|---|---|---|---|---|---|
| | Weight | Min | Max | Weight | Min | Max |
| Energy Density | 25.0000 | 47.4503 | 60.8611 | 23.81% | 46.32% | 52.53% |
| Power Density | 10.0000 | 0.0000 | 17.5809 | 9.52% | 0.00% | 11.52% |
| Cycles | 10.0000 | 0.0000 | 9.0117 | 9.52% | 0.00% | 5.85% |
| Energy efficiency | 5.0000 | 0.0000 | 13.8487 | 4.76% | 0.00% | 8.72% |
| LCA | 5.0000 | 1.0064 | 117.4076 | 4.76% | 1.00% | 54.00% |
| Cost | 30.0000 | 41.0875 | 52.6556 | 28.57% | 42.76% | 48.91% |
| Maturity | 10.0000 | 0.0000 | 6.7511 | 9.52% | 0.00% | 6.98% |
| userfriendly | 10.0000 | 0.0000 | 0.0000 | 9.52% | 0.00% | 0.00% |

Back to results of scenario *Manufactures BEV 2005*

Scenario: Manufactures BEV 2012

- Short Name: Man BEV 12
- Description:
- Color: 5
- Symbol: 9
- Category: Scenarios
- Enabled: Yes

Evaluations Preferences Results

Evaluations for scenario *Manufactures BEV 2012*

| | Energy Density | Power Density | Cycles | Energy efficiency | LCA | Cost | Maturity | userfriendly |
|---|---|---|---|---|---|---|---|---|
| PbAc | 40 | 250 | 1000.0 | 85 | 331 | 6432 | 100 | 100 |
| NiCd | 60 | 200 | 2000.0 | 75 | 427 | 11286 | 100 | 100 |
| NiMH | 70 | 350 | 2000.0 | 75 | 364 | 12684 | 100 | 100 |
| Li-Ion | 150 | 400 | 2000.0 | 95 | 122 | 4504 | 100 | 100 |
| NaNiCl | 150 | 200 | 2000.0 | 90 | 129 | 4059 | 100 | 60 |

Back to scenario *Manufactures BEV 2012*

Preferences for scenario *Manufactures BEV 2012*

| | Energy Density | Power Density | Cycles | Energy efficiency | LCA | Cost | Maturity | userfriendly |
|---|---|---|---|---|---|---|---|---|
| Function Type | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Minimized | False | False | False | False | True | True | False | False |
| P | 25 | 25 | 50 | 5 | 50 | 50 | 20 | 20 |
| Q | 5 | 5 | 10 | 2 | 20 | 20 | 10 | 10 |
| S | 1.17647058823529 | 5.55555555555556E-02 | 0.117647058823529 | 1 | 0.32258064516129 | 5.17812758906379E-03 | 1 | 0 |
| Unit | Wh/kg | W/kg | # | % | EcoPoints | EUR | % | |
| Scale | (Numerical) | (Numerical) | (Numerical) | (Numerical) | (Numerical) | (Numerical) | (Numerical) | (Numerical) |
| Weight | 25 | 10 | 10 | 5 | 5 | 30 | 10 | 10 |

Back to scenario *Manufactures BEV 2012*

Results for scenario *Manufactures BEV 2012*

- Rankings
- Scores
- PROMETHEE I
- PROMETHEE II
- GAIA Planes
- Actions Profiles
- Walking Weights
- Stability Intervals

Back to scenario *Manufactures BEV 2012*

Scores for scenario *Manufactures BEV 2012*

| | Energy Density | Power Density | Cycles | Energy efficiency | LCA | Cost | Maturity | userfriendly |
|---|---:|---:|---:|---:|---:|---:|---:|---:|
| PbAc | -1.0000 | 0.0000 | -1.0000 | 0.0000 | -0.4793 | 0.2119 | 0.0000 | 0.2500 |
| NiCd | -0.3958 | -0.7500 | 0.2500 | -0.7500 | -0.5207 | -0.6917 | 0.0000 | 0.2500 |
| NiMH | -0.1042 | 0.6339 | 0.2500 | -0.7500 | -0.5000 | -0.7441 | 0.0000 | 0.2500 |
| Li-Ion | 0.7500 | 0.8661 | 0.2500 | 1.0000 | 0.7500 | 0.5831 | 0.0000 | 0.2500 |
| NaNiCl | 0.7500 | -0.7500 | 0.2500 | 0.5000 | 0.7500 | 0.6408 | 0.0000 | -1.0000 |

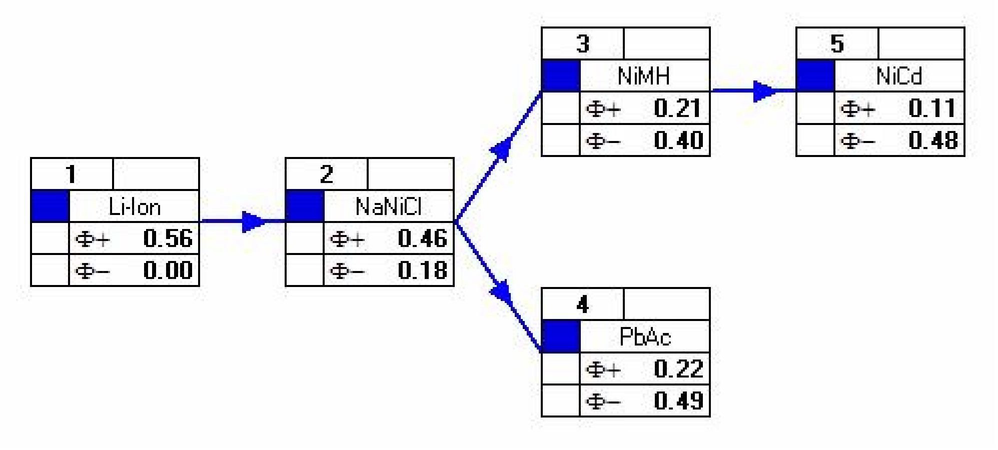
Back to results of scenario *Manufactures BEV 2012*

Rankings for scenario *Manufactures BEV 2012*

| | Phi Plus | Phi Minus | Phi Net | Ranking |
|---|---:|---:|---:|---:|
| PbAc | 0.2207 | 0.4925 | -0.2718 | 4 |
| NiCd | 0.1071 | 0.4833 | -0.3762 | 5 |
| NiMH | 0.2133 | 0.4022 | -0.1889 | 3 |
| Li-Ion | 0.5586 | 0.0000 | 0.5586 | 1 |
| NaNiCl | 0.4569 | 0.1786 | 0.2783 | 2 |

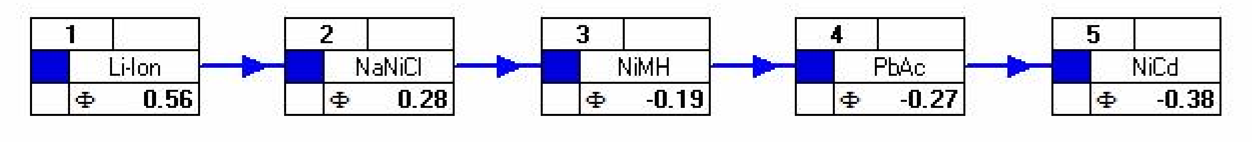
Back to results of scenario *Manufactures BEV 2012*

Partial Ranking (PROMETHEE I)



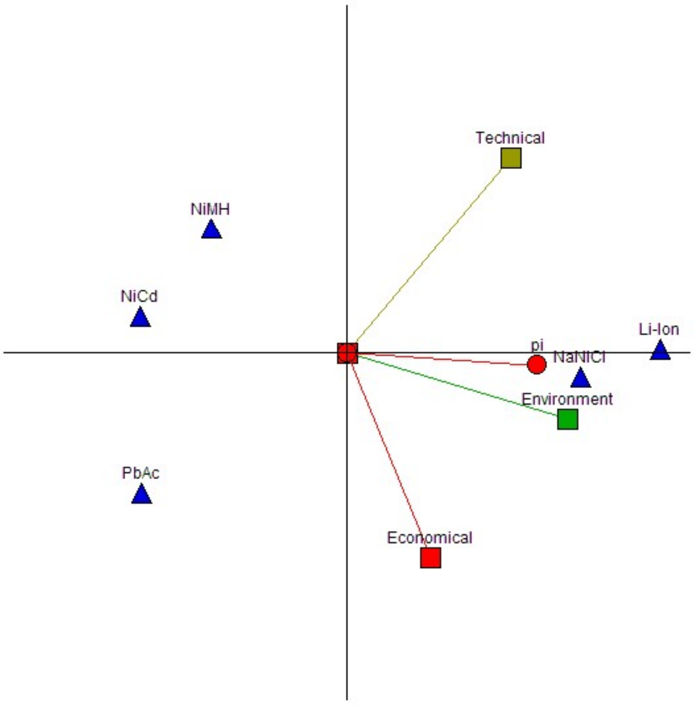
Back to results of scenario *Manufactures BEV 2012*

Complete Ranking (PROMETHEE II)

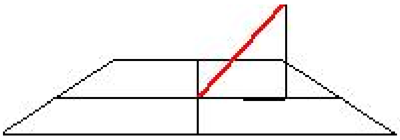


Back to results of scenario *Manufactures BEV 2012*

GAIA Planes



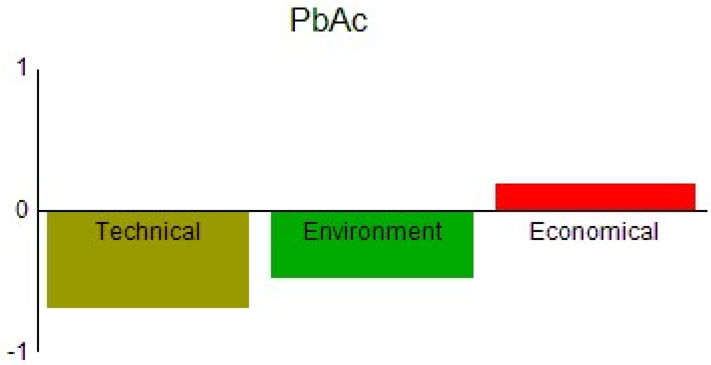
Decision Stick



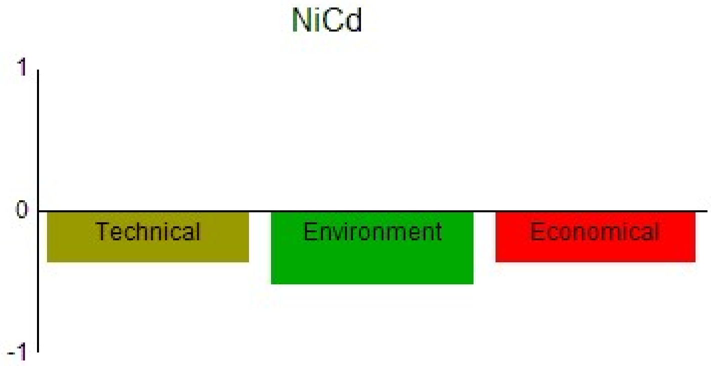
Back to results of scenario *Manufactures BEV 2012*

Actions Profiles

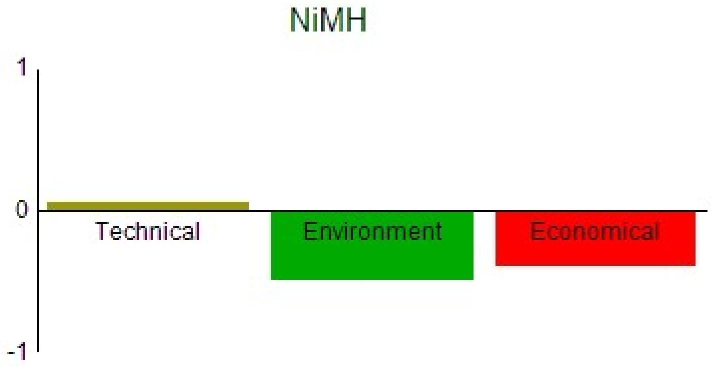
Action : PbAc



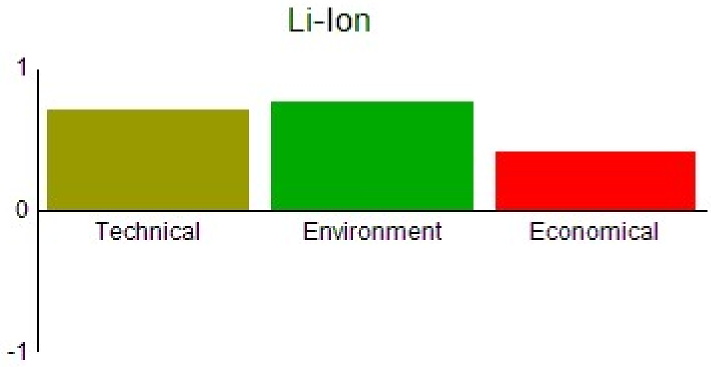
Action : NiCd



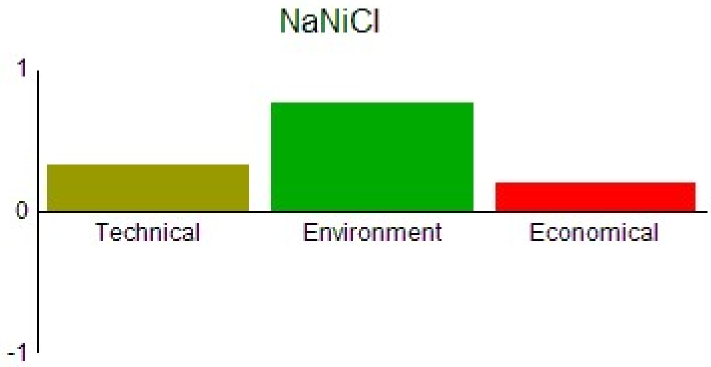
Action : NiMH



Action : Li-Ion

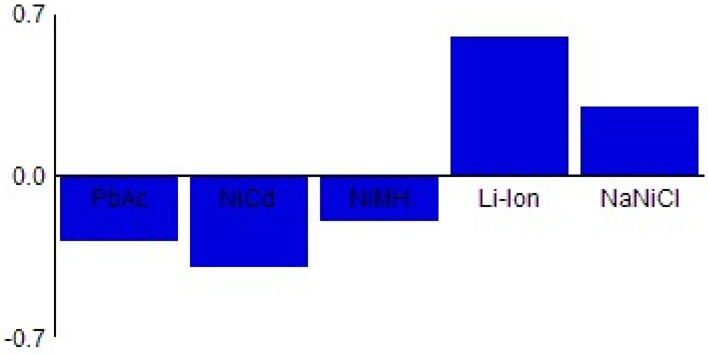


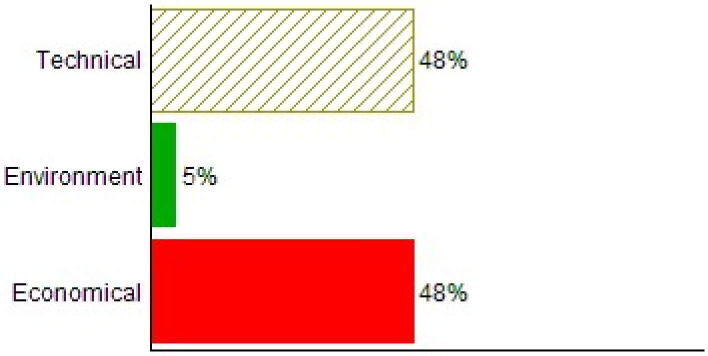
Action : NaNiCl



Back to results of scenario *Manufactures BEV 2012*

Walking Weights





Back to results of scenario *Manufactures BEV 2012*

Stability Intervals for scenario *Manufactures BEV 2012*
Level=5

| | Absolute values | | | Relative values (%) | | |
|---|---|---|---|---|---|---|
| | Weight | Min | Max | Weight | Min | Max |
| Energy Density | 25.0000 | 38.3935 | 83.5163 | 23.81% | 41.11% | 60.29% |
| Power Density | 10.0000 | 0.0000 | 17.5809 | 9.52% | 0.00% | 11.52% |
| Cycles | 10.0000 | 0.0000 | 9.0117 | 9.52% | 0.00% | 5.85% |
| Energy efficiency | 5.0000 | 0.0000 | 13.8487 | 4.76% | 0.00% | 8.72% |
| LCA | 5.0000 | 0.0000 | 425.6223 | 4.76% | 0.00% | 80.97% |
| Cost | 30.0000 | 29.7811 | 65.1696 | 28.57% | 35.13% | 54.23% |
| Maturity | 10.0000 | 0.0000 | 6.7511 | 9.52% | 0.00% | 6.98% |
| userfriendly | 10.0000 | 0.0000 | 0.0000 | 9.52% | 0.00% | 0.00% |

Back to results of scenario *Manufactures BEV 2012*

Scenario: Manufactures HEV 2005

- Short Name: Man HEV 05
- Description:
- Color: 5
- Symbol: 9
- Category: Scenarios
- Enabled: Yes

Evaluations Preferences Results

Evaluations for scenario *Manufactures HEV 2005*

| | Energy Density | Power Density | Cycles | Energy efficiency | LCA | Cost | Maturity | userfriendly |
|---|---|---|---|---|---|---|---|---|
| PbAc | 25 | 350 | 1.0 | 83 | 14 | 432 | 100 | 100 |
| NiCd | 30 | 500 | 3.0 | 73 | 10 | 624 | 100 | 100 |
| NiMH | 55 | 1500 | 3.0 | 70 | 3 | 456 | 100 | 100 |
| Li-Ion | 70 | 2000 | 3.0 | 90 | 4 | 684 | 50 | 100 |
| NaNiCl | 125 | 200 | 3.0 | 86 | 23 | 2976 | 0 | 60 |

Back to scenario *Manufactures HEV 2005*

Preferences for scenario *Manufactures HEV 2005*

| | Energy Density | Power Density | Cycles | Energy efficiency | LCA | Cost | Maturity | userfriendly |
|---|---|---|---|---|---|---|---|---|
| Function Type | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Minimized | False | False | False | False | True | True | False | False |
| P | 25 | 25 | 50 | 5 | 50 | 50 | 20 | 20 |
| Q | 5 | 5 | 10 | 2 | 20 | 20 | 10 | 10 |
| S | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Unit | Wh/kg | W/kg | # | % | EcoPoints | Euro | % | |
| Scale | (Numerical) | (Numerical) | (Numerical) | (Numerical) | (Numerical) | (Numerical) | (Numerical) | (Numerical) |
| Weight | 10 | 30 | 5 | 5 | 5 | 30 | 10 | 10 |

Back to scenario *Manufactures HEV 2005*

Results for scenario *Manufactures HEV 2005*

- Rankings
- Scores
- PROMETHEE I
- PROMETHEE II
- GAIA Planes
- Actions Profiles
- Walking Weights
- Stability Intervals

Back to scenario *Manufactures HEV 2005*

Scores for scenario *Manufactures HEV 2005*

| | Energy Density | Power Density | Cycles | Energy efficiency | LCA | Cost | Maturity | userfriendly |
|---|---|---|---|---|---|---|---|---|
| PbAc | -0.9375 | -0.5000 | -1.0000 | 0.1667 | -0.3936 | 0.4801 | 0.5000 | 0.2500 |
| NiCd | -0.5625 | 0.0000 | 0.2500 | -0.7083 | -0.1945 | 0.1026 | 0.5000 | 0.2500 |
| NiMH | 0.0000 | 0.5000 | 0.2500 | -0.7917 | 0.8645 | 0.4188 | 0.5000 | 0.2500 |
| Li-Ion | 0.5000 | 1.0000 | 0.2500 | 0.9583 | 0.6355 | -0.0015 | -0.5000 | 0.2500 |
| NaNiCl | 1.0000 | -1.0000 | 0.2500 | 0.3750 | -0.9118 | -1.0000 | -1.0000 | -1.0000 |

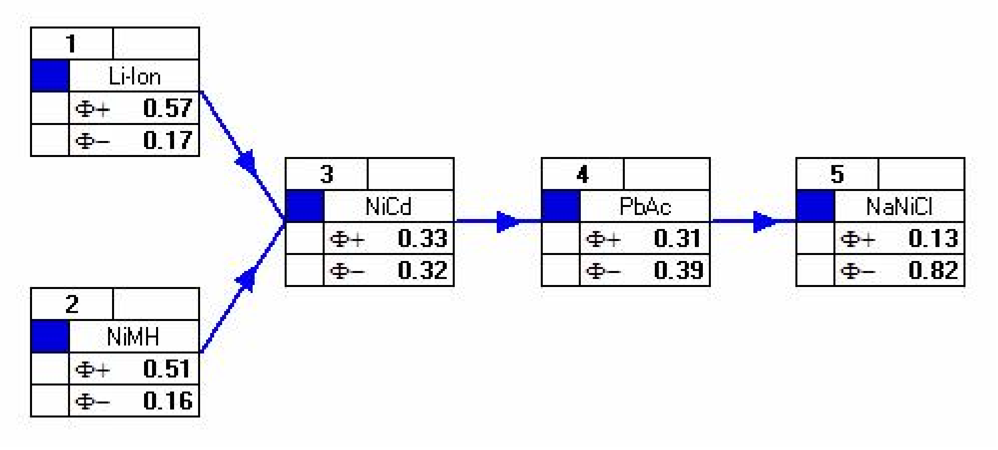
Back to results of scenario *Manufactures HEV 2005*

Rankings for scenario *Manufactures HEV 2005*

| | Phi Plus | Phi Minus | Phi Net | Ranking |
|---|---|---|---|---|
| PbAc | 0.3115 | 0.3935 | -0.0820 | 4 |
| NiCd | 0.3320 | 0.3159 | 0.0161 | 3 |
| NiMH | 0.5061 | 0.1567 | 0.3493 | 2 |
| Li-Ion | 0.5694 | 0.1725 | 0.3969 | 1 |
| NaNiCl | 0.1349 | 0.8152 | -0.6803 | 5 |

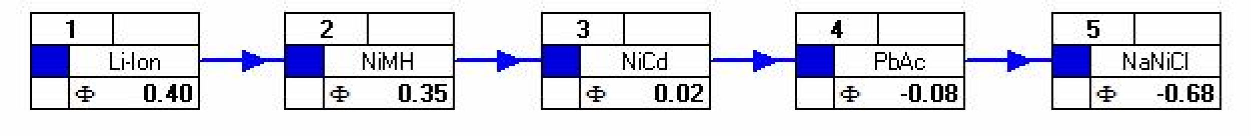
Back to results of scenario *Manufactures HEV 2005*

Partial Ranking (PROMETHEE I)



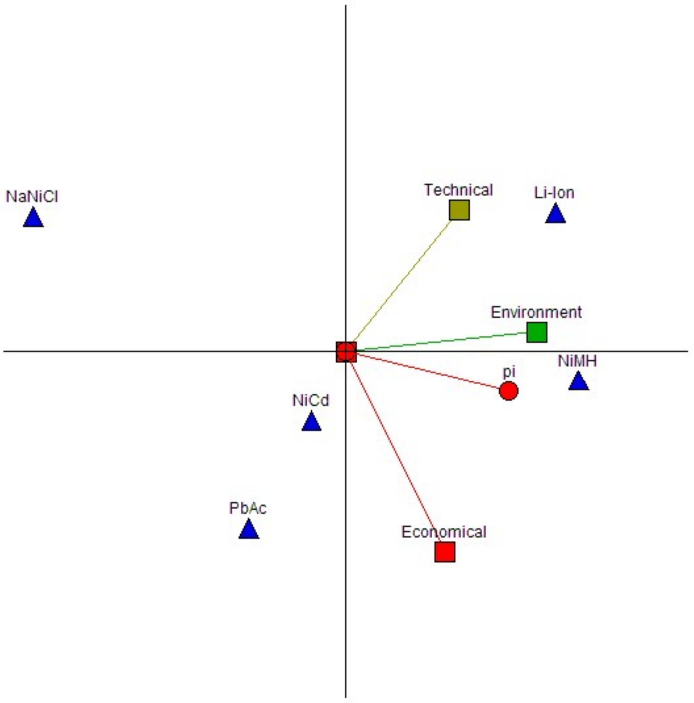
Back to results of scenario *Manufactures HEV 2005*

Complete Ranking (PROMETHEE II)

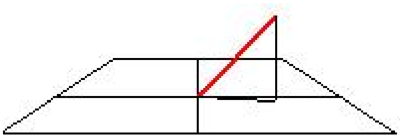


Back to results of scenario *Manufactures HEV 2005*

GAIA Planes



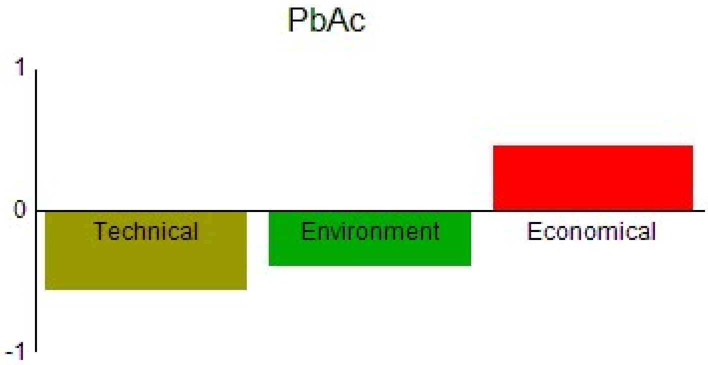
Decision Stick



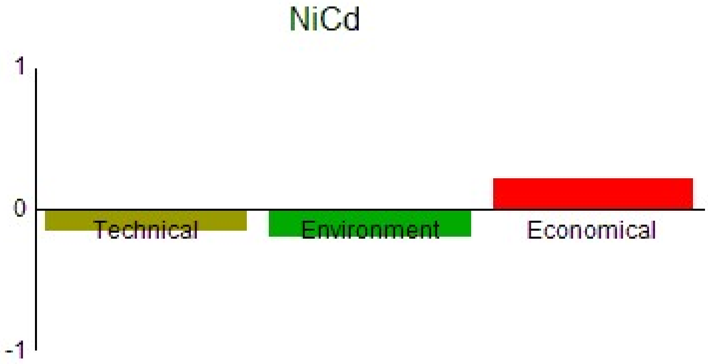
Back to results of scenario *Manufactures HEV 2005*

Actions Profiles

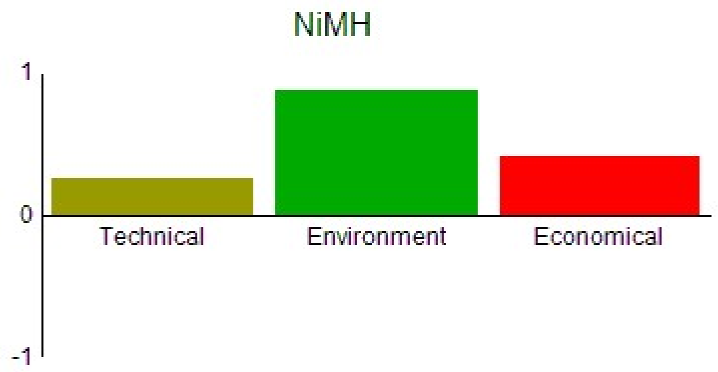
Action : PbAc



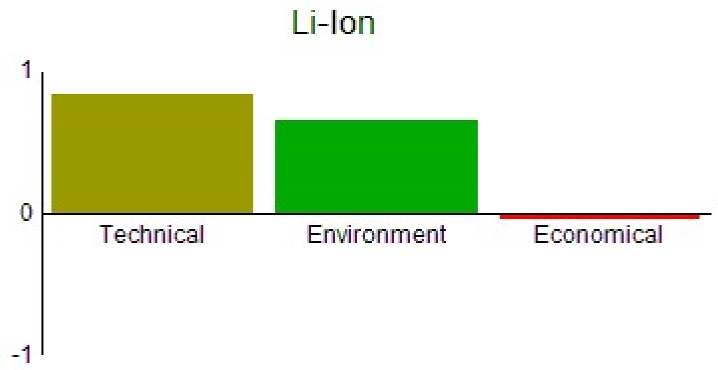
Action : NiCd



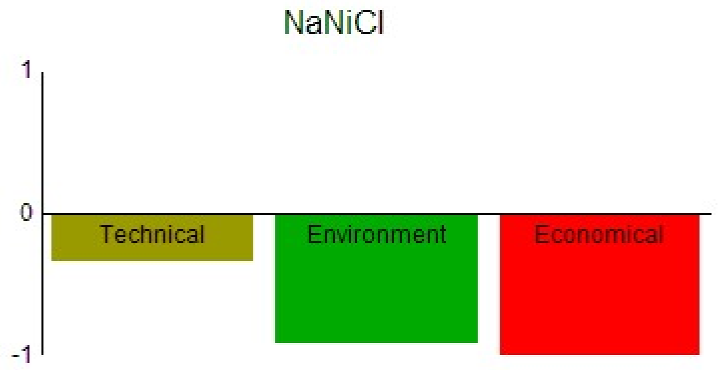
Action : NiMH



Action : Li-Ion

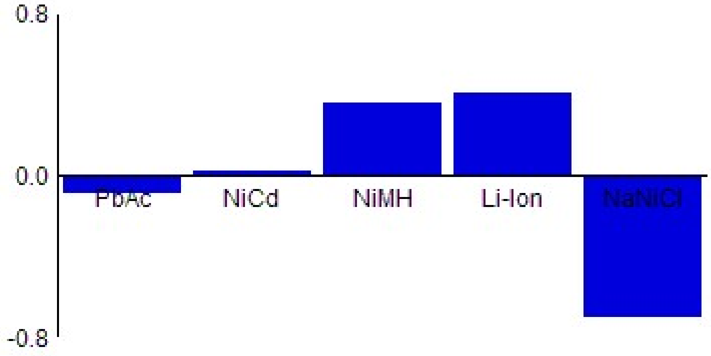


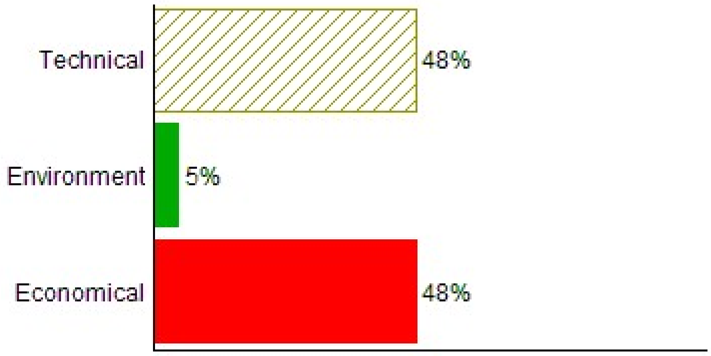
Action : NaNiCl



Back to results of scenario *Manufactures HEV 2005*

Walking Weights





Back to results of scenario *Manufactures HEV 2005*

Stability Intervals for scenario *Manufactures HEV 2005*
Level=5

| | Absolute values | | | Relative values (%) | | |
|---|---|---|---|---|---|---|
| | Weight | Min | Max | Weight | Min | Max |
| Energy Density | 10.0000 | 41.3092 | 319.2596 | 9.52% | 42.89% | 85.30% |
| Power Density | 30.0000 | 0.0000 | -1.0000 | 28.57% | 0.00% | 100.00% |
| Cycles | 5.0000 | 0.5000 | 1.7500 | 4.76% | 7.69% | 22.58% |
| Energy efficiency | 5.0000 | 0.5000 | 1.2500 | 4.76% | 7.69% | 17.24% |
| LCA | 5.0000 | 0.0000 | 26.8253 | 4.76% | 0.00% | 21.15% |
| Cost | 30.0000 | 6.3110 | 61.0519 | 28.57% | 10.29% | 52.61% |
| Maturity | 10.0000 | 0.3333 | 2.0000 | 9.52% | 5.26% | 25.00% |
| userfriendly | 10.0000 | 0.0000 | 0.0000 | 9.52% | 0.00% | 0.00% |

Back to results of scenario *Manufactures HEV 2005*

## Scenario: Manufactures HEV 2012

- Short Name: Man HEV 12
- Description:
- Color: 5
- Symbol: 9
- Category: Scenarios
- Enabled: Yes

Evaluations Preferences Results

Evaluations for scenario *Manufactures HEV 2012*

| | Energy Density | Power Density | Cycles | Energy efficiency | LCA | Cost | Maturity | userfriendly |
|---|---|---|---|---|---|---|---|---|
| PbAc | 25 | 600 | 1.5 | 85 | 5 | 384 | 100 | 100 |
| NiCd | 30 | 600 | 3.0 | 75 | 9 | 624 | 100 | 100 |
| NiMH | 55 | 2500 | 3.0 | 75 | 2 | 456 | 100 | 100 |
| Li-Ion | 70 | 4000 | 3.0 | 95 | 2 | 360 | 100 | 100 |
| NaNiCl | 80 | 600 | 3.0 | 90 | 8 | 624 | 100 | 60 |

Back to scenario *Manufactures HEV 2012*

Preferences for scenario *Manufactures HEV 2012*

| | Energy Density | Power Density | Cycles | Energy efficiency | LCA | Cost | Maturity | userfriendly |
|---|---|---|---|---|---|---|---|---|
| Function Type | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Minimized | False | False | False | False | True | True | False | False |
| P | 25 | 25 | 50 | 5 | 50 | 50 | 20 | 20 |
| Q | 5 | 5 | 10 | 2 | 20 | 20 | 10 | 10 |
| S | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Unit | Wh/kg | W/kg | # | % | EcoPoints | Euro | % | |
| Scale | (Numerical) | (Numerical) | (Numerical) | (Numerical) | (Numerical) | (Numerical) | (Numerical) | (Numerical) |
| Weight | 10 | 30 | 5 | 5 | 5 | 30 | 10 | 10 |

Back to scenario *Manufactures HEV 2012*

Results for scenario *Manufactures HEV 2012*

- Rankings
- Scores
- PROMETHEE I
- PROMETHEE II
- GAIA Planes
- Actions Profiles
- Walking Weights
- Stability Intervals

Back to scenario *Manufactures HEV 2012*

Scores for scenario *Manufactures HEV 2012*

| | Energy Density | Power Density | Cycles | Energy efficiency | LCA | Cost | Maturity | userfriendly |
|---|---|---|---|---|---|---|---|---|
| PbAc | -0.9375 | -0.5000 | -1.0000 | 0.0000 | -0.2863 | 0.3077 | 0.0000 | 0.2500 |
| NiCd | -0.5625 | -0.5000 | 0.2500 | -0.7500 | -0.6364 | -0.3974 | 0.0000 | 0.2500 |
| NiMH | 0.0000 | 0.5000 | 0.2500 | -0.7500 | 0.7532 | 0.1066 | 0.0000 | 0.2500 |
| Li-Ion | 0.6339 | 1.0000 | 0.2500 | 1.0000 | 0.7468 | 0.3806 | 0.0000 | 0.2500 |
| NaNiCl | 0.8661 | -0.5000 | 0.2500 | 0.5000 | -0.5773 | -0.3974 | 0.0000 | -1.0000 |

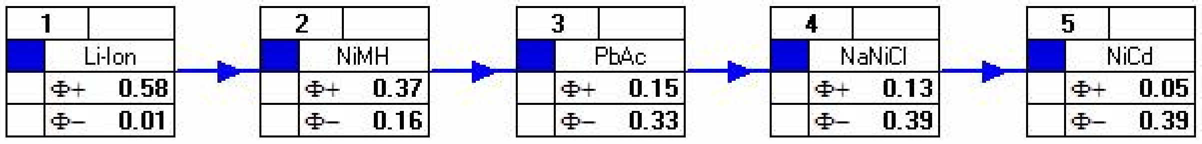
Back to results of scenario *Manufactures HEV 2012*

Rankings for scenario *Manufactures HEV 2012*

| | Phi Plus | Phi Minus | Phi Net | Ranking |
|---|---|---|---|---|
| PbAc | 0.1457 | 0.3274 | -0.1817 | 3 |
| NiCd | 0.0536 | 0.3939 | -0.3403 | 5 |
| NiMH | 0.3665 | 0.1573 | 0.2092 | 2 |
| Li-Ion | 0.5849 | 0.0112 | 0.5737 | 1 |
| NaNiCl | 0.1301 | 0.3910 | -0.2609 | 4 |

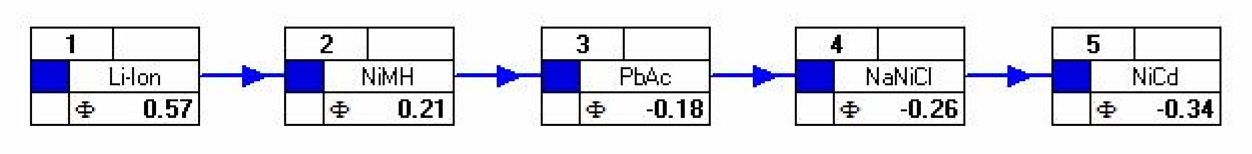
Back to results of scenario *Manufactures HEV 2012*

Partial Ranking (PROMETHEE I)



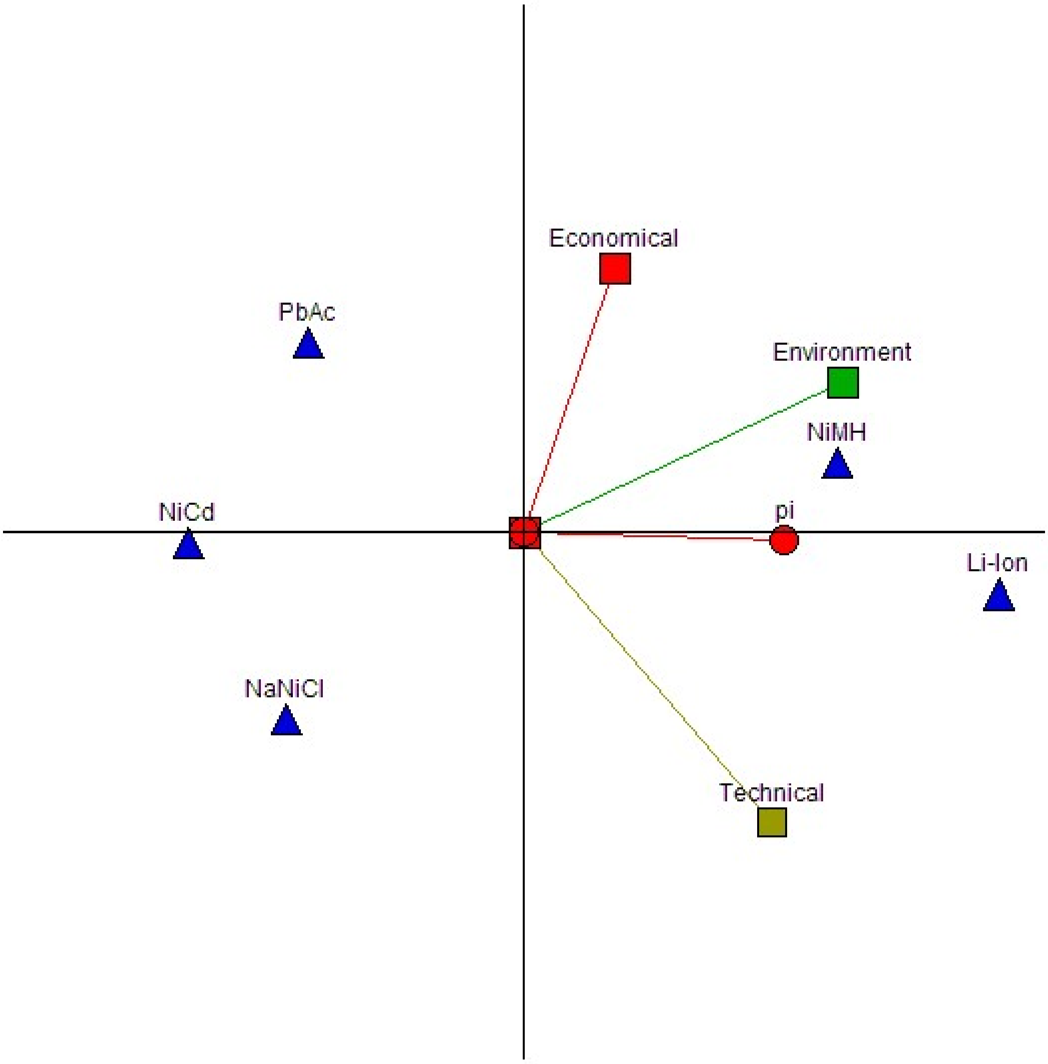
Back to results of scenario *Manufactures HEV 2012*

Complete Ranking (PROMETHEE II)

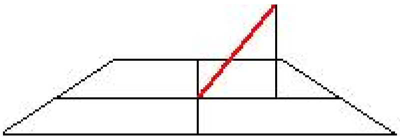


Back to results of scenario *Manufactures HEV 2012*

GAIA Planes



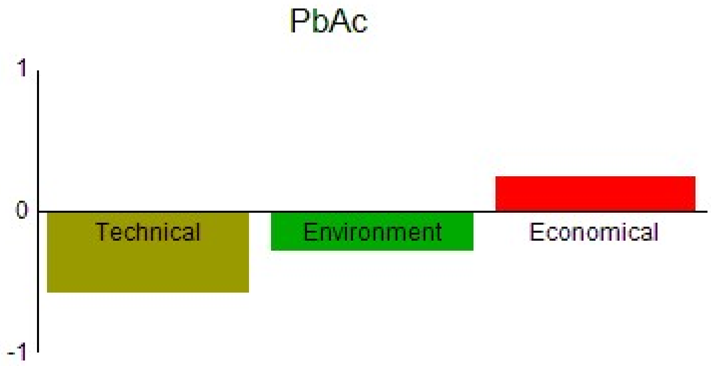
Decision Stick



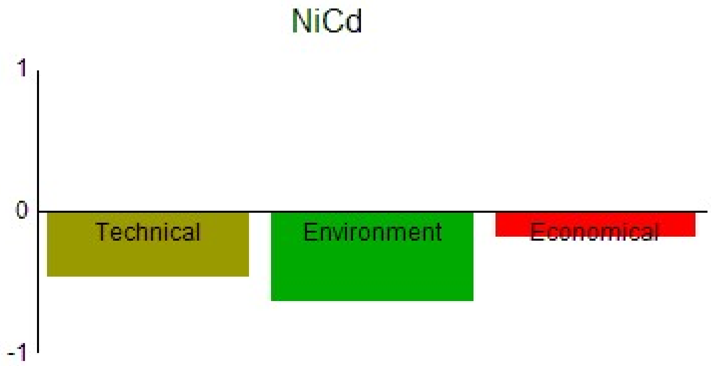
Back to results of scenario *Manufactures HEV 2012*

Actions Profiles

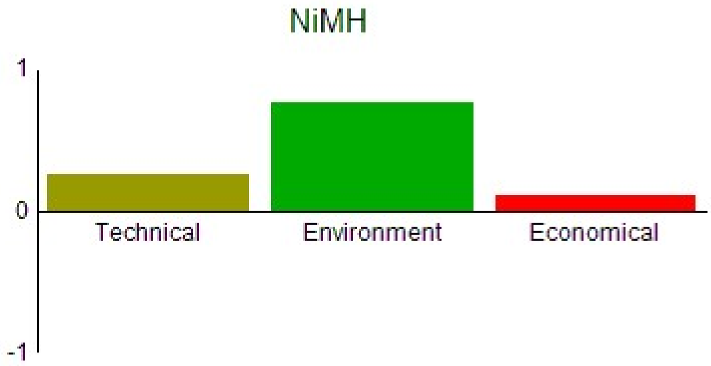
Action : PbAc



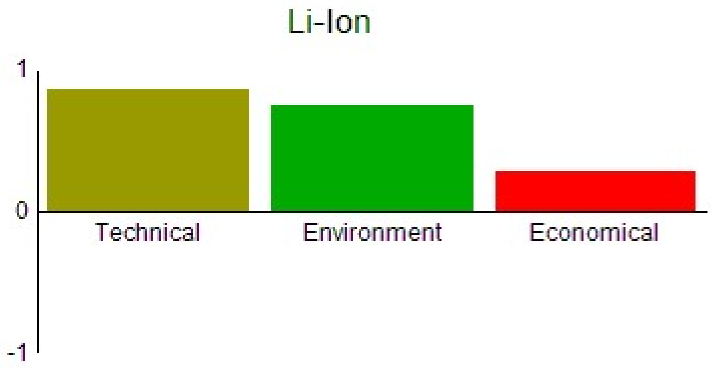
Action : NiCd



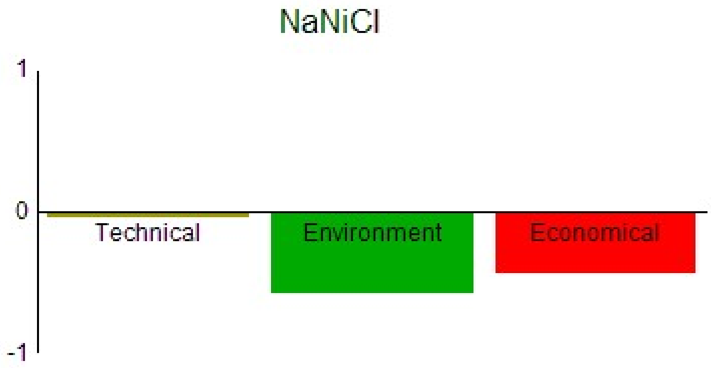
Action : NiMH



Action : Li-Ion

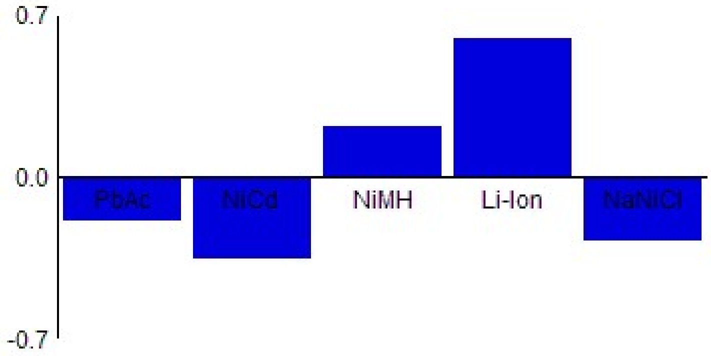


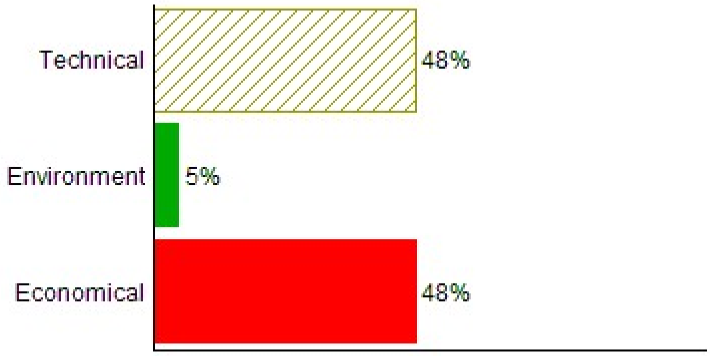
Action : NaNiCl



Back to results of scenario *Manufactures HEV 2012*

Walking Weights





Back to results of scenario *Manufactures HEV 2012*

Stability Intervals for scenario *Manufactures HEV 2012*
Level=5

| | Absolute values | | | Relative values (%) | | |
|---|---|---|---|---|---|---|
| | Weight | Min | Max | Weight | Min | Max |
| Energy Density | 10.0000 | 29.7156 | 65.5360 | 9.52% | 35.08% | 54.37% |
| Power Density | 30.0000 | 0.0000 | -1.0000 | 28.57% | 0.00% | 100.00% |
| Cycles | 5.0000 | 0.5000 | 1.7500 | 4.76% | 7.69% | 22.58% |
| Energy efficiency | 5.0000 | 0.5000 | 1.2500 | 4.76% | 7.69% | 17.24% |
| LCA | 5.0000 | 0.0000 | 5918.5720 | 4.76% | 0.00% | 98.34% |
| Cost | 30.0000 | 37.6346 | 83.3244 | 28.57% | 40.63% | 60.24% |
| Maturity | 10.0000 | 0.3333 | 2.0000 | 9.52% | 5.26% | 25.00% |
| userfriendly | 10.0000 | 0.0000 | 0.0000 | 9.52% | 0.00% | 0.00% |

Back to results of scenario *Manufactures HEV 2012*

Scenario: Political BEV 2005

- Short Name: Pol B 05
- Description:
- Color: 5
- Symbol: 9
- Category: Scenarios
- Enabled: Yes

Evaluations Preferences Results

Evaluations for scenario *Political BEV 2005*

| | Energy Density | Power Density | Cycles | Energy efficiency | LCA | Cost | Maturity | userfriendly |
|---|---|---|---|---|---|---|---|---|
| PbAc | 40 | 250 | 500.0 | 83 | 503 | 10085 | 100 | 100 |
| NiCd | 60 | 200 | 1350.0 | 73 | 544 | 17355 | 100 | 100 |
| NiMH | 70 | 350 | 1350.0 | 70 | 491 | 20254 | 60 | 100 |
| Li-Ion | 125 | 400 | 1000.0 | 90 | 278 | 25338 | 60 | 100 |
| NaNiCl | 125 | 200 | 1000.0 | 86 | 234 | 17109 | 80 | 60 |

Back to scenario *Political BEV 2005*

Preferences for scenario *Political BEV 2005*

| | Energy Density | Power Density | Cycles | Energy efficiency | LCA | Cost | Maturity | userfriendly |
|---|---|---|---|---|---|---|---|---|
| Function Type | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Minimized | False | False | False | False | True | True | False | False |
| P | 25 | 25 | 50 | 5 | 50 | 50 | 20 | 20 |
| Q | 5 | 5 | 10 | 2 | 20 | 20 | 10 | 10 |
| S | 1.17647058823529 | 5.55555555555556E-02 | 0.117647058823529 | 1 | 0.32258064516129 | 5.17812758906379E-03 | 1 | 0 |
| Unit | Wh/kg | W/kg | # | % | EcoPoints | EUR | % | |
| Scale | (Numerical) | (Numerical) | (Numerical) | (Numerical) | (Numerical) | (Numerical) | (Numerical) | (Numerical) |
| Weight | 25 | 15 | 5 | 5 | 50 | 30 | 10 | 10 |

Back to scenario *Political BEV 2005*

Results for scenario *Political BEV 2005*

- Rankings
- Scores
- PROMETHEE I
- PROMETHEE II
- GAIA Planes
- Actions Profiles
- Walking Weights
- Stability Intervals

