SUBAT: SUSTAINABLE BATTERIES

Work package 5: Overall Assessment

Final Public Report

Report prepared by

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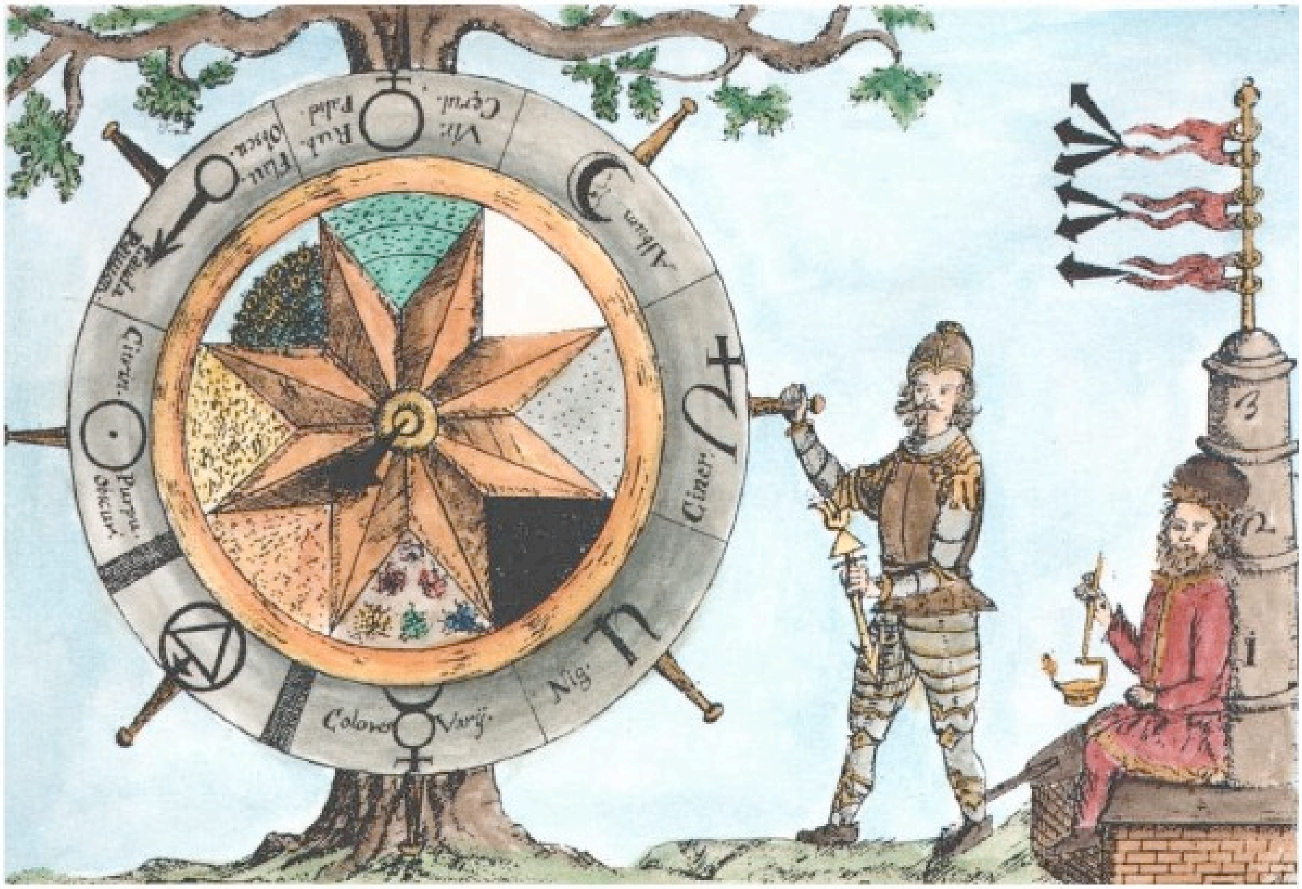

SUBAT Partnership

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.

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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.