Back to scenario *Political BEV 2005*

Scores for scenario *Political BEV 2005*

| | Energy Density | Power Density | Cycles | Energy efficiency | LCA | Cost | Maturity | userfriendly |
|---|---|---|---|---|---|---|---|---|
| PbAc | -1.0000 | 0.0000 | -1.0000 | 0.1667 | -0.4561 | 0.8579 | 0.7500 | 0.2500 |
| NiCd | -0.3958 | -0.7500 | 0.5625 | -0.7083 | -0.4908 | -0.0865 | 0.7500 | 0.2500 |
| NiMH | -0.1042 | 0.6339 | 0.5625 | -0.7917 | -0.4448 | -0.2495 | -0.7500 | 0.2500 |
| Li-Ion | 0.7500 | 0.8661 | -0.0625 | 0.9583 | 0.6417 | -0.4504 | -0.7500 | 0.2500 |
| NaNiCl | 0.7500 | -0.7500 | -0.0625 | 0.3750 | 0.7500 | -0.0715 | 0.0000 | -1.0000 |

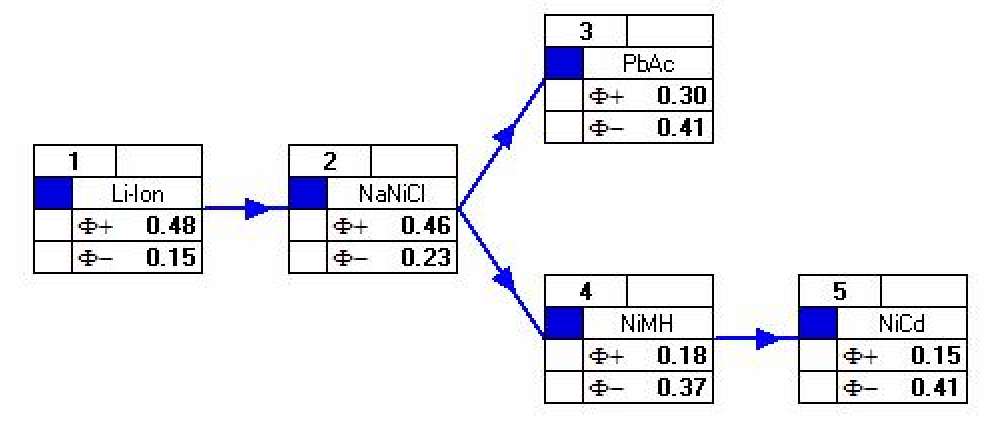
Back to results of scenario *Political BEV 2005*

Rankings for scenario *Political BEV 2005*

| | Phi Plus | Phi Minus | Phi Net | Ranking |
|---|---|---|---|---|
| PbAc | 0.3049 | 0.4131 | -0.1082 | 3 |
| NiCd | 0.1476 | 0.4077 | -0.2601 | 5 |
| NiMH | 0.1765 | 0.3696 | -0.1931 | 4 |
| Li-Ion | 0.4825 | 0.1505 | 0.3320 | 1 |
| NaNiCl | 0.4569 | 0.2275 | 0.2295 | 2 |

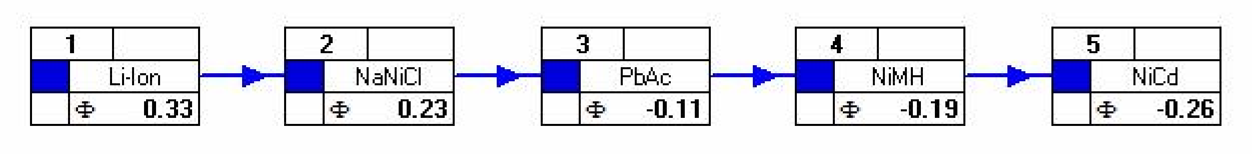
Back to results of scenario *Political BEV 2005*

Partial Ranking (PROMETHEE I)



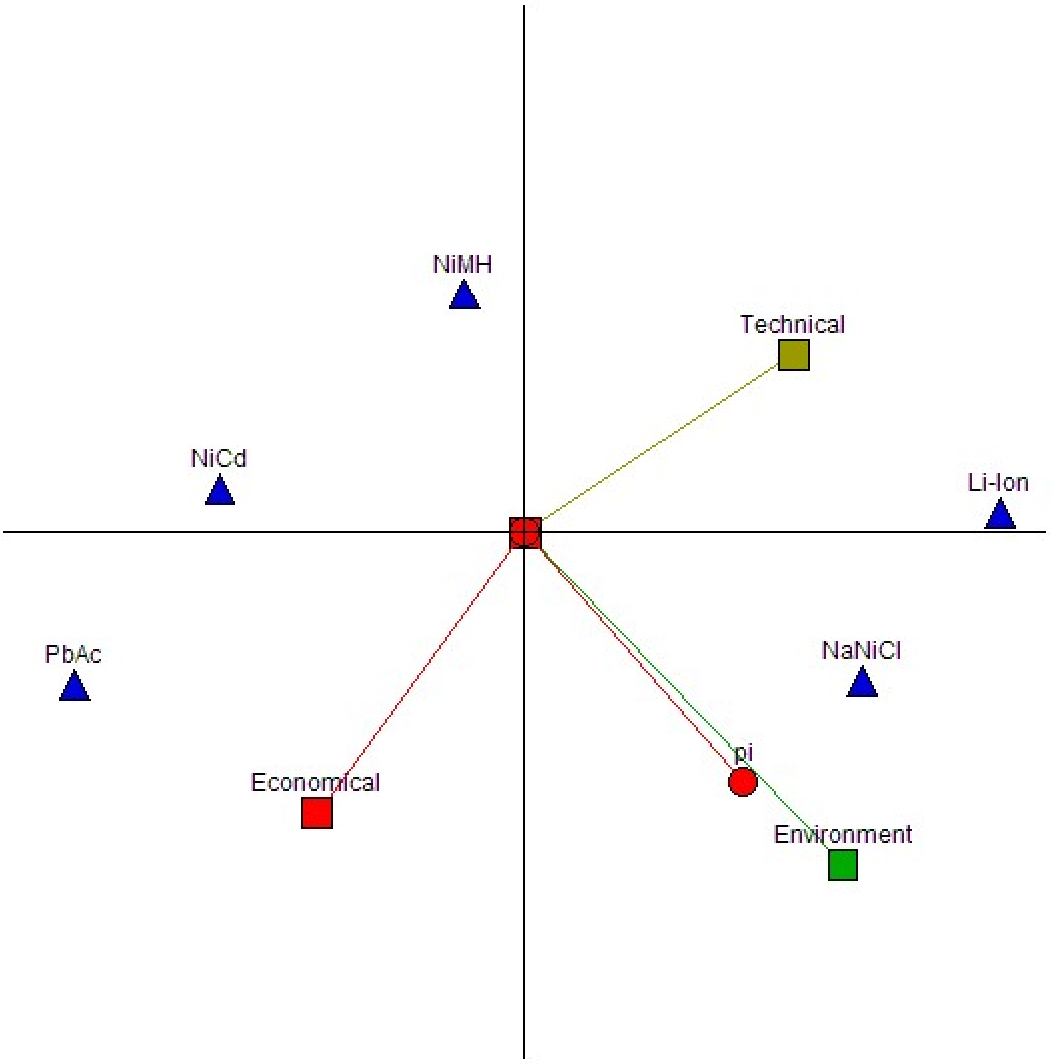
Back to results of scenario *Political BEV 2005*

### Complete Ranking (PROMETHEE II)

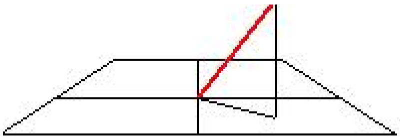


Back to results of scenario *Political BEV 2005*

### GAIA Planes



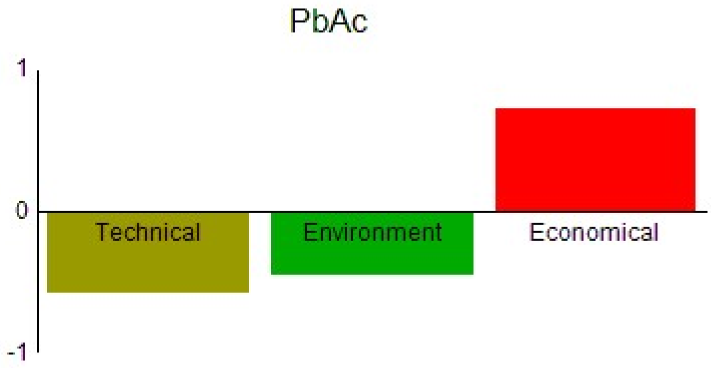
### Decision Stick



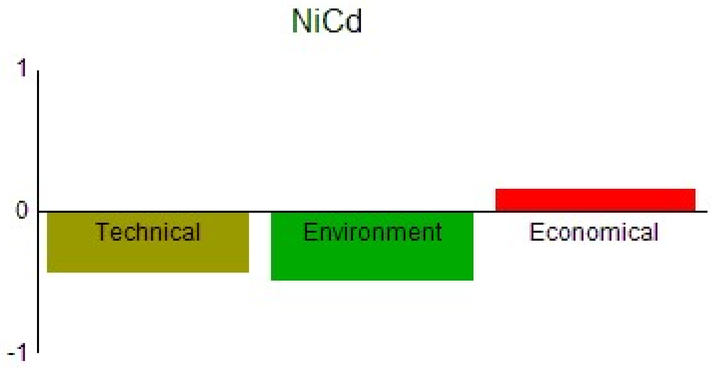
Back to results of scenario *Political BEV 2005*

Actions Profiles

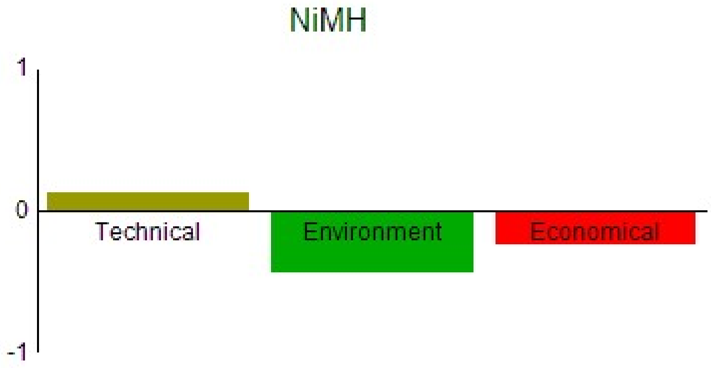
Action : PbAc



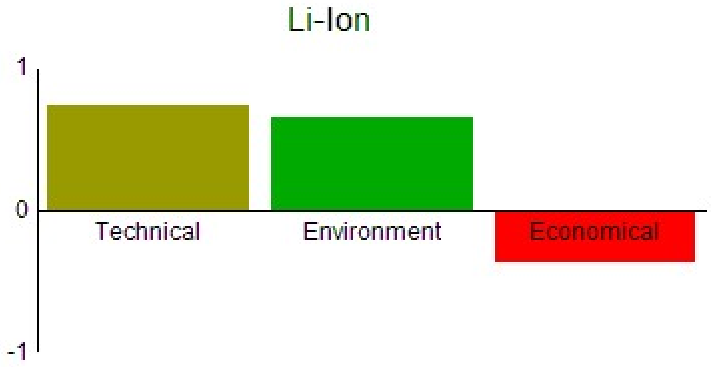
Action : NiCd



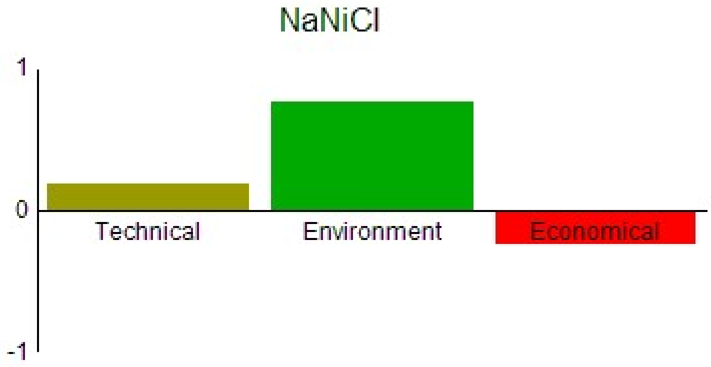
Action : NiMH



Action : Li-Ion

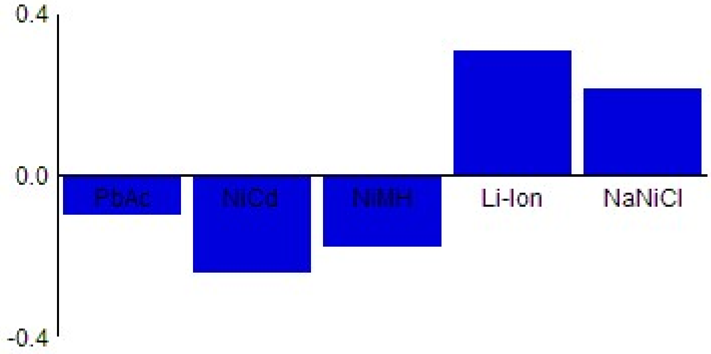


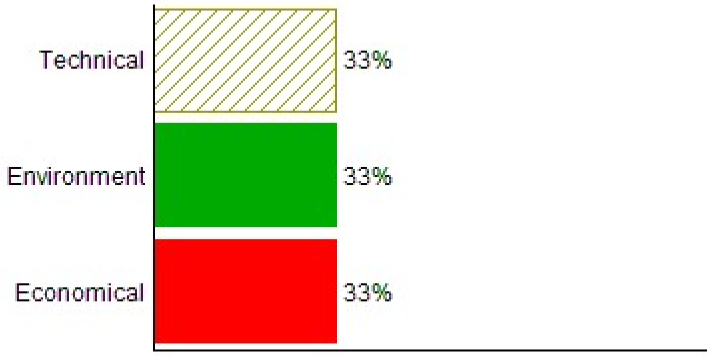
Action : NaNiCl



Back to results of scenario *Political BEV 2005*

Walking Weights





Back to results of scenario *Political BEV 2005*

Stability Intervals for scenario *Political BEV 2005*
Level=5

| | Absolute values | | | Relative values (%) | | |
|---|---|---|---|---|---|---|
| | Weight | Min | Max | Weight | Min | Max |
| Energy Density | 25.0000 | 31.8258 | 68.2266 | 16.67% | 24.14% | 40.56% |
| Power Density | 15.0000 | 0.0000 | 17.5809 | 10.00% | 0.00% | 11.52% |
| Cycles | 5.0000 | 0.0000 | 9.0117 | 3.33% | 0.00% | 5.85% |
| Energy efficiency | 5.0000 | 0.0000 | 13.8487 | 3.33% | 0.00% | 8.72% |
| LCA | 50.0000 | 8.0021 | 192.0502 | 33.33% | 7.41% | 65.76% |
| Cost | 30.0000 | 36.7985 | 75.2529 | 20.00% | 26.90% | 42.94% |
| Maturity | 10.0000 | 0.0000 | 6.7511 | 6.67% | 0.00% | 6.98% |
| userfriendly | 10.0000 | 0.0000 | 0.0000 | 6.67% | 0.00% | 0.00% |

Back to results of scenario *Political BEV 2005*

Scenario: Political BEV 2012

- Short Name: Pol BEV 12
- Description:
- Color: 5
- Symbol: 9
- Category: Scenarios
- Enabled: Yes

Evaluations Preferences Results

Evaluations for scenario *Political BEV 2012*

| | Energy Density | Power Density | Cycles | Energy efficiency | LCA | Cost | Maturity | userfriendly |
|---|---|---|---|---|---|---|---|---|
| PbAc | 40 | 250 | 1000.0 | 85 | 331 | 6432 | 100 | 100 |
| NiCd | 60 | 200 | 2000.0 | 75 | 427 | 11286 | 100 | 100 |
| NiMH | 70 | 350 | 2000.0 | 75 | 364 | 12684 | 100 | 100 |
| Li-Ion | 150 | 400 | 2000.0 | 95 | 122 | 4504 | 100 | 100 |
| NaNiCl | 150 | 200 | 2000.0 | 90 | 129 | 4059 | 100 | 60 |

Back to scenario *Political BEV 2012*

Preferences for scenario *Political BEV 2012*

| | Energy Density | Power Density | Cycles | Energy efficiency | LCA | Cost | Maturity | userfriendly |
|---|---|---|---|---|---|---|---|---|
| Function Type | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Minimized | False | False | False | False | True | True | False | False |
| P | 25 | 25 | 50 | 5 | 50 | 50 | 20 | 20 |
| Q | 5 | 5 | 10 | 2 | 20 | 20 | 10 | 10 |
| S | 1.17647058823529 | 5.55555555555556E-02 | 0.117647058823529 | 1 | 0.32258064516129 | 5.17812758906379E-03 | 1 | 0 |
| Unit | Wh/kg | W/kg | # | % | EcoPoints | EUR | % | |
| Scale | (Numerical) | (Numerical) | (Numerical) | (Numerical) | (Numerical) | (Numerical) | (Numerical) | (Numerical) |
| Weight | 25 | 15 | 5 | 5 | 50 | 30 | 10 | 10 |

Back to scenario *Political BEV 2012*

Results for scenario *Political BEV 2012*

- Rankings
- Scores
- PROMETHEE I
- PROMETHEE II
- GAIA Planes
- Actions Profiles
- Walking Weights
- Stability Intervals

Back to scenario *Political BEV 2012*

Scores for scenario *Political BEV 2012*

| | Energy Density | Power Density | Cycles | Energy efficiency | LCA | Cost | Maturity | userfriendly |
|---|---|---|---|---|---|---|---|---|
| PbAc | -1.0000 | 0.0000 | -1.0000 | 0.0000 | -0.4793 | 0.2119 | 0.0000 | 0.2500 |
| NiCd | -0.3958 | -0.7500 | 0.2500 | -0.7500 | -0.5207 | -0.6917 | 0.0000 | 0.2500 |
| NiMH | -0.1042 | 0.6339 | 0.2500 | -0.7500 | -0.5000 | -0.7441 | 0.0000 | 0.2500 |
| Li-Ion | 0.7500 | 0.8661 | 0.2500 | 1.0000 | 0.7500 | 0.5831 | 0.0000 | 0.2500 |
| NaNiCl | 0.7500 | -0.7500 | 0.2500 | 0.5000 | 0.7500 | 0.6408 | 0.0000 | -1.0000 |

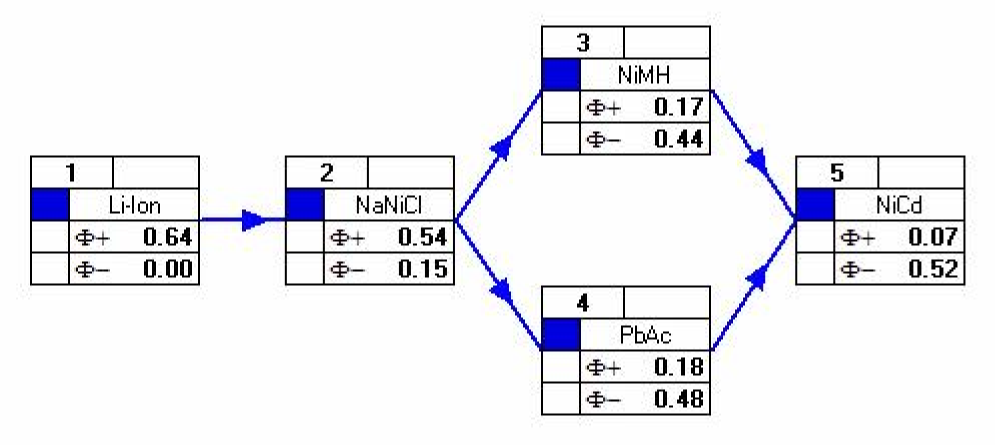
Back to results of scenario *Political BEV 2012*

Rankings for scenario *Political BEV 2012*

| | Phi Plus | Phi Minus | Phi Net | Ranking |
|---|---|---|---|---|
| PbAc | 0.1774 | 0.4781 | -0.3007 | 4 |
| NiCd | 0.0667 | 0.5195 | -0.4529 | 5 |
| NiMH | 0.1660 | 0.4354 | -0.2695 | 3 |
| Li-Ion | 0.6366 | 0.0000 | 0.6366 | 1 |
| NaNiCl | 0.5365 | 0.1500 | 0.3865 | 2 |

Back to results of scenario *Political BEV 2012*

Partial Ranking (PROMETHEE I)

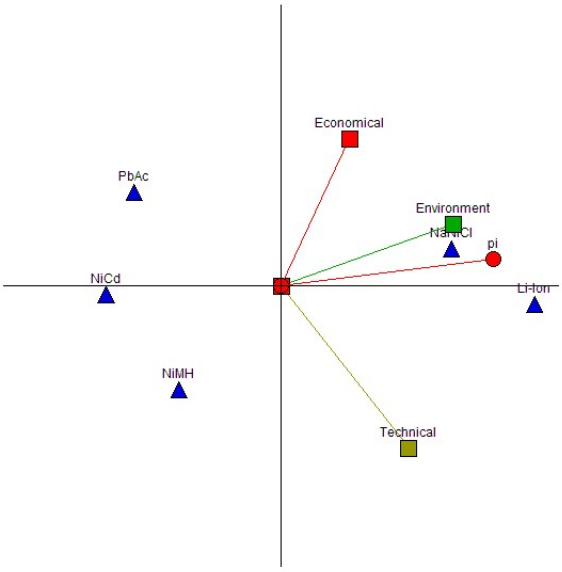


Back to results of scenario *Political BEV 2012*

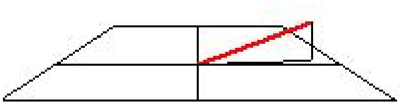
Complete Ranking (PROMETHEE II)

Back to results of scenario *Political BEV 2012*

GAIA Planes



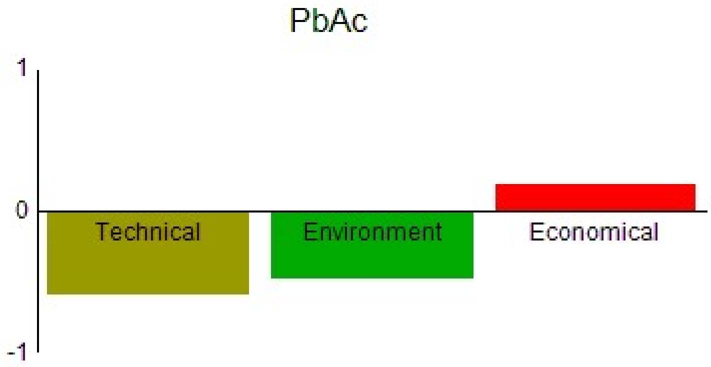
Decision Stick



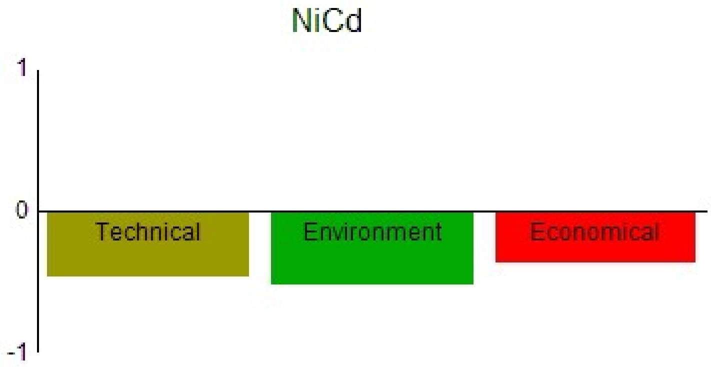
Back to results of scenario *Political BEV 2012*

Actions Profiles

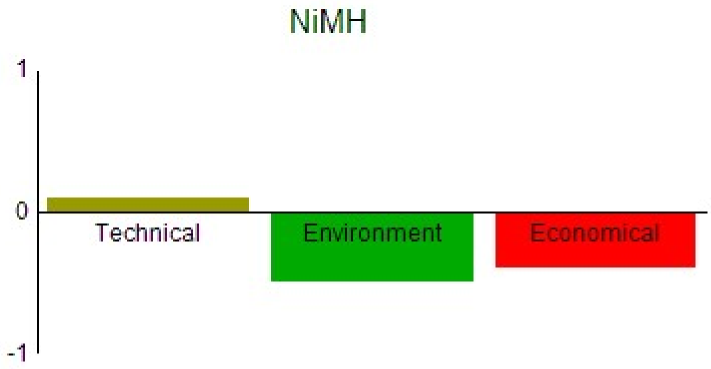
Action : PbAc



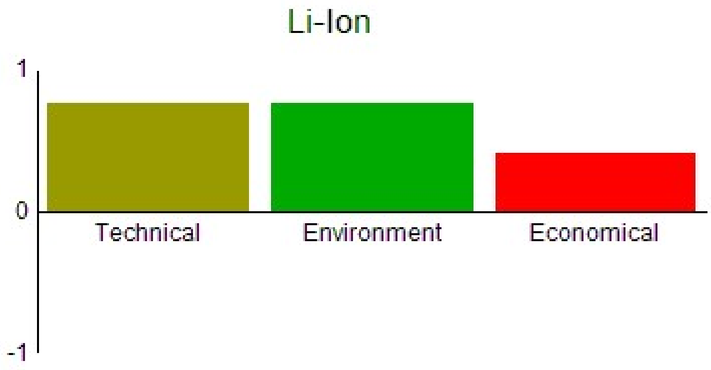
Action : NiCd



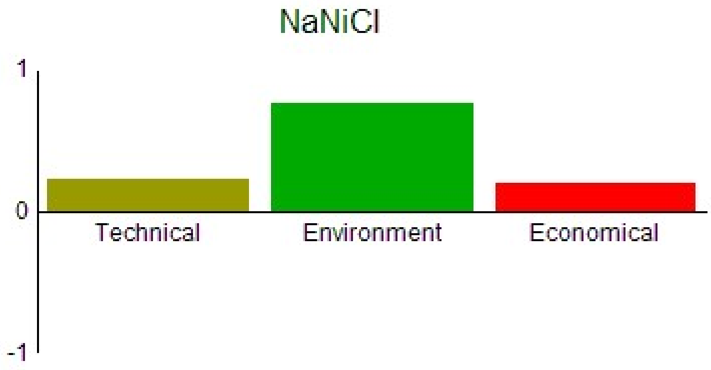
Action : NiMH



Action : Li-Ion

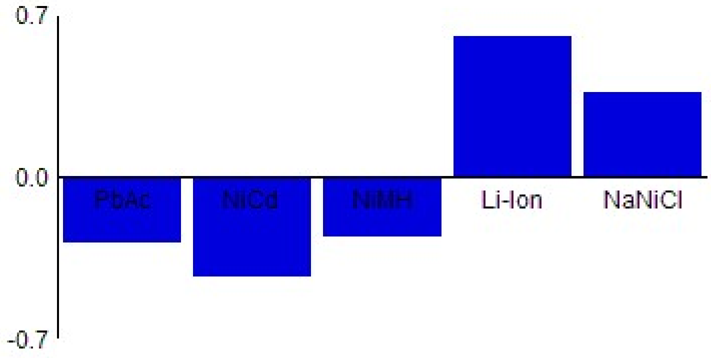


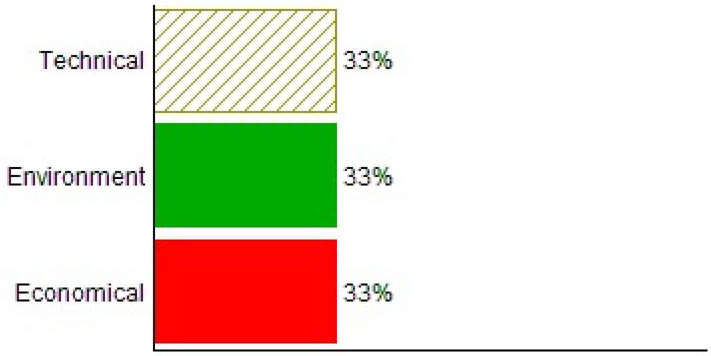
Action : NaNiCl



Back to results of scenario *Political BEV 2012*

Walking Weights





Back to results of scenario *Political BEV 2012*

Stability Intervals for scenario *Political BEV 2012*
Level=5

| | Absolute values | | | Relative values (%) | | |
|---|---|---|---|---|---|---|
| | Weight | Min | Max | Weight | Min | Max |
| Energy Density | 25.0000 | 43.1839 | 229.6023 | 16.67% | 30.16% | 69.66% |
| Power Density | 15.0000 | 0.0000 | 113.1055 | 10.00% | 0.00% | 34.90% |
| Cycles | 5.0000 | 0.0000 | -1.0000 | 3.33% | 0.00% | 100.00% |
| Energy efficiency | 5.0000 | 0.0000 | 82.0085 | 3.33% | 0.00% | 27.06% |
| LCA | 50.0000 | 0.0000 | 276.7190 | 33.33% | 0.00% | 73.46% |
| Cost | 30.0000 | 7.9039 | 58.1766 | 20.00% | 7.32% | 36.78% |
| Maturity | 10.0000 | 0.0000 | -1.0000 | 6.67% | 0.00% | 100.00% |
| userfriendly | 10.0000 | 0.0000 | 118.7266 | 6.67% | 0.00% | 34.54% |

Back to results of scenario *Political BEV 2012*

Scenario: Political HEV 2005

- Short Name: Pol HEV 05
- Description:
- Color: 5
- Symbol: 9
- Category: Scenarios
- Enabled: Yes

Evaluations Preferences Results

Evaluations for scenario *Political HEV 2005*

| | Energy Density | Power Density | Cycles | Energy efficiency | LCA | Cost | Maturity | userfriendly |
|---|---|---|---|---|---|---|---|---|
| PbAc | 25 | 350 | 1.0 | 83 | 14 | 432 | 100 | 100 |
| NiCd | 30 | 500 | 3.0 | 73 | 10 | 624 | 100 | 100 |
| NiMH | 55 | 1500 | 3.0 | 70 | 3 | 456 | 100 | 100 |
| Li-Ion | 70 | 2000 | 3.0 | 90 | 4 | 684 | 50 | 100 |
| NaNiCl | 125 | 200 | 3.0 | 86 | 23 | 2976 | 0 | 60 |

Back to scenario *Political HEV 2005*

Preferences for scenario *Political HEV 2005*

| | Energy Density | Power Density | Cycles | Energy efficiency | LCA | Cost | Maturity | userfriendly |
|---|---|---|---|---|---|---|---|---|
| Function Type | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Minimized | False | False | False | False | True | True | False | False |
| P | 25 | 25 | 50 | 5 | 50 | 50 | 20 | 20 |
| Q | 5 | 5 | 10 | 2 | 20 | 20 | 10 | 10 |
| S | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Unit | Wh/kg | W/kg | # | % | EcoPoints | Euro | % | |
| Scale | (Numerical) | (Numerical) | (Numerical) | (Numerical) | (Numerical) | (Numerical) | (Numerical) | (Numerical) |
| Weight | 10 | 30 | 5 | 5 | 50 | 30 | 10 | 10 |

Back to scenario *Political HEV 2005*

Results for scenario *Political HEV 2005*

- Rankings
- Scores
- PROMETHEE I
- PROMETHEE II
- GAIA Planes
- Actions Profiles
- Walking Weights
- Stability Intervals

Back to scenario *Political HEV 2005*

Scores for scenario *Political HEV 2005*

| | Energy Density | Power Density | Cycles | Energy efficiency | LCA | Cost | Maturity | userfriendly |
|---|---|---|---|---|---|---|---|---|
| PbAc | -0.9375 | -0.5000 | -1.0000 | 0.1667 | -0.3936 | 0.4801 | 0.5000 | 0.2500 |
| NiCd | -0.5625 | 0.0000 | 0.2500 | -0.7083 | -0.1945 | 0.1026 | 0.5000 | 0.2500 |
| NiMH | 0.0000 | 0.5000 | 0.2500 | -0.7917 | 0.8645 | 0.4188 | 0.5000 | 0.2500 |
| Li-Ion | 0.5000 | 1.0000 | 0.2500 | 0.9583 | 0.6355 | -0.0015 | -0.5000 | 0.2500 |
| NaNiCl | 1.0000 | -1.0000 | 0.2500 | 0.3750 | -0.9118 | -1.0000 | -1.0000 | -1.0000 |

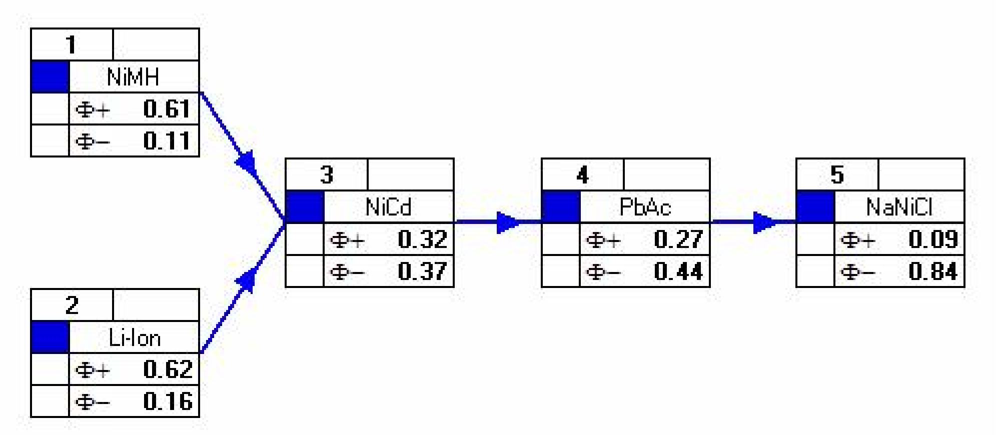
Back to results of scenario *Political HEV 2005*

Rankings for scenario *Political HEV 2005*

| | Phi Plus | Phi Minus | Phi Net | Ranking |
|---|---|---|---|---|
| PbAc | 0.2666 | 0.4421 | -0.1755 | 4 |
| NiCd | 0.3240 | 0.3712 | -0.0471 | 3 |
| NiMH | 0.6136 | 0.1097 | 0.5039 | 1 |
| Li-Ion | 0.6236 | 0.1551 | 0.4685 | 2 |
| NaNiCl | 0.0944 | 0.8442 | -0.7498 | 5 |

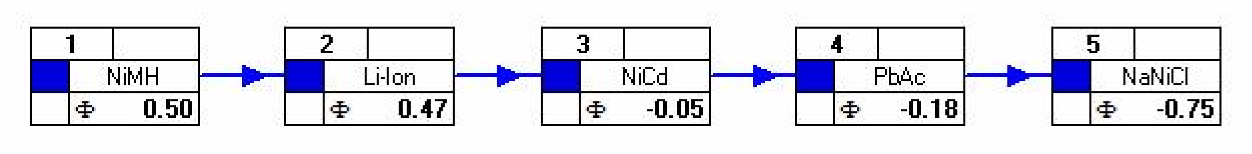
Back to results of scenario *Political HEV 2005*

Partial Ranking (PROMETHEE I)



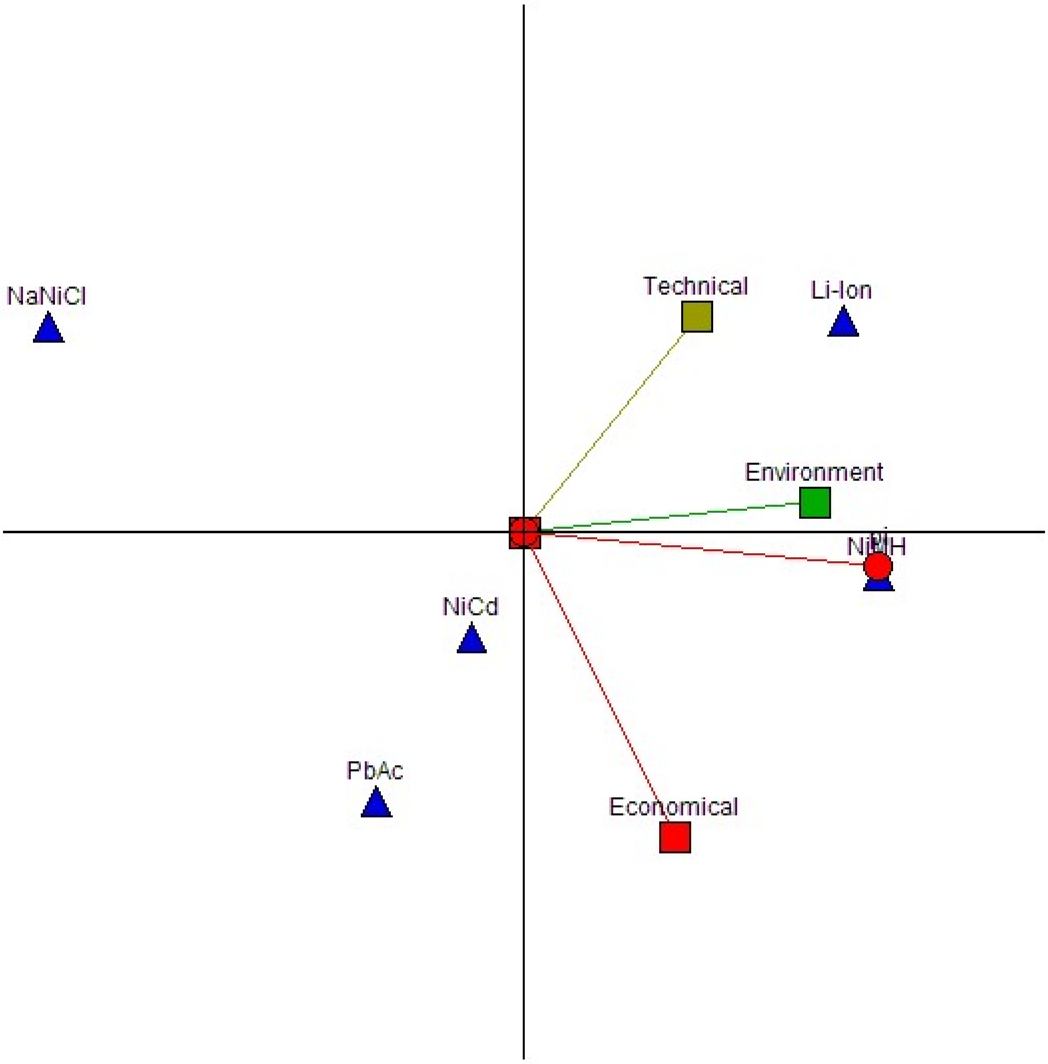
Back to results of scenario *Political HEV 2005*

Complete Ranking (PROMETHEE II)

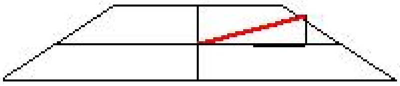


Back to results of scenario *Political HEV 2005*

GAIA Planes



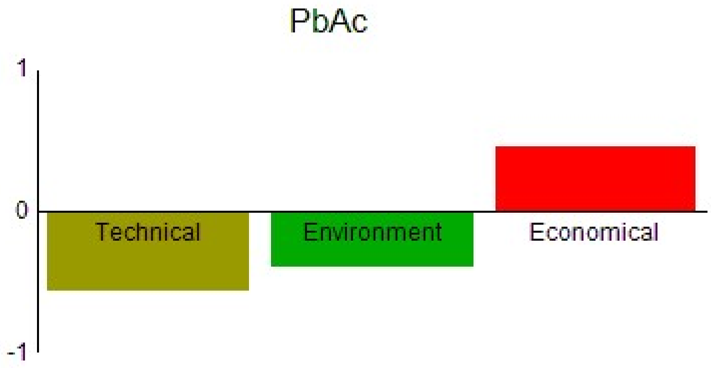
Decision Stick



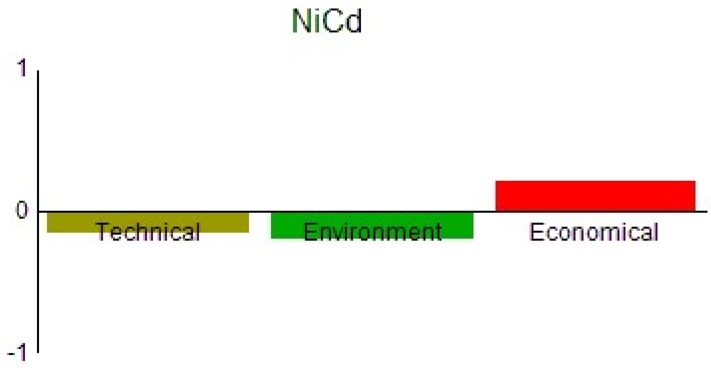
Back to results of scenario *Political HEV 2005*

Actions Profiles

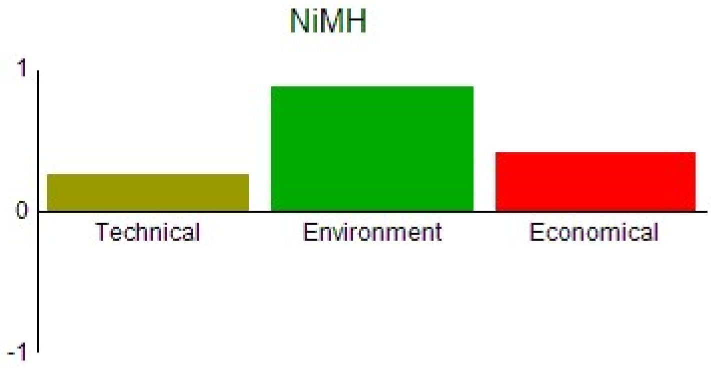
Action : PbAc



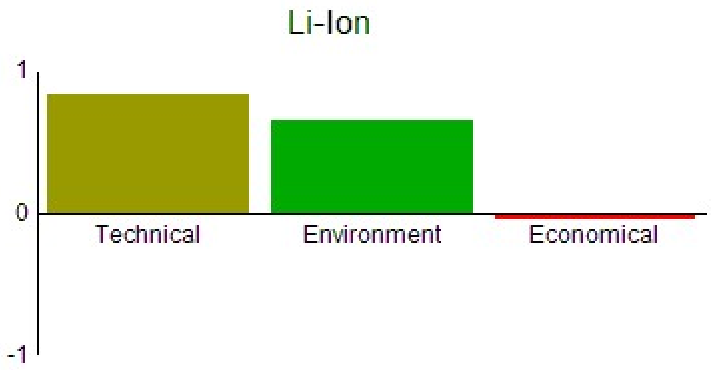
Action : NiCd



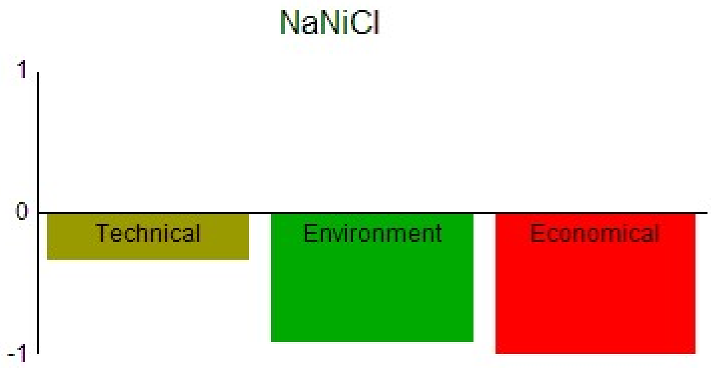
Action : NiMH



Action : Li-Ion

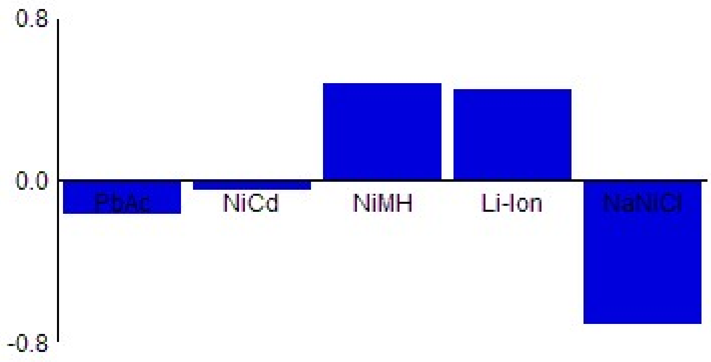


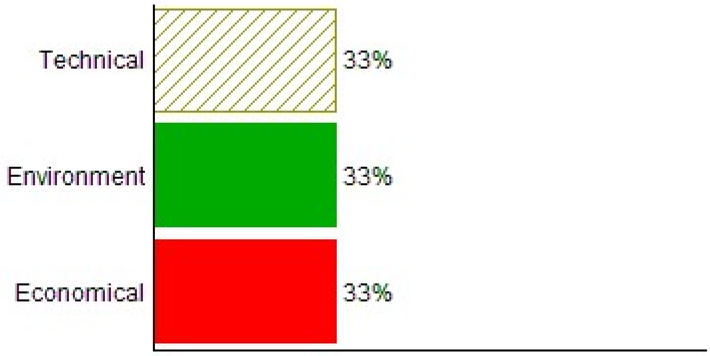
Action : NaNiCl



[Back to results of scenario *Political HEV 2005*]

Walking Weights





Back to results of scenario *Political HEV 2005*

Stability Intervals for scenario *Political HEV 2005*
Level=5

| | Absolute values | | | Relative values (%) | | |
|---|---|---|---|---|---|---|
| | Weight | Min | Max | Weight | Min | Max |
| Energy Density | 10.0000 | 3.3225 | 59.2281 | 6.67% | 3.22% | 37.20% |
| Power Density | 30.0000 | 0.0000 | -1.0000 | 20.00% | 0.00% | 100.00% |
| Cycles | 5.0000 | 0.5000 | 1.7500 | 3.33% | 7.69% | 22.58% |
| Energy efficiency | 5.0000 | 0.5000 | 1.2500 | 3.33% | 7.69% | 17.24% |
| LCA | 50.0000 | 26.8253 | -1.0000 | 33.33% | 21.15% | 100.00% |
| Cost | 30.0000 | 38.2648 | 135.0019 | 20.00% | 27.68% | 57.45% |
| Maturity | 10.0000 | 0.3333 | 2.0000 | 6.67% | 5.26% | 25.00% |
| userfriendly | 10.0000 | 0.0000 | 0.0000 | 6.67% | 0.00% | 0.00% |

Back to results of scenario *Political HEV 2005*

Scenario: Political HEV 2012

- Short Name: Pol HEV 12
- Description:
- Color: 5
- Symbol: 9
- Category: Scenarios
- Enabled: Yes

Evaluations Preferences Results

Evaluations for scenario *Political HEV 2012*

| | Energy Density | Power Density | Cycles | Energy efficiency | LCA | Cost | Maturity | userfriendly |
|---|---|---|---|---|---|---|---|---|
| PbAc | 25 | 600 | 1.5 | 85 | 5 | 384 | 100 | 100 |
| NiCd | 30 | 600 | 3.0 | 75 | 9 | 624 | 100 | 100 |
| NiMH | 55 | 2500 | 3.0 | 75 | 2 | 456 | 100 | 100 |
| Li-Ion | 70 | 4000 | 3.0 | 95 | 2 | 360 | 100 | 100 |
| NaNiCl | 80 | 600 | 3.0 | 90 | 8 | 624 | 100 | 60 |

Back to scenario *Political HEV 2012*

Preferences for scenario *Political HEV 2012*

| | Energy Density | Power Density | Cycles | Energy efficiency | LCA | Cost | Maturity | userfriendly |
|---|---|---|---|---|---|---|---|---|
| Function Type | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Minimized | False | False | False | False | True | True | False | False |
| P | 25 | 25 | 50 | 5 | 50 | 50 | 20 | 20 |
| Q | 5 | 5 | 10 | 2 | 20 | 20 | 10 | 10 |
| S | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| Unit | Wh/kg | W/kg | # | % | EcoPoints | Euro | % | |
| Scale | (Numerical) | (Numerical) | (Numerical) | (Numerical) | (Numerical) | (Numerical) | (Numerical) | (Numerical) |
| Weight | 10 | 30 | 5 | 5 | 50 | 30 | 10 | 10 |

Back to scenario *Political HEV 2012*

Results for scenario *Political HEV 2012*

- Rankings
- Scores
- PROMETHEE I
- PROMETHEE II
- GAIA Planes
- Actions Profiles
- Walking Weights
- Stability Intervals

Back to scenario *Political HEV 2012*

Scores for scenario *Political HEV 2012*

| | Energy Density | Power Density | Cycles | Energy efficiency | LCA | Cost | Maturity | userfriendly |
|---|---|---|---|---|---|---|---|---|
| PbAc | -0.9375 | -0.5000 | -1.0000 | 0.0000 | -0.2863 | 0.3077 | 0.0000 | 0.2500 |
| NiCd | -0.5625 | -0.5000 | 0.2500 | -0.7500 | -0.6364 | -0.3974 | 0.0000 | 0.2500 |
| NiMH | 0.0000 | 0.5000 | 0.2500 | -0.7500 | 0.7532 | 0.1066 | 0.0000 | 0.2500 |
| Li-Ion | 0.6339 | 1.0000 | 0.2500 | 1.0000 | 0.7468 | 0.3806 | 0.0000 | 0.2500 |
| NaNiCl | 0.8661 | -0.5000 | 0.2500 | 0.5000 | -0.5773 | -0.3974 | 0.0000 | -1.0000 |

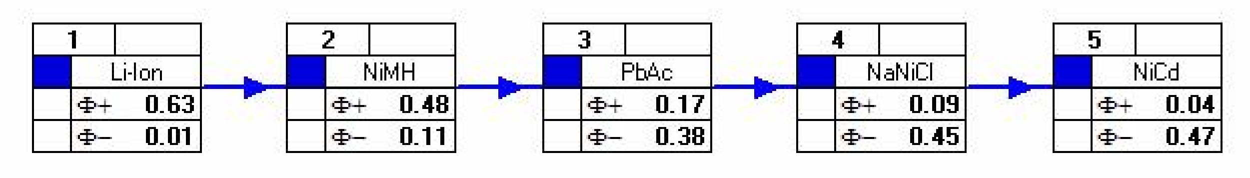
Back to results of scenario *Political HEV 2012*