[1] Losses due to heating

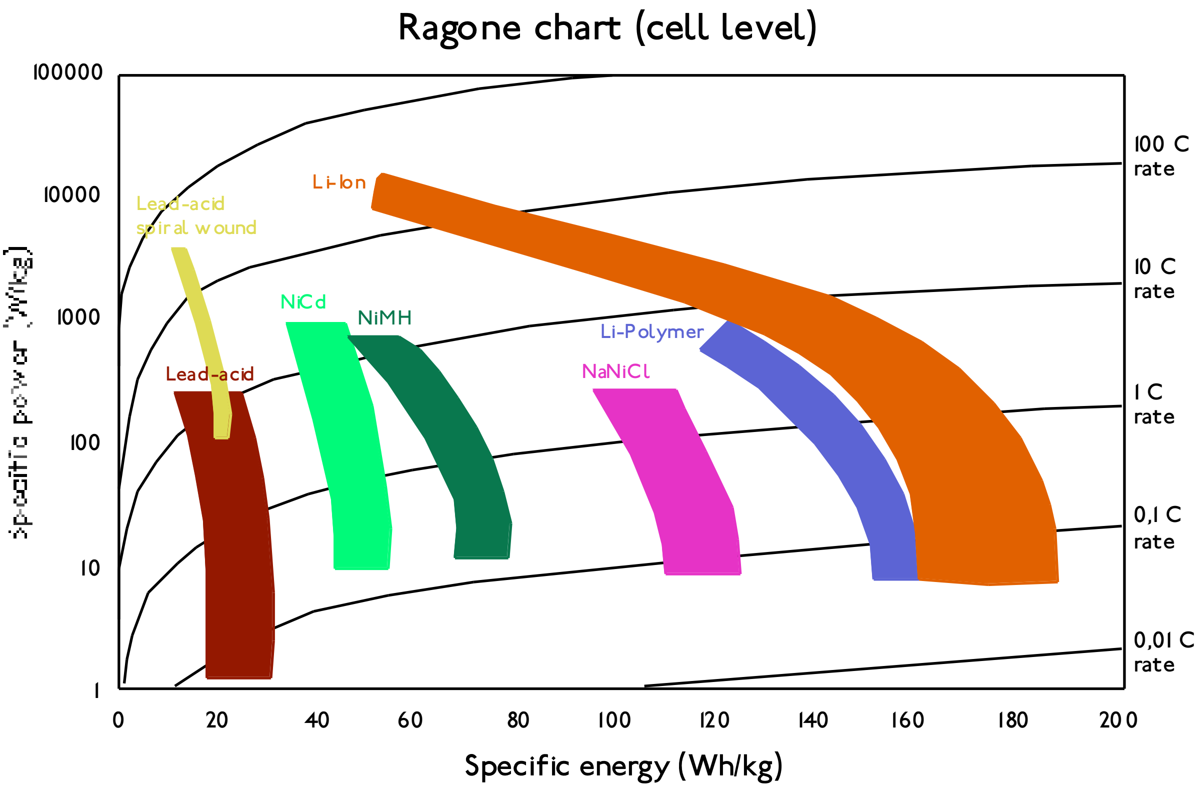


Figure 1: Ragone chart.

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 Effects: anaemia, encephalopathy, peripheral nerve disease, abdominal cramps and kidney impairment. Reproduction or development	Possibility of bioaccumulation
	Pb	N/A	Target: blood, bone narrow, central nervous system, peripheral nervous system, kidney Effects: anaemia, encephalopathy, peripheral nerve disease, abdominal cramps, kidney impairment. Effects on reproduction or development	Possibility of bioaccumulation
	H_2SO_4	Target: Eyes, skin, respiratory tract Effects: Corrosive, lung oedema	Target: lungs, teeth 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 Effects: lung oedema, metal fever	Target: lungs, kidney Effects: proteinuria, lung or kidney dysfunction, probable carcinogenic effect	
	KOH	Target: Eyes, skin, respiratory tract Effects: Corrosive, lung oedema	Target: skin 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 Effects: Corrosive, lung oedema	Target: skin Effects: dermatitis	Hazardous (especially for aquatic organisms)
Li-ion				
	$LiCoO_2$			
	$LiPF_6$	Toxic with skin Harmful if swallowed		
	DMC			
Li-polymer				