Rankings for scenario *Political HEV 2012*

| | Phi Plus | Phi Minus | Phi Net | Ranking |
|---|---|---|---|---|
| PbAc | 0.1661 | 0.3792 | -0.2131 | 3 |
| NiCd | 0.0375 | 0.4666 | -0.4291 | 5 |
| NiMH | 0.4825 | 0.1101 | 0.3724 | 2 |
| Li-Ion | 0.6344 | 0.0088 | 0.6256 | 1 |
| NaNiCl | 0.0911 | 0.4469 | -0.3558 | 4 |

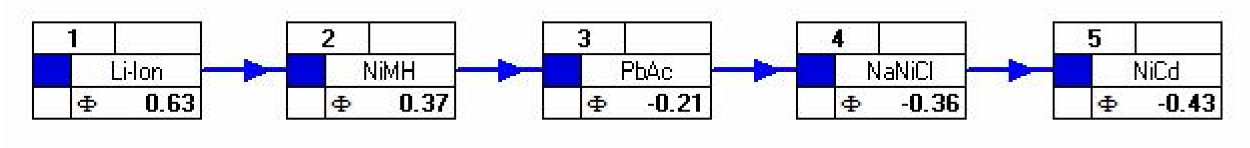
Back to results of scenario *Political HEV 2012*

Partial Ranking (PROMETHEE I)



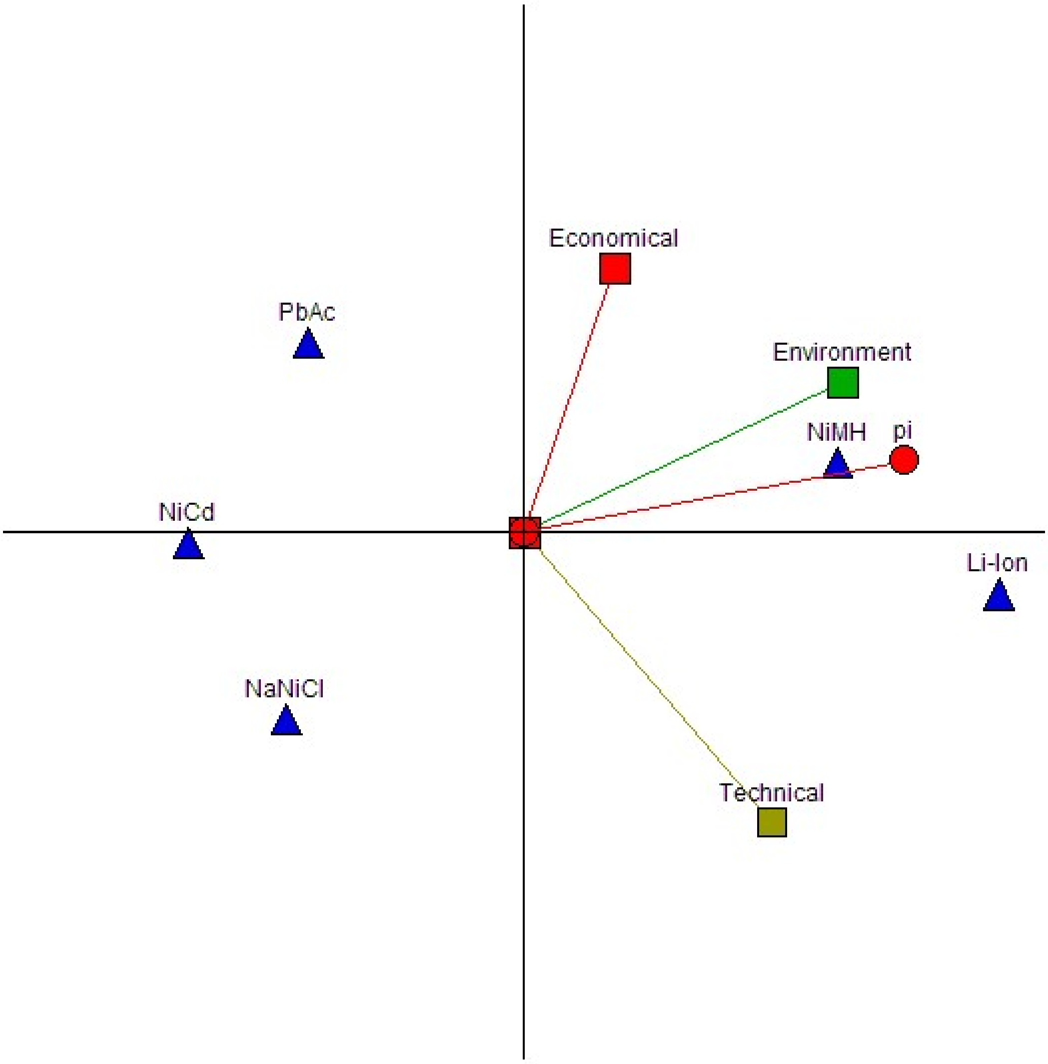
Back to results of scenario *Political HEV 2012*

Complete Ranking (PROMETHEE II)

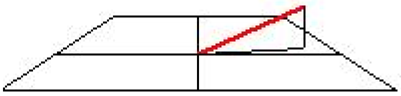


Back to results of scenario *Political HEV 2012*

GAIA Planes



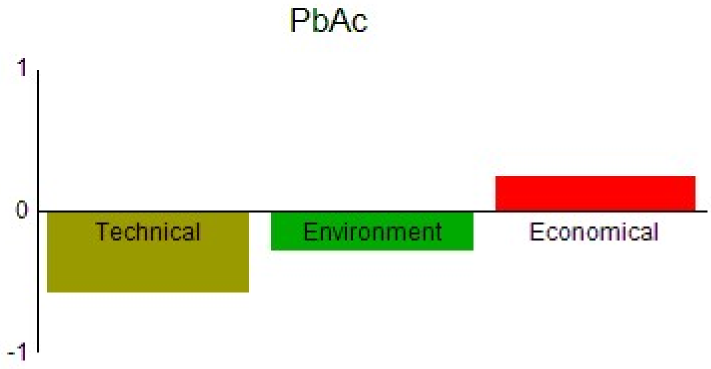
Decision Stick



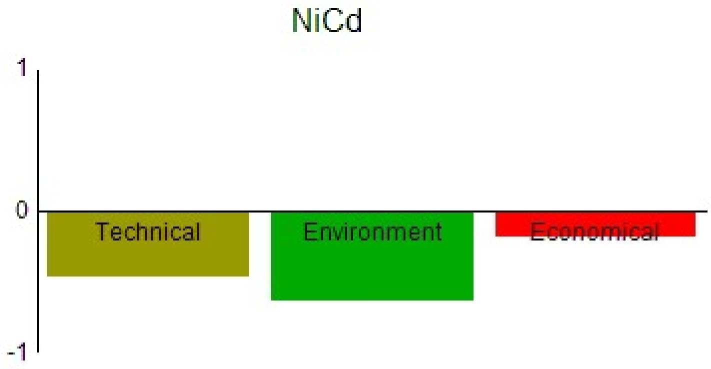
[Back to results of scenario *Political HEV 2012*]

Actions Profiles

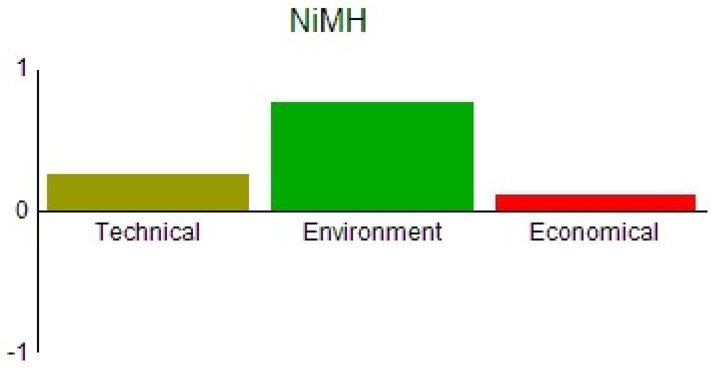
Action : PbAc



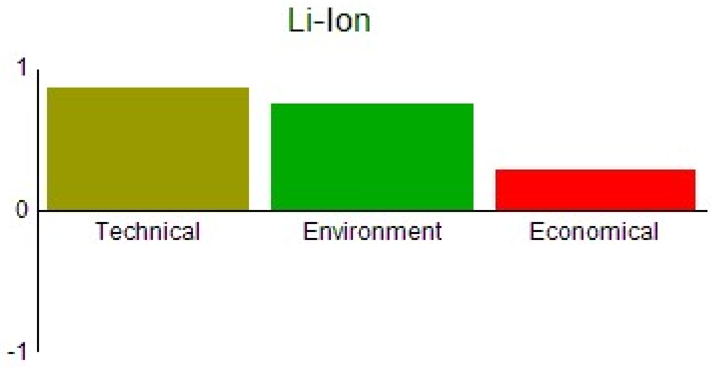
Action : NiCd



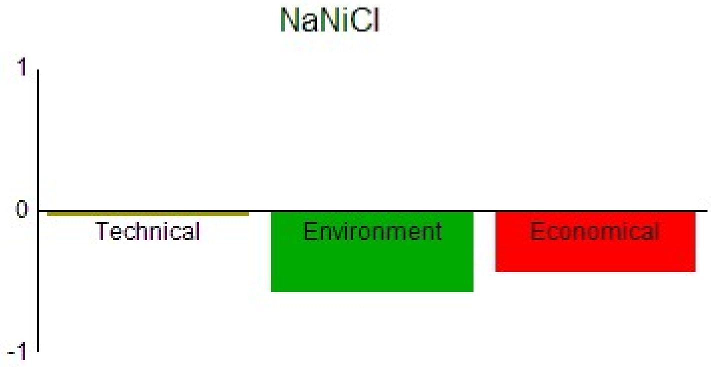
Action : NiMH



Action : Li-Ion

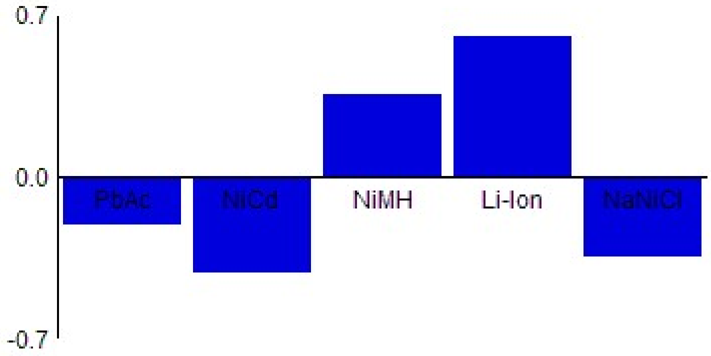


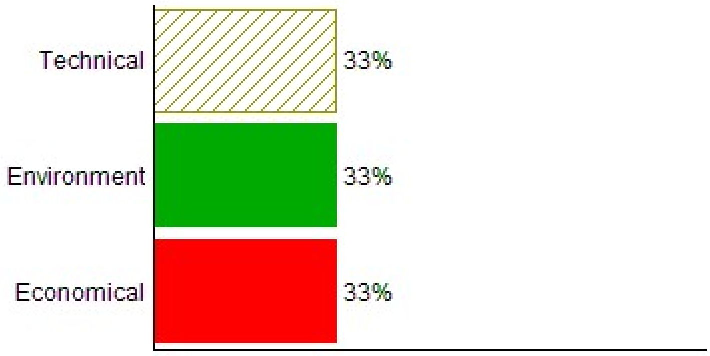
Action : NaNiCl



[Back to results of scenario *Political HEV 2012*]

Walking Weights





Back to results of scenario *Political HEV 2012*

Stability Intervals for scenario *Political HEV 2012*
Level=5

| | Absolute values | | | Relative values (%) | | |
|---|---|---|---|---|---|---|
| | Weight | Min | Max | Weight | Min | Max |
| Energy Density | 10.0000 | 23.2430 | 89.9750 | 6.67% | 18.86% | 47.36% |
| Power Density | 30.0000 | 0.0000 | -1.0000 | 20.00% | 0.00% | 100.00% |
| Cycles | 5.0000 | 0.5000 | 1.7500 | 3.33% | 7.69% | 22.58% |
| Energy efficiency | 5.0000 | 0.5000 | 1.2500 | 3.33% | 7.69% | 17.24% |
| LCA | 50.0000 | 0.0000 | 5918.5720 | 33.33% | 0.00% | 98.34% |
| Cost | 30.0000 | 18.1832 | 93.9579 | 20.00% | 15.39% | 48.44% |
| Maturity | 10.0000 | 0.3333 | 2.0000 | 6.67% | 5.26% | 25.00% |
| userfriendly | 10.0000 | 0.0000 | 0.0000 | 6.67% | 0.00% | 0.00% |

Back to results of scenario *Political HEV 2012*

APPENDIX V

# SUBAT: SUSTAINABLE BATTERIES

## Work package 5: Overall Assessment

## Final Public Report

**Report prepared by**

**J. Matheys and W. Van Autenboer**
**under the supervision of Prof. Dr. ir. J. Van Mierlo**
**Vrije Universiteit Brussel - ETEC**

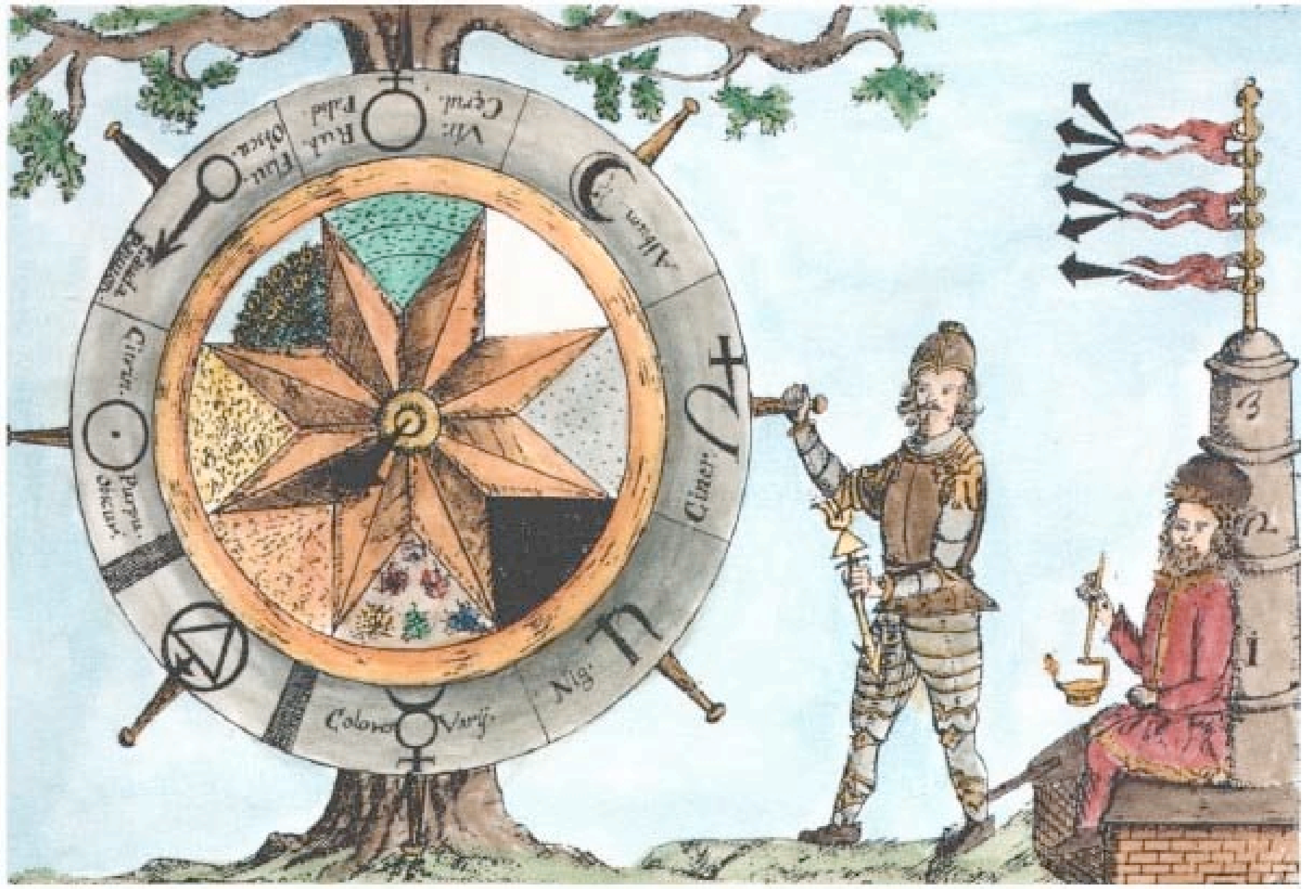


Image © Adam McLean

# SUBAT Partnership

Vrije Universiteit Brussel
Vakgroep Electrotechniek en Energietechnologie
(ETEC)

AVERE

CEI CIVES

CEREVEH

CITELEC

DSEA

Centre d'Etudes Economiques et Sociales de l'Environnement

ULB

*The hermetical allegory of SUBAT*

*This image on the frontispice is Plate IX from "Speculum Veritatis", a famous 17th century hermetical manuscript, in a coloured version by Adam McLean. It shows Cadmus turning the wheel on which the seven traditional metals (clockwise from 9 o'clock: gold, iron, copper, silver, tin, lead and mercury) as well as sulphur are represented. The wheel has to be turned three times (represented by the three flags on the right), going through eight consecutive phases characterized by colour changes, in order to complete the alchemical process. The figure sitting near the oven on the right is Vulcanus.*

*The figure also can be interpreted as highlighting the essence of the SUBAT project, which consists of an appraisal of different battery technologies (represented by the different metals), and in particular the NiCd battery (represented here by Cadmus after whom the cadmium metal was named). The three turns of the wheel stand here for the three pillars of the study (technical, ecological and economical).*

*This allegorical representation reminds us of the wisdom of the old philosophers, which, being of a hermetic nature and thus difficultly accessible for the lesser mind, may largely be forgotten in today's materialistic world, but which, through assiduous study, will provide valuable insights towards the construction of our image of the world.*

APPENDIX V

# Table of contents

## Abbreviations list

AGM = Absorption Glass fibre Mat
BEV = Battery Electric Vehicle
BMS = Battery Management System
C = Capacity
DOD = Depth of discharge
FC = Fuel Cell
F.U. = Functional Unit
HEV = Hybrid Electric Vehicle
GAIA = Geometrcial Analysis for Interactive Assistance
GHG = Greenhouse Gases
ICE = Internal Combustion Engine
LCA = Life Cycle Assessment
LCIA = Life Cycle Impact Assessment
Li-ion = Lithium-Ion Battery
MCA = Multi-Criteria Analysis
NaNiCl = Sodium-Nickel Chloride Battery
NiCd = Nickel-Cadmium Battery
NiMH = Nickel-Metal Hydride Battery
NiZn = Nickel-Zinc Battery
Pb-acid = Lead-acid battery
PROMETHEE = Preference Ranking Organisation Method for Enrichment Evaluations
SLI = Starting, Lighting, Ignition
SOC = Stage of Charge
SUBAT = Sustainable Batteries (EU Project)
VLRA = Valve Regulated Lead Acid Battery
VSP = Vehicle Simulation Program
WP = Work Package
WP1 = Work Package 1 = Technical Assessment
WP2 = Work Package 2 = Environmental Assessment
WP3 = Work Package 3 = Economical Assessment
WP4 = Work Package 4 = Data Collection
WP5 = Work Package 5 = Overall Assessment

# I. Introduction.

The SUBAT-project is a specific targeted research project with the aim to deliver a complete assessment of commercially available and forthcoming battery technologies for battery-electric and hybrid vehicles. This assessment will include a technical (work package 1), an environmental (work package 2) and an economical (work package 3) study of the different battery technologies, including the nickel-cadmium technology. These studies are performed using data gathered in work package 4, while the overall results and conclusions are presented in work package 5.

As a consequence the other purpose is to evaluate the opportunity to keep nickel-cadmium traction batteries for electric vehicles on the exemption list of Directive 2000/53 on End-of-Life Vehicles. Right now, Annex II to the Directive has exempted nickel-cadmium batteries for electric vehicle applications until December 31, 2005.

The aim of this work package (WP 5) is to provide a clear overview of the different work packages and to integrate the results coming from the three individual battery assessments, namely the technical (WP 1), the environmental (WP 2) and the economical assessment (WP 3), into one single overall assessment approach that constitutes an effective decision support tool.

After resuming the main conclusions from the different work packages individually, a Multi-Criteria Analysis, will provide a transparent analysis describing the results of the different assessments. Next to this quantitative analysis a qualitative analysis will give an overall assessment of the different considered battery technologies.

Chapter II of this report gives an overview of work package 1 and chapter III briefly discusses work package 2, while chapter IV summarizes the economical analysis (work package 3).

Finally, chapter V provides an overall overview of the results and recommendations of the SUBAT-project.

# II. Technical Assessment (WP1).

## II .1. Traction batteries: generalities.

The traction battery is the “fuel tank” of the electric vehicle, which is where the energy needed for driving, is stored. It is also the most critical component of the vehicle.

The principle of a battery is very simple: between two different materials (electrodes) immersed in an electrolyte solution a potential difference will occur. Through the years, several battery types have been developed. Only a limited number of electrochemical couples on one hand and of technological implementation on the other hand however can be considered for use in electrically propelled vehicles.

Some technical definitions may be required to help the understanding of the present study. A definition list is provided as appendix 1 of this document.

## II. 2. Technologies.

In this chapter the different battery technologies for electric and hybrid vehicles will be discussed.

### II.2.1. Lead-Acid Battery.

The lead-acid battery was invented by Gaston Planté in 1860. Today, as the oldest and best known electrochemical couple, it is the most widely used traction battery for industrial electric vehicles.

In its basic form, the lead-acid battery consists of a negative plate made from lead metal and a positive plate made from brown lead dioxide, submerged in an electrolyte consisting of diluted sulphuric acid.

Lead-acid batteries are manufactured in different types and sizes according to their application. For electric vehicle traction purposes the following types are considered:

#### Vented batteries

Vented lead-acid batteries are open systems with the electrolyte in liquid form. The vented battery with tubular positive plates is the archetypal traction battery, which is still the most widely used for industrial traction purposes. They may offer a cycle life up to 1500 cycles. This however is only attainable in controlled operating conditions where the batteries receive caring maintenance.

The need for maintenance and regular watering makes these batteries less suitable for use in consumer applications; for this reason, their use in electrically propelled road vehicles is limited to heavy-duty fleet vehicles such as buses.

#### VRLA batteries

In the VRLA (valve-regulated lead-acid) battery, the electrolyte is caught in a gel or in an absorbing glass fibre mat (AGM); water consumption is avoided through the use of hydrogen/oxygen recombination techniques. This battery is maintenance free and does not

require watering. The VRLA battery is sometimes called a “sealed” battery. This name is not correct: the battery is not hermetically sealed, but is fitted with a safety valve to release overpressure (e.g. in case of a surcharge).
They are more expensive than vented batteries however, and their cycle life is shorter (600-800 cycles stated by the manufacturers; 300-500 cycles in practical use). Furthermore, they are sensitive to deep discharges and surcharges and should only be used with specially designed battery chargers.

The last few years, advanced VRLA designs have been developed combining high current discharge and deep cycling capabilities; such batteries are being proposed as cost-effective solutions for electrically propelled vehicles.
The following designs are considered:

- prismatic cells with flat plates and AGM or gelled electrolyte
- prismatic cells with tubular plates and gelled electrolyte for traction purposes
- cylindrical cells with spiral-wound plates and AGM or gelled electrolyte which can be specifically designed for high current and high specific power allowing their use in hybrid applications

## II.2.2. Alkaline batteries.

Batteries with alkaline electrolytes have been developed starting from the late 19th century. Most of these batteries use nickel oxide as positive plate material, with negative plates based on cadmium, iron, zinc, or hydrogen (the latter under form of metal hydrides).

### II.2.2.1. Nickel-Iron battery.

Nickel-iron batteries were popular in the early 20th century, due to their higher specific energy and longer cycle life compared to lead-acid batteries. They received a renewed interest during the 1980s, but have now been completely abandoned due to their poor low-temperature performance and poor energy efficiency resulting in unacceptably high water consumption.

### II.2.2.2. Nickel-Cadmium battery.

**Generalities**

The nickel-cadmium battery also presents a positive electrode made from nickel oxide; the negative electrode however is made of metallic cadmium. The electrolyte consists of a lye solution of potassium hydroxide with an addition of lithium hydroxide, the latter having a stabilizing effect during cycling. The nominal cell voltage is 1.2 Volt.
Its historic development was parallel to nickel-iron and it offers the same characteristics as nickel-iron, such as a quite high specific energy compared to lead-acid, a good resistance to abuse and a long cycle life. Its particular advantages however are a better operation at low temperatures, a slower self-discharge and a higher electrical efficiency leading to less maintenance and water consumption.

Traditionally, nickel-cadmium batteries have been manufactured with steel jars and pocket-plates; in order to decrease weight and thus increase Specific Energy for demanding applications like electric vehicles, advanced plate designs have been proposed.

The *sintered electrode* design makes use of a porous mass of active material (nickel powder) sintered on a steel grid. This process is used by SAFT in France. The elements are packed in polymer jars, either as single cells or as monoblocs, the latter design being the favourite one for electric vehicles. The single cells have widespread applications as railway and aircraft batteries.

Another technology makes use of *fibrous electrodes* consisting of porous conductive fibres which contain active material. These types of batteries have known limited use for electric vehicle applications however.

The sintered electrode nickel-cadmium batteries are fitted on most of the electric vehicles now present on the European market. They present quite interesting opportunities for this application: good cycle life and specific power, ability for fast charging and operating in a wide temperature range. The current cost of these batteries remains high however; this fact has caused several electric vehicle manufacturers, particularly in the USA and Japan, not to consider the use of this battery. Furthermore, the toxicity of cadmium has been cited as an aspect affecting the acceptation of this battery, as can be seen from the SUBAT study itself. Nevertheless, many battery technologies contain some toxic compounds. The most important toxic compounds, grouped per battery technology are summarized in chapter III.

The batteries can be designed in various configurations, according to the chosen application:

- emphasising a high energy density, for traction applications where range is paramount.
- emphasising a high power density, for applications such as hybrid vehicles, where the batteries must be able to deliver power bursts but where deep discharges are less frequent. These batteries are mainly aimed at hybrid heavy-duty vehicles, but have seen limited deployment in practice.

### II.2.2.3. Nickel Zinc battery.

The nickel-zinc battery uses the same type of positive electrode as the nickel-iron and nickel-cadmium, this time with a metallic zinc negative plate. One of its advantages is the higher cell voltage (1.6 V) compared with other alkaline battery types. This allows a specific energy 25% higher than nickel-cadmium.

Nickel-zinc has been the subject of extensive research focusing on its application in electric vehicles. The main drawback of this electrochemical couple however proved to be its unacceptably short cycle life, which is a result of the formation of zinc dendrites on the negative electrode during charging. These dendrites will eventually perforate the separator and short the cell.

A number of research projects on nickel-zinc batteries has been performed in the USA, Korea and the former USSR. A recent research project (PRAZE) funded by the EU aimed at the development of advanced nickel-zinc batteries for use in electric scooters. Although promising results were obtained with the prototype cells, this research has not been continued however due to the French company involved, Sorapec, ceasing its activities.

Recent work on nickel-zinc is being performed by SCPS in France. At this moment, they claim promising results as to cycling ability and lifetime; the research is at this time still focused at the cell level however and complete batteries have not yet been experimented for deployment in vehicles.

The nickel-zinc battery can thus not yet be considered as a commercial product for electric vehicle applications in a short-term future.

### II.2.2.4. Nickel Metal Hydride battery.

The use of hydrogen as negative active material gives a good energy to weight ratio. Storing and maintaining hydrogen gas can be cumbersome however; to this effect, hydrogen can be stored in metal alloys, and thus one obtains the nickel-metal-hydride battery. The alloys used for this purpose are mostly proprietary, and are usually of the types $AB_5$ (e.g. $LaNi_5$) or $AB_2$ (e.g. $TiN_2$).

Nickel-metal hydride batteries possess some characteristics making them suitable for use in electrically propelled vehicles. The fact that they are cadmium free is a selling argument in some markets where the use of cadmium is seen as an environmental concern. From a technical viewpoint however, their specific energy is somewhat higher than nickel-cadmium, and; furthermore, they are well suited to fast charging.
A disadvantage however is their tendency to self-discharge, due to hydrogen diffusion through the electrolyte. Furthermore, high-current operation during charging (which is an exothermic reaction), makes thermal management and cooling of these batteries essential.

Because of this, they have been subject of substantial research and development activities aiming at electrically propelled vehicles. The situation on the worldwide market is described in chapter IV of this study (work package 3).
Their use for battery-electric vehicles has been limited however, with only some small series (a few hundred vehicles in the last years) being manufactured and few research efforts being continued.

On the other hand, the nickel-metal-hydride is used in advanced hybrids, due to its excellent specific power abilities. It fits commercially available hybrids today like the Toyota Prius.
The battery for hybrid use is a power-optimized battery, the design of which reflects the experience gathered with the portable nickel metal hydride battery. This battery is now produced in large series as a commercial product for hybrid vehicles.

### II.2.2.4. Lithium batteries.

Lithium is the lightest metal element known and is under full consideration for high energy batteries. Several secondary battery technologies using lithium have been developed.

- Lithium-ion batteries work through the migration of lithium ions between a carbon anode and a lithium metal oxide alloy cathode. The electrolyte is an organic solution; no metallic lithium is used. Lithium-ion batteries have been proposed for both battery-electric vehicles, where they benefit of their excellent specific energy of up to 200 Wh/kg, and hybrid vehicles, making use of cells specifically designed for high power, where values up to 2000 W/kg can be reached.

- In the lithium-polymer technology, the electrolyte is a solid conductive polymer; the batteries are completely dry and do not contain liquid electrolytes. Several chemistries are being proposed:
    - the lithium-ion-polymer battery, which does not contain metallic lithium and has a chemistry comparable to the lithium-ion battery;

- the lithium-metal-polymer battery, where the negative electrode consists of metallic lithium foil. This battery is now being commercially manufactured for stationary purposes, but has also been considered for traction.

One main issue to be considered somewhat more acutely with lithium batteries compared to other battery technologies is safety. Lithium is very reactive, and abuse conditions such as crashes, fires and excessive temperature rises may cause uncontrolled energy releases which create hazardous situations. The implementation of cell-level management and control systems is thus a dire necessity for any lithium-based system.

Although lithium batteries have taken a considerable share of the portable battery market, one has to recognize that high-power applications such as traction present different challenges. Lithium batteries for traction are now available as prototypes and are on the brink of series production; further optimisation as to life, system safety and stability and production cost is still being performed however, and the lithium systems can today not be considered yet as a fully commercially available product.

## II.2.4. High-temperature batteries: The Sodium-Nickel-Chloride Battery.

The sodium-nickel-chloride battery (known under its brand name Zebra) is characterised by its high operating temperature. It presents interesting opportunities for electrically propelled vehicles due to its high specific energy of typically 100 Wh/kg.
The electrodes of this battery consist, in charged state, of molten sodium and molten nickel chloride; the electrolyte is a solid aluminium oxide ceramic. In discharged state, the electrodes are sodium chloride and nickel.
Batteries consist of individual cells enclosed in a thermally insulating package.
During cycling of the battery, internal resistive losses allow maintaining the operating temperature of 270 °C; cooling even becomes necessary when temperature exceeds 330 °C. When the battery is standing idle for prolonged periods (exceeding 24 hours), additional heating (typically using 100 W power per battery) is needed to keep the battery warm.
Due to this need for additional heating during standstill, the Zebra battery will see its most efficient use in vehicles which are deployed daily and intensively such as public service vehicles and fleet vehicles.

These batteries have been successfully implemented in several electric vehicle designs, and present interesting opportunities for fleet applications. The sodium-nickel-chloride battery is fore mostly an “energy” battery and thus primarily suitable for battery-electric vehicles; its specific power being rather modest for hybrid applications.

## II.2.5. Metal-air batteries.

Metal-air batteries, such as zinc-air and aluminium-air, are not strictly secondary rechargeable electric batteries, but should rather be considered as fuel cells which are “recharged” with new metal electrodes.
Particularly the zinc-air battery has been experimented in electric vehicle applications. The main advantage of these batteries is their high specific energy, which can exceed 200 Wh/kg, well in excess of conventional battery types. The specific power, at most 100 W/kg, is rather modest however.
The main drawback of this battery system is the burden associated with physically replacing spent electrodes in order to recharge the battery. This creates in fact the necessity to establish

a logistic circuit involving the collection, regeneration and redistribution of electrodes. Furthermore, the energetic efficiency of the electrolytic regeneration process is limited. All these factors have impeded the widespread deployment of these batteries and make that they cannot be considered as commercial contenders for general use in electrically propelled vehicles.

### II.2.6. Redox batteries.

Redox batteries are complex electrochemical systems with circulating electrolytes. The heart of the system can be considered as a reversible fuel cell stack, able at both generating electricity from the electrochemical reaction of the electrolytes (discharge), and restoring the original composition of the electrolyte through the injection of electric current (charge).

A well-known example of redox battery is the zinc-bromine battery, which has been experimented in electric vehicle systems giving typical values of 80 Wh/kg for specific energy and 100 W/kg for specific power. Despite these values, the complexity of the system and its needs for ancillary equipment have been major drawbacks for further consideration of these couples for actual vehicle traction purposes.

## II.3. Comparison of battery types.

The following table gives an overview of the key technical performance factors (specific energy in Wh/kg, specific power in W/kg and cycle life) of several battery types, taking into account current and future developments, as well as the difference between energy-oriented (for battery-electric vehicles in Table 1) and power-oriented (for hybrid vehicles in Table 2) batteries. The cycle life for the power batteries (hybrids) is given in relative values, since the actual cycling is dependent on the use pattern of the battery and no standard cycle life tests exist.

It is important to note that the mentioned parameters in the following tables are dependent on the way of use. For example:

- the number of cycles of a battery is dependent on the depth of discharge.
- the on-road number of cycles of a battery is less than the number of cycles in a laboratory test, due to the fact that standardized test cycles are mostly less demanding than real-life exploitation of the battery.
- a battery pack is composed of a number of individual cells. The characteristics of the whole pack are different from the characteristics of a single cell, due to the fact that the individual cells may behave differently among each other.

The battery characteristics are also dependent on the temperature. The temperatures in the table indicate the optimal working temperatures. For the NaNiCl battery this parameter is less relevant, as the battery’s working temperature is always around 300°C.

The characteristics of a battery are dependent on the specific application for which the battery has been developed. HEV batteries (power optimized) and BEV batteries (energy optimized) have different characteristics. These specific characteristics for both applications are detailed in Table 1 and Table 2.

The characteristics of the HEV batteries for the nickel-zinc, sodium-nickel chloride, zinc-bromine and zinc-air batteries have not been inserted in Table 2 due to the fact that these technologies are not widely used (yet) for HEV applications.

**Table 1: Technical characteristics of the studied BEV batteries.**

| Technology | Specific Energy (Wh/kg) | Specific Power (W/kg) (short) | Cycle (number) | Optimal Working Temperature range (°C) | Efficiency (Wh) | Self-discharge | Maintenance | BMS |
|---|---|---|---|---|---|---|---|---|
| Pb-acid (VRLA) | 40 | 250 | 500 | 20-40 | 80-85% | low | no | advisable |
| NiCd | 60 | 200 | 1350 | 0-40 | 70-75% | low | yes | advisable |
| NiMH | 70 | 350 | 1350 | 0-40 | 70% | high | no | advisable |
| NiZn | 75 | 200 | n.a; | 0-40 | 70% | n.a. | no | advisable |
| NaNiCl | 125 | 200 | 1000 | n.a. | 90-95% | high[1] | no | integral |
| Lithium | 125 | 400 | 1000 | 0-40 | 90% | low | no | essential |
| ZnBr | 80 | 100 | n.a. | 20-40 | n.a. | n.a. | yes | essential |
| Zn-air | 200 | 70 | n.a. | 20-40 | n.a. | n.a. | yes | advisable |

**Table 2: Technical characteristics of the studied HEV batteries.**

| Technology | Specific energy (Wh/kg) | Specific Power (W/kg) (short) | Cycle (relative number) |
|---|---|---|---|
| Pb-acid | 25 | 350 | 1 |
| NiCd | 30 | 500 | 3 |
| NiMH | 55 | 1500 | 3 |
| Li-ion | 70 | 2000 | 3 |

In order to compare the different battery types on the level of their performances, one can make use of the so-called Ragone chart, which plots specific energy versus specific power (the latter usually represented on a logarithmic axis), where one can compare easily the different batteries suitable for use in either battery-electric vehicles (which need fore mostly energy) and hybrid vehicles (which need fore mostly power).

In this framework, one should note that the coloured areas on the chart each represent an electrochemical couple, but that several design options are possible to optimize the battery for its application and to locate it in these areas.

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[1] Losses due to heating

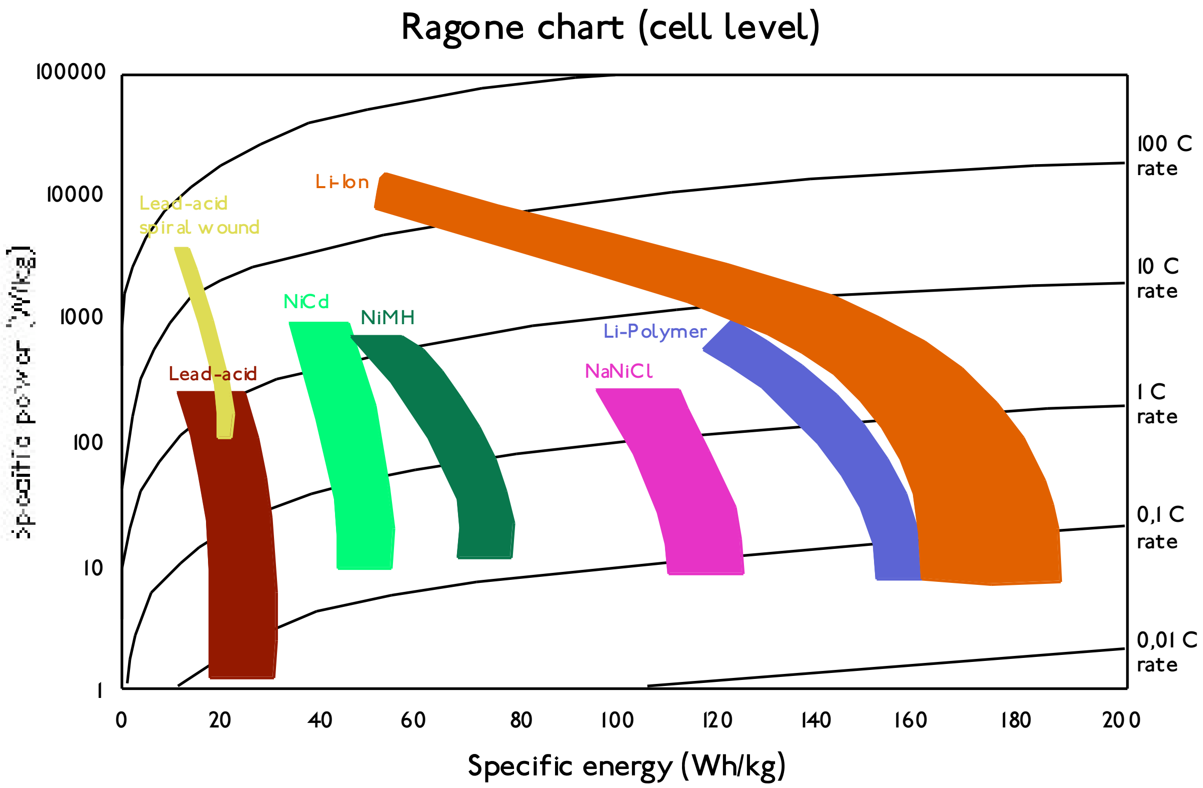

**Figure 1: Ragone chart.**

# III. Environmental Assessment (WP2).

## Methodology

In the second work package of the project, the different battery technologies were analysed individually to allow the comparison of the environmental impacts of the different battery technologies for battery electric vehicles (BEV) and hybrid electric vehicles (HEV). This can be done in a qualitative or a quantitative way.

The impacts of the most widespread technologies (NiCd, NiMH, NaNiCl, Li-ion and Pb-acid) are analyzed quantitatively using Life Cycle Assessment (LCA). Other less widespread technologies (like Zn-air, NiZn, Li-polymer…) were assessed in a qualitative way, as their development does not allow a complete assessment due to a lack of wide spread industrial data.

The first step of the environmental analysis was to list the available technologies for battery and hybrid electric vehicle appliances. Afterwards, an LCA model for the different battery types has been developed and introduced in an LCA software tool. This model allows an individual comparison of the different phases of the life cycle of traction batteries. This makes it possible to identify the heaviest burden on the environment for each life phase of each battery. In this study, the LCA software tool uses a life cycle impact assessment (LCIA) method called eco-indicator 99. LCIA methods try to link each life cycle inventory (LCI) result (elementary flow or other intervention) to its environmental impact(s) [[1]]. Eco-indicator 99 was chosen, for it's a quite standard and widespread methodology. Eco-indicator 99 has a damage-oriented approach. Damage oriented methods try to model the cause-effect chain up to the endpoint (damage). The results are expressed in eco-indicator points. A high amount of eco-indicator points represents a high environmental impact [[2]].

LCA are typically divided into the following steps:
- **Classification**: The LCI results have to be assigned to impact categories. For example $CO_2$ and $CH_4$ can be allocated to the impact category "Global Warming".
- **Characterization**: Once the LCI results are assigned to the impact categories, the characterisation factors should be defined. These factors define the relative contribution of the different LCI results to the impact category. As an example, as the contribution of $CH_4$ to global warming is 21 times higher than the contribution of $CO_2$ this means that if the characterisation factor of $CO_2$ is 1, the characterisation factor of $CH_4$ is 21.
- **Normalization and weighting:** the magnitude of indicator results is calculated relatively to reference information and indicator results coming from the different impact categories are converted to a common unit by using factors based on value-choices.
- **Sensitivity analysis:** in order to be able to evaluate the influence of the most important assumptions, a sensitivity analysis is performed at the end of the LCA. The principle is to change the assumptions and recalculate the LCA to get a better estimation of the effects of the assumptions made.

## Toxicology

All battery technologies contain some more or less toxic compounds. The most important toxic compounds contained in the most widespread battery technologies are listed in Table 3. This table includes the main routes of exposure, as well as the short and long-term health effects and the environmental data for the different compounds. Please note this list is not exhaustive and that some of the very specific compounds of batteries might not have been thoroughly studied toxicologically yet.

**Table 3: Most important toxic compounds in batteries, listed per battery technology.**

| | | Short-term health effects in case of exposure | Long-term health effects in case of exposure | Environmental data |
|---|---|---|---|---|
| Pb-acid | | | | |
| | $PbO_2$ | N/A | Target: blood, bone narrow, central nervous system, peripheral nervous system and kidney<br>Effects: anaemia, encephalopathy, peripheral nerve disease, abdominal cramps and kidney impairment.<br>Reproduction or development | Possibility of bioaccumulation |
| | Pb | N/A | Target: blood, bone narrow, central nervous system, peripheral nervous system, kidney<br>Effects: anaemia, encephalopathy, peripheral nerve disease, abdominal cramps, kidney impairment.<br>Effects on reproduction or development | Possibility of bioaccumulation |
| | $H_2SO_4$ | Target: Eyes, skin, respiratory tract<br>Effects: Corrosive, lung oedema | Target: lungs, teeth<br>Effects: teeth erosion, carcinogenic | Harmful to aquatic organisms |
| Ni-Cd | | | | |
| | $Ni(OH)_2$ | May cause sensitization by skin contact. | Limited evidence of a carcinogenic effect | Toxic to aquatic organisms may cause long-term adverse effects in the aquatic environment. |
| | $Cd(OH)_2$ | Target: Eyes, respiratory tract<br>Effects: lung oedema, metal fever | Target: lungs, kidney<br>Effects: proteinuria, lung or kidney dysfunction, probable carcinogenic effect | |
| | KOH | Target: Eyes, skin, respiratory tract<br>Effects: Corrosive, lung oedema | Target: skin<br>Effects: dermatitis | Hazardous (especially for aquatic organisms) |
| Ni-MH | | | | |
| | $Ni(OH)_2$ | May cause sensitization by skin contact. | Limited evidence of a carcinogenic effect | Toxic to aquatic organisms may cause long-term adverse effects in the aquatic environment. |
| | Nickel hydrides | | | |
| | KOH | Target: Eyes, skin, respiratory tract<br>Effects: Corrosive, lung oedema | Target: skin<br>Effects: dermatitis | Hazardous (especially for aquatic organisms) |
| Li-ion | | | | |
| | $LiCoO_2$ | | | |
| | $LiPF_6$ | Toxic with skin<br>Harmful if swallowed | | |
| | DMC | | | |
| Li-polymer | | | | |

| | | | | |
|---|---|---|---|---|
| | Li | Target: Eyes, skin, respiratory tract<br>Effects: Corrosive, lung oedema | | |
| | $V_2O_5$ | Target: Eyes, skin, respiratory tract<br>Effects: irritation, lung oedema, bronchitis, bronchospasm | Target: lungs<br>Effects: greenish-black discolouration of the tongue | Harmful to aquatic organisms |
| Ni-Zn | | | | |
| | $Ni(OH)_2$ | May cause sensitization by skin contact | Limited evidence of a carcinogenic effect | Toxic to aquatic organisms may cause long-term adverse effects in the aquatic environment. |
| | $MnO_2$ | Target: respiratory tract<br>Effects: irritation | Target: lungs, central nervous system<br>Effects: increase susceptibility to bronchitis, pneumonitis and neurologic, neuropsychiatric disorders (manganism) | Hazardous (especially for aquatic organisms) |
| | KOH | Target: Eyes, skin, respiratory tract<br>Effects: Corrosive, lung oedema | Target: skin<br>Effects: dermatitis | Hazardous (especially for aquatic organisms) |

## III.1. Quantitative analysis.

### III.1.1. Boundary conditions.

Before performing an LCA, the boundary conditions must be defined. The interaction of the functional unit with nature is assessed considering the following life stages of the battery:

- the **extraction** of raw materials
- the **processing activities** of the materials and components
- the **use** of the battery in the vehicle
- the **recycling** of discarded batteries
- the **final disposal** or **incineration**

When considering **geography**, the considered area is the western world. Concerning the assessed **time period**, the current state of the technology was considered. Some other related **other life cycles** (trucks, industrial buildings, electric power plants, roads etc.) have not been considered, since they will not influence the results significantly.

**Self-discharge** of the battery was not included because of the great dependence of this parameter on the way of using the vehicle. Neither was the **maintenance** of the batteries because of the presumption this impact is relatively small. Regarding **electricity** consumption, the European (EU-25) electricity production mix has been considered [3]. It has been considered that the **recycled materials** have the same quality as the original data. A **collection rate** of 100% was assumed (which is realistic for widespread use of the battery considering the weight and volume of the BEV and HEV batteries and considering the answers of various stakeholders to our questionnaires) and a recycling rate of 95% was used for the recuperated materials (except for the Pb-acid recycling technology, which exists since much longer and which is very mature, where the lead metal recycling rate is 98.3%). It was assumed that the electrolyte is neutralized before disposal (except for the lead-acid technology where 90% is recuperated and 10% is neutralized before disposal).

## III.1.2. BEV.

### III.1.2.1. Energy consumption to drive BEV.

Our model is based on a small car like the Peugeot 106. The net weight of the car, including the driver's weight (75kg), is 888 kg. Basically, this kind of car is equipped with a 250kg, 12 kWh battery (47 Wh/kg)[4].

The energy consumptions to drive are calculated for the ECE cycle [5]. As the battery masses will be depending on the applied battery technology, this implies different energy consumptions for each battery technology. These different energy consumptions were simulated and calculated by the Vehicle Simulation Program (VSP) developed at the Vrije Universiteit Brussel [6]. These simulations allow us to determine the specific energy consumption for each battery technology.

When considering the use of the batteries in the vehicle, this phase can be subdivided in 3 parts. First of all, the use phase was studied for an ideal battery (mass = 0 kg, energy efficiency of the battery = 100%; corresponding to the electricity needed to drive the vehicle itself). In a second step, the influences of the varying masses and energy efficiencies of the different battery technologies have been taken into account. This allowed taking the influence of these battery characteristics on the electricity consumption into account.

### III.1.2.2. Choice of the Functional Unit for the BEV batteries: Constant range and constant lifetime distance covered by the vehicle.

The functional unit (F.U.) is the core of any life cycle assessment, since it provides the reference to which all other data in the assessment are normalised (compared). Several F.U. were analysed. The most appropriate F.U. (chosen to perform the LCA) is an F.U. including batteries allowing the vehicle to cover a similar one-charge range (60km) no matter which technology is used. Additionally, the F.U. implies the delivery of a certain amount of cycles (3000), which corresponds to a total vehicle distance of 180000km. Depending on the technology, the required number of batteries needed for the functional unit was determined. The F.U. assuming a constant range seems to be the most appropriate, as it compares the batteries on the basis of the same delivered performances (all the vehicles can deliver exactly the same payload).

*Advantages of this F.U..*

- ☺ The vehicle is able to cover the same distance independently of the technology. As a consequence, the same number of cycles is needed to cover the lifetime distance of the vehicle.
- ☺ The payload delivered by every battery technology is exactly the same (the driver gets exactly the same "service" out of each battery technology)

*Disadvantages of this F.U..*

- ☹ The masses and energy contents differ from one battery technology to another.
- ☹ The assumptions are conceptually more complicated, compared to the other F.U.

The mass of the battery was calculated for each technology using next equation:

$$\text{Range} = \frac{E_{\text{content}}}{E_{\text{consumption}}} = \frac{\text{DOD} \cdot E_{\text{specific}} \cdot m_{\text{battery}} \cdot \eta_{\text{battery}}}{m_{\text{battery}} \cdot \alpha + \beta} \tag{1}$$

Where $E_{\text{specific}}$ stands for the specific energy of the battery,

$m_{\text{battery}}$ stands for the mass of the battery,

$\eta_{\text{battery}}$ stands for the energy efficiency of the battery

□□□□□are the ‘energy’ coefficients calculated with the Vehicle Simulation Programme in function of the vehicle weight (□= 0.054 and □ = 133)

Table 4 lists the battery characteristics corresponding to the F.U..

**Table 4: F.U. constant range characteristics.**

| | Mass (kg) | Energy content of battery pack (kWh) | Range per cycle (km) | Number of cycles | Number of batteries | Lifetime range (km) |
|---|---|---|---|---|---|---|
| Pb-Acid | 344 | 13.78 | 60 | 3000 | 6 | 180000 |
| NiMH | 222 | 15.53 | 60 | 3000 | 2.22 | 180000 |
| NiCd | 253 | 15.16 | 60 | 3000 | 2.22 | 180000 |
| Li-ion | 92 | 11.49 | 60 | 3000 | 3 | 180000 |
| NaNiCl | 97 | 12.07 | 60 | 3000 | 3 | 180000 |

## III.1.2.3. Results for BEV batteries.

The impacts due to the different stages of the life cycle are shown in Table 5 (bearing the F.U. discussed above in mind). Also, it should be kept in mind that the results presented in this report are only valid taking the boundary conditions into consideration.

When considering the life cycle of the batteries, it appeared that energy losses in the battery have a significant impact on the environment (Table 5). However, this impact is strongly dependent on the way electricity is produced. In the present calculations the European electricity production mix has been used, but the impact would be strongly decreased if renewable energy sources were used more intensively. It can be concluded that using the European electricity production mix is a pessimistic scenario. In the future, electricity production will probably imply less emissions and thus a lesser impact on the environment.

The bars in Figure 2 represent the relative environmental impacts of every battery type, considering the Pb-acid technology as a reference (100). The error bars represent the intervals containing all the results obtained during the sensitivity analysis. It should be mentioned that Figure 2 includes the results originating from production, recycling and the energy losses due to the battery mass and to the battery efficiency. Additionally, please note that these results were obtained without environmental data concerning the electrolyte of the Li-ion technology and with (optimistic) estimations concerning the energy consumption to produce the NaNiCl batteries, as the manufacturers provided no realistic data. As a consequence, the environmental rating of these technologies could be worse than the score obtained in this study.

**Table 5: Environmental scores (eco-indicator points) of the life stages of the assessed battery technologies.**

| | Production | Use (weight) | Use (battery efficiency) | Recycling |
|---|---|---|---|---|
| Pb-acid | 1091 | 81.4 | 140 | -809 |
| NiCd | 861 | 59.7 | 243 | -620 |

| | | | | |
|---|---|---|---|---|
| NiMH | 945 | 52.4 | 271 | -777 |
| Li-ion | 361 | 21.7 | 66.9 | -172 |
| NaNiCl | 368 | 22.8 | 99.5 | -256 |

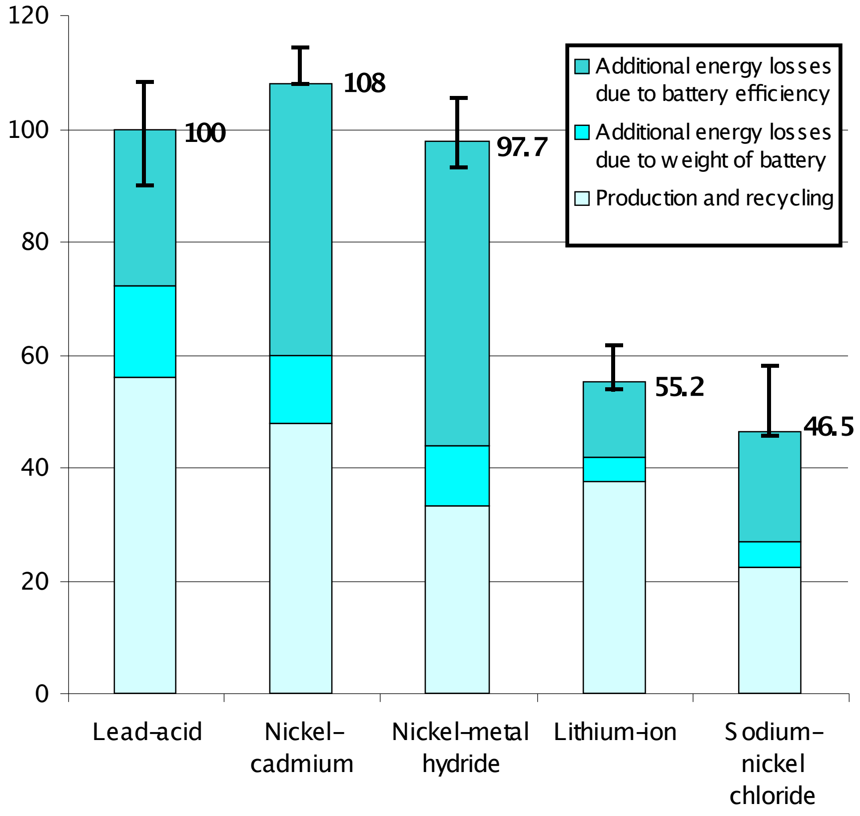

**Figure 2: Graphical overview of the relative environmental scores (including the sensitivity analysis).**

When looking at the environmental impact of the battery solely, it appears that the Pb-acid battery has got the highest impact, followed by NiCd, Li-ion, NiMH and NaNiCl (Table 5).

When including the effects of the losses due to the battery (battery efficiency and battery mass), three battery technologies appear to have a somewhat higher environmental impact compared to the other two (Figure 2). The inclusion of the battery efficiencies results in a higher environmental impact for NiCd and NiMH batteries and a lower one for Li-ion batteries comparatively to the others. The impact of the additional energy losses due to the energy efficiency and the mass of the batteries are dependent on the way electricity is produced. This impact can thus be reduced by reducing the environmental impact of electricity production.

Sensitivity analysis

We should be aware that the type of charger, charging curves, the outdoor temperature, the method of electricity production, the assumed driving cycle and conditions, etc. influence the results.

A zero-impact has been allocated to the Li-ion electrolyte. This is due to the fact that this technology is pretty recent and that the electrolytes are so specific that virtually no environmental data are available for these elements. As these synthetic chemicals are quite complex, it is not unrealistic to consider they have a relatively high score per kg compared to the other electrolytes. As a consequence, we can assume that the real environmental score of the Li-ion battery will be slightly worse than the score obtained with these calculations.

No realistic data concerning energy consumption were obtained from the NaNiCl battery manufacturer. As a consequence, an estimation of the energy consumption has been used to perform this study.

LCA studies are based on a lot of assumptions. As the results have to be reliable, the assumptions have been modified and the consequences on the results were analysed (sensitivity analysis).
The implemented variations included calculations, using different relative sizes of the components of the battery (10% more weight of one component, compensated by an equivalent decrease of another component).

Some data can not be altered in a sensitivity analysis without implying the assessment of a different F.U.. As a consequence, the number of cycles, specific energy, DOD, energy efficiency and different consumption of the vehicle are not included in the sensitivity analysis.

Figure 2 summarizes the sensitivity analysis and demonstrates that the assumptions mentioned in the previous sections did not have any significant impact on the results in the sense that the conclusions remain the same. This demonstrates that the results of this study are reliable and illustrates the robustness of the model.

The impacts of batteries with “one-charge ranges” of 50 or 70 km have been investigated too. The main trends and the conclusions stay identical for each of the “same-range batteries”.

Assuming other electricity production methods, didn’t change the ranking of the different technologies, but the overall impact of the different batteries varies strongly depending on the electricity production method. Sometimes, it’s more efficient to (environmentally) improve the energy production than the battery production and recycling methods.

## III.1.3. HEV.

### III.1.3.1. Technical characteristics.

The main technical characteristics of the different battery technologies are shown in the next table. The role of the battery in an HEV is different from its role in a BEV. In an HEV the ICE (Internal Combustion Engine) delivers the energy, while the battery delivers sudden power boosts. As a consequence, the power plays a more important role when analyzing HEV batteries.

Table 6 lists the battery characteristics corresponding to the F.U..

**Table 6: Technical characteristics of the different HEV battery technologies.**

| | Specific Power (W/kg) | Relative number of cycles |
|---|---|---|
| Pb-Acid | 350 | 1 |
| NiMH | 1500 | 3 |

| | | |
|---|---|---|
| NiCd | 500 | 3 |
| Li-ion | 2000 | 3 |
| NaNiCl | 200 | 3 |

The maximal number of cycles in a battery's lifetime is strongly dependent on the way the battery is used and on the type of cycles we assess (which DOD is assessed). Therefore, and as the main aim of work package 2 is to *compare* the environmental burden of the batteries, the numbers of cycles are given as relative numbers.

### III.1.3.2. Choice of the functional unit for HEV batteries.

Hybrid vehicles are defined as vehicles having either at least two different on-board energy sources or at least two different drivelines. In this work package, the assessed batteries have been assumed to have a power similar to the power of the Toyota Prius (21kW) [[7]] and will be compared on this basis. The quantity of batteries required to obtain this power, is obtained by dividing the desired power by the specific power of each technology. The aim of the study is to compare the relative impacts of the different battery technologies. The assumption has been made that the 21 kW NiMH HEV battery will not have to be replaced during the lifetime of the vehicle[2]. Identical assumptions have been made for the other battery technologies, , except for the Pb-acid, which is assumed to provide three times less cycles. Three lead-acid batteries are thus assumed to be required for the HEV functional unit compared to one for the other technologies.

**Table 7: F.U. hybrid characteristics.**

| | Mass (kg) of F.U. | Number of batteries |
|---|---|---|
| Pb-Acid | 60 | 3 |
| NiMH | 14 | 1 |
| NiCd | 42 | 1 |
| Li-ion | 10.5 | 1 |
| NaNiCl | 105 | 1 |

Based on the specific power (W/kg), the weight of (21kW) battery can be calculated for each battery technology. The environmental impact of the required mass can then be calculated as the impact per kg has been calculated as well.

It should be noted that some of the calculations are purely theoretical, as the technical properties (mainly low specific power) of some technologies practically exclude them from being used for HEV applications.

### III.1.3.3. Results for HEV batteries.

The different impacts for the different parts of the life cycle are shown in Table 8. The additional consumption due to differences in mass of the different batteries is not taken into account in the analysis of HEV batteries. Also, it should be kept in mind that the results presented in this report are only valid taking the boundary conditions into consideration.

The bars in Figure 3 represent the relative environmental impacts of every battery type, considering the lead-acid as a reference. The overall environmental score of the Pb-acid battery has been set to 100. It appears that next to the important mass of the sodium-nickel

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[2] Toyota provides an 8-year-warranty on its Prius batteries.

chloride and lead-acid batteries, these technologies appear to present the worst environmental scores of the quantitatively assessed HEV battery technologies.

**Table 8: Environmental scores (eco-indicator points) of the life stages of the assessed battery technologies.**

| | Production | Recycling | Total |
|---|---|---|---|
| Pb-acid | 95.0 | -70.5 | 24.5 |
| Ni-Cd | 64.4 | -46.4 | 18.0 |
| NiMH | 26.8 | -22.1 | 4.8 |
| Li-ion | 13.7 | -6.6 | 7.1 |
| NaNiCl | 133.0 | -92.6 | 40.4 |

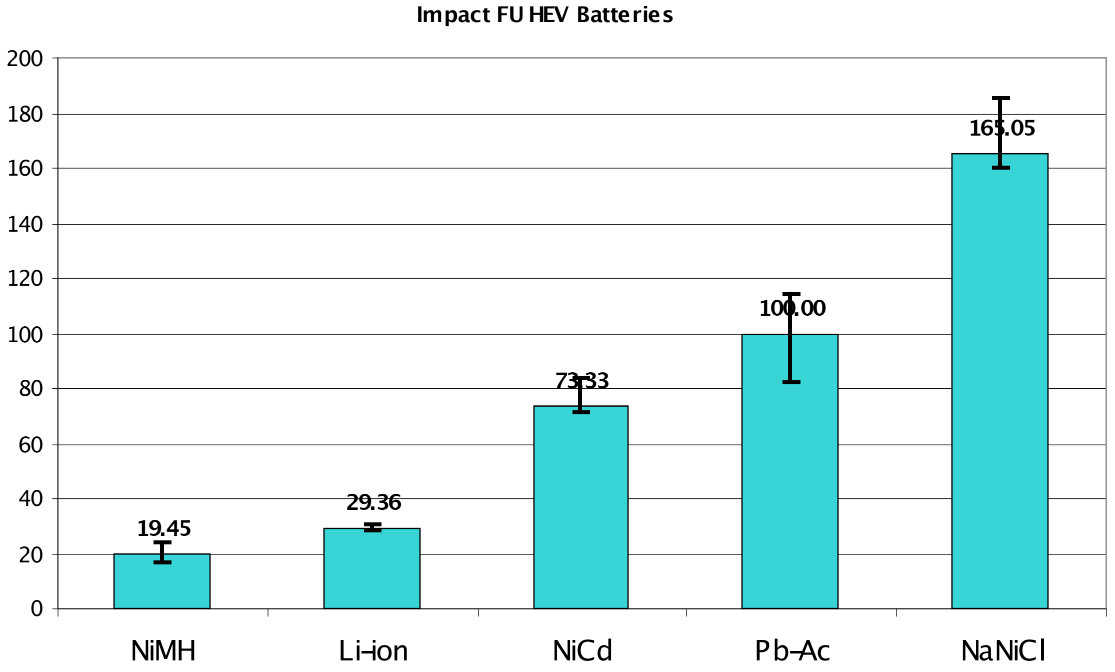


**Figure 3: Graphical overview of the relative environmental scores of HEV batteries (including the sensitivity analysis).**

**Table 8** and Figure 3 show the relative impact of the different technologies (Pb-acid is set to 100 as a reference). The NiMH obtains the best environmental rating, followed by the Li-ion, NiCd, Pb-acid and NaNiCl. Please note that these results were obtained without environmental data concerning the electrolyte of the Li-ion technology and with (optimistic) estimations concerning the energy consumption to produce the NaNiCl batteries, as the manufacturers provided no realistic data. As a consequence, the environmental rating of these technologies could be worse than the score obtained in this study. However, it should be noted that, due to their low specific power, these battery technologies are better suited for BEV applications than for HEV applications.

Sensitivity analysis

The sensitivity analysis mainly assessed the same variations of the assumptions for the BEV (concerning average battery composition, energy consumption, etc.).

Figure 3 demonstrates that the variation of the assumptions mentioned before did not have any significant impact on the results in the sense that the conclusions remain the same. This demonstrates that the results of this study are reliable and robust.

### III.1.5. Discussion of the results.

- Importance of recycling

The impacts of the assembly and production phases can be compensated to a large extent when the collection and recycling of batteries is efficient and performed on a large scale.

- Importance of the efficiency and electricity production method

As an important part of the environmental part of the batteries are due to energy losses (battery efficiency and battery weight), the efficiency of the batteries, as well as the way the electricity is produced play a significant role in the overall environmental impact of the batteries.

- Application

As could be observed in the previous chapters, depending on the “application” (i.e. BEV or HEV) and the corresponding (technical) parameters, the global environmental rating of a specific battery technology is different. This implies that it is not possible to state univocally that a certain technology **is** environmentally friendly, while the other is not. Actually, it can only be stated that a battery technology is environmentally friendly *compared to another* in a *particular application*.

When analyzing the results of this study, it should be kept in mind that the environmental impacts of the batteries of electric vehicles are small (whatever the used battery technology might be) compared to the environmental burden caused by vehicles equipped with internal combustion engines. Therefore the results of this study should be seen as an indication on how to even enhance the environmental friendliness of electric vehicles [8].

Objectively, from a technical point of view, only three of the considered technologies (NiCd, NiMH and Li-ion) form a potential solution for HEV vehicles (like the Toyota Prius). In practice however, NiMH and Li-ion are the two only battery technologies to be considered by the manufacturers for use in HEV nowadays. Pb-acid and NaNiCl batteries are not appropriate because of their high weight. For other kinds of HEV vehicles (for example busses), the weight not a big issue, and consequently, these technologies are technically more realistic for these applications. However, this study shows that these technologies are not advisable from an environmental point of view.

These results illustrate that BEV and HEV batteries should be discussed separately.

## III.2. Qualitative analysis.

In the previous chapter, the most common battery technologies have been discussed environmentally in a quantitative way. However, some other interesting but less widespread battery technologies are described in this part of the study in a qualitative way.

Not all of the necessary data to perform a quantitative LCA study are available for these less widespread technologies. Regarding development, most of these technologies are on a research level and are not available commercially yet. Some of the (laboratory) technical data have to be confirmed on-road. Some of the data described below are not generally accepted yet and can change in the future.

A rough evaluation of the potential environmental impact for BEV or HEV applications of these technologies is given in the next sections.

## III.2.1. Different technologies.

### III.2.1.1. Nickel-Zinc.

**Composition**

This battery consists of a nickel electrode (mainly nickel hydroxide) (20%), a zinc electrode (zinc oxide and calcium oxide) (30%), separators (6%), electrolyte (24%) and casting/connectors (~20%) [].

**Recycling**

No detailed recycling plan has yet been formulated, but the battery does not contain any particularly hazardous materials. The untreated batteries would probably be considered as hazardous waste due to the corrosive (alkaline) electrolyte, but this could be recovered to eliminate that problem.

The nickel-zinc battery contains valuable raw materials, such as nickel, and is highly recyclable. Reclaiming and recycling nickel-zinc batteries is straightforward and makes sense both from an environmental and an economic point of view. The NiZn batteries can be recycled using similar methods as for the recycling of NiMH and NiCd batteries.

**Overall**

The nickel-zinc technology intrinsically shows some advantages from an environmental point of view. However, these advantages are mitigated by the low number of cycles resulting in a relatively high quantity of batteries needed during the vehicle lifetime. Concerning the HEV, at this stage of development, the environmental impact can be assumed to be quite high, as the specific power of the nickel-zinc battery is low.

### III.2.1.2 Lithium-ion-Polymer and lithium-metal.

**Composition**

The lithium-ion-polymer batteries have cathodes consisting of lithium “Metal” oxides, where “Metal” stands for cobalt, nickel or manganese. They have carbon/graphite anodes and have a jelly, polymeric electrolyte.

Lithium metal batteries have a cathode consisting of vanadium oxide and an anode formed by a lithium foil, while their electrolyte is a solid polymer [].

**Recycling**

The lithium-polymer battery recycling is an area where work is needed. It seems some work is underway to process the lithium-polymer batteries in an appropriate way, but no data have been published and no data were available for this study. Many constituents are common to this technology and the lithium-ion technology, but the use of a solid polymer could complicate the dismantling and recovery as new materials with new properties are introduced.

**Technical parameters**

The technical performances (specific power, specific energy and number of cycles) of Li-polymer and Li-metal are a bit lower than the performances of lithium ion batteries [9].

**Overall**

These cells may be used in EV/HEV in the future as the polymer technology mitigates the safety issues related to the lithium-ion technology. The technical characteristics involve that the environmental impacts of the lithium-polymer and lithium-metal batteries are expected to be somewhat higher than the environmental impact of the lithium-ion batteries. This is due to the higher amount of material needed to assemble these batteries.

### III.2.1.3. Zinc-air.

**Composition**

Zinc-air batteries consist of zinc anodes (39% of the weight of the battery), have got carbon (air) cathodes (12%) and have potassium hydroxide as an electrolyte (28%) [10].

**Recycling**

In this system, spent zinc anodes are removed from the battery and are processed electrochemically. The battery materials are non-toxic and should be quite easy to handle although no detailed recycling scheme has been proposed yet. The cells contain KOH, which should be neutralized, but apart from the zinc anodes, which are recycled during the lifetime of the battery, the used materials are steel, carbon, plastic, copper and nickel.

A complete environmental impact assessment of the zinc-air system should take the emissions and waste due to batteries mechanical recharging (direct environmental impact) into account.

**Technical parameters**

Due to its relatively low specific power (70-100 W/kg), the zinc-air technology is not suitable for HEV applications. Nevertheless, thanks to their high energy densities (200 Wh/kg), Zn-air batteries are suitable for BEV applications. One of the disadvantages of this kind of batteries is the need for mechanical recharging.

Theoretically, the number of cycles of the Zn-air battery is very high, as the electrodes are refreshed every cycle.

**Overall**

Zn-air batteries can be a good choice for fleet applications, because in this case it is possible to use a centralized plant for zinc anodes regeneration. From an environmental point of view, there are no crucial concerns, as the components of the Zn-air battery don't present any major toxicity. But the specificity of this technology (mechanical recharging) implies a difficult comparison of this kind of batteries with the others.

### III.2.1.4. Vanadium redox, Zinc bromine, Polysulfide-bromine (Redox batteries).

**Composition**

Redox batteries are electrochemical systems where oxidation and reduction take place on inert electrodes and involve only ionic species in solution. Therefore the active materials are stored outside the cells of the battery and circulate through the battery to provide the energy.

**Recycling**

For a number of other storage technologies redox batteries recycling seems very feasible, although it has not yet been tested in practice [10].

**Technical parameters**

Prototypes of Zinc-bromine batteries have a specific energy of 80 Wh/kg and a specific power of 100 W/kg. Reliable data on the lifetime aren't available for the moment due to the fact that this system has only been tested on a prototype scale in vehicle applications up to now and that research activities have been abandoned on motive power applications. The low specific power results in the conclusion that this battery seems inadequate for HEV applications. The other redox batteries have similar characteristics and accordingly similar conclusions can be drawn for these technologies.

**Overall**

The amount of data available concerning this technology is too low to discuss their potential environmental impact. What can be told for sure is that this application is not suitable for HEV application.

### III.2.1.5. Nickel-iron.

Nickel-iron batteries have similar performance characteristics as nickel-cadmium batteries. Therefore this technology theoretically can be a substitute for nickel-cadmium batteries. But, low energy efficiency (50-60%) causes excessive water consumption. This disadvantage compared to nickel-cadmium batteries makes this battery not accepted for commercial EV or HEV use.

The electrodes of this battery can easily be recycled and the recycled materials can be used in the steel industry.

### III.2.1.6. Silver-zinc.

Silver-zinc batteries have good specific energy and specific power characteristics. The lifetime cycles are very low compared to the other discussed technologies in this report (maximum 250 cycles).

## III.2.2. Discussion of the qualitative analysis.

Just like for all the technologies, it’s important to define the application where the battery is going to be used and to choose an appropriate reference basis before comparing the different technologies. As previously discussed in the sections dedicated to the quantitative analyses, the technical parameters influence the required battery mass and number of batteries needed for the functional unit. The technologies described in this part of the study are not commercially widespread. Additional research is needed, to obtain technological improvements and lower the environmental impact of these technologies.

This qualitative analysis gave an overview of the composition of the batteries, their possible recycling methods, their main characteristics, etc. The short discussions summarized the practical feasibility for different applications.

As has been shown in the previous chapters of this study, recycling of the spent batteries is important, because it can save resources and lower the total environmental impact of the life cycle of the batteries. Of course this conclusion is valid for the batteries discussed in this chapter too.

Of course, the technical and economical parameters should be taken into account too when determining which technologies are fitting the requirements of BEV or HEV.

# IV. Economical Assessment (WP3).

## IV. 1. Costs and Prices of Battery Technologies for Traction Applications and Relation with the world Market Trends.

For all types of electrically propelled vehicles (pure electric or hybrids), the battery is one of the most expensive components even when the power train configuration leads to a battery of small size. Investigations and studies have been performed for each type of technology showing a technical interest for the concerned applications. But, as the SUBAT purpose is to make an overall assessment (technical, environmental and economical) of all the battery technologies able to have an interest in the electric or hybrid vehicle field, the costs and prices comparisons becomes very difficult and specific hypothesis have to be assumed as well as specific evaluation methods must be developed.

### IV. 1.1. Today Price Estimation for a Specific Technology.

#### IV. 1.1.1. Estimation method used.

Assuming the hypothesis of a well known technology, commercialized at a high production level (this level is a function of the technology) and produced by several battery manufacturers in the world under close design and chemical composition (case of NiMH for example), the today cost and price estimation can be made using the following steps:

- technology study to establish the different types of materials needed and the relative amount of each for a typical battery cell
- technical performances study to establish the characteristics of the typical cells to be evaluated (if cells composition are different in the case of high power or high energy applications),
- comparison of chemical composition of typical cells depending on the different battery manufacturers
- mean value estimation of the cells chemical composition (and impact on the cost calculation leading in some cases to minimum and maximum values)
- data collection and analysis of the raw material prices (leading in all cases to minimum and maximum values)
- cell cost of goods estimation (two cases: high energy and high power, see table 9)
- cell cost evaluation taking into account the labour costs and the accessory costs in order to make the battery with a given number of cells

At this stage of the evaluation, it becomes necessary to choose battery technical specifications for a given application in order to obtain reliable cost and price of the vehicle component. Depending on the application the calculated battery price can be different for several reasons:

- the size of the battery is different depending on the technical performances in energy (BEV) or power (HEV)
- the accessories costs are not always function of the battery size
- the battery design can be completely different

The following battery definitions were chosen (Table 8), leading to three different batteries (the two last columns lead to the same type of results).

**Table 9 : Different reference type of BEV and HEV.**

| **Vehicle type** | **Mild Hybrid** | **Full Hybrid** | **Full Hybrid with 40 km ZEV (Dual mode)** | **BEV** |
|---|---|---|---|---|
| Energy (kWh) | 0,4 | 1,2 | 10 | 30 |
| Power (10s, kW) | 12 | 40 | 50 | 50 |
| Voltage (V) | 42 | 270 | 270 | 270 |
| Cost and Price units | €/kW | €/kW | €/kWh | €/kWh |

**Table 10 : Example of cost of goods estimation for a typical high energy cell in 2004 (Li-ion case).**

| **2004** | **W %** | **unit max (€/kg)** | **unit min (€/kg)** | **W (g)** | **Max Cost** | **Min. Cost** | **% (max)** | **% (min)** |
|---|---|---|---|---|---|---|---|---|
| Cathode active material | 33 | 45 | 38 | 330 | 14.85 | 12.54 | 47.00 | 45.44 |
| Collector (Al) & other Al | 8.5 | 21 | 19 | 85 | 1.79 | 1.62 | 5.65 | 5.85 |
| Anode active material | 17 | 21 | 18 | 170 | 3.57 | 3.06 | 11.30 | 11.09 |
| Collector (Cu) & other Cu | 12 | 15 | 14 | 120 | 1.80 | 1.68 | 5.70 | 6.09 |
| Separator | 1,5 | 140 | 120 | 15 | 2.10 | 1.80 | 6.65 | 6.52 |
| Electrolyte | 19 | 21 | 20 | 190 | 3.99 | 3.80 | 12.63 | 13.77 |
| Packaging (Al) | 9 | 3.5 | 3.1 | 90 | 3.50 | 3.10 | 11.08 | 11.23 |
| **Cell cost of goods** | | | | 1000 | **31.60** | **27.60** | | |
| | | | | **€/kWh** | **219** | **192** | | |

The complete battery cost and price is then estimated using the two following steps:

- battery production cost evaluation (BMS, assembly cost, labour cost and accessories costs)
- battery price (other manufacturing costs, overheads and margin)

This last step causes a major problem in the price estimation. The manufacturing and Company costs used in this step mostly have a value between 30 and 45% of the battery price. Data are not public and only estimations of the values can be made using the known habits of the Industrial Companies. In order to obtain reliable values the method used consists in choosing a minimum and a maximum value in agreement with the most common values.

Results are then expressed in terms of battery price, €/kWh for energy type batteries and €/kW for power type batteries.

These results are then compared to all known battery price (In the case of purchase by volumes) and cost studies made since 1999.

This method has been used in the case of NiMH, Li-Ion and NaNiCl. For Lead-Acid technology the method seems to be unusable. Because of a very high number of technology improvements made since several years by all the specialized companies, it becomes impossible to analyse the relations between the improved technical performances and the resulting price of the battery. A standard VRLA AGM battery with classical performances announced at a price of about 120 €/kWh is sold at more than 300 €/kWh in the case of advanced bipolar VRLA type. But as the technical performances of Lead-Acid are always

poor compared with the other technologies, the hypothesis has been assumed that Lead-Acid is of interest for vehicle manufacturers only if the price remains low. Only one manufacturer in the world (SAFT) commercializes NiCd batteries for traction application and this market is continuously decreasing since 2000. Prices of this manufacturer have been chosen without any complementary estimation.
Concerning more recent (or less developed) technologies like Lithium-Metal-Polymer, new types of Ni-Zn, Zn-Air, Redox batteries, prices could not be evaluated with a reasonable level of reliability and comparisons with the other technologies become impossible taking into account the great difference in industrial development levels.

### IV.1.1.2. Production costs, manufacturing costs and prices.

All results are expressed in terms of battery prices but only production costs evaluation are really reliable and mainly function of the active material costs. But in order to obtain an order of magnitude of the future real price has been estimated the price corresponding to a given production cost using a mean value of the overheads and company costs. These results are made to be compared between each other and very carefully used as absolute value because of the close relation between the market situation and their values (in case of great competition overheads and margin decrease).

### IV.1.1.3. Notion of minimum and maximum price values.

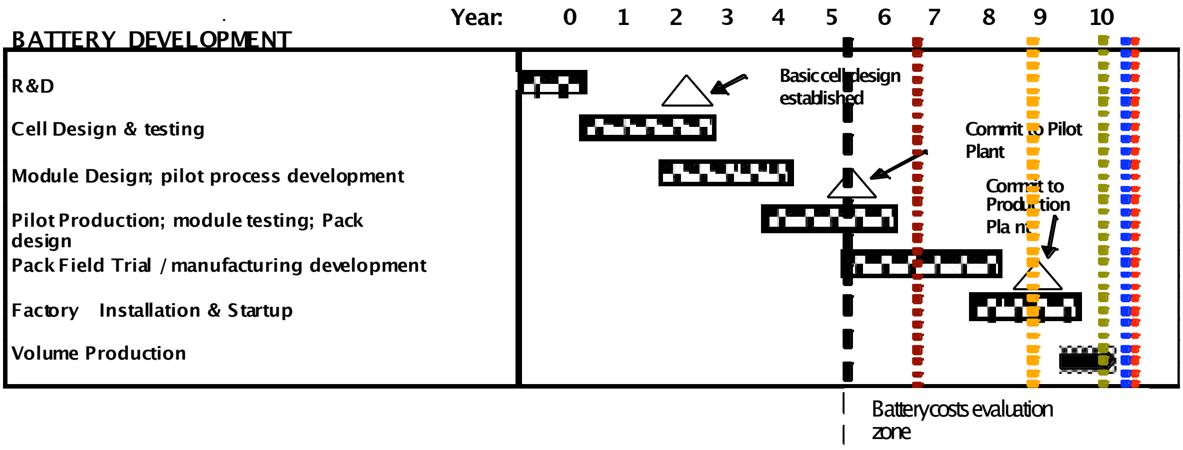
The minimum and maximum price (and cost) values have not the same meaning than usually and are function of the technology studied. In fact, most often, the maximum price value is a value taking into account the mean value of all the criteria. The minimum price value can be very different following the type of technology. For a mature technology, produced since a long time like Lead-Acid, minimum price is really the minimum value of price that can be found on the market. For an advanced technology like Lithium based, this minimum price is the result of the minimization of all the criteria. Then, the result is not an estimated minimum price but the lower boundary of the estimation (it seems impossible to find a price under this value).

## IV.1.2. 2012 price estimations.

All the 2012 prices estimations are made in € (2004) with a standard ratio of 1.25 for €/$.
These evaluations are made using all the known data and several market trends analysis. Assumptions are made in each technology case taking into account the different factors able to have an influence on the results. These factors are different following the different technologies studied and will be given in a specific chapter after the main results presentation.

### IV.1.2.1. Today's Battery level of development.

Cost and price estimations are highly depending on the development level of each studied battery technology. As we try to compare all the available technologies in 2012, it becomes necessary to create estimation methods usable for different levels of development. In such conditions the results obtained have to be used carefully taking into account the following situation (Figure 4) describing the battery development level of all the studied battery technologies in 2004.



*(Lithium based, NaNiCl, NiMH, NiCd, Lead-Acid)*

**Figure 4: Battery development level [11].**

### IV.1.2.2. The “scale effect” (or volume effect)

One of the main factors is the “scale effect” corresponding to the decrease of price as a result of the increase of production volume for a battery manufacturer. This “scale effect” has been studied by many specialists for more than ten years in order to define a relation between battery price and production volume. This relation is a function of the type of process (technology) and probably of the type of organization of the manufacturer. But in all the cases the relation obtained is of “asymptotic” shape with a fast decrease of price for low volume and after a given value of production volume a very slow decrease of price when volume increase.

This fact leads to the following conclusion:

- it is impossible to compare different technology prices if the stages of industrial development are too different
- prices evaluations and comparison can only be made if the technology studied have reached the pilot production scale and have already a market even small (the uncertainty becomes too high for more recent technologies). But some qualitative forecasting can be made
- prices given or estimated for a new technology at the laboratory level are not reliable

The purpose is to estimate a value of the potential prices in 2012 of the different battery technologies assuming that they are used for large vehicle production volumes (it seems that this production volume value is of about 10 000 vehicles/year for BEV, and 50 000 vehicles/year for mild hybrids) called “mass production”. The “scale effect” is then always in the asymptotic part of the relation between price and production volume.

### IV.1.2.3. Active material costs and production volume.

Active material costs are the main part of the production costs for a battery in “mass production” (between 60 to 80% following the costs of battery assembly and BMS). Two very different cases have to be studied:

- for Lead-Acid and Nickel based (NiCd, NiMH, etc), the battery industry consumption of raw material is a minor part of the whole world industry consumption of this material, and the prices are set by the market without any relation with the battery production volume,

- for Lithium based in case of mass production the raw material consumption of lithium based traction battery industry will be the greatest of this type of product in the world. The prices are then function of the battery production volume, and a decrease of these raw material prices can be forecasted if the battery market grows.

### IV.1.2.4. Improvement of technical performances.

If a battery for a given application decreases in weight because of an improvement of the technical performances (specific power for hybrids or specific energy for BEV), then the battery cost decrease as well (not always the price). This fact is the result of a decreasing need in active material for a given application. The active material used for a given technology can be also substituted by other giving the same performances for a lower price.
Taking into account the following elements:

- technology improvements potential are very different following the different technologies,
- relations between prices and performances are impossible to foresee,
- it’s impossible to forecast more than 5 to 7 years before the material changes that can occur for a technology at the pilot stage as Lithium based,

Today’s best known performances were chosen as the base of our estimation without any future improvement consideration. These potential improvements will be discussed in a second phase for each technology studied.

## IV.1.3. Main results.

### IV.1.3.1. Today prices comparison.

In all cases a standard ratio of € 1 = $ 1.25 has been chosen.

**Table 11 : Price estimations for five battery technologies in 2005.**

**BEV Battery of 30 kWh**

| | weight (kg) | min. price € | max. price € | €/kWh min. | €/kWh max. |
|---|---|---|---|---|---|
| **Lead-Acid** | 850 | 3 480 | 4 530 | 116 | 151 |
| **NiCd** | 550 | 14 700 | 21 600 | 490 | 720 |
| **NiMH** | 430 | 16 770 | 19 980 | 559 | 666 |
| **NaNiCl** | 270 | 13 500 | 15 000 | 450 | 500 |
| **Li-Ion** | 270 | 21 000 | 25 800 | 700 | 860 |

**Mild Hybrid Battery of 12 kW, 0.4 kWh**

| | weight (kg) | min. price € | max. price € | €/kW min. | €/kW max. |
|---|---|---|---|---|---|
| **Lead-Acid** | 66 | 144 | 180 | 12 | 15 |
| **NiCd** | 23 | 624 | 648 | 52 | 54 |
| **NiMH** | 15 | 552 | 720 | 46 | 60 |
| **NaNiCl** | 60 | 2 976 | 3 372 | 248 | 281 |
| **Li-Ion** | 7 | 528 | 624 | 44 | 52 |

**Full Hybrid Battery of 40 kW and 1.2 kWh**

| | weight (kg) | min. price € | max. price € | €/kW min. | €/kW max. |
|---|---|---|---|---|---|
| **Lead-Acid** | 111 | 480 | 600 | 12 | 15 |

| | | | | | |
|---|---|---|---|---|---|
| **NiCd** | 75 | 2 080 | 2 160 | 52 | 54 |
| **NiMH** | 38 | 1 520 | 1 840 | 38 | 46 |
| **NaNiCl** | 200 | 9 920 | 11 240 | 248 | 281 |
| **Li-Ion** | 27 | 2 280 | 2 720 | 57 | 68 |

*Note : The grey rows (NaNiCl in the hybrid cases, and Lead-Acid in the full hybrid case) are given only for comparison. They do not have any technical reality because NaNiCl batteries are made only for energy applications (no power version available today) and the Lead-Acid battery weight (111kg) for full hybrid is not convenient for the design of this type of vehicle.*

### IV.1.3.1.1. Lead-Acid.

Because of a high number of new design and new types of material introduced during the last ten years in this type of old technology, it becomes very difficult to make a reliable relation between price and performances. As the main interest of Lead-Acid is its low price, a mean value of the prices given by many battery manufacturers for VRLA type convenient for the given applications today available was chosen. For hybrid applications, as power and life cycle seem to be not acceptable for the standard VRLA, many major companies have started R&D programs in order to increase the Lead-Acid properties. But corresponding increase of costs (and prices) seems to be high (prices of about 250 €/kWh can be found in the literature).

### IV.1.3.1.2. NiCd.

NiCd batteries for traction applications are now produced by only one company in the world. Prices and costs are known and now only function of the active material prices. As these material prices are closely linked to Nickel price, their costs have increase of more than 100% since 1999. NiCd batteries are produced in a fully automated industrialized plant and only purchase volumes have an effect on the price. A minimum value of the price corresponding to the purchase in volume price and a maximum value corresponding to the low volume price has been chosen.

### IV.1.3.1.3. NiMH.

The NiMH battery production cost is a function of the active material prices closely linked with the Nickel market price. This market is very volatile since 1998 and it becomes very difficult to make any long term forecast. Our costs estimations are based on the today Nickel price (about 14$/kg) and an estimated ratio between Nickel (metal) price and active material of NiMH electrodes prices.

The power version of NiMH battery (for hybrids) is today in mass production and the technology is mature. It is not exactly the same for the energy version (BEV). It was assumed that all the estimated values of active material prices were the same in the two cases.

In the case of NiMH for hybrid battery, the battery assembly and BMS costs are a function of the battery and vehicle design, reduced costs for the smaller one (mild hybrid) in agreement with the most common solutions chosen by the first industrial projects has been assumed.

### IV.1.3.1.4. Lithium based.

Lithium based batteries are at the pilot stage for the most developed technologies (Li-Ion with liquid electrolyte), but the technology is not really mature today and many technologies are in competition in order to reduce the active material prices and to increase the safety. As it seems to be the technology with the highest potential, it is important to evaluate its potential price in the future. Today’s price is not really a mass production price but only a price estimated with the today active material prices and a large production volume (mass production with no effect on the raw material prices).

All the known technologies (at the pilot stage) are taken into account by evaluation of a mean chemical composition (for each type of cells) and a minimum and maximum price of the active material as a function of their nature (Co, Mn, Ni Li(O)).

As the technical performances increase very rapidly for this technology, consequences on the cost estimations have been taken into account (number of cells for a given battery) based on the short term performances targets of several battery manufacturers.

### IV.1.3.1.4. NaNiCl (ZEBRA).

NaNiCl battery is produced by only one battery manufacturer in the world (MES-DEA). For the today prices (as for NiCd), the real today prices of the company for large orders has been chosen.

## IV.1.3.2. 2012 prices estimation.

The different prices estimations for the different technologies are given in Table 14. These results are based on assumptions as described in the previous paragraphs.

**Table 12 : Price estimations for 2012.**

**2012 Battery Prices in € (2004)**

**BEV Battery of 30 kWh**

| | weight (kg) | min. price € | max. price € | €/kWh min. | €/kWh max. |
|---|---|---|---|---|---|
| **Lead-Acid** | 850 | 4 733 | 6 161 | 158 | 205 |
| **NiCd** | 550 | 14 700 | 21 600 | 490 | 720 |
| **NiMH** | 430 | 16 770 | 19 980 | 559 | 666 |
| **NaNiCl** | 270 | 6 360 | 7 500 | 212 | 250 |
| **Li-Ion** | 270 | 10 800 | 14 310 | 360 | 477 |

**Mild Hybrid Battery of 12 kW, 0.4 kWh**

| | weight (kg) | min. price € | max. price € | €/kW min. | €/kW max. |
|---|---|---|---|---|---|
| **Lead-Acid** | 66 | 196 | 245 | 16 | 20 |
| **NiCd** | 23 | 624 | 648 | 52 | 54 |
| **NiMH** | 15 | 552 | 720 | 46 | 60 |
| **NaNiCl** | 60 | 2 976 | 3 372 | 248 | 281 |
| **Li-Ion** | 7 | 276 | 384 | 23 | 32 |

**Full Hybrid Battery of 40 kW and 1.2 kWh**

| | weight (kg) | min. price € | max. price € | €/kW min. | €/kW max. |
|---|---|---|---|---|---|
| **Lead-Acid** | 111 | 653 | 816 | 16 | 20 |
| **NiCd** | 75 | 2 080 | 2 160 | 52 | 54 |
| **NiMH** | 38 | 1 520 | 1 840 | 38 | 46 |
| **NaNiCl** | 200 | 9 920 | 11 240 | 248 | 281 |
| **Li-Ion** | 27 | 1 200 | 1 600 | 30 | 40 |

*Note : The grey rows (NaNiCl in the hybrid cases, and Lead-Acid in the full hybrid case) are given only for comparison. They do not have any technical reality because NaNiCl batteries are made only for energy applications (no power version today available) and the Lead-Acid battery weight (111kg) for full hybrid is not convenient for the design of this type of vehicle.*

### IV.1.3.2.1. Lead-Acid.

For 2012 costs (and prices) evaluation a lead-acid battery design that can be cost convenient has been chosen as in the previous case Prices evaluation has been made taking into account no real increase in power or energy performances and an increase of cost in relation with the high market price of lead and all the data given by the battery manufacturers (an increase of about 36% in 2012 and € (2004) has been anticipated by most of the lead-acid battery manufacturers).

### IV.1.3.2.2. NiCd.

No real increase of the market of NiCd "traction" battery can be expected in the next years, on the contrary a decrease of the BEV NiCd batteries market can be anticipated in relation with the environmental Cd problems and regulations and the development of more efficient technologies.

In this situation no decrease of cost and price can be expected and the battery cost will be closely linked with the Nickel prices variation. The same prices between 2005 and 2012 (in 2004 €) have been chosen to keep.

### IV.1.3.2.3. NiMH.

The same prices (and costs) have been kept between 2005 and 2012 (in € 2004) for NiMH technology assuming the following elements:

- nickel market is very volatile but mean value will be high (between 10 and 15 $/kg) leading to nearly constant prices of active material
- no "scale effect" can be expected for this technology
- technical improvements will not be high enough to have an influence on the price
- the R&D activity for the development of advanced NiMH batteries for BEV applications has significantly decreased. No major battery manufacturer is now focusing on this technology for energy applications

Two complementary results have to be considered:

- relation between NiMH battery prices and Nickel price (see Figure 5)
- prices that could be used by the Chinese battery manufacturers specialized in this technology (see specific paragraph)

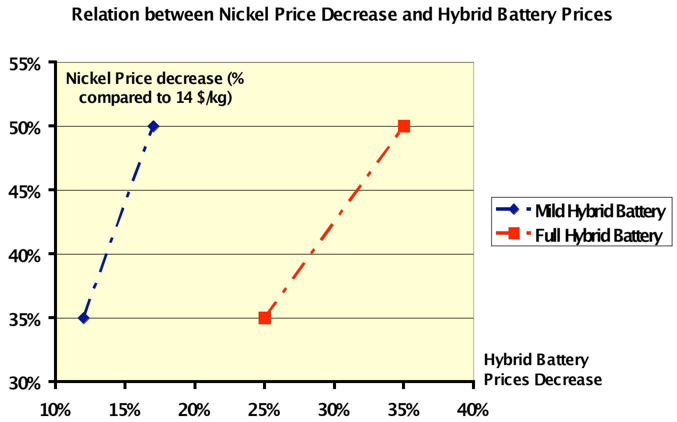


**Figure 5 : Relation between Nickel Price Decrease and Hybrid Battery Prices.**

### IV.1.3.2.4. Lithium based.

Estimations are more difficult for the lithium technology because of an intense R&D activity all over the world leading to an uncertainty concerning the technical performances and the type of active material (and cost) that will be used in 2012.

The following assumptions have been taken:

- mass production of energy (BEV) and power versions (Hybrids) and decreasing active material costs
- BMS and other electronic accessories are mass produced leading to a high decrease of price
- for mild hybrid battery part of the electronic components has been included in the vehicle control unit
- new technology developments lead to a decrease of active material costs and technical performances corresponding to the best laboratory performances known today
- comparison are made with the Lithium based portable battery market
- the minimum price is calculated on the basis of the best known data of all the previous factors
- the maximum price is calculated on the basis of mean value of the previous factors

As for NiMH the special case of Chinese battery manufacturer has to be taken into account (see specific paragraph).

### IV.1.3.2.5. NaNiCl.

The NaNiCl battery cost in mass production case have been studied and published by MES-DEA in 2002. Our estimations have been made using this published data and complementary evaluations taking into account the raw material price changes and some elements coming from a complete analysis of the technology and the production process. Results are only an order of magnitude of future prices because all the process costs can’t be checked up.

## IV.1.3.3.The specific case of Chinese Manufacturers.

Since 1998, the Chinese Government and some private investor have started a dynamic politic of development of the battery industry. In relation with the national R&D program (863 program) many of the major Chinese battery companies have focused on traction battery development based on NiMH and lithium technologies.

This merging Chinese industry is in a very different situation compared to European, Japanese and American one for two main reasons:

- for NiMH and Lithium based a great amount of the raw material needed are coming from China,
- Chinese manufacturing costs (as for the other industries) are much lower.

It is today impossible to anticipate the prices that will be used by Chinese Manufacturers in 2012, but it seems probable that the technical performances will be of the same order compared to the other country companies and the prices will be lower.

A first estimation has been made using the information obtained during a special mission made recently for SUBAT project:

- NiMH for energy applications (BEV): a decrease of cost of about 50% seems to be possible, leading to a decrease of price of probably more.
- NiMH for power applications (hybrids) are not really developed in China for the moment,

- Lithium based for energy application: a decrease of cost between 20 and 30% seems to be possible ,
- Lithium based for power application: a decrease of cost between 30 and 40% seems to be possible.

## IV.2. World Traction Battery Market and Trends to 2012.

As far as only the Battery Market for traction applications is concerned, the future battery market trends are closely related with the forecast of Hybrids and Battery Electric Vehicle Markets (Advanced Vehicles). The main purpose of this study is to evaluate the probability of mass production of each type of battery technology in 2012. It is then necessary to study the long term forecast for advanced vehicles and the corresponding battery needs. Taking into account only the passenger and light duty car market (96% of the total vehicle market) in a first step, the main factors that will drive the market are:

- policy factors (laws, regulation and public subsidy) concerning the local pollution, the $CO_2$ emission (GHG) and perhaps the oil consumption,
- the oil market price pressure,
- the price of advanced vehicles compared to an internal combustion one,
- the increase of sense of civic responsibility concerning the air pollution problems.

The consequences of these factors on the vehicle market can be studied only considering four different markets: Europe, Japan, America and China.

### IV.2.1. European Market.

Market of about 17 million of vehicles in 2004, this market is mainly driven by three factors: the European Union laws and regulations concerning the local pollution (Euro IV and Euro V), fuel economy and $CO_2$ emission incentives and price of vehicles. It is also characterised by small vehicles with small engines and a high amount of new type of eco-diesel engines.

A complete analysis of all the data made for several scenarios of development leads to the following conclusions:

- advanced vehicle market will start and increase to a value between 3 and 8% of the total passenger car market (500 000 to 1.4 millions of vehicles) in 2012 depending on the scenario chosen
- mild hybrid type will prevail, probably equipped with a 42V battery pack of about 0.2 to 0.4 kWh and 9 to 12 kW (10s) leading to a battery weight between 1 800 to 4 000 t.
- competition will prevail between advanced lead-acid, NiMH and Lithium based
- ratio will depend on relative cost for Lead-Acid and NiMH and of cost and safety for Lithium based
- market seems to be too small by itself to induce a world increase of the new technology battery market
- BEV market will remain a niche market (between 30 000 to 100 000 vehicles/year) using probably mainly lithium based batteries

### IV.2.2. Japanese Market.

Market of about 13 millions of vehicles in 2004 (with Korea), this market is mainly driven by fuel economy, increase of comfort and vehicle price. It is also characterized by a great majority of small gasoline engines, midsize cars and strong incentives towards fuel economy and $CO_2$ emission reduction (a mean value of 25% in ten years). Laws and regulations for local pollution are less important (but standard values are comparable to European one) in relation with the type of fuel used.

A complete analysis of all the data made for several scenarios of development leads to the following conclusions:

- advanced vehicle market has started in 2004 and will increase to a value between 5 and 10% of the total passenger car market (perhaps more) leading to values between 650 000 and 1.5 million of vehicles/year in 2012. But as this market is also driven by the US market these values can be higher if the US Car Manufacturers are not able to compete on this market
- full hybrid type will prevail equipped with high voltage batteries but probably all types of mild and full hybrids will be produced
- competition will prevail between NiMH and Lithium based batteries probably manufactured in China under (or not) Japanese licence (8 000 to about 30 000 t of batteries) and in the case of success of current lithium based development projects (cost and safety) lithium based have probably the best future
- this market is enough to induce a mass production market for the new battery technologies concerned (in this case the consumption of active material is greater than the portable battery market)
- BEV market will remain very low and it seems to be too early to forecast any development of FC vehicle market

## IV.2.3. The North American Market.

Market of about 18 million of vehicles in 2004, this market is mainly driven by comfort and vehicle performances and for a part by incentives of several administrations (California and other states). It is also characterized by large cars (SUV, trucks etc), large gasoline engines and low fuel price. It becomes possible that very stringent regulations appear before 2012 concerning the local pollution, but no reliable forecast can be done.