	Li	Target: Eyes, skin, respiratory tract Effects: Corrosive, lung oedema		
	V_2O_5	Target: Eyes, skin, respiratory tract Effects: irritation, lung oedema, bronchitis, bronchospasm	Target: lungs 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 Effects: irritation	Target: lungs, central nervous system Effects: increase susceptibility to bronchitis, pneumonitis and neurologic, neuropsychiatric disorders (manganism)	Hazardous (especially for aquatic organisms)
	KOH	Target: Eyes, skin, respiratory tract Effects: Corrosive, lung oedema	Target: skin 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:

$$\text{Range} = \frac{E_{\text{content}}}{E_{\text{consumption}}} = \frac{\text{DOD} \cdot E_{\text{specific}} \cdot m_{\text{battery}} \cdot \eta_{\text{battery}}}{m_{\text{battery}} \cdot \alpha + \beta} \qquad \textbf{(1)}$$

Where $E_{specific}$ stands for the specific energy of the battery,

$m_{battery}$ stands for the mass of the battery,

$\eta_{battery}$ stands for the energy efficiency of the battery

α and β are the 'energy' coefficients calculated with the Vehicle Simulation Programme in function of the vehicle weight (α= 0.054 and β = 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

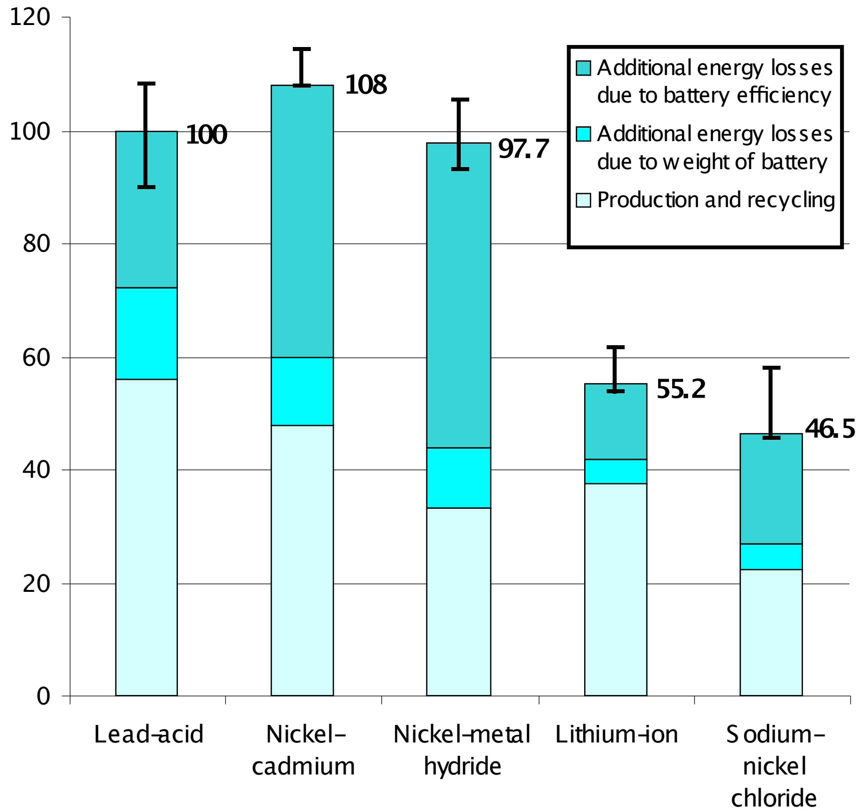


Figure 2: Graphical overview of the relative environmental scores (including the sensitivity analysis).