A complete analysis of all the data made for several scenarios of development leads to the following conclusions:

- the advanced vehicle market has started in 2004 and will increase driven more by the increase of comfort and performances without any increase of consumption than other reasons. It will probably reach values between 4 and 8% of the total passenger car market (700 000 to 1.5 million of vehicles/year)
- on the opposite of European Market large or powered hybrid vehicles will prevail probably of all types depending on the market segment
- part of this production will come from Asia (Japan, Korea and perhaps China) and it seems that nearly all the corresponding battery packs will come from Asia too
- competition will prevail between Lead-Acid (for the smaller part), NiMH and Lithium based
- this battery market can be considered as comparable to the Japanese one (manufacturers, volume and consequences)
- there is no reason to have any change of the BEV market that now nearly does not exist

## IV.2.4. The Chinese Market.

This Market is a new one, from about 4 million of vehicles in 2003 and with a yearly increase of more than 12%, it becomes possible to reach a size of more than 8 million of vehicles/year in 2012. As a new one, it is not so well known than the others and it becomes difficult to make reliable forecast. But some of the main characteristics can be described and consequences can be analysed assuming several different scenarios

This market will be mainly driven by fuel economy and governmental policy and hypothesis of a rapid growth of ultra-low-emission vehicles can be done for the following reasons:

- Chinese oil consumption increases very rapidly (about 30% per year) even though more than 50% is imported today
- local pollution has dramatically increased the last few years in all the main Chinese towns
- China is one of the main world producer of active material for NiMH and Lithium based batteries
- development of advanced vehicle market could be a way to improve the development of Chinese car industry
- on the opposite of all the other markets, Chinese authorities can have a direct impact on the vehicle market changes

Consequences on the advanced vehicle market could be the following:

- development of low prices little hybrids of all types, advanced electric vehicles and US type hybrids at the same time
- development of the electric two wheelers market (very important in China)
- development of the hybrid and electric bus market

In all cases the Chinese traction battery market will increase based on an internal production and consumption. This increase could have a consequence on the other markets (European and US) with an important decrease of the battery prices (NiMH, Lithium based).

# V. SUBAT Overall Assessment.

## V.1. Introduction.

The purpose of this work package is to compile and integrate the results and conclusions of work packages 1, 2 and 3. This chapter provides a description of the criteria used to perform the overall analysis, followed by an explanation on how these criteria are used (methodology) and a discussion of the output of the analysis.

### V.1.1. The MCA criteria.

Multi-criteria analysis (MCA) is a method used to evaluate and compare different options/scenarios according to different criteria in a quantitative way. The purpose of the MCA is to combine the conclusions of WP1 (technical assessment), WP2 (environmental assessment) and WP3 (economical assessment) and to make an overall assessment.
For these different WP's the **most relevant parameters** were chosen. The used criteria are listed and grouped per category in Table 13. The same criteria are used for BEV and HEV vehicles.

**Table 13: The different chosen criteria for the MCA and their meanings.**

| | | |
|---|---|---|
| Technical | Specific energy | BEV: indication of the technical performance |
| | Specific power | BEV: indication of possibility of fast charging<br>HEV: indication of technical performance |
| | Cycle | Indication of the life time of the battery and of the number of replacements needed |
| | Energy efficiency | Indication of the energy losses in the battery |
| Environmental | LCA | Environmental burden during lifetime (assembly + recycling). The losses due to mass and energy efficiency of the batteries are included in the BEV values. |
| Economical | Cost | Total cost of the battery pack |
| | Maturity | Indication of the maturity of the technology |
| | User friendly | Technical limitations of technology for the users |

Some of the criteria are considered to be more important than others. This is reflected in the different weighting factors for the different criteria. These weighting factors are different for HEV and BEV batteries.

Important to note is that the cost and de LCA-scores are calculated for the lifetime of the vehicle (to be compared with the WP2 F.U.). The required battery masses as well as the number of replacements have been calculated taking (amongst others) the number of cycles delivered by each battery technology into account. The indicated cost and environmental impact are based on these masses and replacements.

The importance allocated by the different stakeholders to each of these criteria differs and as a consequence, it seemed interesting to consider different perspectives (different weights depending on the stakeholder) towards the studied issues. The basic perspective considered in this study is the political perspective. Additionally, a consumer's as well as a car manufacturer's perspective have been included in the analysis and in the discussion. The influence on the global result for the two other perspectives will be discussed in paragraph V.3. of this report (p.48).

The political perspective allocates an equal importance to technical, environmental and economical component. The weighting of the different criteria for the political perspective can be found in Table 14.

**Table 14: Weighting factor for HEV and BEV for the Political scenario.**

| | Technical parameters (50) | | | | Environmental parameters (50) | Economical parameters (50) | | |
|---|---|---|---|---|---|---|---|---|
| Politics. | Specific energy | Specific Power | Cycles | Energy efficiency | LCA | Cost | Maturity | User friendly |
| BEV | 25 | 15 | 5 | 5 | 50 | 30 | 10 | 10 |
| HEV | 10 | 30 | 5 | 5 | 50 | 30 | 10 | 10 |

It is important to keep in mind that the environmental impact and the cost are calculated to cover a certain target distance and that some technical parameters are influencing the results of these calculations.

The used values for the different criteria for technologies may be real values or relative values. As the aim of the study is to *compare* different battery technologies, this doesn’t influence the results of the study in any way.

The political perspective is based on a balanced approach of the situation. As a consequence, similar weights have been attributed to the three main categories (technical, environmental, economical). Within the technical criteria of the BEV batteries, a high weight was allocated to energy content (specific energy) of the battery, as this parameter determines the performance of a BEV in an important way (range, weight etc.). On the other hand, the power plays a crucial role for HEV and as a consequence, a higher weight was allocated to the specific power when analyzing HEV batteries. The number of cycles delivered by each battery technology as well as the respective energy efficiencies, have been considered as important to HEV as to BEV batteries.

As the environmental analysis performed in WP2 is based on an overall approach of the environmental impacts, the result of the LCA can be considered to be the only required parameter for the environmental parameter category. As a consequence, the entire weight of the environmental category is allocated to the LCA result.

From an economical point of view, the cost of the battery obviously is the most important parameter. This parameter has thus been allocated the highest weight. However, some other elements have to be taken into account. The maturity of the technology reflects the needs for extra research and development investments. Also, technicians are more comfortable with a mature technology than with technology in development, and the formation of these technicians can require some investments. The user friendliness reflects the inconveniences implied by each technology. User friendliness can be seen as an advantage when selling the EV (battery) to the costumer.
All along this chapter, it should be kept in mind that the presented results and calculations are based on (and as a consequence are only valid) taking the specific assumptions related to each WP into account. These conditions have been detailed in each of the specific WP. Consequently, the presented and discussed results in this chapter must be seen in this context.

### V.1.2. Methodology.

A commercial available software tool - Decision Lab[3] - was used to perform the MCA. PROMETHEE-GAIA (**P**reference **R**anking **O**rganisation **Meth**od for **E**nrichment **E**valuations - **G**eometrcial **A**nalysis for **I**nteractive **A**ssistance) methodology was used [12].

The MCA allows the calculation of positive and negative preference flows for each alternative. The positive flow is expressing how much an alternative is *dominating* ($\varphi^+$ or attractiveness) the other ones, and the negative flow how much it is *dominated* ($\varphi^-$ or weakness) by the other ones. Based on these flows, the PROMETHEE I partial ranking is obtained. PROMETHEE I does not compare conflicting actions. On the other hand PROMETHEE II provides a complete ranking ($\varphi$-values). It is based on the balance of the two preference flows. The information looks stronger but some part of it gets lost in the process.

The information relative to a decision problem including *k* criteria can be represented in a *k*-dimensional space. The GAIA plane is obtained by projection of this information on a plane such that only as few information as possible gets lost. Points represent alternatives and axes represent criteria. The conflicting character of the criteria appears clearly: criteria expressing similar preferences on the data are oriented in the same direction, conflicting criteria are pointing in opposite directions. It is also possible to appreciate clearly the quality of the alternatives with respect to the different criteria [13].

In addition to the representation of the alternatives and criteria, the projection of the weights vector in the GAIA plane corresponds to another axis ($\pi$, the PROMETHEE decision axis or decision stick) that shows the direction of the compromise resulting from the weights allocated to the criteria. The decision-maker is thus invited to consider the alternatives located in that direction. When the weights are modified, the positions of the alternatives and the criteria remain the same, only the decision axis $\pi$ is changing. The software allows using the weights vector as a *decision stick* to orientate the decision. The movements of the stick corresponding to modifications of the weights are directly displayed in the 3D-view window of the GAIA screen. The closer the point representing an alternative is to the end of the decision stick (in the *k*-dimensional space), the better it is expected to be. Decision-makers particularly appreciate this sensitivity analysis tool [14].

## V.2. Political perspective.

### V.2.1. BEV 2005.

### V.2.1.1. Input data.

The used data are originating, and are eventually adapted, from the different work packages and can be found in Table 15.

**Table 15: MCA data for BEV 2005**

| | Specific Energy | Specific Power | Cycles | Energy efficiency | LCA | Cost | Maturity | User friendly |
|---|---|---|---|---|---|---|---|---|
| PbAc | 40 | 250 | 500 | 83 | 503 | 10085 | 100 | 100 |

---

[3] http://www.visualdecision.com/

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| NiCd | 60 | 200 | 1350 | 73 | 544 | 17355 | 100 | 100 |
| NiMH | 70 | 350 | 1350 | 70 | 491 | 20254 | 60 | 100 |
| Li-Ion | 125 | 400 | 1000 | 90 | 278 | 25338 | 60 | 100 |
| NaNiCl | 125 | 200 | 1000 | 86 | 234 | 17109 | 80 | 60 |

The technical data are originating from work package 1 and didn't need any adaptation before assessing them in this work package.

The data of the LCA shown in Table 15 are the environmental scores of the functional unit for the different battery technologies obtained through SimaPro® in WP2. The data concerning the cost of the different technologies are the results of calculations based on data obtained in WP3. The costs per kWh have been multiplied by the required number of batteries to deliver 3000 cycles and by the capacity (in kWh) of the batteries in the functional unit. The data concerning the maturity reflect the relative states of development of the different battery technologies.

The user friendliness of the batteries has been set to 100 for all batteries except for the sodium-nickel chloride battery. These values are all relative values. Which is not a problem at all since in an MCA the values are compared to each other, so only relative values have to be taken into account. All the battery technologies include some inconveniences. Nickel batteries (nickel-cadmium and nickel-metal hydride) show a memory effect. The state-of-charge of the lead-acid battery is quite difficult to measure in an accurate way, while the lithium-ion batteries still imply some safety issues. On the other hand sodium-nickel is a hot battery, which comes with an energy loss, and its consequent discharging of the battery, even when not using the battery. This inconvenience is perceived as being more important than the ones of the other battery technologies and thus the user friendliness of this technology has been set to 60% of these other technologies.

### V.2.1.2. Results and discussion BEV 2005.

According to the political scenario, both PROMETHEE I and II (Figure 6 & Figure 7) provide similar and differentiable rankings for the BEV batteries in 2005. In a decreasing order of preference, following ranking is obtained: lithium-ion, sodium-nickel chloride, lead-acid, nickel-metal hydride and nickel-cadmium. As can be seen in the GAIA-plane (Figure 8) and in the action profile (Figure 9), the preference for the lithium-ion and the sodium-nickel chloride technologies are mainly due to the technical and environmental performances of the lithium-ion batteries and to the environmental performance of the sodium-nickel chloride batteries. The relatively good score of the lead-acid technology is mainly due to its economical advantages.

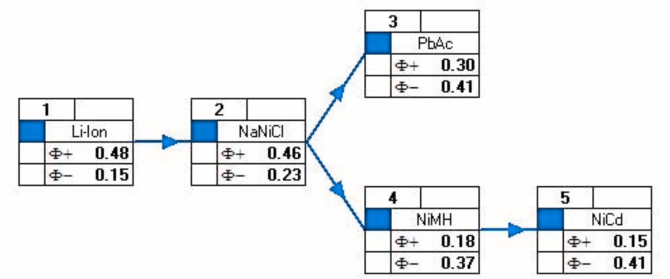


**Figure 6: Partial Ranking PROMETHEE I for BEV 2005.**

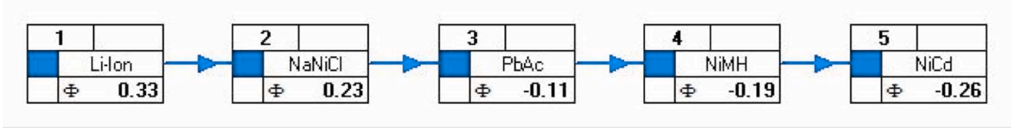


Figure 7: Partial Ranking PROMETHEE II for BEV 2005.

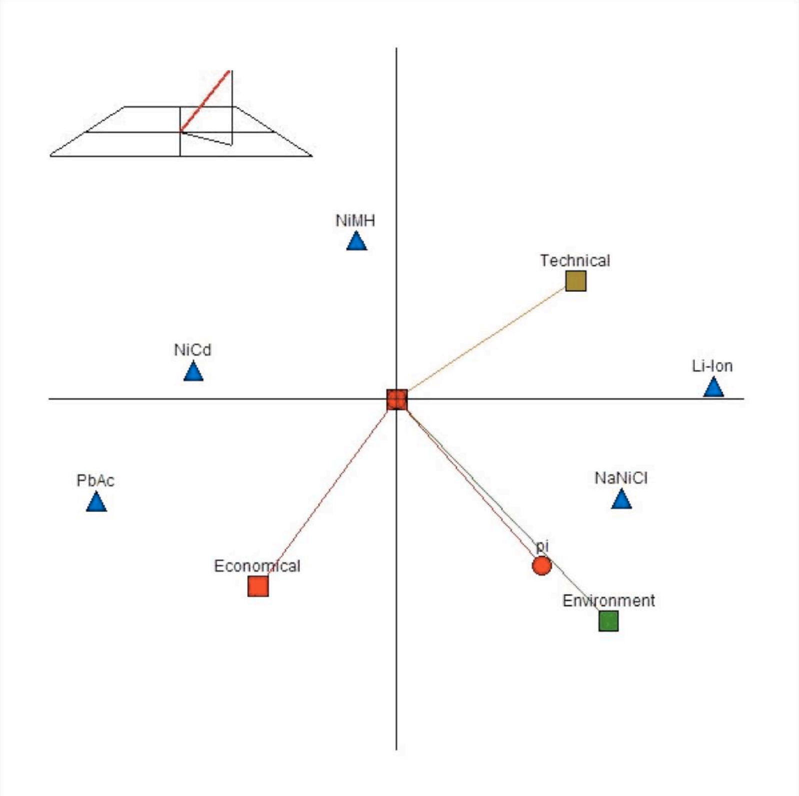


Figure 8: GAIA Plane for BEV 2005.

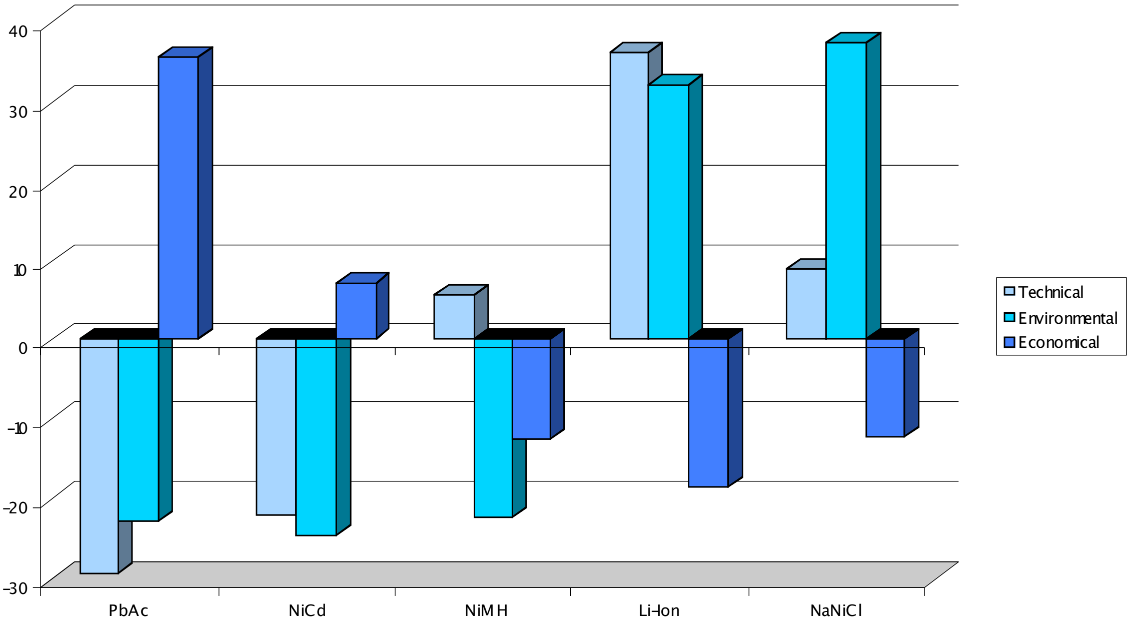


Figure 9: Action Profile BEV 2005.

## V.2.2. BEV 2012.

Expected progress for the BEV batteries by 2012 has been included in the calculations and an assessment of the different battery technologies has been performed for the year 2012.

### V.2.2.1. Input data.

The used data are originating from the different work packages and can be found in Table 16. The input data have been obtained in a comparable way as the input data for BEV 2005 (paragraph V.2.1.1.).

**Table 16: MCA data for BEV 2012**

| | Specific Energy | Specific Power | Cycles | Energy efficiency | LCA | Cost | Maturity | User friendly |
|---|---|---|---|---|---|---|---|---|
| PbAc | 40 | 250 | 1000 | 85 | 331 | 6432 | 100 | 100 |
| NiCd | 60 | 200 | 2000 | 75 | 427 | 11286 | 100 | 100 |
| NiMH | 70 | 350 | 2000 | 75 | 364 | 12684 | 100 | 100 |
| Li-Ion | 150 | 400 | 2000 | 95 | 122 | 4504 | 100 | 100 |
| NaNiCl | 150 | 200 | 2000 | 90 | 129 | 4059 | 100 | 60 |

The *relative* user friendliness's of the different batteries were considered to remain similar to the ones considered in for BEV batteries in 2005.

### V.2.2.2. Results and discussion BEV 2012.

According to the political scenario, both PROMETHEE I and II plots (Figure 10 & Figure 11) provide quite similar rankings for the BEV batteries in 2012 and in 2005. The main difference resides in the improvement of the economical performances of (mainly) the Li-ion and of the NaNiCl batteries compared to the other technologies, optimizing the overall scores of the lithium-ion and sodium-nickel chloride batteries. This also appears clearly in the GAIA-plane (Figure 12) and in the action profile (Figure 13).

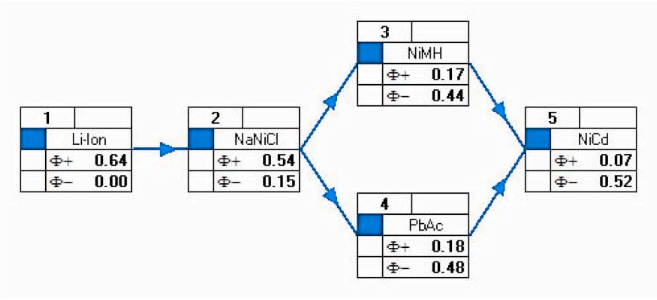


Figure 10: Partial Ranking PROMETHEE I for BEV 2012.

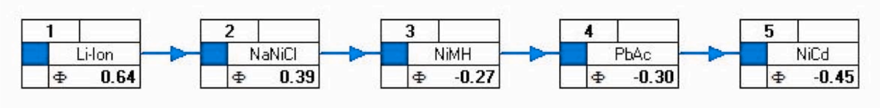


Figure 11:Complete Ranking PROMETHEE II for BEV 2012.

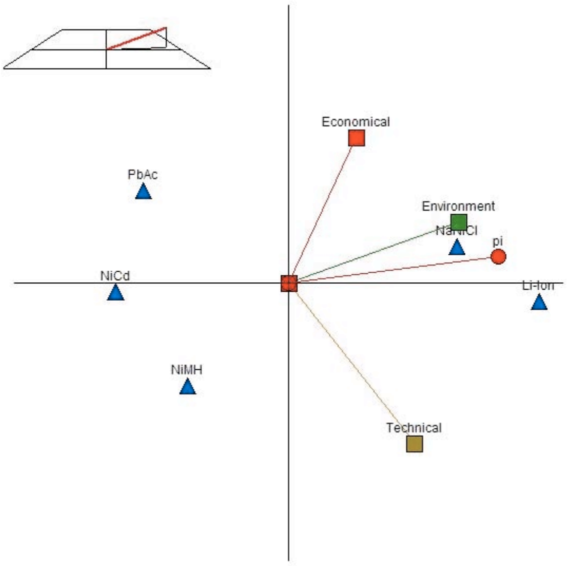


Figure 12: GAIA Plane for BEV 2012.

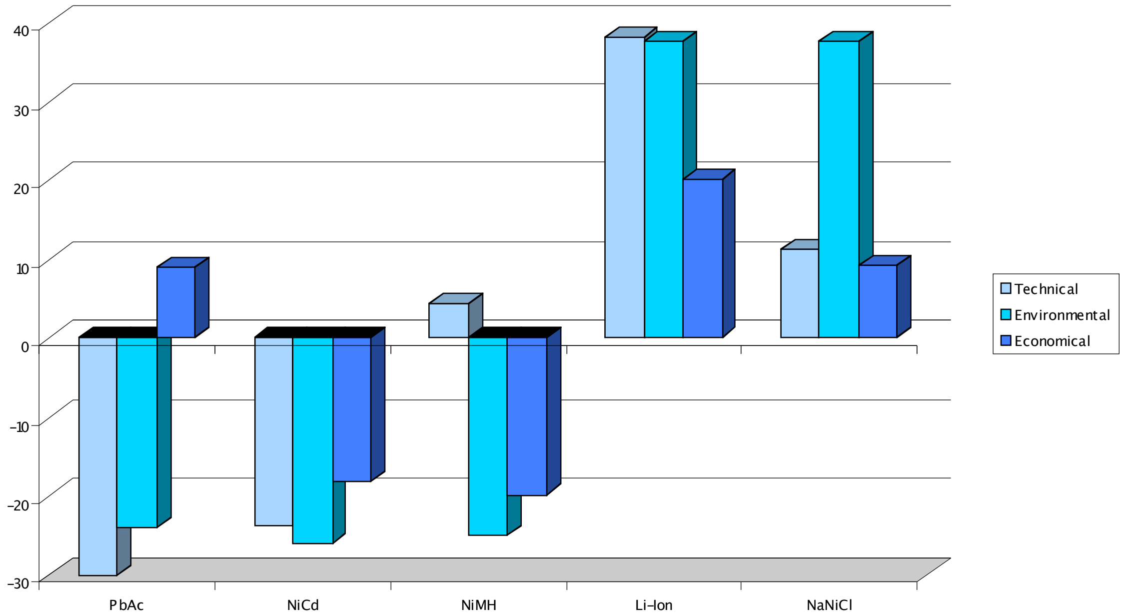


Figure 13: Action Profile BEV 2012.

## V.2.3. HEV 2005.

The output provided by the MCA software regarding HEV in 2005 is presented in the following sections.

### V.2.3.1. Input data.

The used data are originating from the different work packages and can be found in Table 17. The input data have been obtained in a comparable way as the input data for BEV 2005 (paragraph V.2.1.1.).

**Table 17: MCA data for HEV 2005.**

| | Specific Energy | Specific Power | Cycles | Energy efficiency | LCA | Cost | Maturity | User friendly |
|---|---|---|---|---|---|---|---|---|
| PbAc | 25 | 350 | 1.0 | 83 | 14 | 432 | 100 | 100 |
| NiCd | 30 | 500 | 3.0 | 73 | 10 | 624 | 100 | 100 |
| NiMH | 55 | 1500 | 3.0 | 70 | 3 | 456 | 100 | 100 |
| Li-Ion | 70 | 2000 | 3.0 | 90 | 4 | 684 | 50 | 100 |
| NaNiCl | 125 | 200 | 3.0 | 86 | 23 | 2976 | 0 | 60 |

### V.2.3.2. Results and discussion HEV 2005.

According to the political scenario, both the PROMETHEE I and II plots (Figure 14 and Figure 15) show that the nickel-metal hydride and the lithium-ion technologies seem to be the best fitted options for HEV applications. These are followed by the nickel-cadmium, the lead-acid and finally, the sodium-nickel chloride technology. When studying the results shown by the GAIA-plane (Figure 16) and the action profile plots (Figure 17), it appears clearly that the sodium-nickel chloride batteries are not a suitable option for HEV as their score is amongst the worst for each category. This is mainly due to the low power performances of these batteries. On the other hand, these plots confirm the good technical performances of the lithium-ion and to a lesser extent of nickel-metal hydride batteries. The latter are nowadays the most widely used batteries for the HEV types considered in this study.

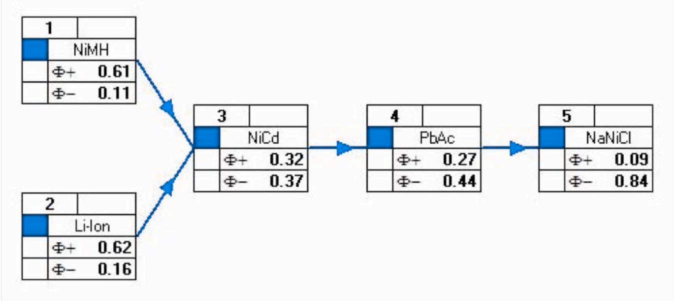


**Figure 14: Partial Ranking PROMETHEE I for HEV 2005.**

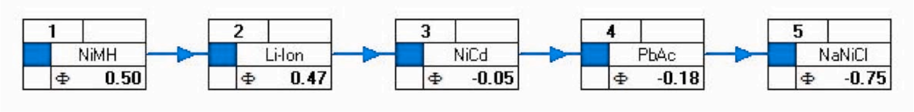


**Figure 15: Complete Ranking PROMETHEE II for HEV 2012.**

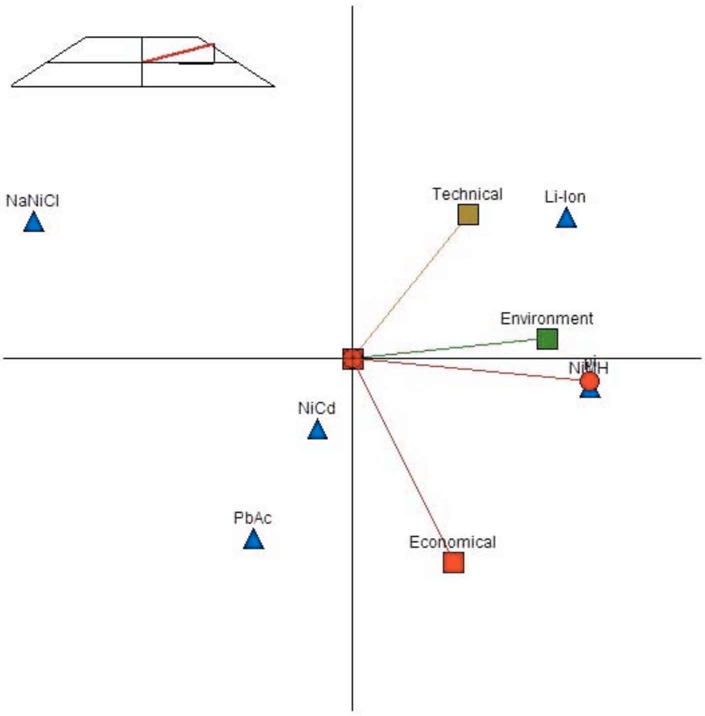


Figure 16: GAIA Plane for HEV 2005.

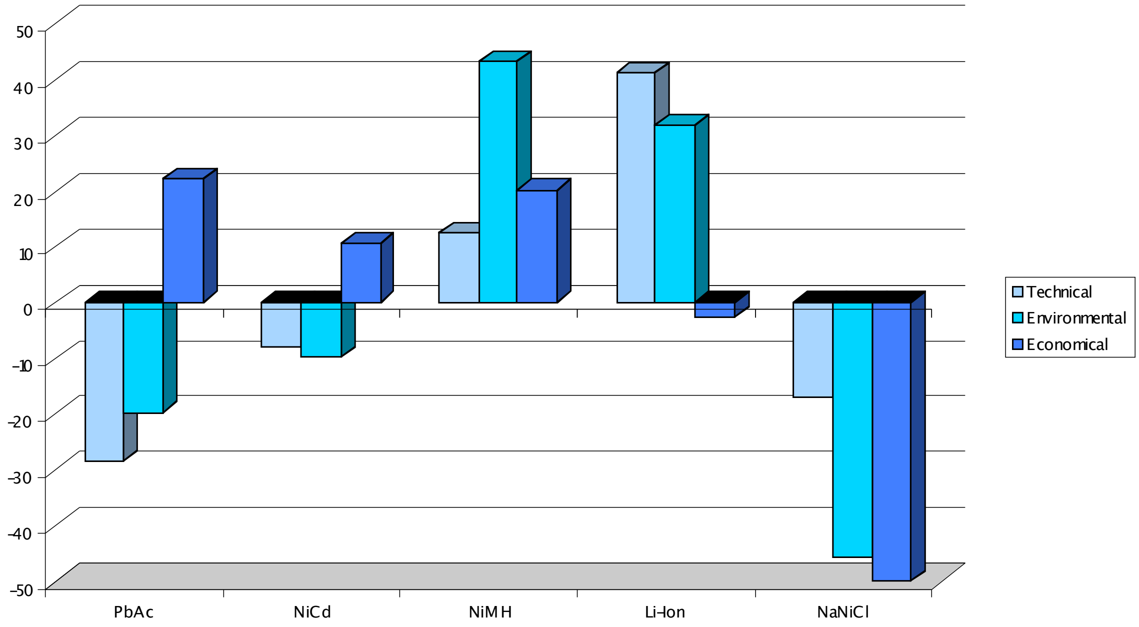


Figure 17: Action Profile for HEV 2005.

## V.2.4. HEV 2012.

Expected progress for the HEV batteries by 2012 has been included in the calculations and an assessment of the different battery technologies has been performed for the year 2012.

### V.2.4.1. Input data.

The used data are originating from the different work packages and can be found in Table 18. The input data have been obtained in a comparable way as the input data for BEV 2005 (paragraph V.2.1.1.).

**Table 18: MCA data for HEV 2012**

| | Specific Energy | Specific Power | Cycles | Energy efficiency | LCA | Cost | Maturity | User friendly |
|---|---|---|---|---|---|---|---|---|
| PbAc | 25 | 600 | 1.5 | 85 | 5 | 384 | 100 | 100 |
| NiCd | 30 | 600 | 3.0 | 75 | 9 | 624 | 100 | 100 |
| NiMH | 55 | 2500 | 3.0 | 75 | 2 | 456 | 100 | 100 |
| Li-Ion | 70 | 4000 | 3.0 | 95 | 2 | 360 | 100 | 100 |
| NaNiCl | 80 | 600 | 3.0 | 90 | 8 | 624 | 100 | 60 |

Considering efforts to develop all the batteries, the relative maturities of the different technologies have been considered to be comparable by the year 2012.

The *relative* user friendliness's of the different batteries were considered to remain similar to the ones considered in for BEV batteries in 2005.

### V.2.4.2. Results and discussion HEV 2012.

Taking the proposed technical progress into account, the political perspective for HEV 2012 results in lithium-ion battery technology appearing to become the most adapted technology for HEV applications, while nickel-metal hydride batteries remains a viable alternative. On the other hand, the three other technologies still clearly come out as less adapted options.

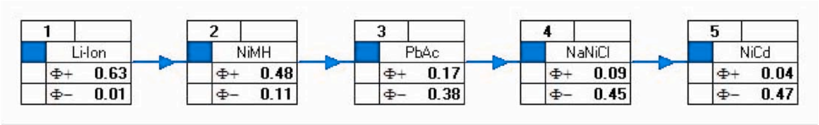


**Figure 18: Partial Ranking PROMETHEE I for HEV 2012.**

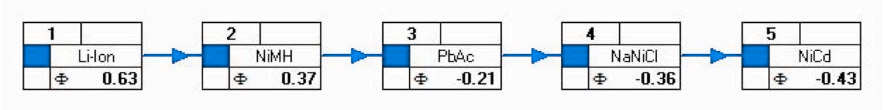


**Figure 19: Complete Ranking PROMETHEE II for HEV 2012.**

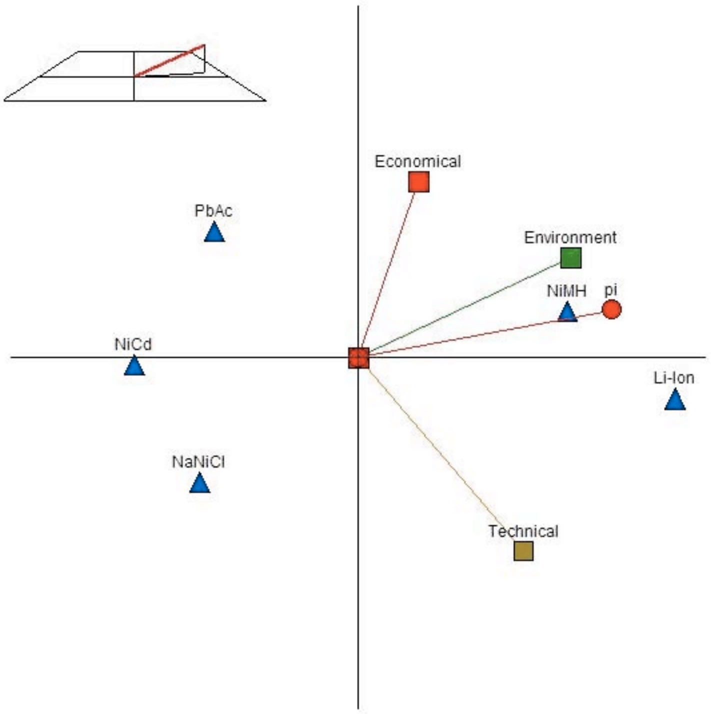


Figure 20: GAIA Plane for HEV 2012.

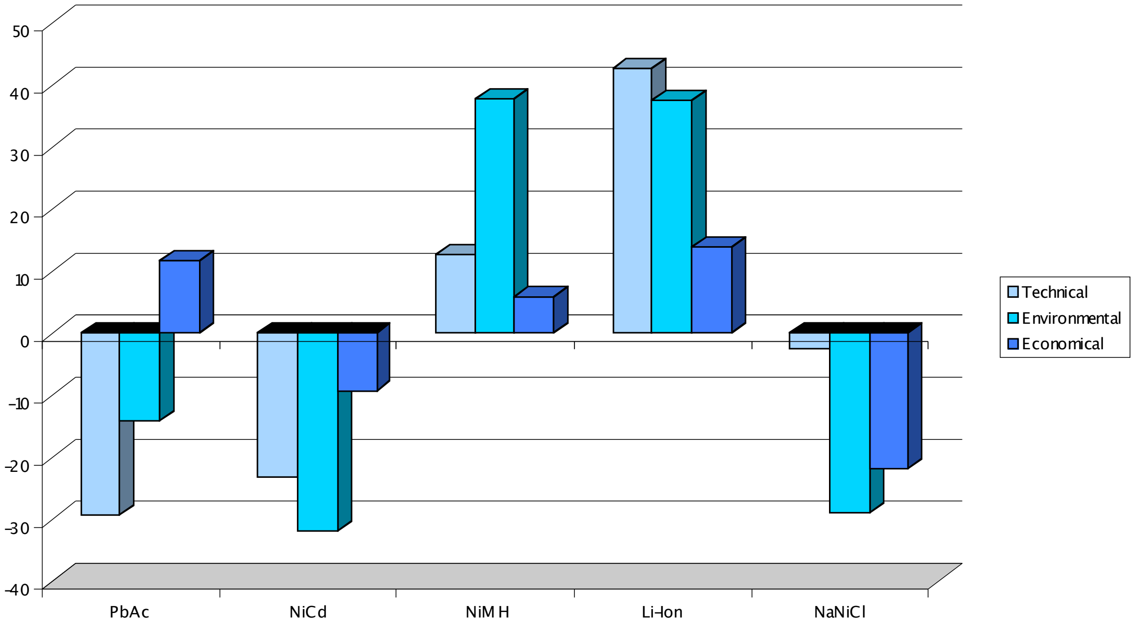


Figure 21: Action Profile for HEV 2012.

## V.3. Consumers and manufacturers perspectives.

As mentioned before, different perspectives are assessed and compared in this study. In the previous section, the results were shown from a political perspective. This section evaluates the results when analyzing them from the two other perspectives: the consumer’s perspective and the car manufacturer’s perspective. Each stakeholder group will pay more or less attention than another to the different criteria. As a consequence, the weights of the different criteria were adapted to the assessed group. The impact of these different weights on the global MCA result will be discussed too.
These perspectives can be seen as a kind of sensitivity analysis of the MCA results.

### V.3.1. Importance environment, technical and economical parameters.

The relative importance allocated to the technical, environmental and economical parameters to the total of the different stakeholder perspectives is shown in Figure 22. The weights of the different criteria of these categories are discussed in the next paragraph.

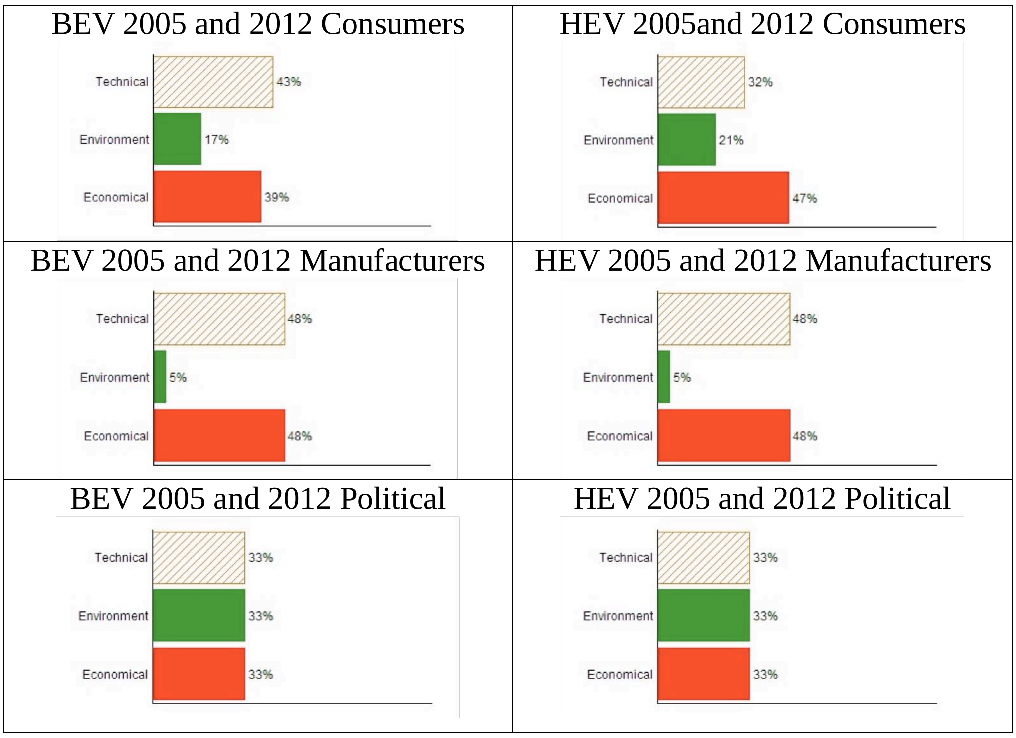


**Figure 22: Importance allocated to the technical, environmental and economical criteria for the different stakeholders.**

Figure 22 illustrates clearly that the political perspective attributes an equal importance to the technical, environmental and economical parameters (as has been described in the previous chapter).
Consumers and car manufactures are assumed to pay more attention to the technical and economical criteria compared to the environmental ones. This is especially the case considering the car manufacturers perspective, where the importance of the environment is minimized compared to the technical and economical parameters.

## V.3.2. Weighting.

There are also differences in weighting within the technical and economical categories. This can be explained by the relatively higher or lower importance of one of the other criteria compared to another considering a specific perspective (consumer, political, manufacturer).
The weighting coefficients for the different perspectives are shown for BEV batteries in Table 19 and for HEV batteries in Table 20.

**Table 19: Weighting criteria for BEV**

| BEV | Specific energy | Specific Power | Cycles | Energy efficiency | LCA | Cost | Maturity | User friendly |
|---|---|---|---|---|---|---|---|---|
| Consumer | 30 | 5 | 15 | 0 | 20 | 30 | 5 | 10 |
| Political | 25 | 15 | 5 | 5 | 50 | 30 | 10 | 10 |
| Manufacturer | 25 | 10 | 10 | 5 | 5 | 30 | 10 | 10 |

**Table 20: Weighting criteria for HEV**

| HEV | Specific Energy | Specific Power | Cycles | Energy efficiency | LCA | Cost | Maturity | User friendly |
|---|---|---|---|---|---|---|---|---|
| Consumer | 5 | 20 | 5 | 0 | 20 | 30 | 5 | 10 |
| Political | 10 | 30 | 5 | 5 | 50 | 30 | 10 | 10 |
| Manufacturer | 10 | 30 | 5 | 5 | 5 | 30 | 10 | 10 |

These tables illustrate that the relative importance of the criteria in a category can vary depending on the chosen perspective. Before discussing the MCA results of the different perspectives, a short explanation is given about the choice of the specific weights for each parameter.

**<u>Discussion of the different weightings within each category of the BEV batteries</u>**

*i. The consumer perspective compared to the political perspective*

- Technical:
  - The energy efficiency is not as important as it is in the political perspective, as the consumer doesn’t often consider this parameter when buying a car. The number of cycles determines the lifetime of the battery and as a consequence, the consumer will prefer a long-lasting battery. The specific energy is relatively more important, because this parameter will influence the range of the vehicle, which is considered very important to the consumer. The consumer might not pay much attention to the specific power since he expected the vehicle to drive like all other vehicles.
- Economical
  - The maturity is less important to the consumer compared to the politicians or the car manufacturers as the latter two mainly prefer a mature technology for reasons of sufficient production capacity and for the absence of safety concerns. Consumers usually will probably pay less attention to these factors. As a result, the cost and user friendliness become more important economical criteria.

*ii. The manufacturer perspective compared to the political perspective*

- Technical:
  - The weighting factors of the technical parameters for the car manufacturer perspective are comparable to the ones used in the political perspective. The main difference is that the car manufacturers are presumed to think the number of cycles (and its consequent number of battery replacements) is relatively more important than the specific power (fast charging), as it can be used as a more convincing sales asset.
- Economical:
  - The weighting of the three economical criteria remain the same.

**<u>Discussion of the different weightings within each category of the HEV batteries</u>**

*i. The consumer perspective compared to the political perspective*

- Technical:
  - The energy efficiency is not so important, because this criterion is not often considered by the consumer when buying a car.
  - The specific energy for HEV is found relative less important, the specific power is even important and the number of cycle (or the life time) of the battery is more important.

- Economical:
  - The maturity is of less importance to the consumer compared to the political and to the car manufacturers perspective as the latter two pay more attention to the maturity for reasons of sufficient production capacity and for the absence of safety concerns. As a result, the cost and user friendliness become more important economical criteria.

*ii. The manufacturer perspective compared to the political perspective*

- Technical and economical:
  - The weighting of each of the different criteria within the econo

### V.3.3.1. BEV 2005.

The PROMETHEE I graphical output for the different perspectives for BEV in 2005 are shown in Figure 23.

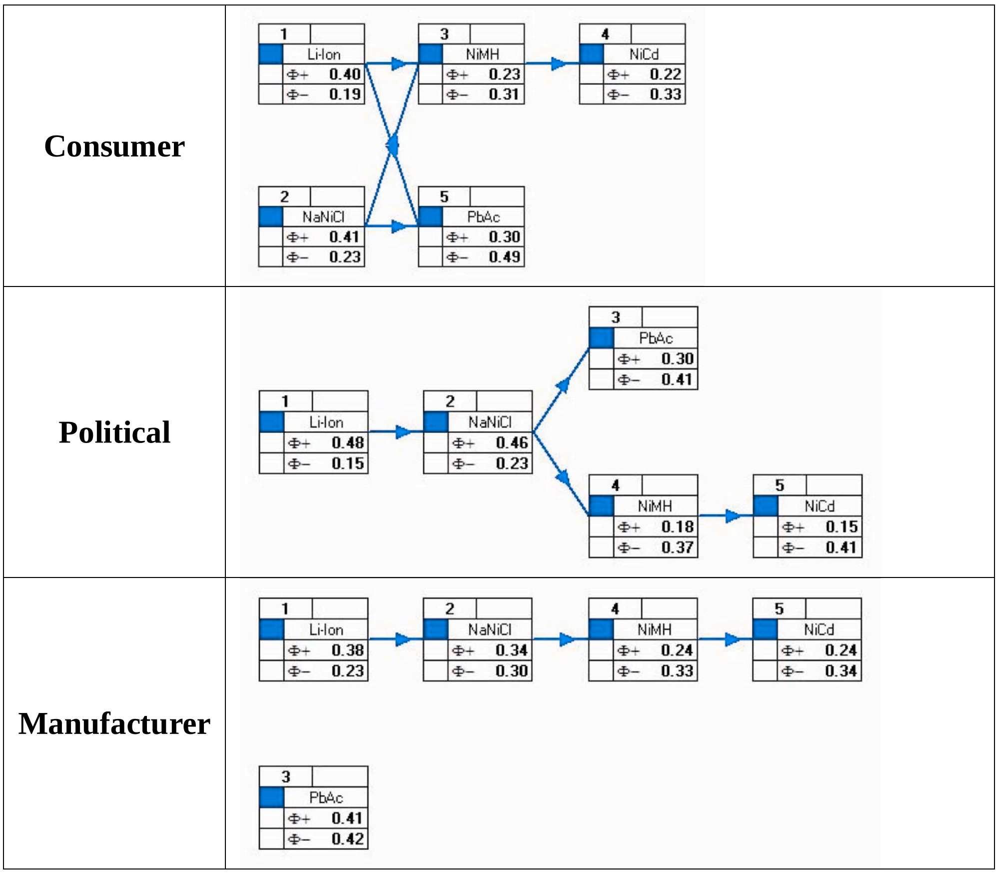


**Figure 23: PROMETHEE I results for different perspectives for BEV 2005**

The PROMETHEE I method couldn’t classify lead-acid in the manufacturer perspective, as lead-acid is strongly preferred to the other technologies and the other technologies are strongly preferred over lead-acid for other criteria as well. In the PROMETHEE II method the lead-acid ranks between sodium-nickel chloride and nickel-metal hydride.

Nevertheless, the overall ranking remains the same for the manufacturer and the consumer perspective: lithium-ion and sodium-nickel chloride are the preferred technologies, while currently, the nickel-metal hydride, nickel-cadmium and lead-acid technologies seem to be less suitable options for BEV.

## V.3.3.2. BEV 2012.

The PROMETHEE I graphical output for the different perspectives for BEV in 2012 are shown in Figure 24.

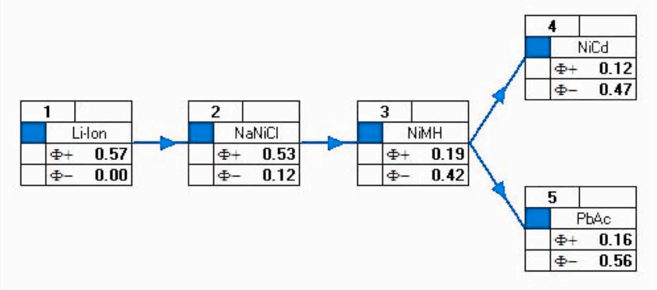
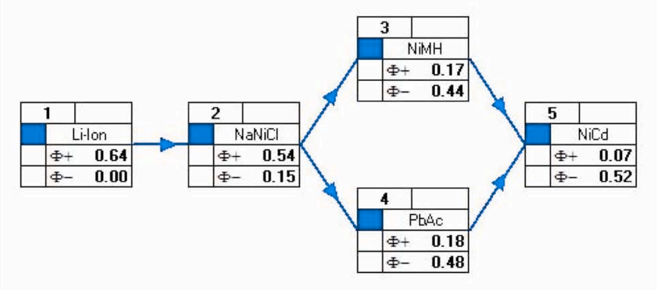
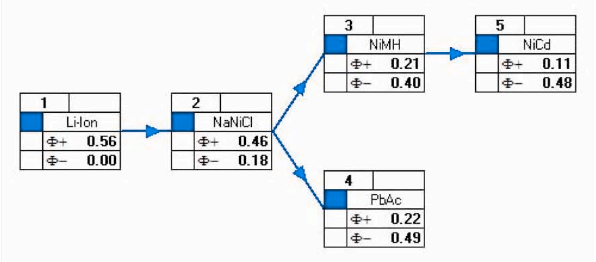
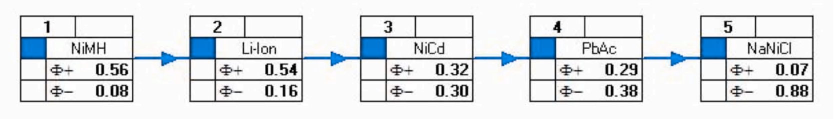
| | |
|---|---|
| **Consumer** |  |
| **Political** |  |
| **Manufacturer** |  |

**Figure 24: PROMETHEE I results for different perspectives for BEV 2012**

The political preference is comparable to the consumer and manufacturer preferences. Based on the assumptions and weighting criteria, lithium-ion appears to be the preferred option for BEV in 2012, followed by sodium-nickel chloride, nickel-metal hydride, lead-acid and nickel-cadmium.