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

[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

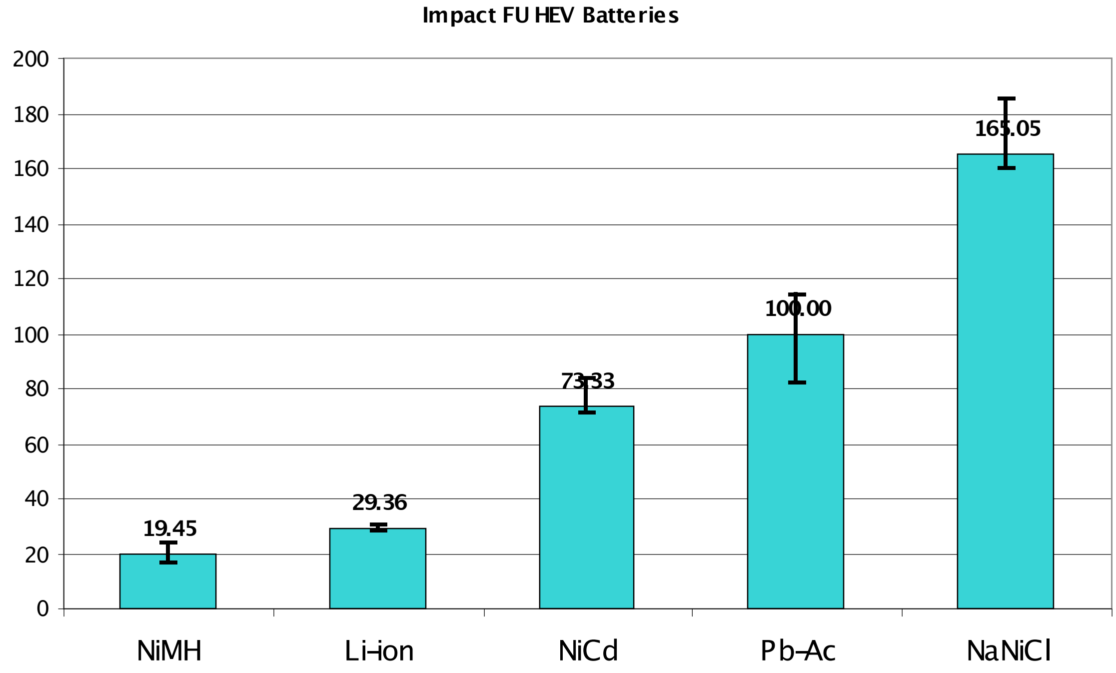


Figure 3: Graphical overview of the relative environmental scores of HEV batteries (including the sensitivity analysis).

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.

<u>Sensitivity analysis</u>

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.

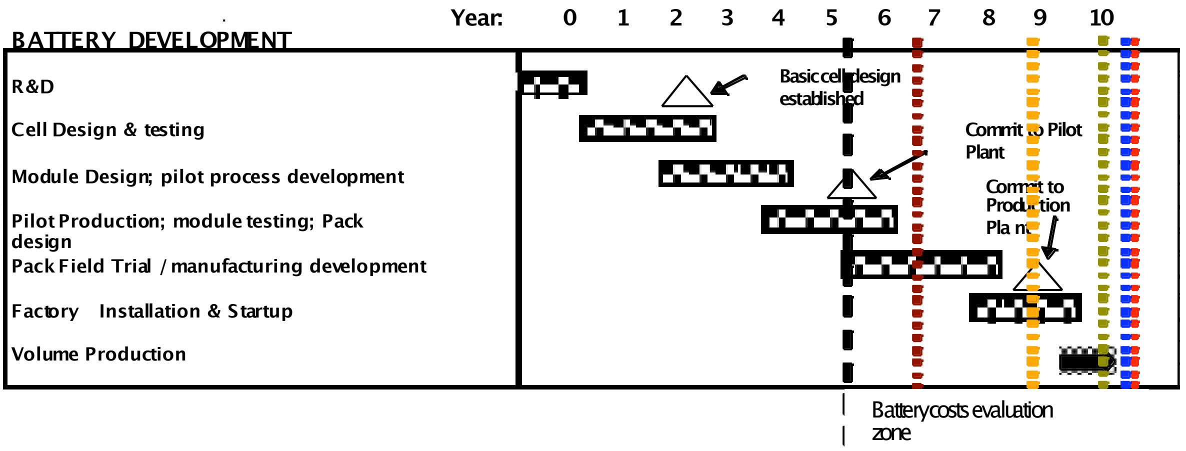
The minimum and maximum price (and cost) values have not the same meaning than usually and are function of the technology studied. In fact, most often, the maximum price value is a value taking into account the mean value of all the criteria. The minimum price value can be very different following the 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)