## V.3.3.3. HEV 2005.

The PROMETHEE I graphical outputs for the different perspectives for HEV in 2005 are shown in Figure 25.

| | |
|---|---|
| **Consumer** |  |

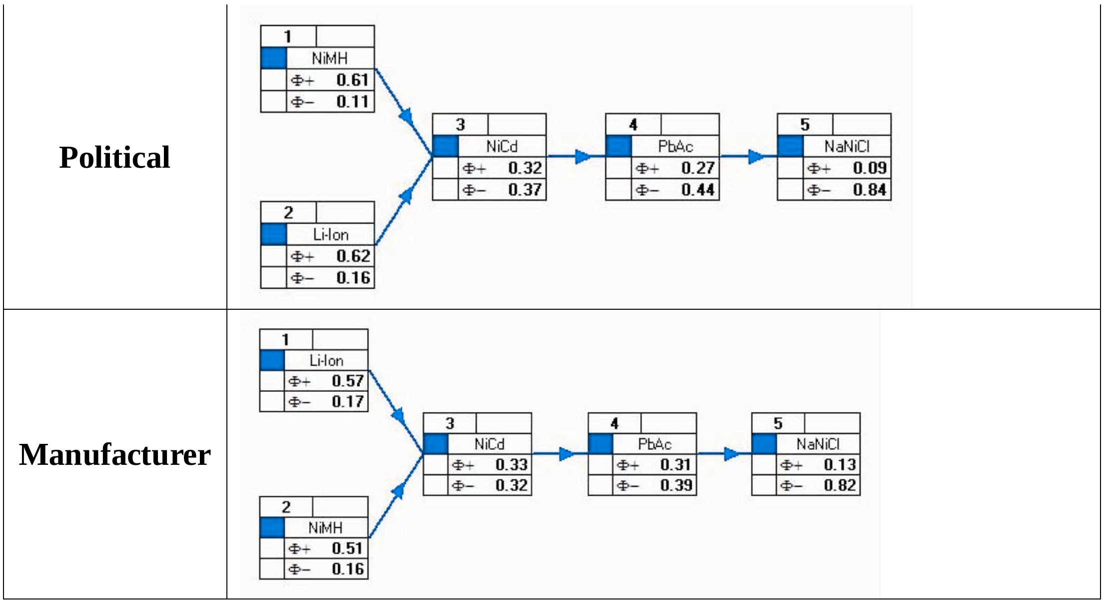


**Figure 25: PROMETHEE I results for different perspectives for HEV 2005**

The ranking of the different battery technologies for HEV in 2005 is almost the same for the different perspectives. The slight preference of lithium-ion over nickel-metal hydride batteries in the case of the car manufacturers is the only difference.

### V.3.3.4. HEV 2012.

The PROMETHEE I graphical outputs for the different perspectives for HEV in 2012 are shown in Figure 26.

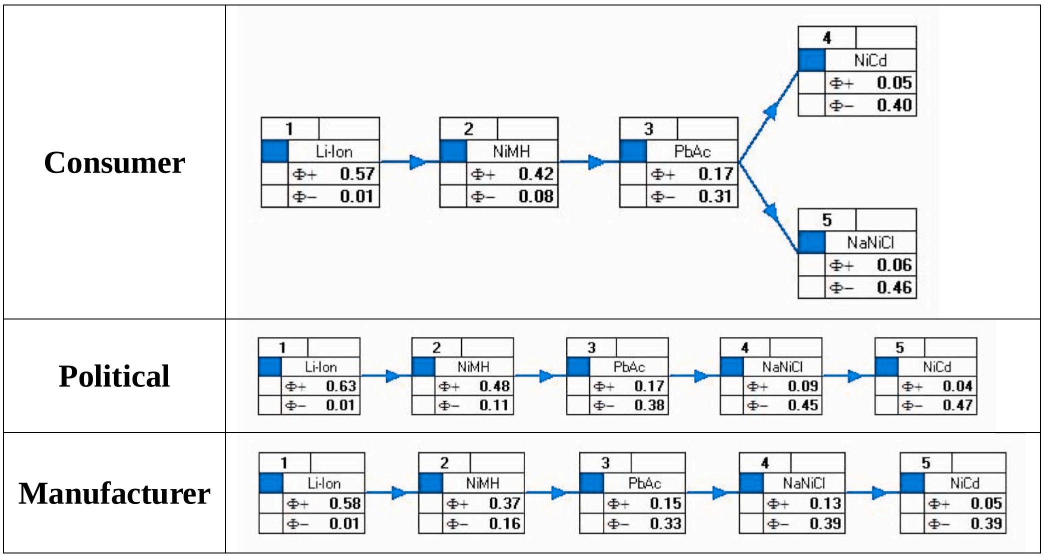


**Figure 26: PROMETHEE I results for different perspectives for HEV 2012**

The ranking of the different battery technologies for HEV in 2012 is almost the same from every perspective. The only difference resides in the impossibility to determine the worst option in the case of the consumer perspective.

### V.3.4. Overall conclusion for the different perspectives.

Independently of the chosen perspective, the overall MCA results remain consistent. Despite the existence of slight differences between the different scenarios, the only variation in the ranking of the batteries will appear when considering the less suitable technologies. This illustrates that the conclusions obtained using the political perspective remain valid for the other perspectives as well.

### V.3.5. Influence of the battery data on the results, the Eurobat proposal.

The Subat study was reviewed by several experts, amongst whom Eurobat. Eurobat proposed some adapted data originating from the lead-acid and the lithium-ion battery producers. The proposed data are listed in . The main differences compared to the original Subat data (Table 15) are some different energy densities and different numbers of cycles for some battery technologies. Especially, the number of cycles of the lithium-ion battery was proposed to be set to 3000 instead of 1000. Since the number of cycles can defines the number of battery replacements during the life of the vehicle, this can influence the results significantly. The adapted values are embolded in, these adapted data also influenced the italicized values (LCA and Cost). The data used previously by the consortium are barred and marked in red.

**Table 21: Battery data proposed by Eurobat for BEV batteries.**

| | Specific Energy (kWh/kg) | Specific Power (kW/kg) | Cycles | Energy Efficiency (%) | LCA | Cost | Maturity | User friendly |
|---|---|---|---|---|---|---|---|---|
| PbAc | **35**<br>~~40~~ | 250 | **700**<br>~~500~~ | 83 | *512* | *8576* | 100 | 100 |
| NiCd | **40**<br>~~60~~ | 200 | **2000**<br>~~1350~~ | 73 | *607* | *12350* | 100 | 100 |
| NiMH | **55**<br>~~70~~ | **250**<br>~~350~~ | **2000**<br>~~1350~~ | 70 | *494* | *14016* | 60 | 100 |
| Li-ion | **110**<br>~~125~~ | 400 | **3000**<br>~~1000~~ | **93**<br>~~90~~ | *164* | *8489* | 60 | 100 |
| NaNiCl | **100**<br>~~125~~ | 200 | 1000 | 86 | *271* | *17278* | 80 | 60 |

Of course the use of other battery data includes variations on the results of the technical, environmental and economical assessments and as a consequence on the results of the overall assessment and the multi-criteria analysis.

The Subat-consortium took the proposed data into account and assessed them in the context of the BEV batteries in 2005. In other words, the data included in the MCA were adapted and the calculations were performed once over to evaluate their influence on the results.

A graphical representation of these conclusions is also presented in Figure 27 and Figure 28.

This illustrates that the assumptions made regarding the battery data clearly influence the overall results of the analysis, but nevertheless this also shows that the results presented in the main text are pretty stable and thus reliable.

In general, similar rankings were obtained for the different battery technologies for the BEV 2005 situation. But some shifts did occur however. Amongst others, Eurobat proposed an improvement of the data for the number of cycles of the lithium-ion batteries. This resulted in an improved φ-value of this technology for the different perspectives. On the other hand, no major adaptations were proposed for the NaNiCl battery technology. The consequence is a worsening of the φ-values allocated to this technology. Next to this worsening, the φ-values of the nickel-cadmium technology were reduced quite strongly as well when using the Eurobat data. On the other hand, the evaluation of the NiMH and of the lead-acid battery remained quite stable when using the Eurobat data.

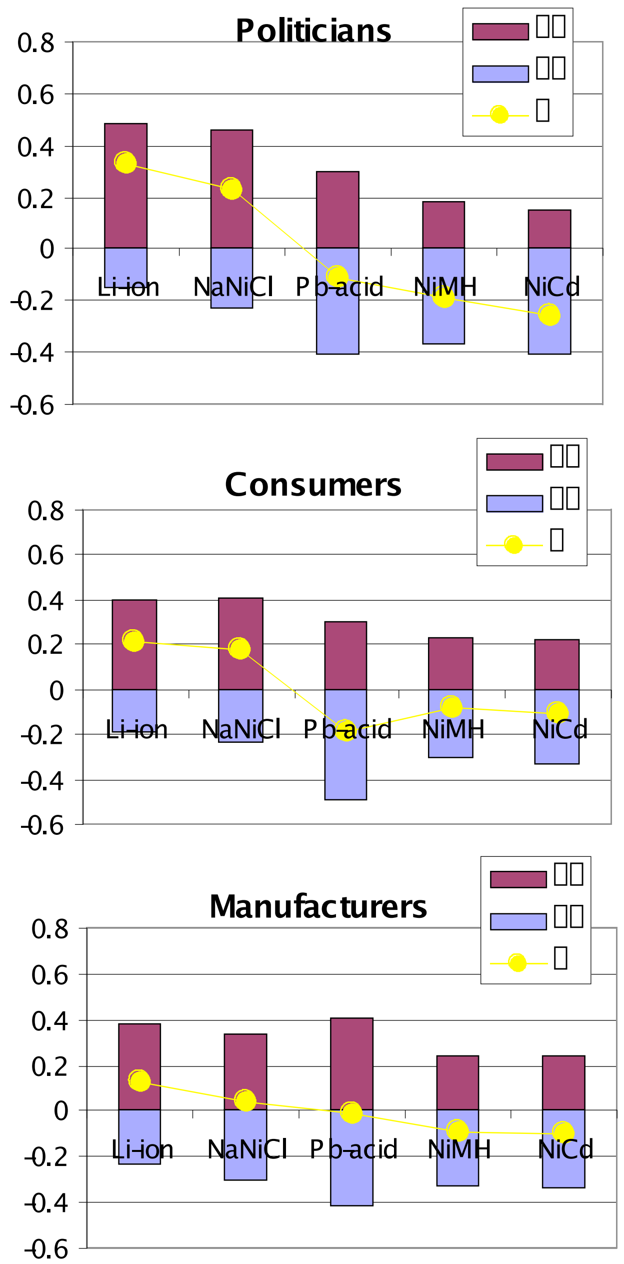


**Figure 27: Graphical overview of the results for BEV batteries (in 2005) based on the Subat data.**

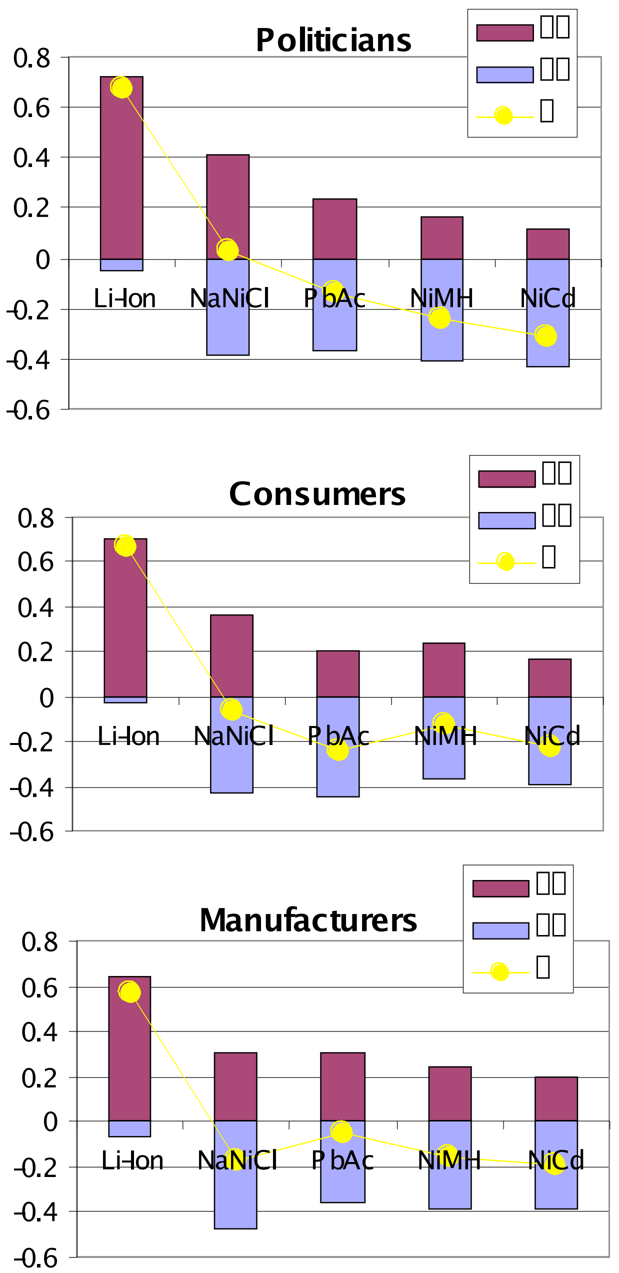


**Figure 28: Graphical representation of the results for BEV batteries (in 2005) based on the Eurobat data.**

## V.4. General Conclusion.

The general conclusions of this study have to be seen in the context of the different work packages (technical, environmental and economical analysis) and are the result of the compilation and integration of the conclusions of all these work packages. Also it should always be kept in mind, that the results and conclusions of the different work packages, as well as the overall conclusions of the study, are based on a number of assumptions, which have been explained in the different WP, and consequently can only be considered valid taking these assumptions into account.

The comparison of different products is always a difficult issue, as many parameters have to be taken into account. The assessment of battery technologies for hybrid and electric vehicles does not form an exception to this rule. However, this study includes an overall and multidisciplinary approach of the problem and resulted in some objective and complete conclusions.

It should be mentioned that some research and development is performed in this field regarding other battery technologies than the five technologies (lead-acid, nickel-cadmium, nickel-metal hydride, lithium-ion, sodium-nickel chloride) discussed in the multi-criteria analysis. However these technologies didn’t appear comparable yet to the previously mentioned or able to being used as a large-scale substitute in BEV and HEV applications, it’s not excluded some interesting applications or products could spin-off from these efforts in the future. Qualitative technical, environmental and economical evaluations of many of these technologies are provided in the respective work packages.

Also, the conclusions drawn in this study are only valid for the mentioned applications (BEV and HEV). They should not be extrapolated to other battery applications (planes, trains, stationary batteries, etc.) without a prior thorough study.

Regarding the BEV, nowadays (2005), and considering the three aspects (work packages) of this study into account, it appears that the lithium-ion technologies are the most suitable solutions, followed by sodium-nickel chloride, lead-acid, nickel-metal hydride and nickel cadmium.

The preference for the lithium-ion and the sodium-nickel chloride technologies is mainly due to the technical and environmental performances of these two technologies. The relatively good score of the lead-acid technology is mainly due to its economical advantages. But considering only the economical aspect, NiCd technology remains the only usable technology in the short term, the other technologies remaining too expensive for an industrial application.

The study provides quite similar rankings for the BEV batteries in 2012 compared to 2005. The main difference resides in the improvement of the economical performances of (mainly) the lithium-ion and of the sodium-nickel chloride batteries compared to the other technologies, optimizing the overall scores of the lithium-ion and sodium-nickel chloride batteries.

At the present time (2005), the nickel-metal hydride technology, followed by the lithium-ion technology seems to be the best fitted option for HEV applications. These are followed by the nickel-cadmium, the lead-acid and finally, the sodium-nickel chloride technology. It appears quite clearly that the sodium-nickel chloride batteries are not a suitable option for the considered type of HEV as their score is amongst the worst for each category. These days nickel-metal hydride batteries are the most widely used in HEV in the world.

It should be mentioned that the NaNiCl batteries are not yet available in the power-optimized version (HEV) and that Pb-acid batteries present a heavy weight for full hybrid applications.

Assuming the proposed technical progress occurs, the lithium-ion battery technologies appear to become the most adapted technologies for HEV applications by 2012 if safety problems are solved, while nickel-metal hydride batteries remains a viable alternative. On the other hand, the three other technologies still clearly come out as less adapted options.

Regarding the evolution of the rankings, it’s noticeable that no major changes will occur by 2012. Lithium-ion batteries will remain the most appropriate option for BEV, and the nickel-metal hydride will be superseded by the lithium-ion technology, while remaining an acceptable alternative for HEV.

***- Technical comments***

Pb-acid batteries present low performances regarding specific energy. This leads to very high battery weights, mainly for BEV.

As the NaNiCl batteries are high-temperature batteries, energy is lost whenever the vehicles are left out of duty. This hamper can largely be bypassed when using this technology in fleet applications, where the vehicles are generally used intensively (public transportation, delivery services etc.), but it seems difficult to forecast the use of such a solution for the passenger car market.

One main issue to be considered with lithium batteries is safety. Lithium is very reactive, and uncontrolled overcharge of the battery may give rise to uncontrolled energy releases, which pose hazardous situations. Consequently, the implementation of cell-level management systems has been a dire necessity for any lithium-based system. Even with all the electronic safety systems, the use of an organic electrolyte leads to some difficulties in the field of abuse tolerance. Although lithium batteries have taken a considerable share of the portable battery market, one has to recognize that high-power applications such as traction present different challenges and today, the lithium systems cannot be considered yet as a high scale commercially available product.

***- Environmental comments***

When looking at the environmental impact of the BEV battery solely, it appears that the Pb-acid battery has got the highest impact, followed by NiCd, Li-ion, NiMH and NaNiCl.

When including the effects of the losses due to the battery (battery efficiency and battery mass) for BEV, three battery technologies: NiCd, Pb-acid and NiMH, appear to have a somewhat higher environmental impact compared to the other two (Li-ion and NaNiCl).

When considering the life cycle of the batteries, the energy losses in the battery have a significant impact on the environment. However, this impact is strongly dependent on the way electricity is produced and can be reduced by using renewable energy sources.

Coming to HEV applications, the NiMH obtains the best environmental rating, followed by the Li-ion, NiCd, Pb-acid and NaNiCl.

Batteries sometimes include toxic compounds. Specifically concerning the environmental issues related to cadmium, the adverse effects of cadmium on human health are known since a long time and as a consequence, there are several reasons to try to avoid the use of cadmium. Regarding the NiCd technology, it should be mentioned that cadmium is directly linked with zinc in the natural mineral and consequently is an unavoidable by-product of zinc production. This production of cadmium should be dealt with and it seems advisable to deal with it in a way human and environmental exposures are minimized. The use of this cadmium in industrial or BEV batteries doesn’t seem to be the worst option in this regard.

### - *Economical comments*

The battery forms an important cost in the overall cost of (especially battery) electric vehicles. As a consequence, their price has got an important i

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http://www.visualdecision. com.

## Appendix 1: Definitions

a. The cell voltage (V), this is the nominal voltage of one single cell in the battery, expressed in Volts. This voltage is a nominal value, corresponding to the voltage of a fully charged battery at no load.

b. The <u>capacity</u> C (Ah), this is the amount of charge, or in other words the amount of electricity the battery can store, expressed in Ampère-hours (Ah).

For most battery types, the use recommended is only a certain percentage (e.g. 80 %) of the capacity; this is called a 80 % discharge.

c. The <u>energy content</u> E (kWh), this is the amount of energy the battery can store like the capacity dependent on the discharge current;

d. The <u>specific energy</u>, (Wh/kg). The Specific Energy allows a relationship to establish between battery weight and energy content. It is typical for any type of battery.

e. The <u>energy density</u>, expressed in watt-hours per litre (Wh/l). This is a measurement for the battery volume in function of the energy content.

f. The <u>specific power</u>, (W/kg) is a measure for the maximum power (or the maximum current) the battery can deliver, and thus for the performances (acceleration, maximum speed) of the vehicle.

g. The <u>internal resistance</u>, (mΩ) gives the electrical resistance of the internal parts of the battery. It varies in function with the state of charge (SOC) and temperature and will have an influence on voltage variations during discharge and on the power density.

h. The <u>energetical efficiency</u> is the ratio of the discharged energy (Wh) and the energy necessary to bring the battery back to its initial state of charge:

The <u>ampere-hour efficiency</u>, this is the ratio of the discharge (expressed in Ah) and the charge necessary to bring the battery back to its initial state of charge:

The percent value of the energetical efficiency is lower than for the Ah-efficiency, since voltage during discharge is lower than voltage during charge. Both quantities are fundamentally different and should never be compared with each other!

i. The <u>charge factor</u>, (%). This is the inverse of the Ah-efficiency.

The charge factor gives an indication of the “extra” charge which is put into the battery during the final charge phase.

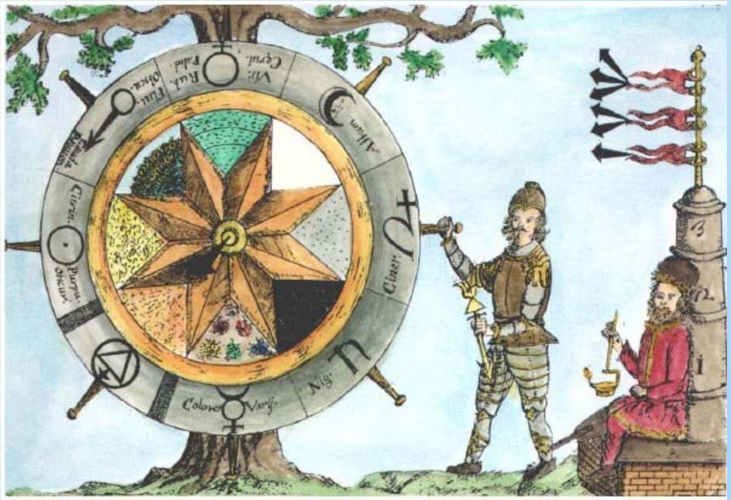
k. The <u>cycle life</u> of the battery, expressed in number of cycles. A cycle is a charge followed by a discharge; the life cycle is considered as terminated when the battery capacity falls under a predefined value (e.g. 80 % of nominal capacity).

APPENDIX VI

# SUBAT

## "Sustainable Batteries”

Action 8.1.B.1.6
Assessment of Environmental Technologies
for Support of Policy Decision



Frederic Vergels

# SUBAT

APPENDIX VI

## January 2004 to Mach 2005

## Partners

### Universities

Vrije Universiteit Brussel
Vakgroep Electrotechniek en Energietechnologie
(ETEC)

DSEA

**Pisa University**

ULB

Centre
d' Etudes
Economiques
et
Sociales
de l' Environnement

### Associations

AVERE

CEREVEH

CEI
CIVES

CITELEC

# Background of the project

- European end-of-life directive (2000/53/EC), limiting the use of heavy metals in all vehicles put on the market after 1 July 2003
- Exemption for nickel-cadmium batteries in electric vehicles until 31 December 2005 (Annex II)
- Study to examine
  - advisability to maintain Ni-Cd in electric vehicle applications
  - progressive substitution

# SUBAT Objective

APPENDIX VI

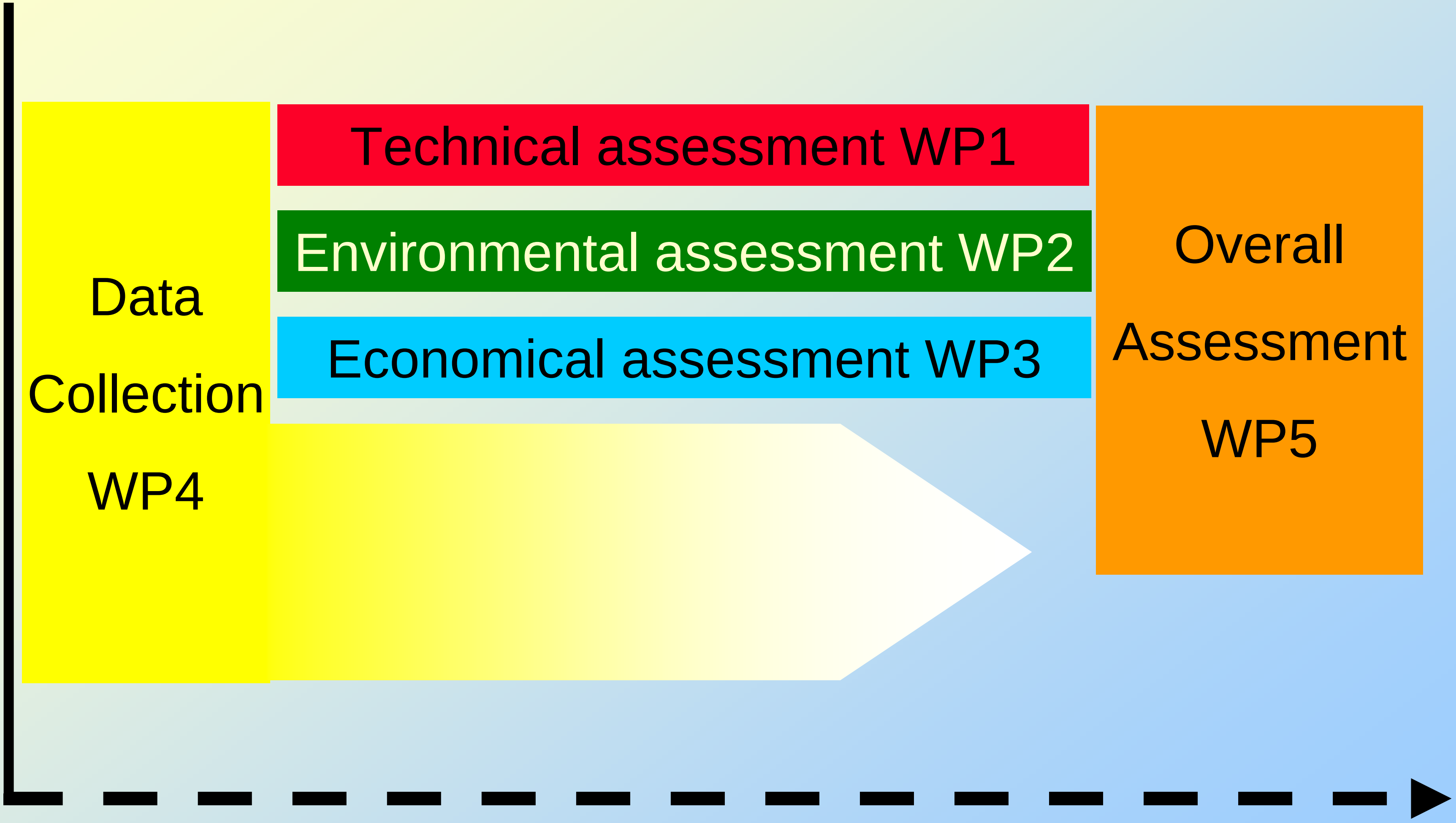
- Deliver a complete assessment of commercially available and forthcoming battery technologies for battery-electric and hybrid vehicles

# Scope of SUBAT

APPENDIX VI

- TRACTION batteries
- Providing energy and power for the propulsion of vehicles
- Traction batteries are industrial batteries
- Not automotive (SLI) or consumer batteries!

# Organization and results



Data Collection WP4

Technical assessment WP1

Environmental assessment WP2

Economical assessment WP3

Overall Assessment WP5

# WP1: Technical Assessment

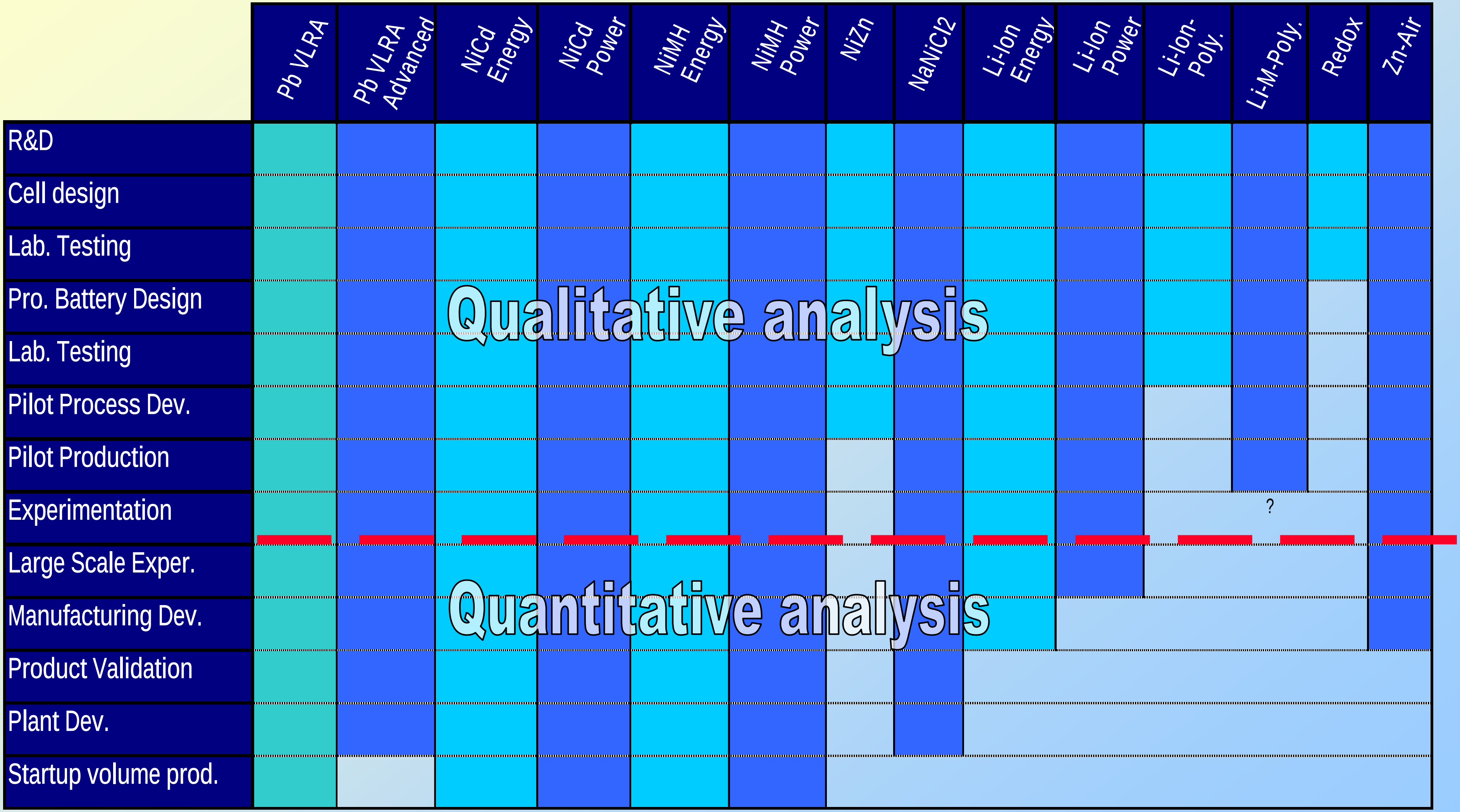
Peter Van den Bossche

# Technical Assessment

**SUBAT**

APPENDIX V

## Level of Development



| | Pb VLRA | Pb VLRA Advanced | NiCd Energy | NiCd Power | NiMH Energy | NiMH Power | NiZn | NaNiCl2 | Li-Ion Energy | Li-Ion Power | Li-Ion-Poly. | Li-M-Poly. | Redox | Zn-Air |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| R&D | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| Cell design | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| Lab. Testing | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| Pro. Battery Design | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | □ | ■ |
| Lab. Testing | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | □ | ■ |
| Pilot Process Dev. | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | □ | ■ | □ | ■ |
| Pilot Production | ■ | ■ | ■ | ■ | ■ | ■ | □ | ■ | ■ | ■ | □ | ■ | □ | ■ |
| Experimentation | ■ | ■ | ■ | ■ | ■ | ■ | □ | ■ | ■ | ■ | □ | ? | □ | ■ |
| Large Scale Exper. | ■ | ■ | ■ | ■ | ■ | ■ | □ | ■ | ■ | ■ | □ | □ | □ | ■ |
| Manufacturing Dev. | ■ | ■ | ■ | ■ | ■ | ■ | □ | ■ | ■ | □ | □ | □ | □ | ■ |
| Product Validation | ■ | ■ | ■ | ■ | ■ | ■ | □ | ■ | □ | □ | □ | □ | □ | □ |
| Plant Dev. | ■ | ■ | ■ | ■ | ■ | ■ | □ | ■ | □ | □ | □ | □ | □ | □ |
| Startup volume prod. | ■ | □ | ■ | ■ | ■ | ■ | □ | □ | □ | □ | □ | □ | □ | □ |

# Lead-acid battery

APPENDIX VI

- Widespread in industrial traction applications
- Low specific energy (30Wh/kg) hampers use in high-performance road vehicles
- Used for heavy-duty road vehicles
- VRLA: life performance to improve

# Nickel-Cadmium

APPENDIX VI

- Specific energy 50 Wh/kg
- Specific power 200 W/kg
- Good cycle life (> 1300)
- Most widespread use for battery-electric road vehicles in Europe today

# Nickel-Metal Hydride

- Slightly better performance compared to NiCd
- Power-optimised types now widely used in  hybrid vehicles
- Energy-optimised types not industrially manufactured

# Nickel-zinc

- Good energy density
- Limited life?
- Promising research at cell level
- Vehicle batteries not available yet

# Lithium batteries

APPENDIX VI

- Technologies
  - Lithium-ion
  - Lithium-ion-polymer
  - Lithium-metal-polymer
- High specific energy and power
- Operational issues
  - Abuse tolerance
- Pilot phase

# Sodium-Nickel-Chloride

- Good specific energy (100 Wh/kg)
- Operates at 300 °C
- Particularly suited for intensively used vehicles
- Small-scale production facilities

# Zinc-air battery

APPENDIX VI

- Not a battery, but a kind of fuel cell
- Mechanical recharging
- Logistic burden!

| | Pb VLRA | Pb VLRA Advanced | NiCd Energy | NiMH Energy | NiZn | NaNiCl2 | Li-Ion Energy | Li-Ion-Poly. | Li-M-Poly. | Zn-Air |
|---|---|---|---|---|---|---|---|---|---|---|
| ENERGY (Wh/kg) | 🟥 36 | 🟥 40 | 🟧 60 | 🟨 70 | 🟨 75 | 🟩 125 | 🟩 125 | 🟩 125 | 🟩 130? | 🟧 Not a Battery, chemical refuelling |
| LIFE (~years) | 🟥 2 | 🟧 3 | 🟩 6 | 🟩 6 | 🟧 ? | 🟨 5? | 🟩 6 | 🟩 ? | 🟩 ? | |
| BMS | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟥 | 🟥 | 🟥 | 🟥 | |
| SAFETY | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟥 | 🟧 | 🟧 ? | |
| EFFICIENCY (Wh %) | 🟨 80 | 🟨 80 | 🟧 75 | 🟧 70 | 🟧 70 | 🟩 90 | 🟩 90 | 🟩 90 | 🟩 ? | |
| SELF DISCHARGE | 🟩 | 🟩 | 🟩 | 🟧 | 🟨 ? | 🟥 | 🟩 | 🟩 | 🟩 | |
| MAINTENANCE | 🟩 | 🟩 | 🟨 | 🟩 | 🟨 | 🟨 | 🟩 | 🟩 | 🟩 ? | |
| POWER (W/kg short) | 🟧 250 | 🟧 250 | 🟧 200 | 🟩 350 | 🟧 200 | 🟧 200 | 🟩 400 | 🟩 400 | 🟩 ? | |
| POWER (low temp.) | 🟥 | 🟧 | 🟩 | 🟧 | 🟨 ? | 🟩 | 🟨 | 🟨 | 🟨 ? | |
| CHARGE friendl. | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟧 ? | |

**good or high** 🟩 🟨 🟧 🟥 **bad or low**

# TECHNOLOGIES for BATTERY ELECTRIC VEHICLE

## (Cell Level)

# Technical Assessment

| | Pb VLRA | Pb VLRA Advanced | NiCd Power | NiMH Power | NiZn | NaNiCl2 | Li-Ion Power | Li-Ion-Poly. | Li-M-Poly. | Zn-Air |
|---|---|---|---|---|---|---|---|---|---|---|
| POWER (W/kg short) | 🟥 350 | 🟧 500 | 🟧 500 | 🟩 1500 | 🟧 ? | 🟥 ? | 🟩 2000 | 🟩 2000 | 🟨 ? | 🟧 Not a Battery, chemical refuelling |
| ENERGY (Wh/kg) | 🟥 25 | 🟧 30 | 🟧 30 | 🟨 55 | 🟧 ? | 🟩 ? | 🟩 70 | 🟩 70 | 🟩 70 | |
| Life (years) | 🟥 2 | 🟥 3 | 🟩 6 | 🟩 6 | 🟨 ? | 🟨 ? | 🟩 6 | 🟩 ? | 🟩 ? | |
| POWER (low temp.) | 🟩 | 🟩 | 🟩 | 🟧 | 🟧 ? | 🟩 | 🟨 | 🟨 | 🟨 | |
| EFFICIENCY (Wh %) | 🟨 80 | 🟨 80 | 🟧 75 | 🟧 70 | 🟧 ? | 🟩 90 | 🟩 90 | 🟩 90 | 🟩 ? | |
| SAFETY | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟧 | 🟨 | 🟨 | |
| SELF DISCHARGE | 🟩 | 🟩 | 🟩 | 🟨 | 🟨 ? | 🟥 | 🟩 | 🟩 | 🟩 | |
| MAINTENANCE | 🟩 | 🟩 | 🟧 | 🟩 | 🟧 ? | 🟨 | 🟩 | 🟩 | 🟩 | |

good or high 🟩 🟨 🟧 🟥 bad or low

## TECHNOLOGIES for HYBRID VEHICLES

## (Cell Level)

# Technical Assessment

APPENDIX VI

# WP2: Environmental Assessment

Julien Matheys

# Environmental Assessment

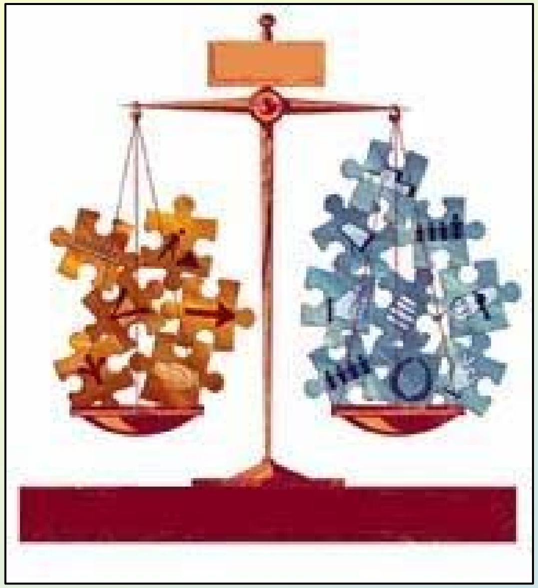
APPENDIX VI

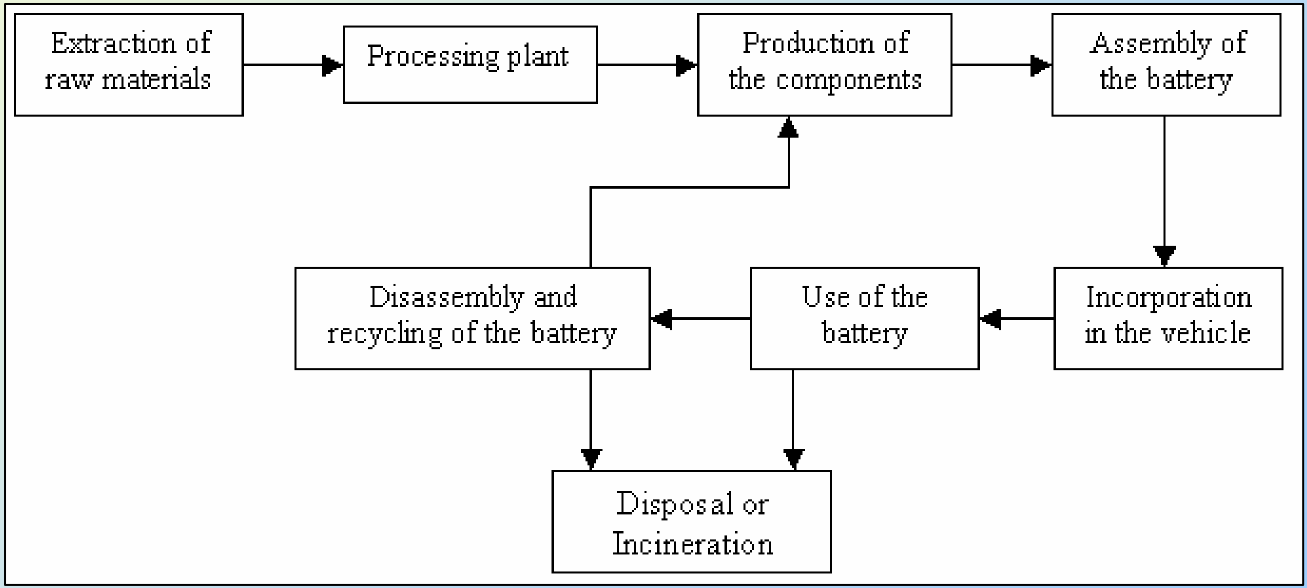
## Assessed technologies

| Qualitative and quantitative analysis | Qualitative analysis |
|---|---|
| Lead-acid | Lithium-ion Polymer |
| Nickel-cadmium | Zinc-air |
| Nickel-metal Hydride | Nickel-zinc |
| Sodium-nickel Chloride | Redox batteries |
| Lithium-ion | … |

# Life-cycle of a battery

- **“Cradle-to-grave” approach**





- **Eco-indicator 99 →Eco-indicator points**
- **Software → Simapro 6.01**

# Functional Unit BEV

APPENDIX VI

- **3000 cycles**
- **60 km range**

**180000km**

| | $E_{density}$ (Wh/kg) | # Cycles | Energy efficiency | Losses due to heating |
|---|---|---|---|---|
| **Pb-acid** | **40** | **500** | **82.5%** | |
| **NiCd** | **60** | **1350** | **72.5%** | |
| **NiMH** | **70** | **1350** | **70.0%** | |
| **Li-ion** | **125** | **1000** | **90.0%** | |
| **NaNiCl** | **125** | **1000** | **92.5%** | **7.2%** |

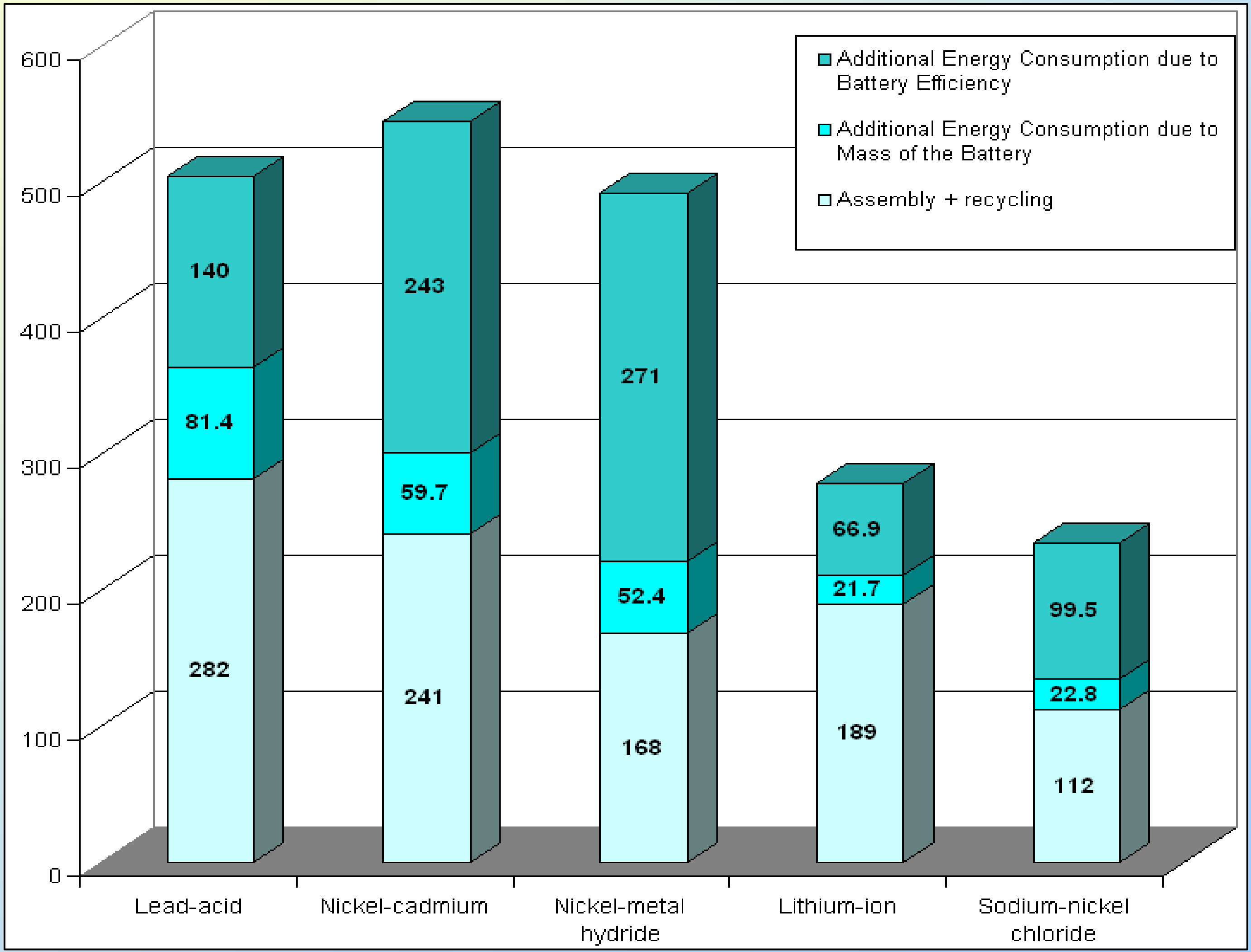
# Environmental Impact Assessment

Including:

Additional energy consumption **battery efficiency**

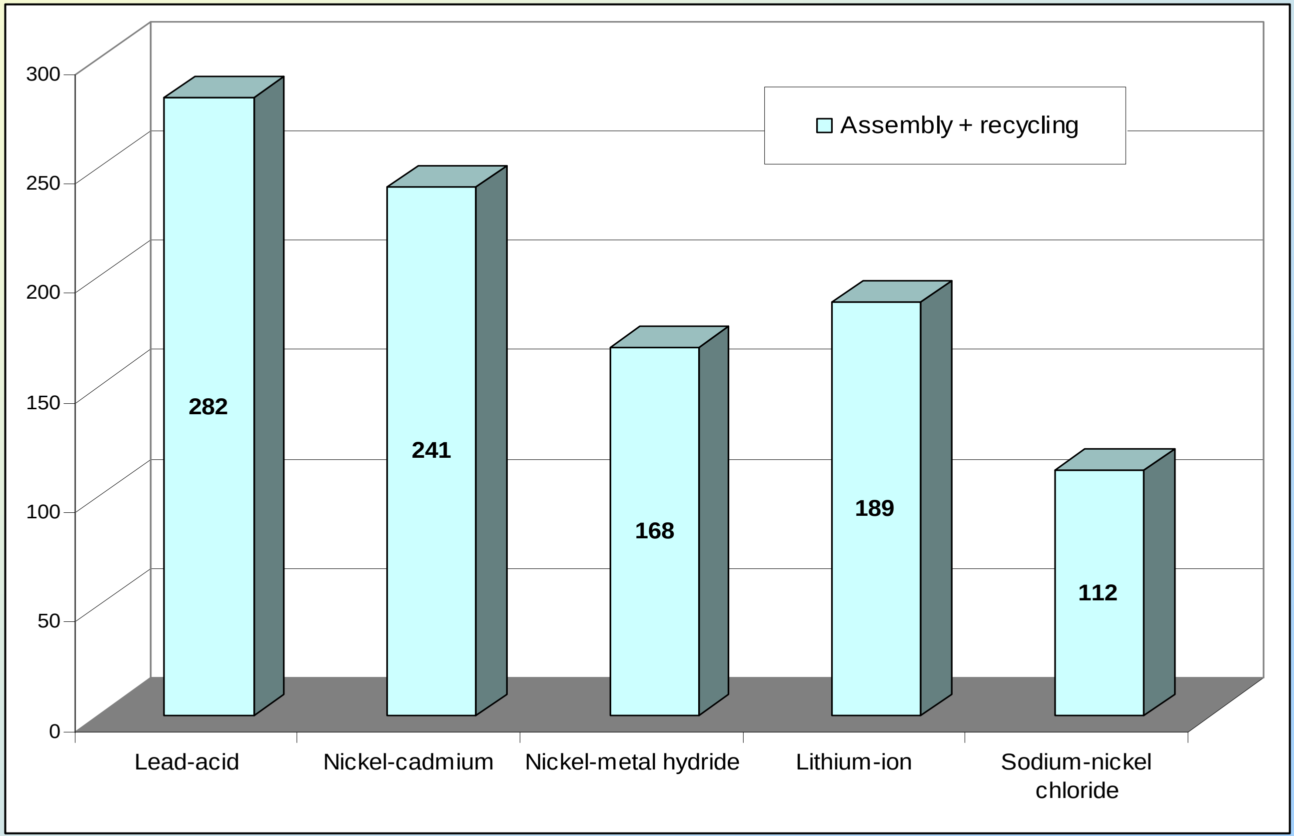
Additional energy consumption **battery mass**

Assembly and recycling



# Environmental Impact Assessment

## Including Assembly and Recycling
## (without additional energy consumption due to battery)



Importance of Battery efficiency

(Environmental impact is depending on electricity production method)

# Overall impact

| | **Production** | Additional Energy Consumption due to mass & battery efficiency | **Recycling** | Total |
|---|---|---|---|---|
| **Pb-acid** | **1091** | 221 | **-809** | 503 |
| **NiCd** | **861** | 303 | **-620** | 544 |
| **NiMH** | **945** | 323 | **-777** | 491 |
| **Li-ion** | **361** | 89 | **-172** | 278 |
| **NaNiCl** | **368** | 122 | **-256** | 234 |

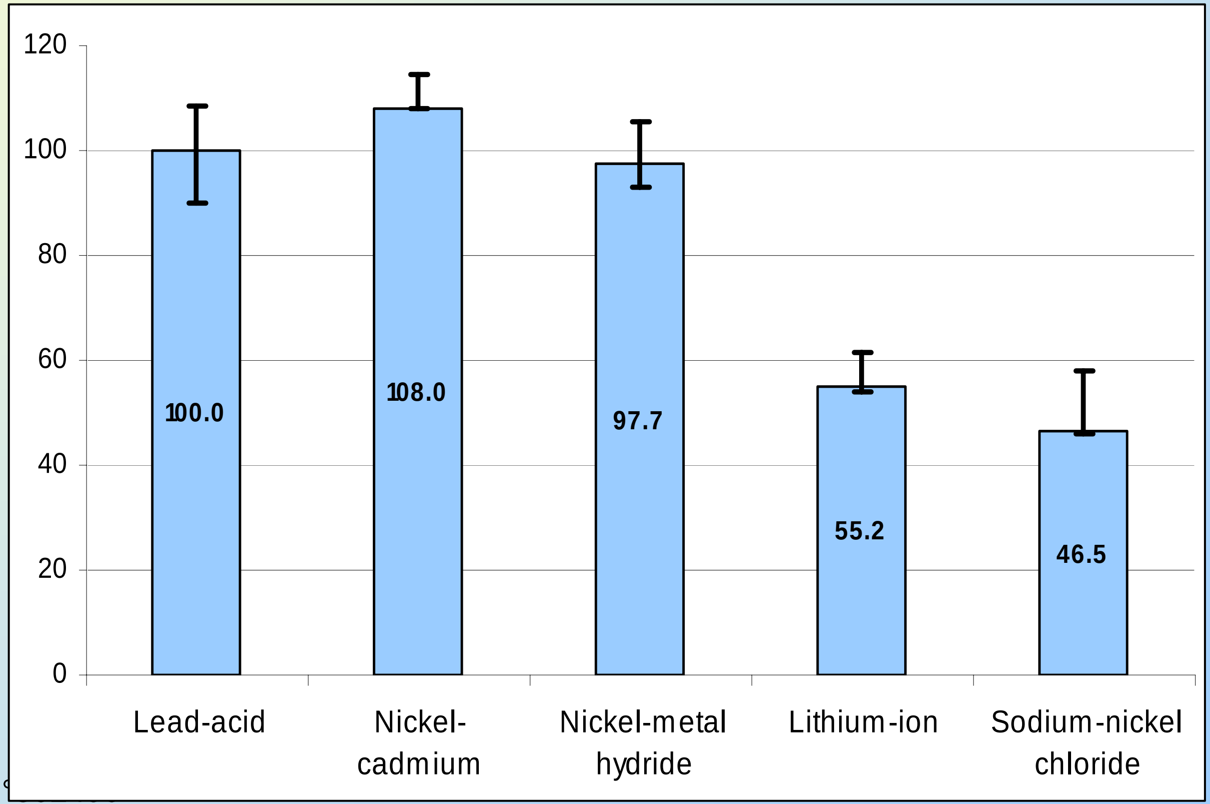
Importance of Recycling!!!