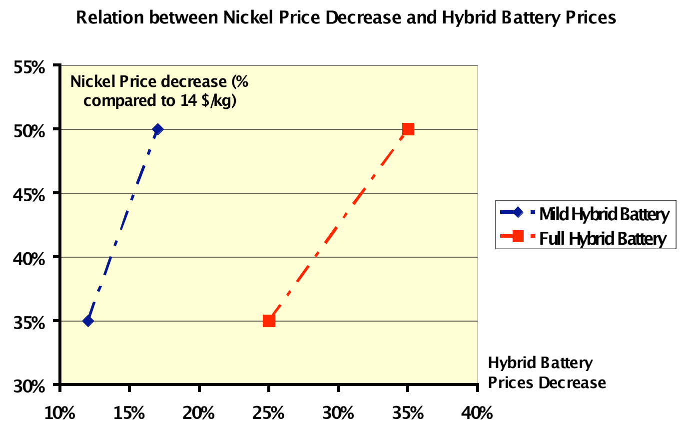


Figure 5 : Relation between Nickel Price Decrease and Hybrid Battery Prices.

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 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* (φ^+ or attractiveness) the other ones, and the negative flow how much it is *dominated* (φ^- 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 (φ-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 (π, 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 π 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.

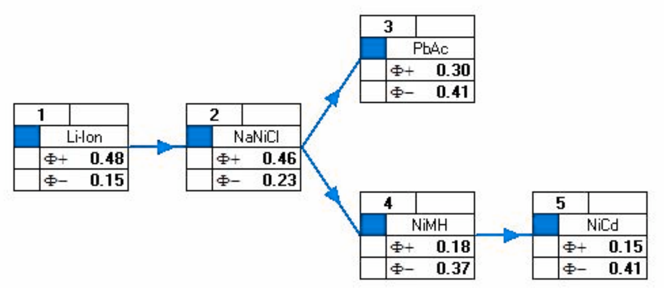


Figure 6: Partial Ranking PROMETHEE I for BEV 2005.

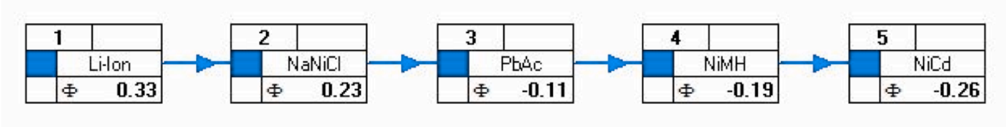


Figure 7: Partial Ranking PROMETHEE II for BEV 2005.

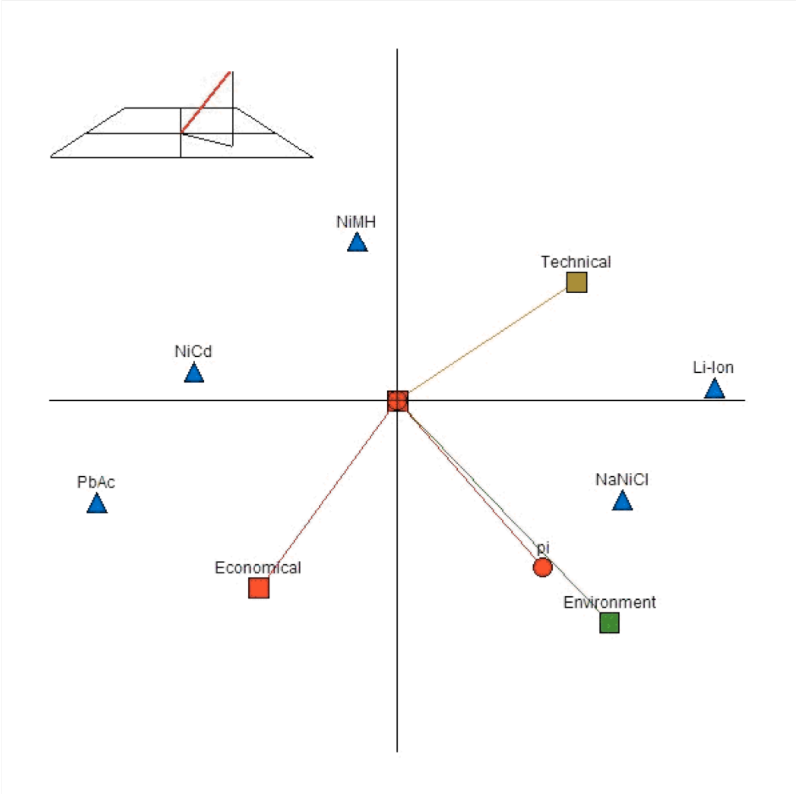


Figure 8: GAIA Plane for BEV 2005.