# Sensitivity analysis BEV

APPENDIX VI

Including:

- different relative sizes of the components
- varying recycling rates
- varying recycling efficiencies
- varying required amounts of energy for production&recycling



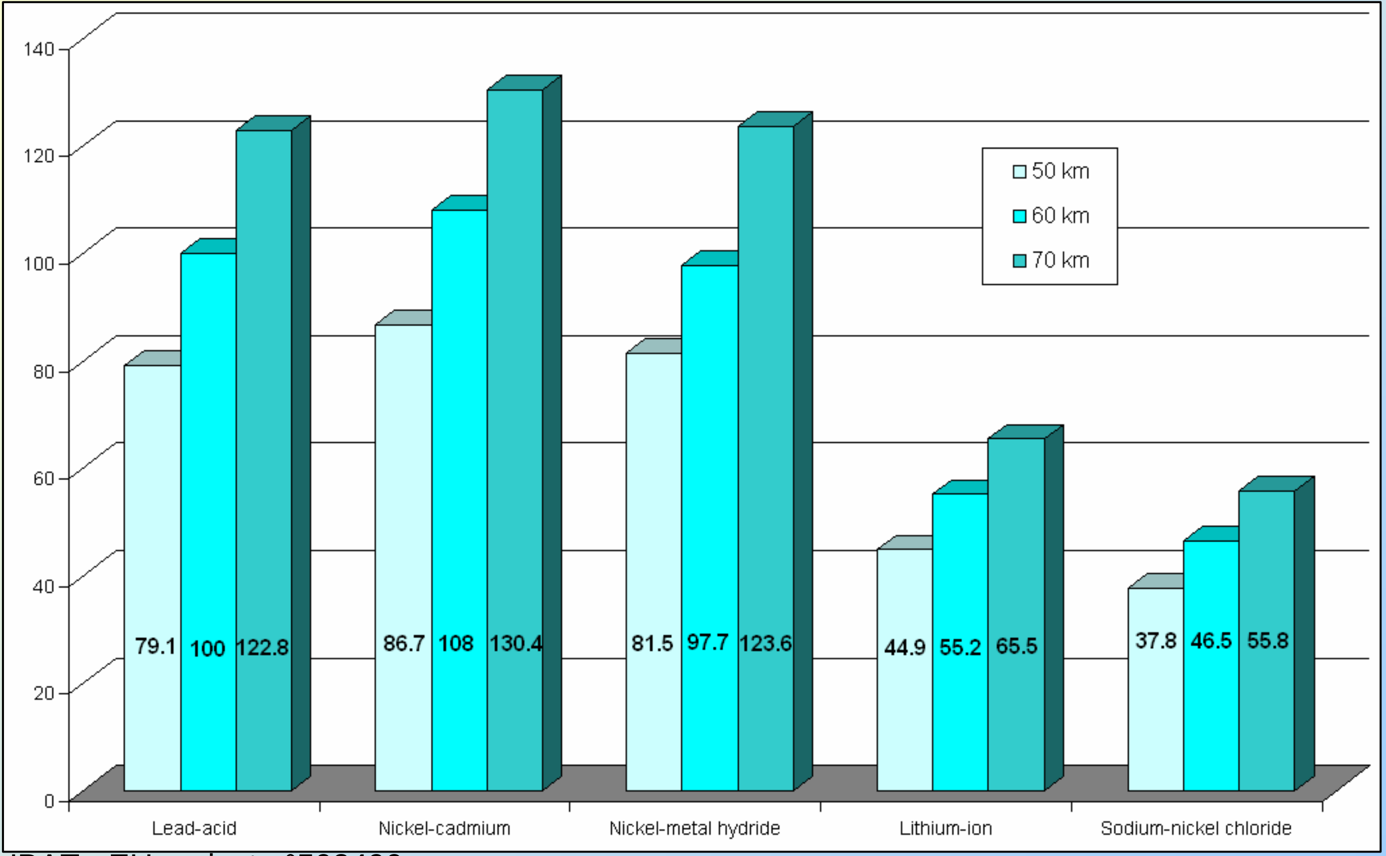
APPENDIX VI

# Varying one-charge ranges

- As a kind of sensitivity analysis: 50km – 60km – 70km

Different battery weights

Influence on consumption



Conclusions remain valid

# LCA-Functional Unit HEV

21kW

| | Specific Power (W/kg) | Relative number of Cycles | Number of Batteries | Mass (kg) of F.U. |
|---|---|---|---|---|
| **Pb-acid** | **350** | **1** | **3** | **60** |
| **NiCd** | **500** | **3** | **1** | **42** |
| **NiMH** | **1500** | **3** | **1** | **14** |
| **Li-ion** | **2000** | **3** | **1** | **10** |
| **NaNiCl** | **200** | **3** | **1** | **105** |

APPENDIX VI

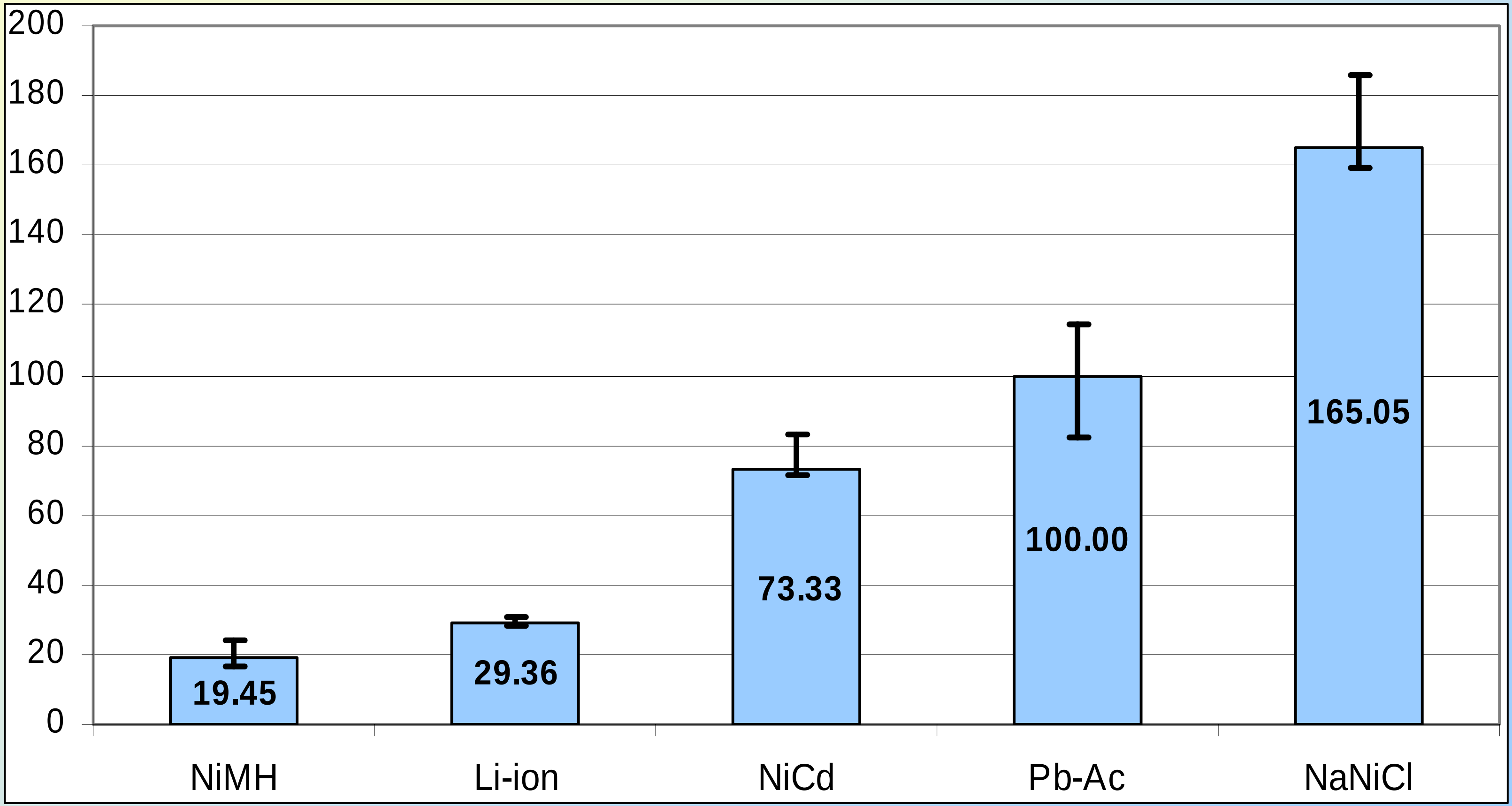
# Overall Impact HEV

| | Production | Recycling | Total |
|---|---|---|---|
| **Pb-acid** | **95.0** | **-70.5** | **24.5** |
| **NiCd** | **64.4** | **-46.4** | **18.0** |
| **NiMH** | **26.8** | **-22.1** | **4.8** |
| **Li-ion** | **13.7** | **-6.6** | **7.1** |
| **NaNiCl** | **133.0** | **-92.6** | **40.4** |

- However, practically, only NiMH and Li-ion batteries are considered for HEV applications.

# Sensitivity analysis HEV

Practically, only NiMH and Li-ion batteries
are considered for HEV applications



# LCA Conclusions

APPENDIX VI

BEV:

- Li-ion and NaNiCl
  - Somewhat more environmentally friendly than Pb-acid, NiCd and NiMH (incl. or excl. use phase)
- Impact of the use phase can be decreased by using renewables for electricity production

HEV:

- Li-ion and NiMH
  - Lowest environmental impact

Importance of

- Recycling
- Technical parameters
- Application

# WP3: Economical Assessment

Claude Ades

# Economical Assessment

APPENDIX VI

# Cost and Price of Battery Technologies

## Method used

(All 2012 prices in 2004 € with €/$=1.25)

All Costs and Prices are estimated for typical battery packs:

- BEV 30 kWh
- Mild HEV 0.4 kWh, 12 kW (short)
- Full HEV 1.2 kWh, 40 kW (short)

- ***Lead-Acid***
  - 2005 Standard VLRA AGM mean prices (Battery Manufacturers)
  - 2012 Standard VLRA AGM mean prices + evaluation of 7 years increase influence of advanced VLRA techno. and Lead price
- ***NiCd***
  - 2005 Standard energy and power battery mean prices (Battery Manufacturers)
  - 2012 Same prices (2004 €)
- ***$NaNiCl_2$*** (Zebra) only Energy
  - 2005 Standard prices (Battery Manufacturer)
  - 2012 New evaluation of mass production cost, manufacturing cost and price using the world market and Battery Manufacturer data

# Economical Assessment
# Cost and Price of Battery Technologies

APPENDIX VI

- ***NiMH and Lithium-Ion*** (2005 and 2012)
  - Mean Chemical Composition study vs Energy and Power versions
  - Typical cells for estimation
  - Material prices study in the case of battery mass production
  - Cell cost of goods estimations (power and energy)
  - Cell cost of production
  - Module and/or battery cost of production
  - Accessories costs
  - Manufacturing cost
  - Battery price (mass production)

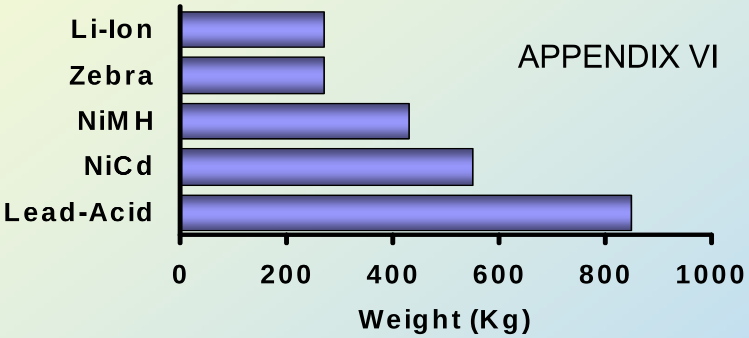
And for all **mass production hypothesis in 2012**

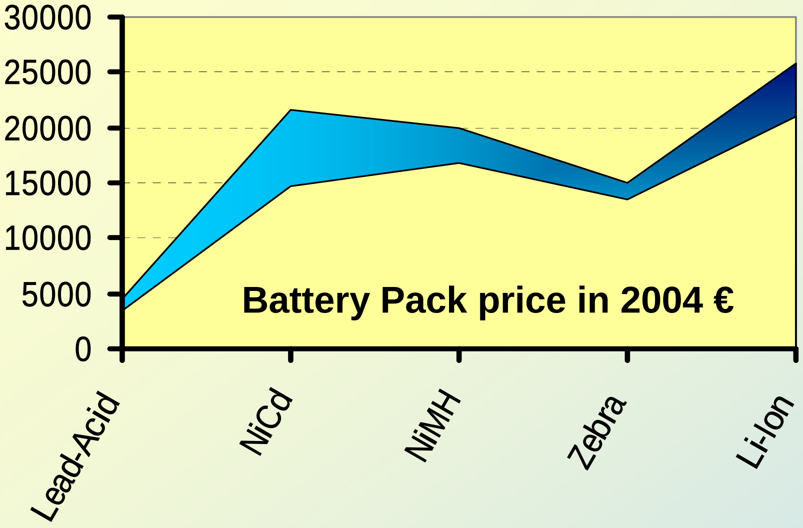
BUT…

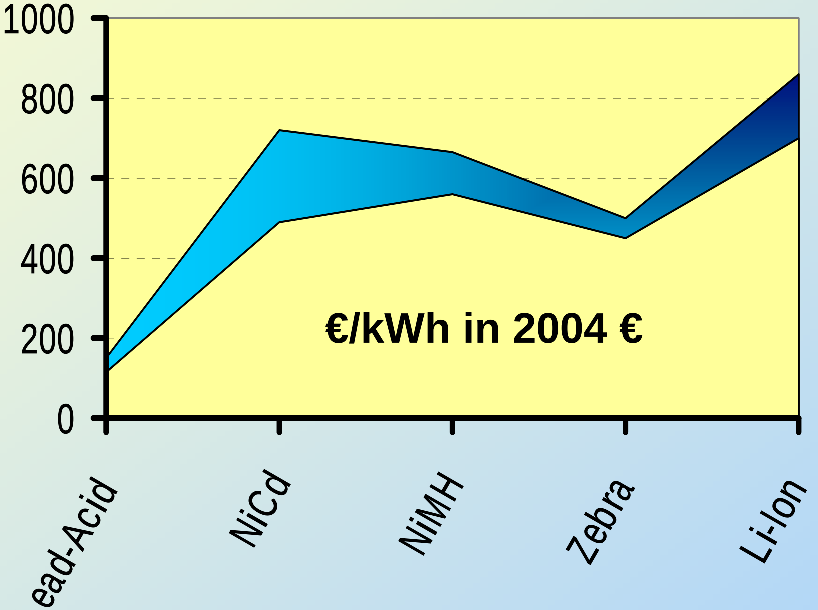
- Prices are not real future prices
- Only a proportional value of production cost
- Influence of the market pressure

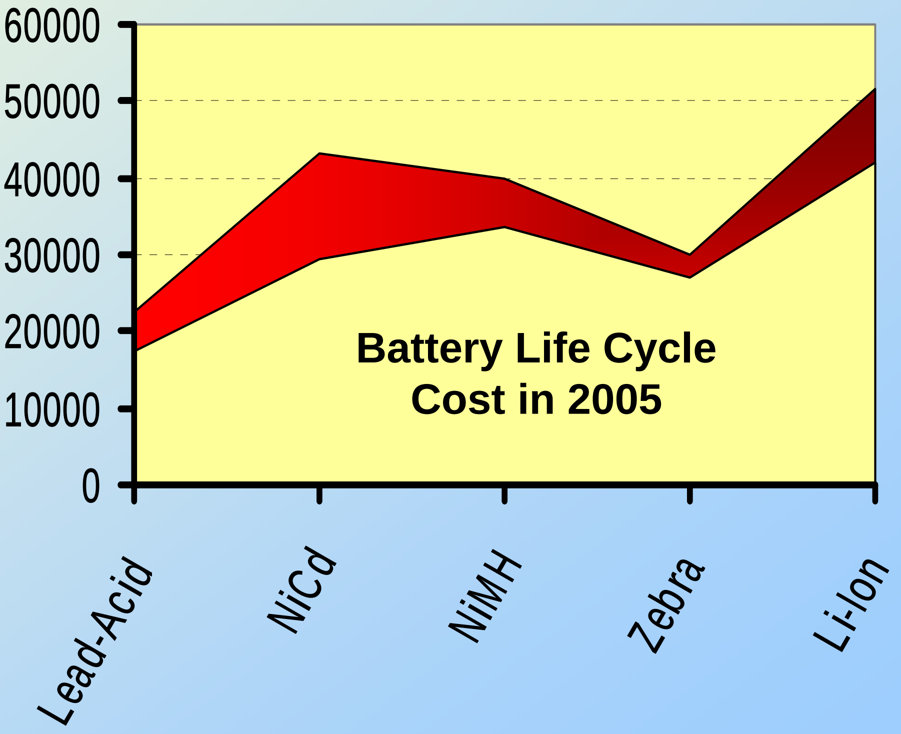
# BEV Battery of 30 kWh 2005

APPENDIX VI



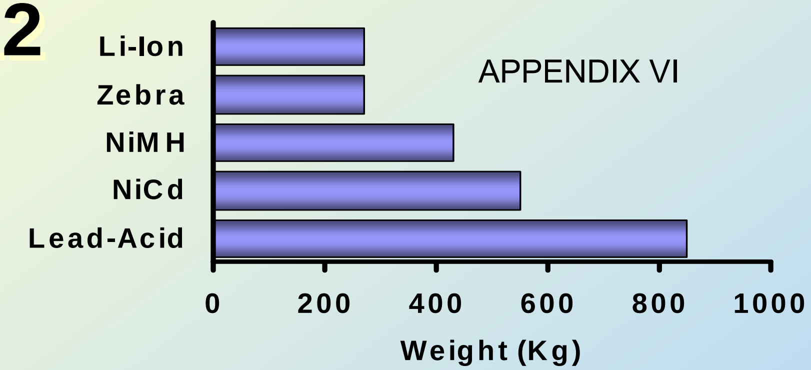

Battery Pack price in 2004 €

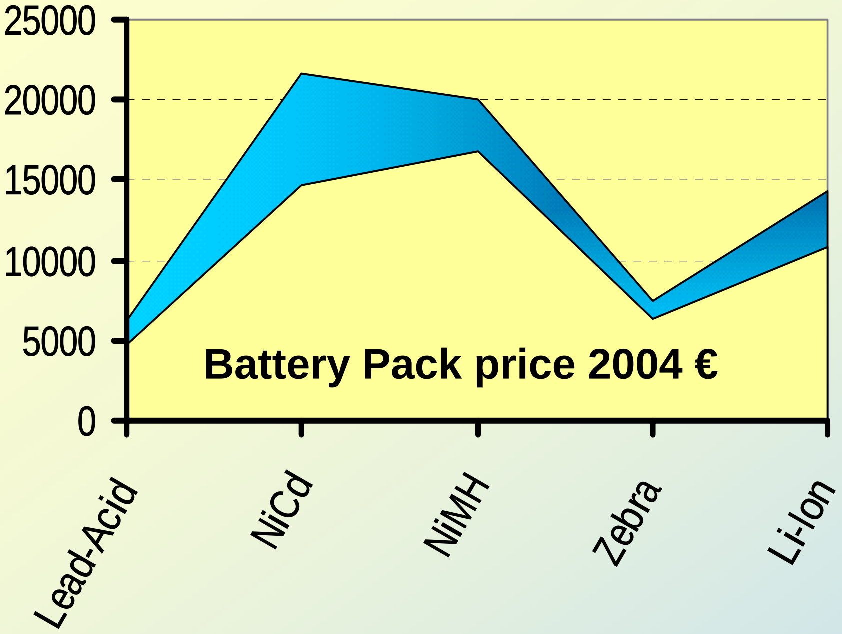

€/kWh in 2004 €

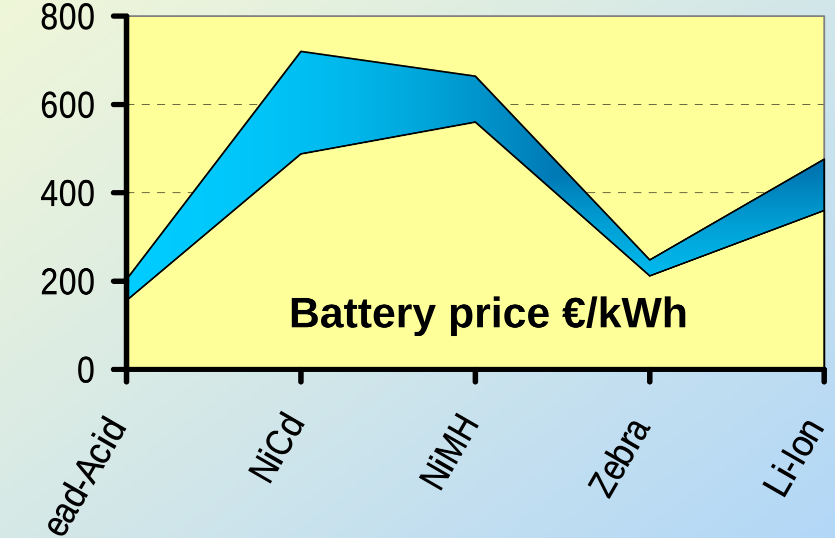

Battery Life Cycle Cost in 2005

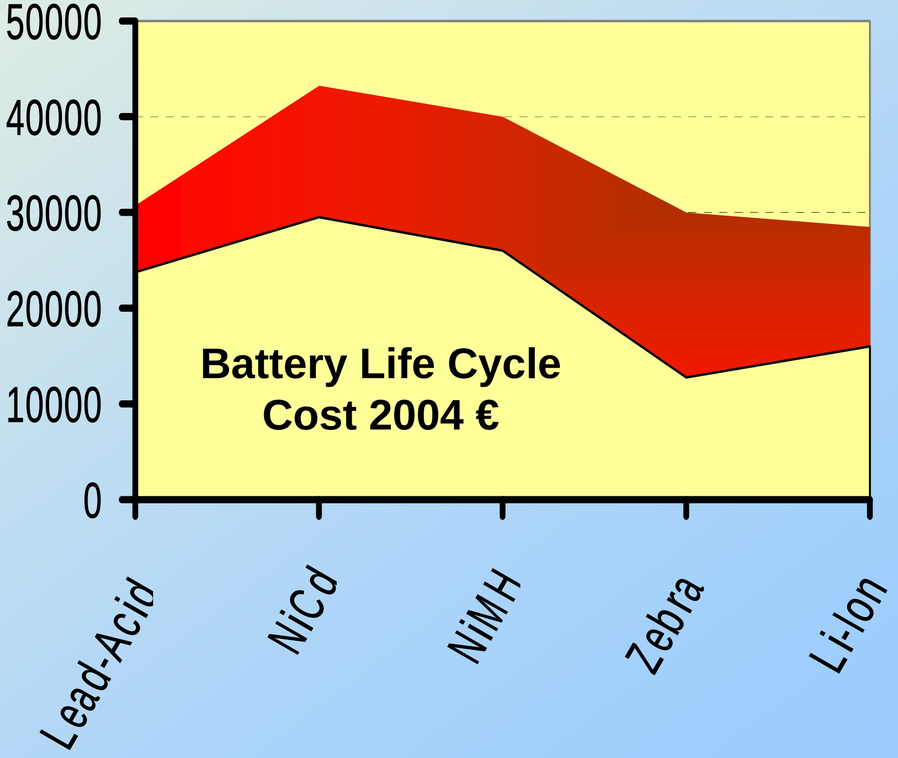
# BEV Battery of 30 kWh, 2012

APPENDIX VI



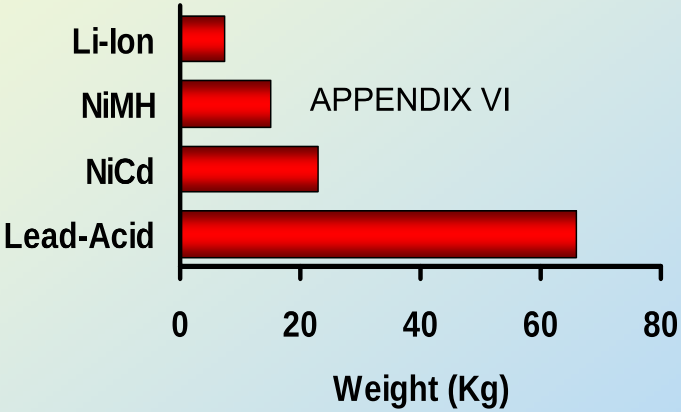

Battery Pack price 2004 €

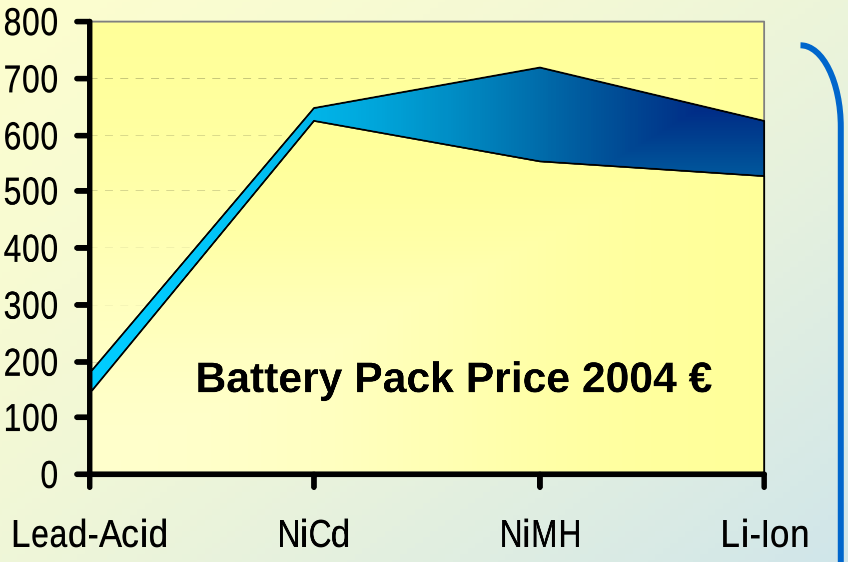

Battery price €/kWh

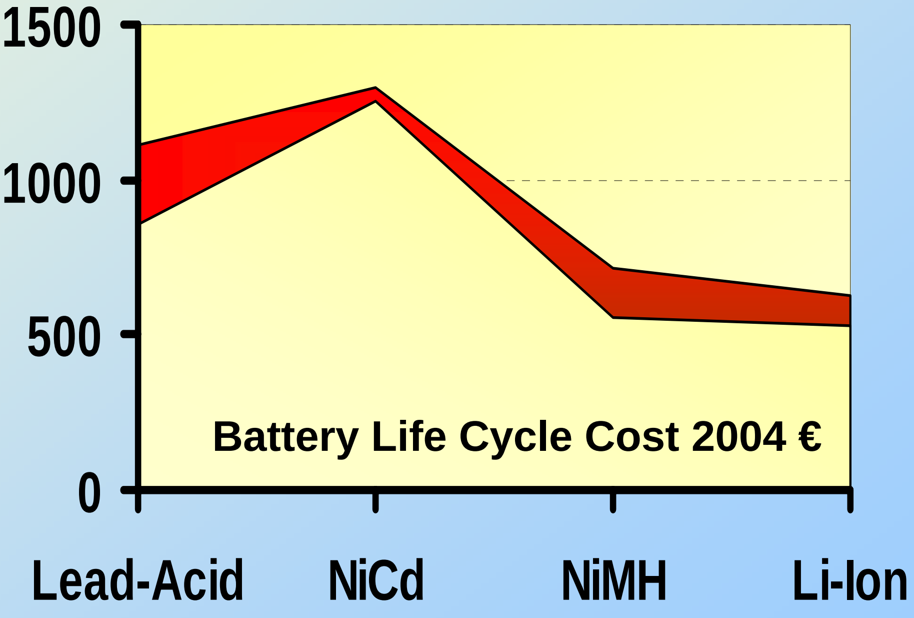

Battery Life Cycle Cost 2004 €

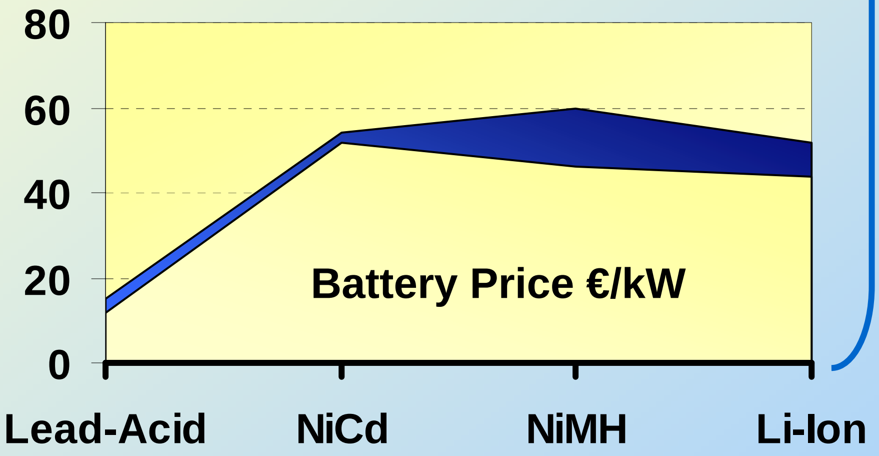
# Mild Hybrid Battery (0.4 kWh, 12 kW)
# 2005

APPENDIX VI



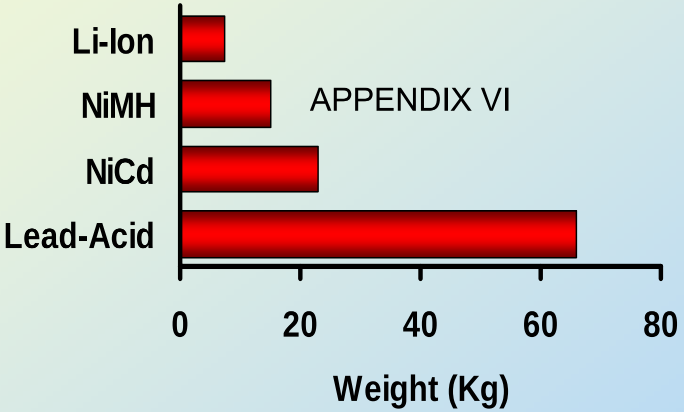

Battery Pack Price 2004 €

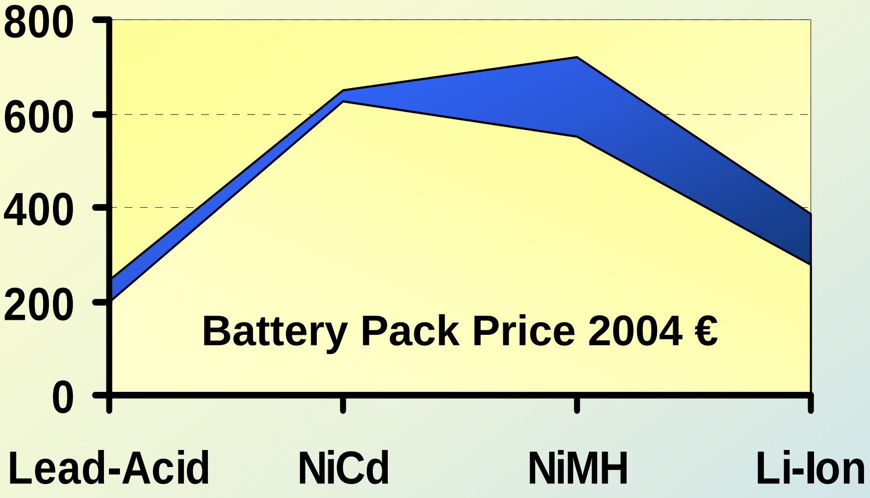

Battery Life Cycle Cost 2004 €

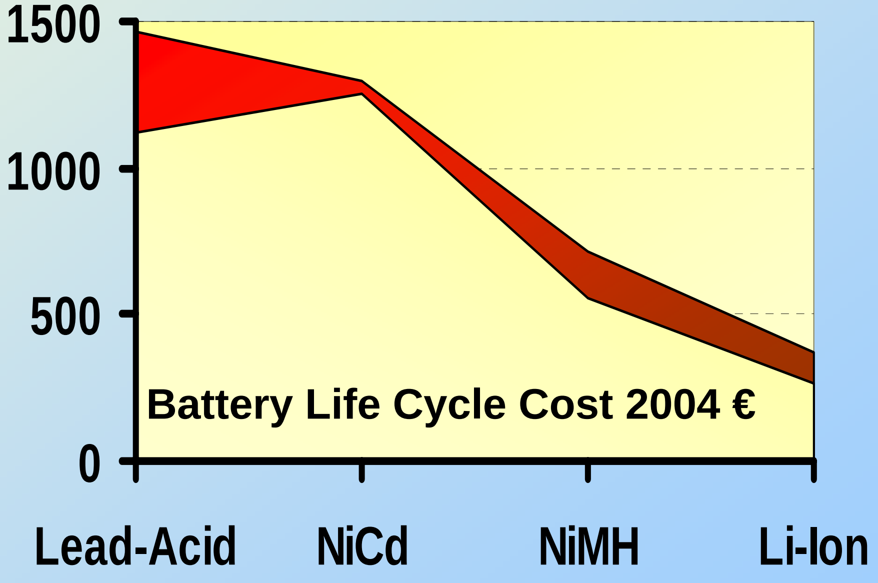

Battery Price €/kW

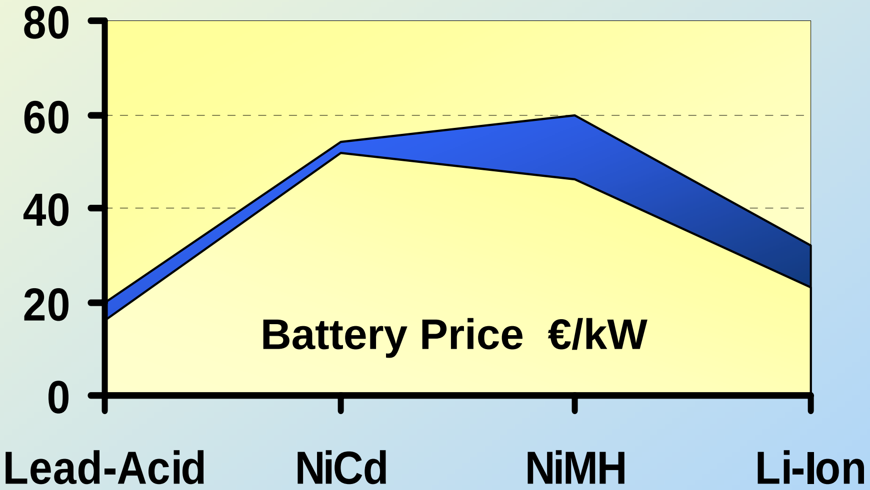
# Mild Hybrid Battery (0.4 kWh, 12 kW) 2012

APPENDIX VI



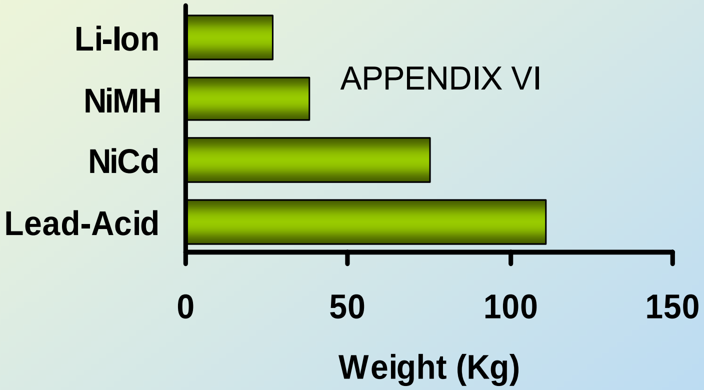

Battery Pack Price 2004 €

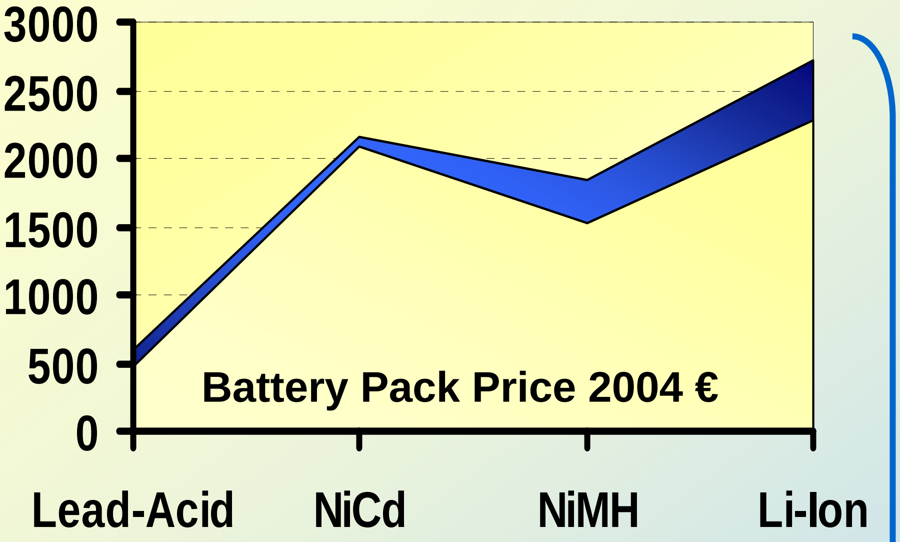

Battery Life Cycle Cost 2004 €

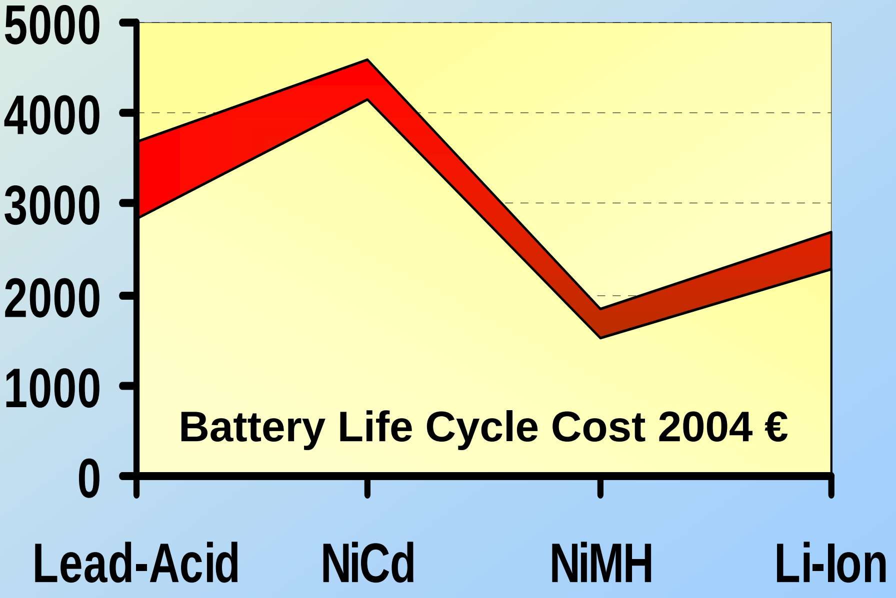

Battery Price €/kW

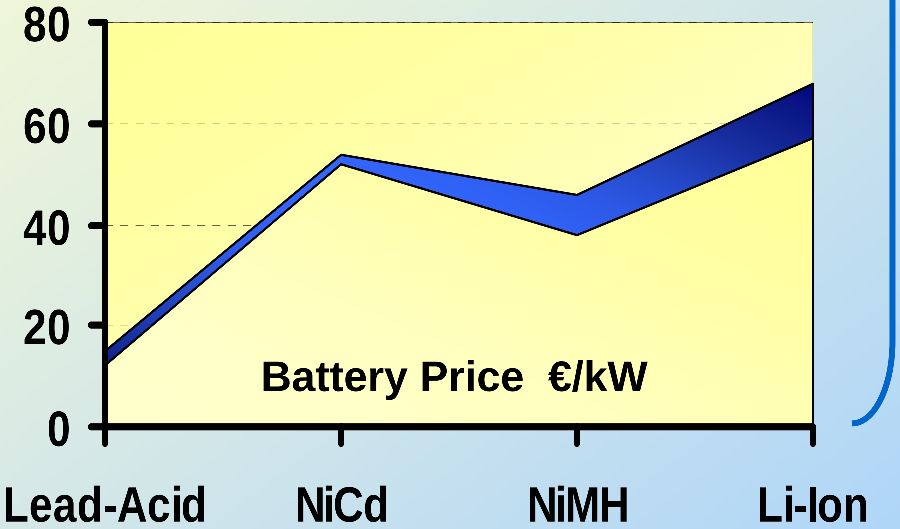
# Full Hybrid Battery (1.2 kWh, 40 kW) 2005

APPENDIX VI



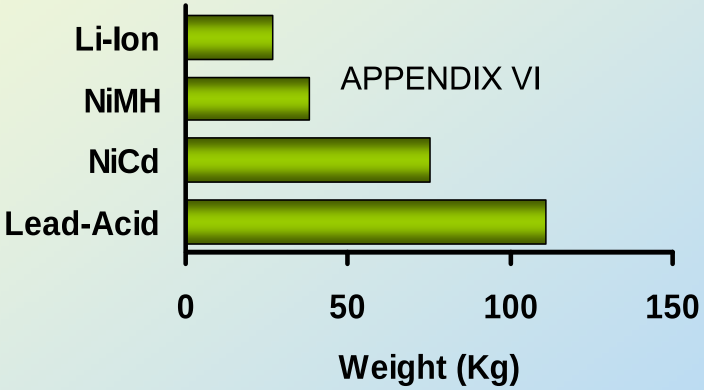

Battery Pack Price 2004 €

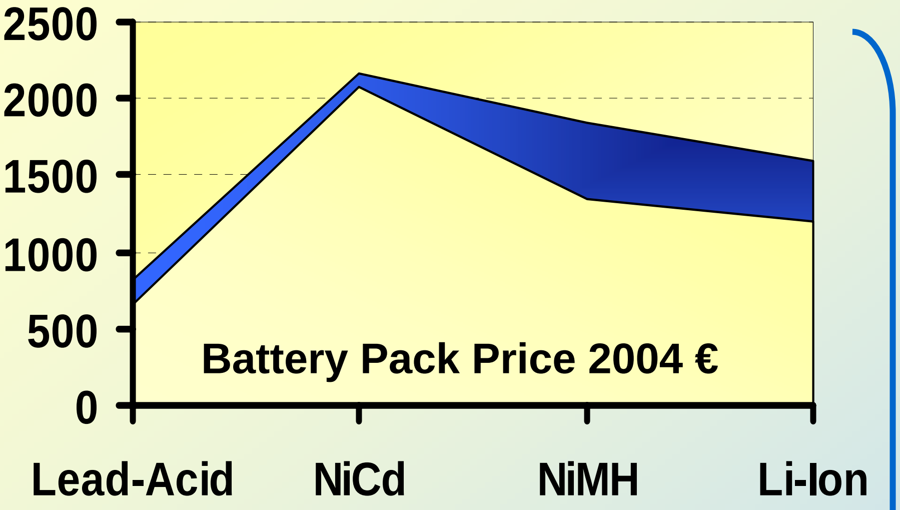

Battery Life Cycle Cost 2004 €

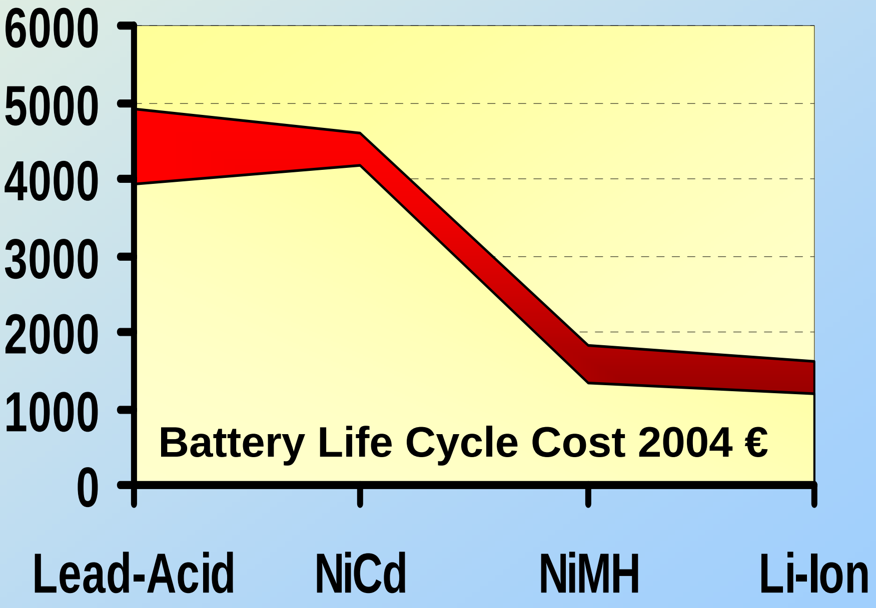

Battery Price €/kW

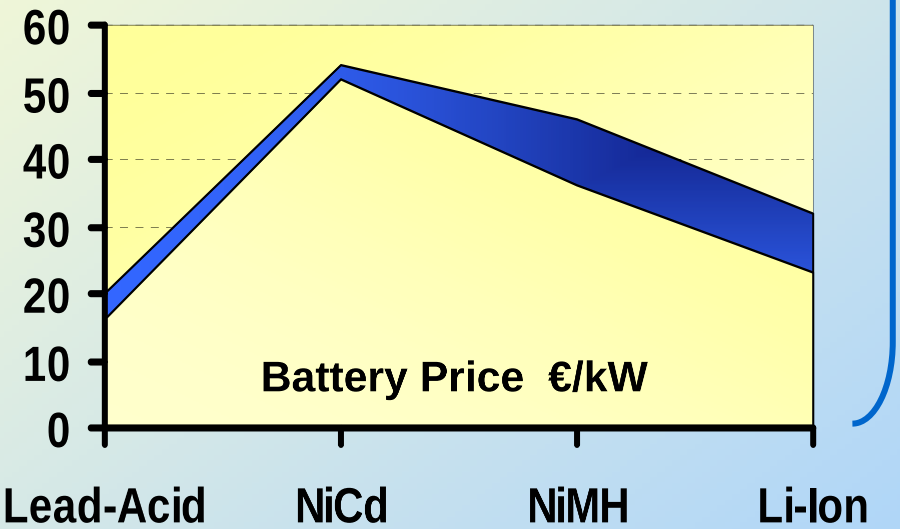
# Full Hybrid Battery (1.2 kWh, 40 kW) 2012

APPENDIX VI




Battery Pack Price 2004 €


Battery Life Cycle Cost 2004 €


Battery Price €/kW

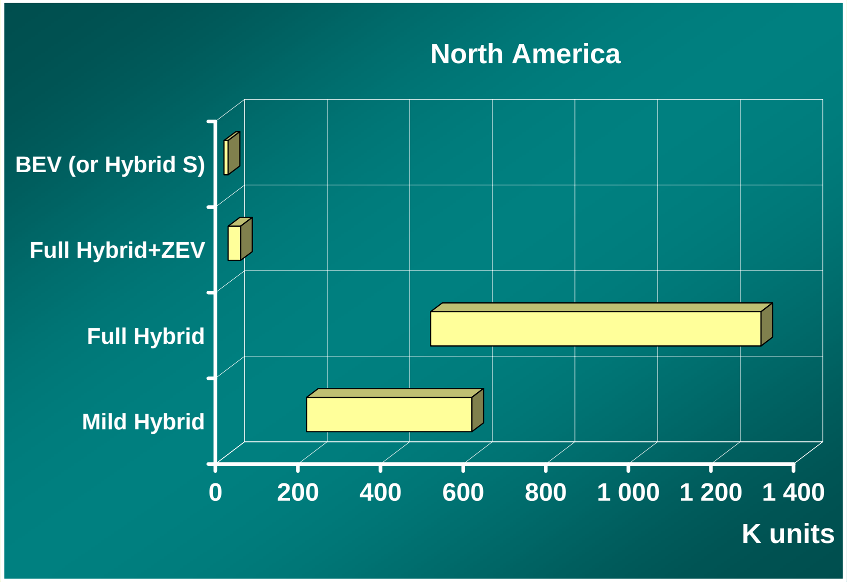
# “Traction” Battery Market Study

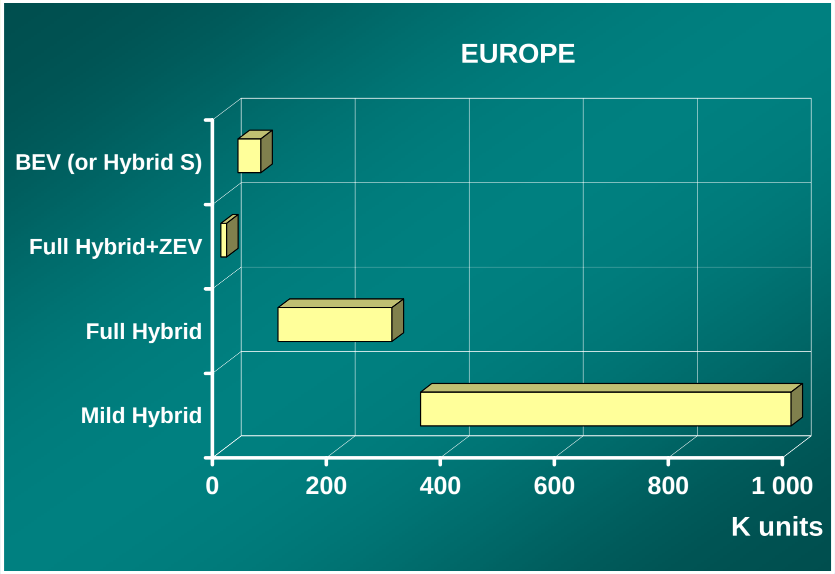
- WP3: Economical Assessment Part II
- What could be the “traction” battery market in 2012 ?

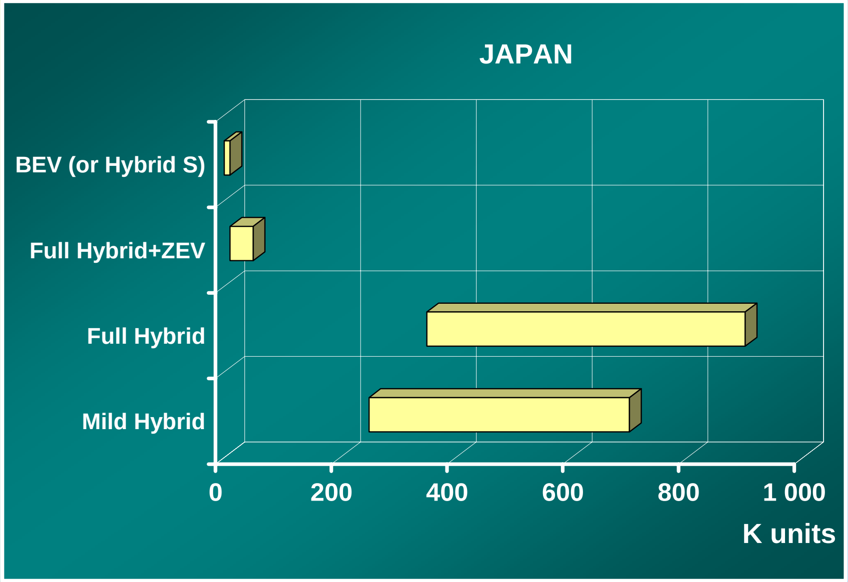
# "Advanced" Vehicle World Market in 2012

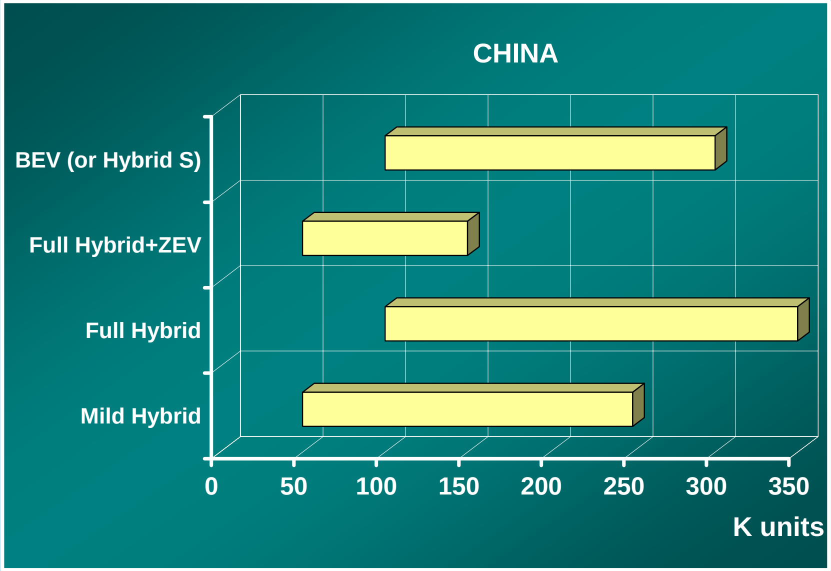
APPENDIX VI

## (estimation of passenger car and light duty market)



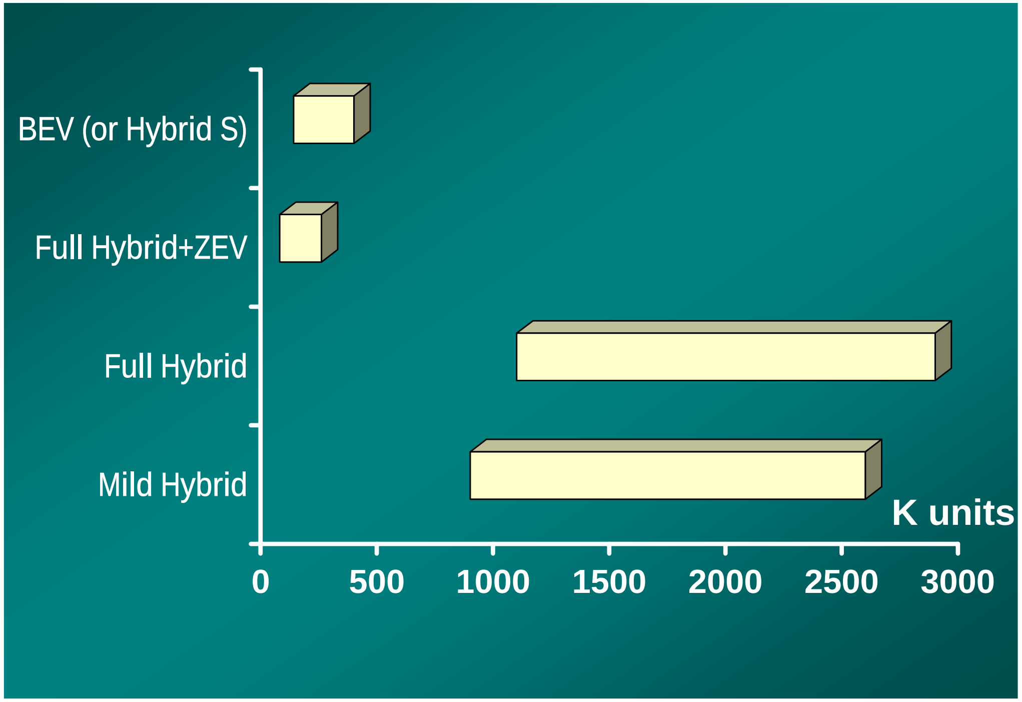






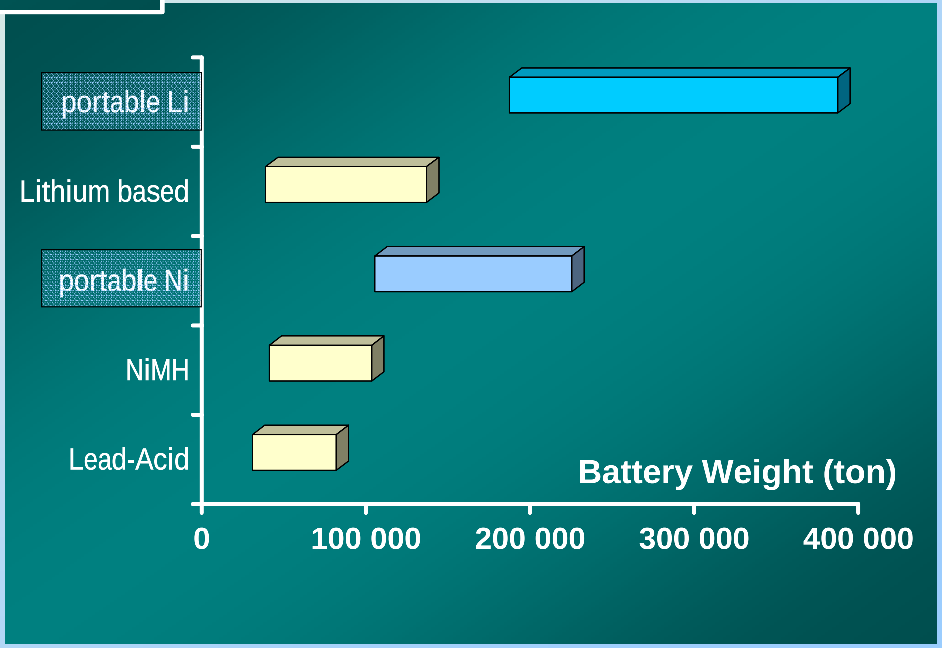
# “Advanced” Vehicle World Market in 2012

(estimation of passenger car and light duty market)



# Secondary Battery World Market in 2012

(“advanced” vehicle market compared to portable one)



APPENDIX VI

# WP5: Overall Assessment

Joeri Van Mierlo

# Overall Assessment

APPENDIX VI

- Overview and compilation of results of WP1, 2 and 3
  - Technical
  - Environmental
  - Economical
- Qualitative analysis
  - See previous WPs
- Quantitative analysis of
  - 5 battery technologies (Alternatives)
  - 8 parameters (Criteria’s)
  - 4 (+1) scenario’s
  - 3 perspectives (Weightings)

# MultiCriteria Analysis (MCA)

## Methodology

PROMETHEE

(Preference Ranking Organisation Method for Enrichment Evaluations)

- Positive preference flows (φ+ or attractiveness):
  - – how much an option is preferred to the others
- Negative preference flows (φ- or weakness):
  - – how much the other options dominate the option

- PROMETHEE I = partial ranking
- PROMETHEE II = complete ranking (strict ranking)

# MultiCriteria Analysis (MCA)

APPENDIX VI

- Representation:
  - GAIA-plane: Geometrical Analysis for Interactive Assistance
    - k criteria represented in k-dimensional space
    - GAIA-plane = projection of this k-dimensional space
    - “Decision stick” shows the optimal compromise resulting from the different criteria
- Software
  - Decision lab

# Overview

APPENDIX VI

| | | **Scenario's** | | | | |
|---|---|---|---|---|---|---|
| | | **Battery Electric Vehicle** | | **Hybrid Electric Vehicle** | | **Eurobat** |
| | | **2005** | **2012** | **2005** | **2012** | **2005** |
| **Perspectives** | **Political** | **X** | **X** | **X** | **X** | **X** |
| | **Manufacturer** | **X** | **X** | **X** | **X** | **X** |
| | **Consumer** | **X** | **X** | **X** | **X** | **X** |

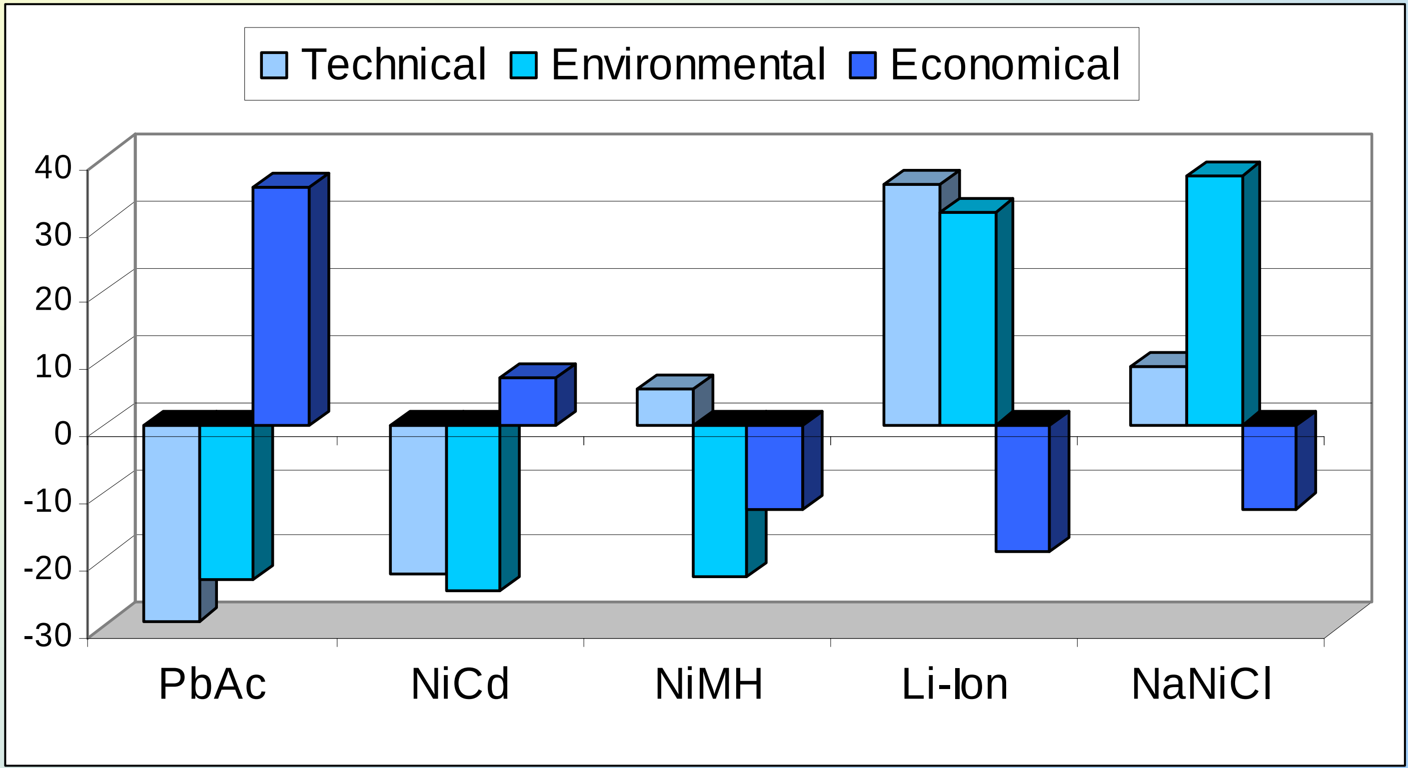
| **Criteria** | |
|---|---|
| **Technical** | **Specific Energy** |
| | **Specific Power** |
| | **Number of Cycles** |
| | **Energy efficiency** |
| **Environmental** | **LCA** |
| **Economical** | **Cost** |
| | **Maturity** |
| | **User friendliness** |

# Example: BEV 2005 – Politicians

APPENDIX VI

| | *Technical parameters* | | | | *Environmental parameters* | *Economical parameters* | | |
|---|---|---|---|---|---|---|---|---|
| | **Energy Density** | **Power Density** | **Cycles** | **Energy Efficiency** | **LCA** | **Cost** | **Maturity** | **User-friendly** |
| ***Weights*** | 25 | 15 | 5 | 5 | 50 | 30 | 10 | 10 |
| PbAc | ***40*** | ***250*** | ***500*** | ***83*** | ***503*** | ***10085*** | ***100*** | ***100*** |
| NiCd | ***60*** | ***200*** | ***1350*** | ***73*** | ***544*** | ***17355*** | ***100*** | ***100*** |
| NiMH | ***70*** | ***350*** | ***1350*** | ***70*** | ***491*** | ***20254*** | ***60*** | ***100*** |
| Li-Ion | ***125*** | ***400*** | ***1000*** | ***90*** | ***278*** | ***25338*** | ***60*** | ***100*** |
| NaNiCl | ***125*** | ***200*** | ***1000*** | ***86*** | ***234*** | ***17109*** | ***80*** | ***60*** |

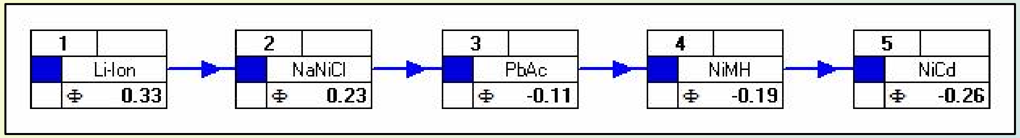
# Results: Comparison BEV 2005



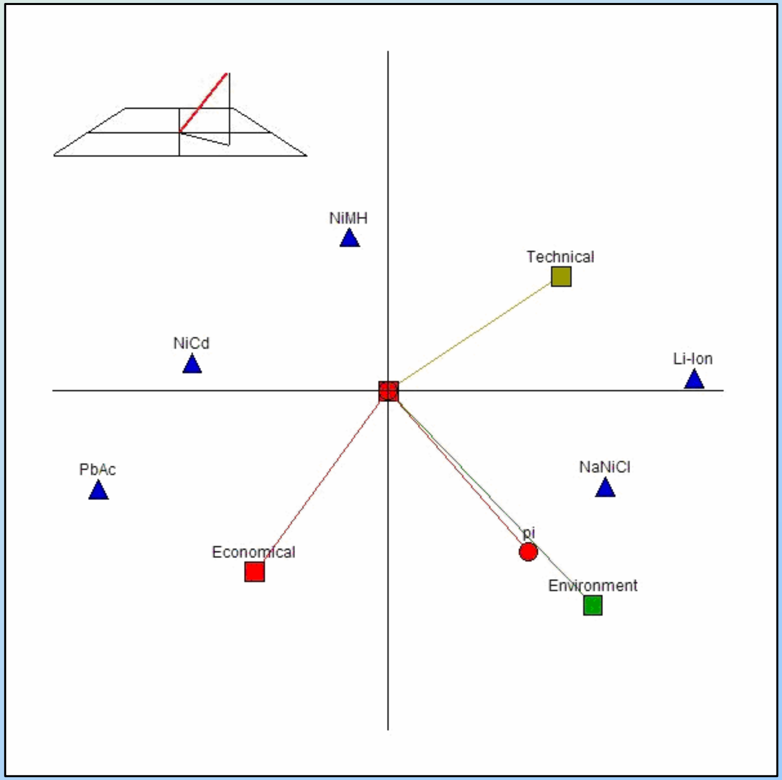
APPENDIX VI

# Results for BEV 2005

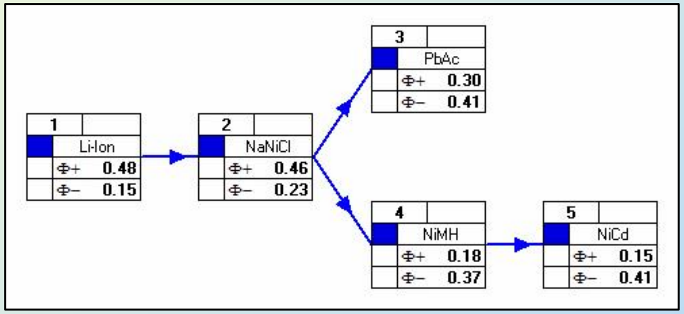
- Complete Ranking PROMETHEE II



GAIA plane

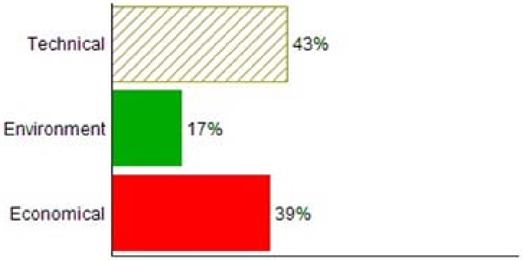
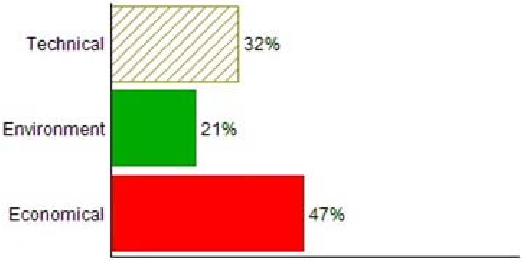
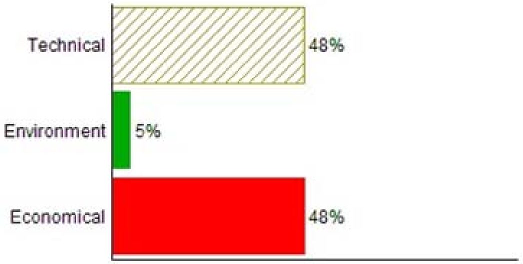
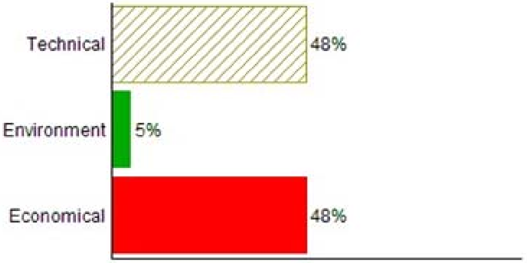
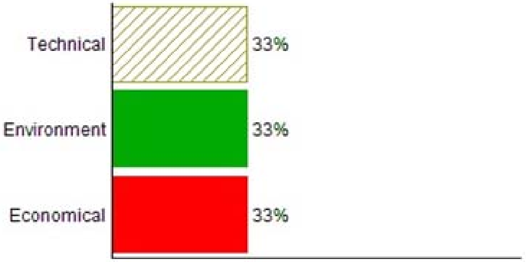
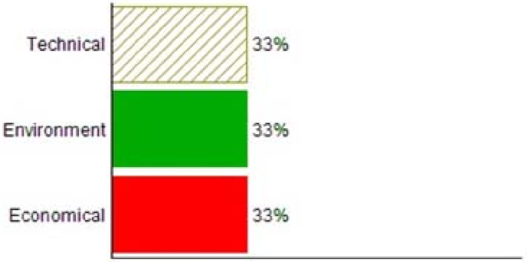


- Partial Ranking PROMETHEE I



# Perspectives - Weighting

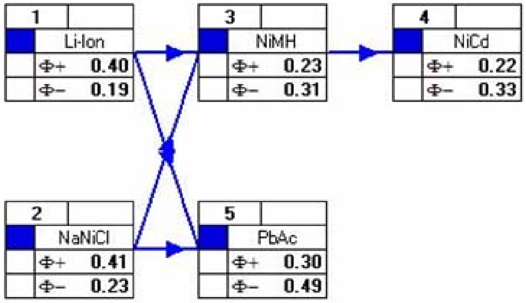
APPENDIX VI

| | BEV | HEV |
|---|---|---|
| Consumers |  |  |
| Manufacturers |  |  |
| Politicians |  |  |

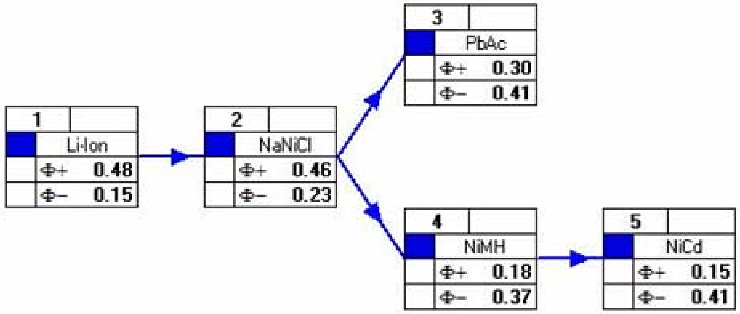
# Results BEV 2005

APPENDIX VI

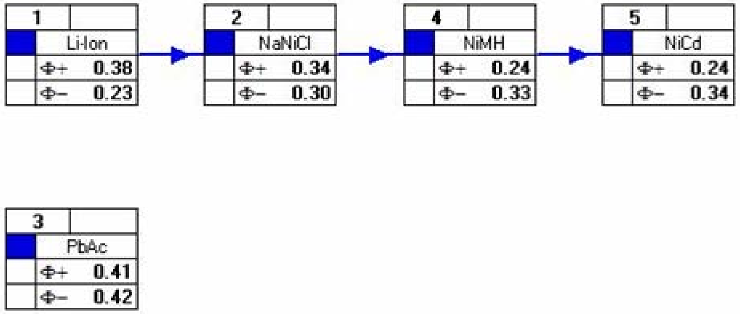
**Consumer**



**Political**

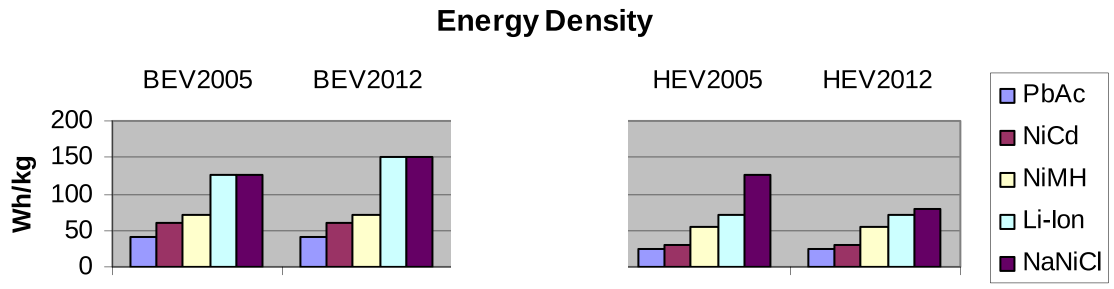


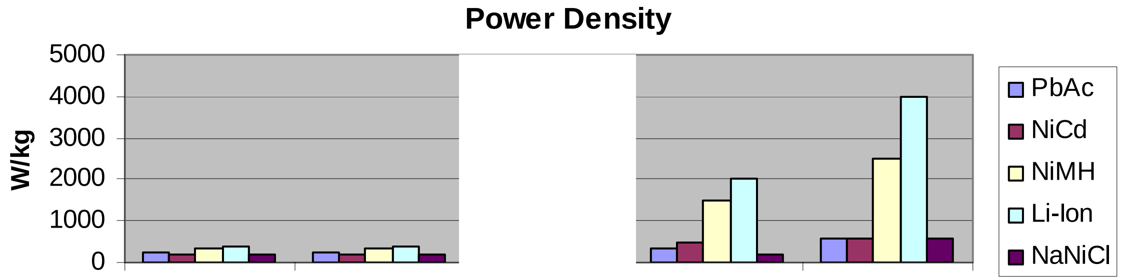
**Manufacturer**



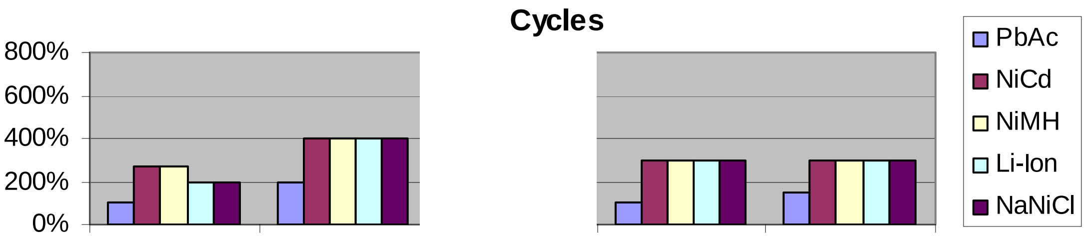
# Criteria: Technical Parameters

APPENDIX VI

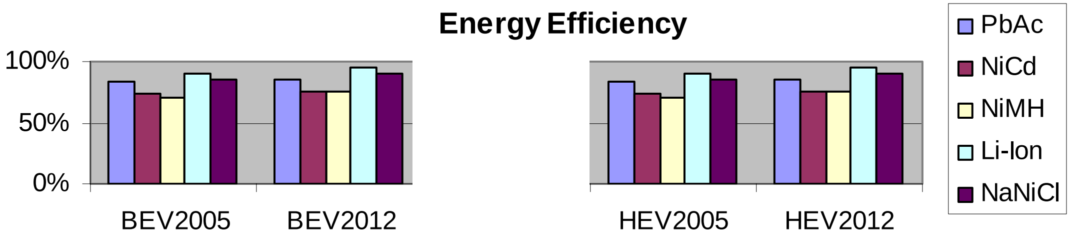




BEV: relative values cycles (ref: Pb-acid = 500 cycles)

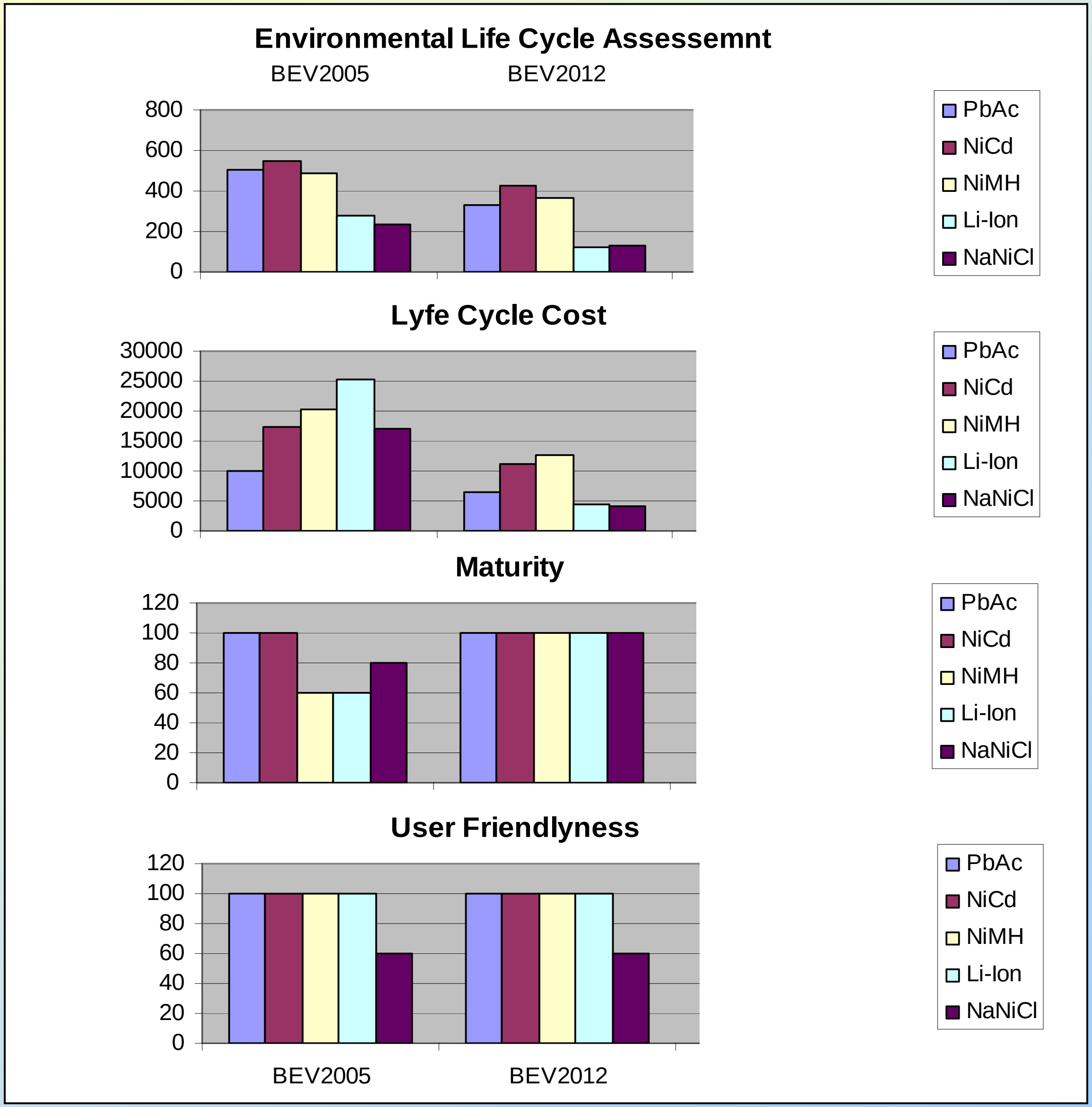


HEV: relative values cycles (ref: Pb-acid = 100%)



# Criteria: Envir. & Econ. Parameters

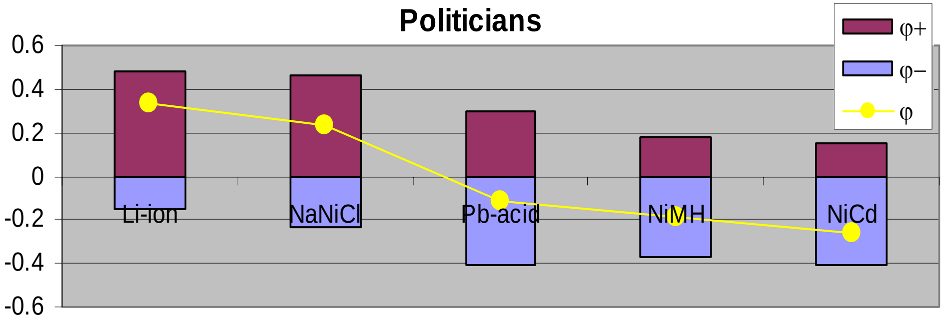
APPENDIX VI

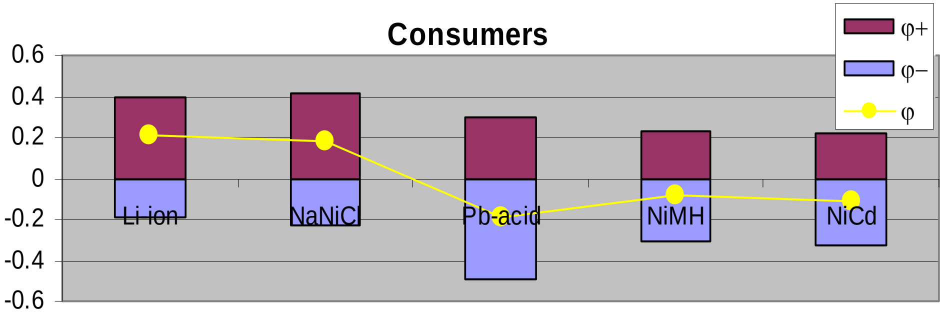


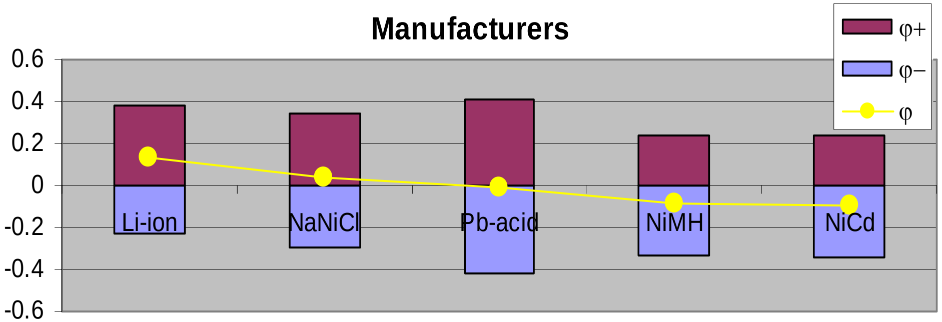
# Conclusions Overall Assessement

APPENDIX VI

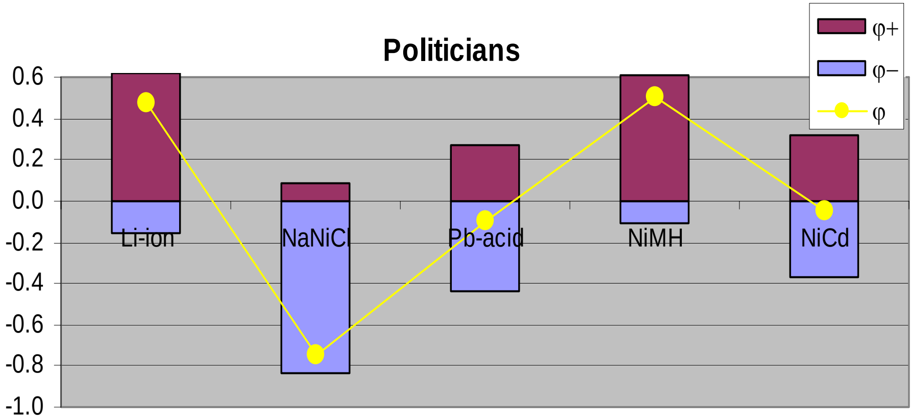
## Battery Electric Vehicle 2005

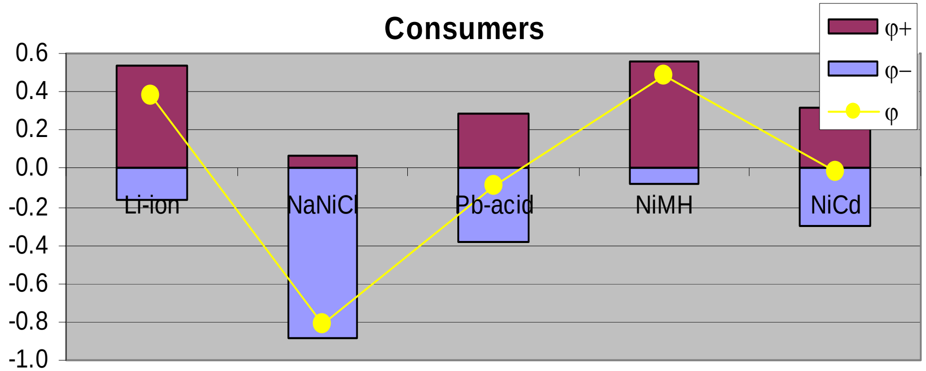

Politicians

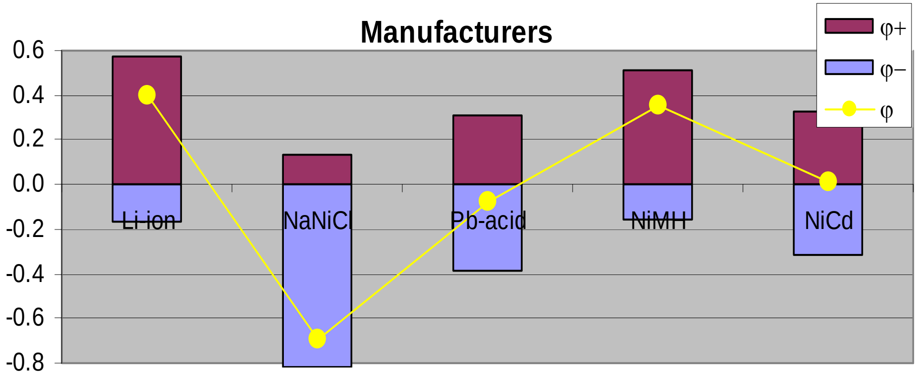

Consumers


Manufacturers

## Hybrid Electric Vehicle 2005

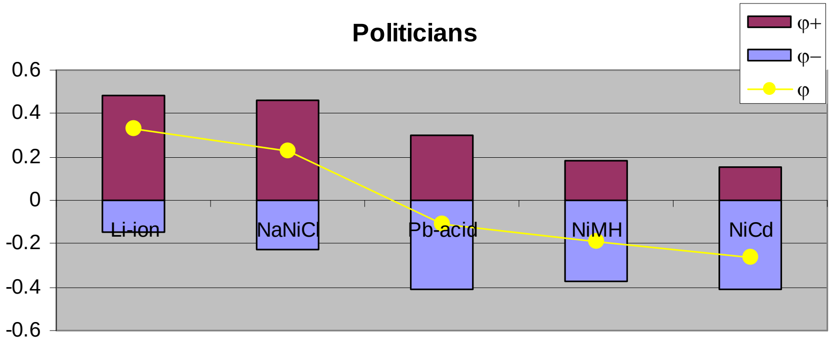

Politicians

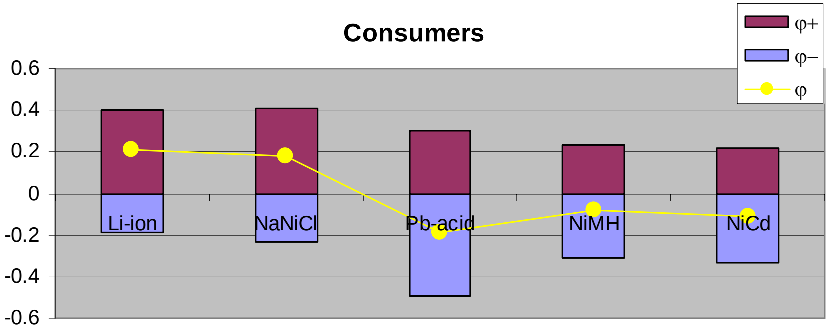

Consumers

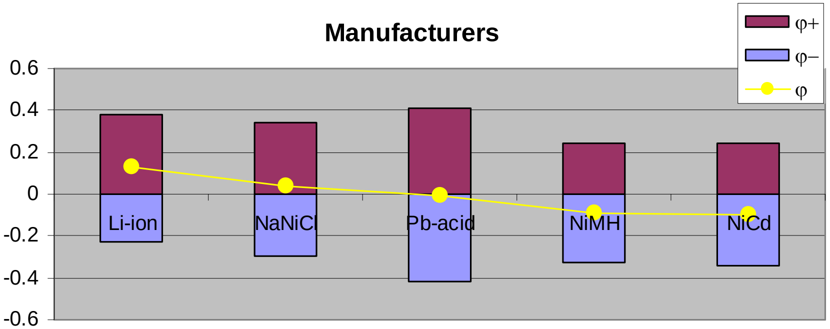

Manufacturers

# Conclusions Overall Assessement

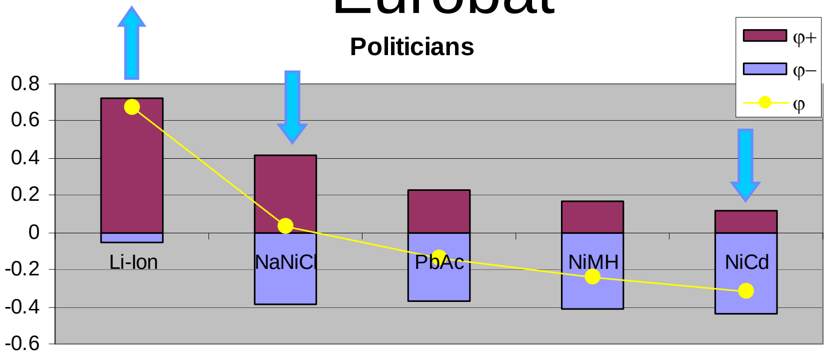
## Subat

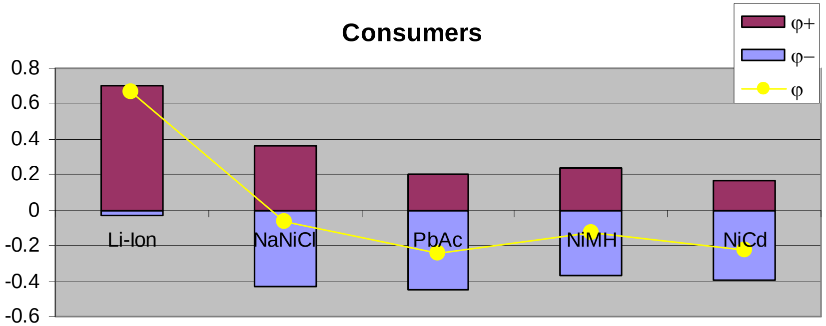

**Politicians**

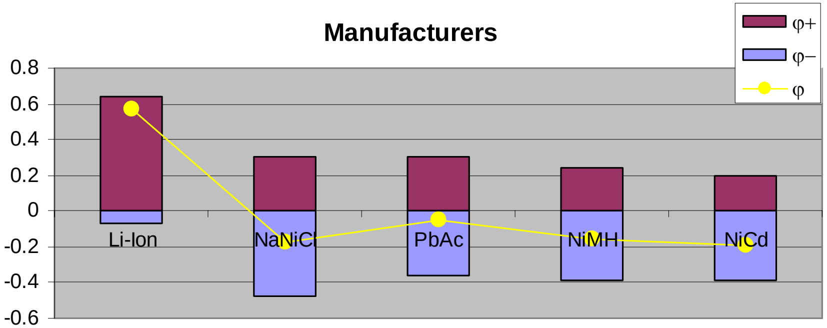

**Consumers**


**Manufacturers**

## Eurobat


**Politicians**


**Consumers**


**Manufacturers**

MCA results remain consistent independently of the chosen perspective

# Conclusions

| | φ | |
|---|---|---|
| | BEV 2005 | BEV 2012 |
| 1 | Li-ion | Li-ion |
| 2 | NaNiCl | NaNiCl |
| 3 | Pb-acid | NiMH |
| 4 | NiMH | Pb-acid |
| 5 | NiCd | NiCd |

| φ | |
|---|---|
| HEV 2005 | HEV 2012 |
| NiMH | Li-ion |
| Li-ion | NiMH |
| NiCd | Pb-acid |
| Pb-acid | NaNiCl |
| NaNiCl | NiCd |

- MCA results remain consistent independently of the chosen perspective.

# Conclusions

# Conclusions

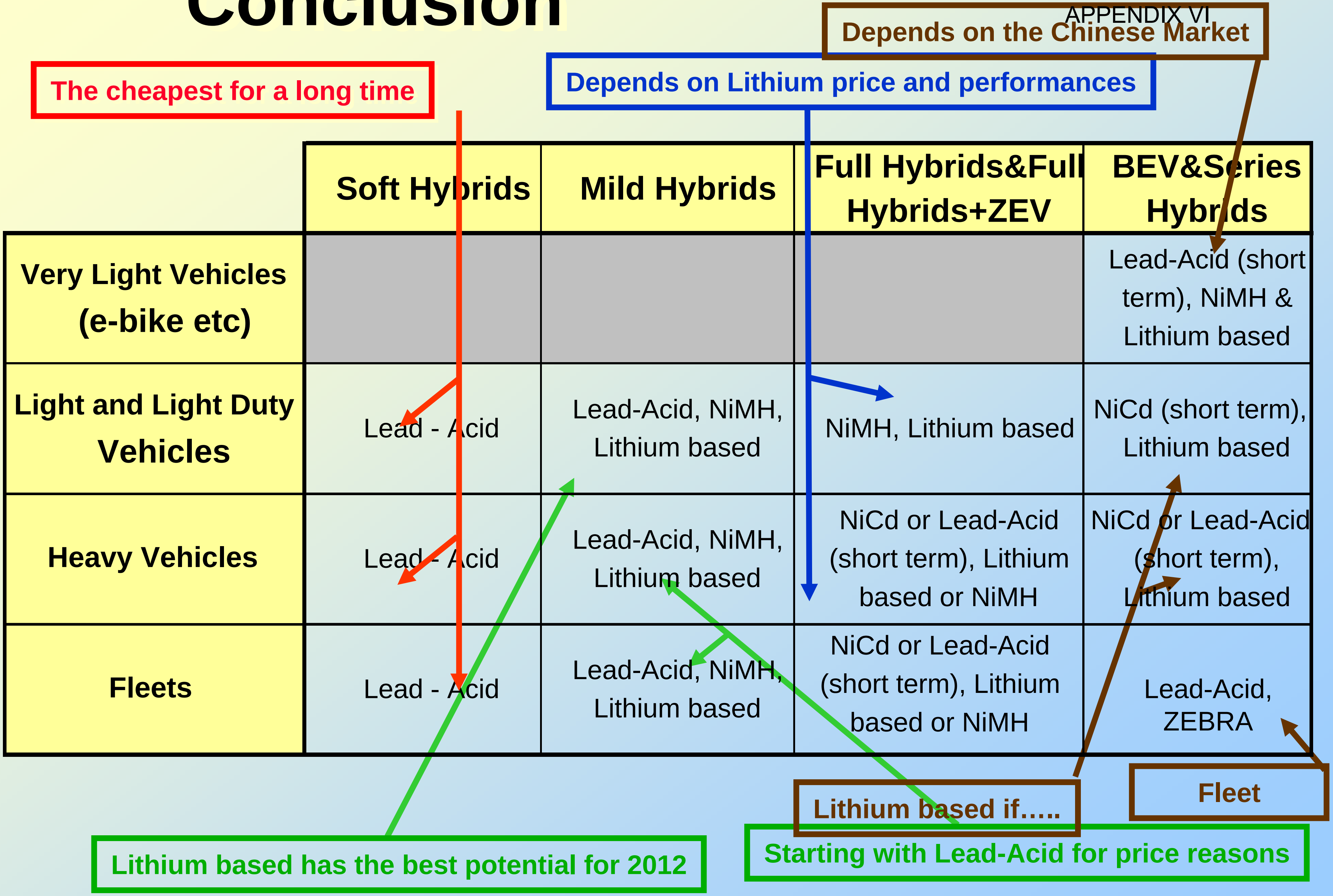
- Technical assessment
  - – Li and NaNiCl best performance
- Environmental assessment
  - – Li and NaNiCl lowest environmental impact
  - – Cd fatal production issue
- Economical assessment
  - – Pb cheapest battery for long time
  - – Li price decrease potential

# Conclusions

APPENDIX VI

- Pb
  - suited for heavy vehicles
- Ni-Cd
  - only available solution for light-duty battery-electric vehicles
- NiMH
  - for hybrid vehicles
- Li
  - available for 2010?
- NaNiCl
  - for fleet applications
- NiZn & others
  - No EV batteries available yet

# Conclusion



Depends on the Chinese Market

Depends on Lithium price and performances

The cheapest for a long time

| | Soft Hybrids | Mild Hybrids | Full Hybrids&Full Hybrids+ZEV | BEV&Series Hybrids |
|---|---|---|---|---|
| Very Light Vehicles (e-bike etc) | | | | Lead-Acid (short term), NiMH & Lithium based |
| Light and Light Duty Vehicles | Lead - Acid | Lead-Acid, NiMH, Lithium based | NiMH, Lithium based | NiCd (short term), Lithium based |
| Heavy Vehicles | Lead - Acid | Lead-Acid, NiMH, Lithium based | NiCd or Lead-Acid (short term), Lithium based or NiMH | NiCd or Lead-Acid (short term), Lithium based |
| Fleets | Lead - Acid | Lead-Acid, NiMH, Lithium based | NiCd or Lead-Acid (short term), Lithium based or NiMH | Lead-Acid, ZEBRA |

Lithium based if…..

Fleet

Lithium based has the best potential for 2012

Starting with Lead-Acid for price reasons

# More info
(public report and presentation)

http://www.battery-electric.com

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