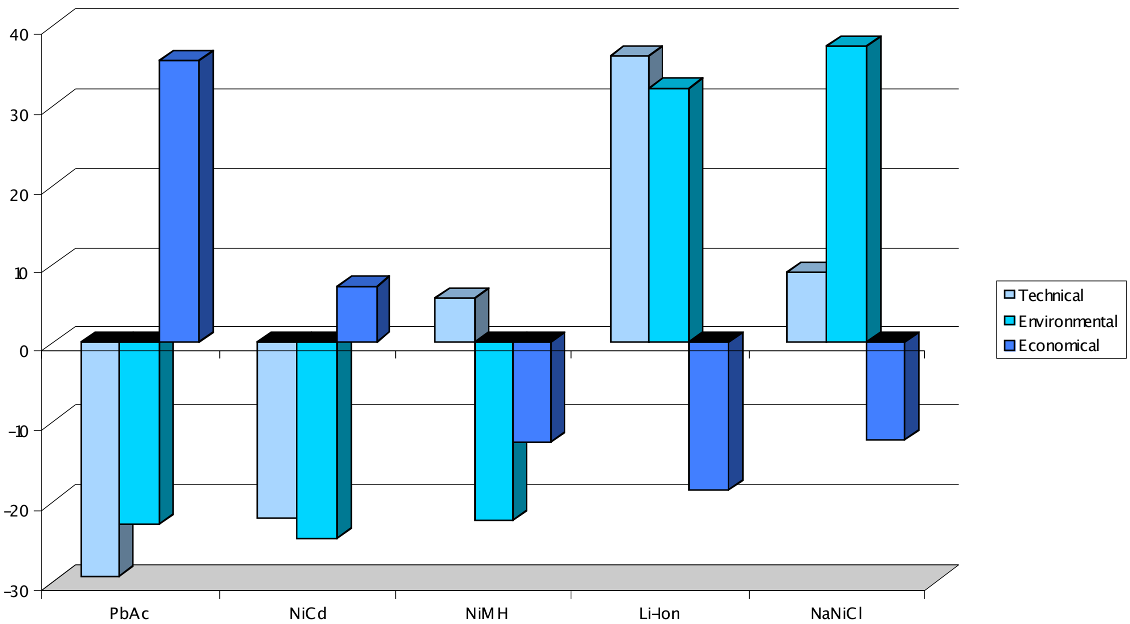


Figure 9: Action Profile BEV 2005.

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).

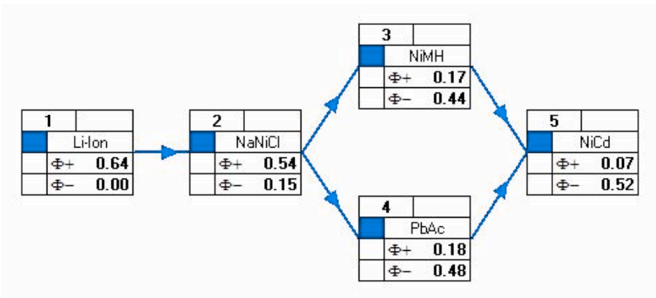


Figure 10: Partial Ranking PROMETHEE I for BEV 2012.

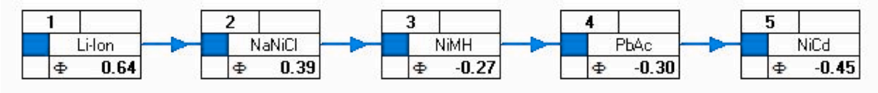


Figure 11:Complete Ranking PROMETHEE II for BEV 2012.

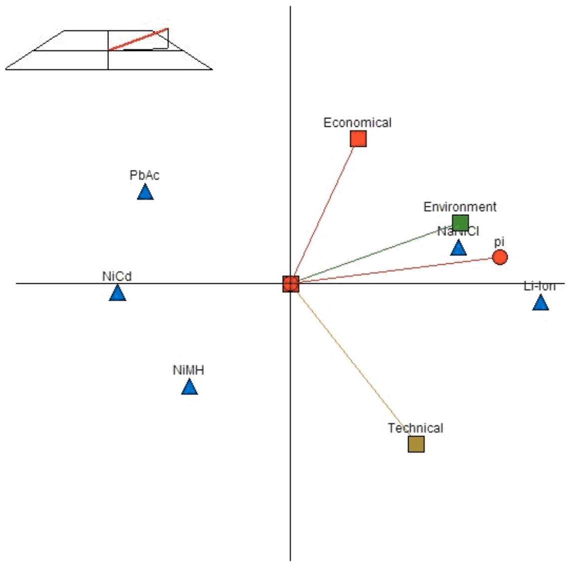


Figure 12: GAIA Plane for BEV 2012.

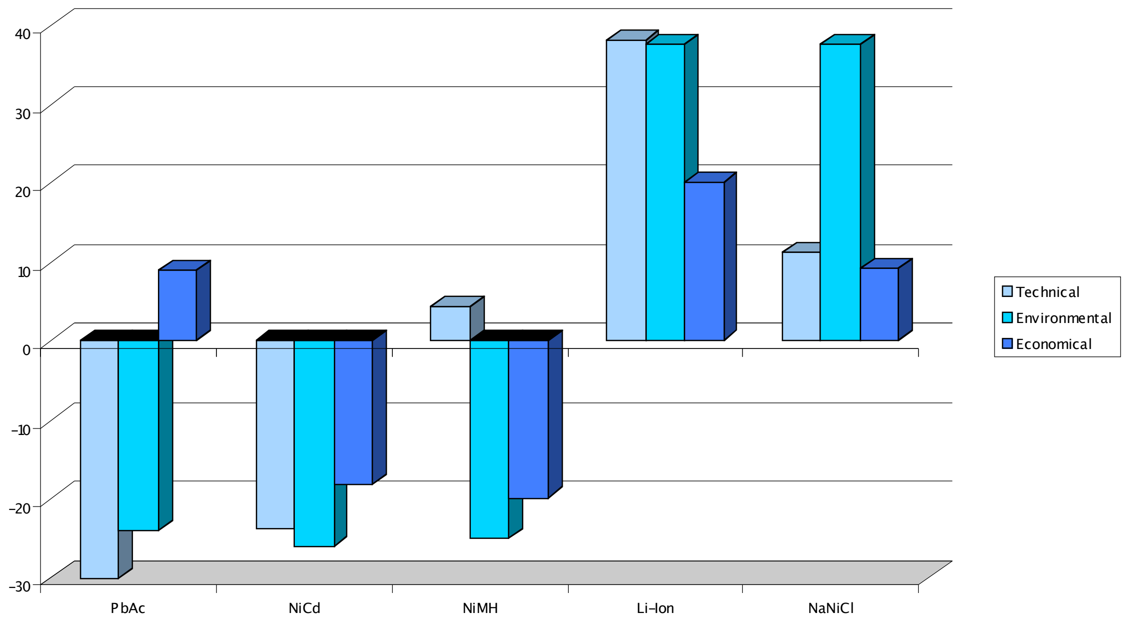


Figure 13: Action Profile BEV 2012.

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.

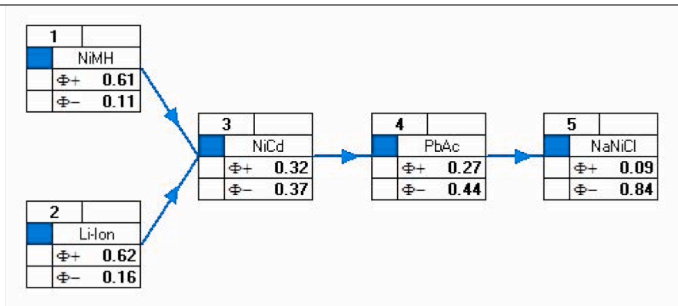


Figure 14: Partial Ranking PROMETHEE I for HEV 2005.

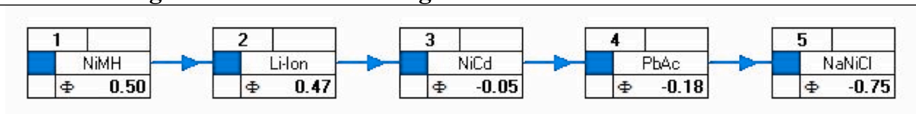


Figure 15: Complete Ranking PROMETHEE II for HEV 2012.

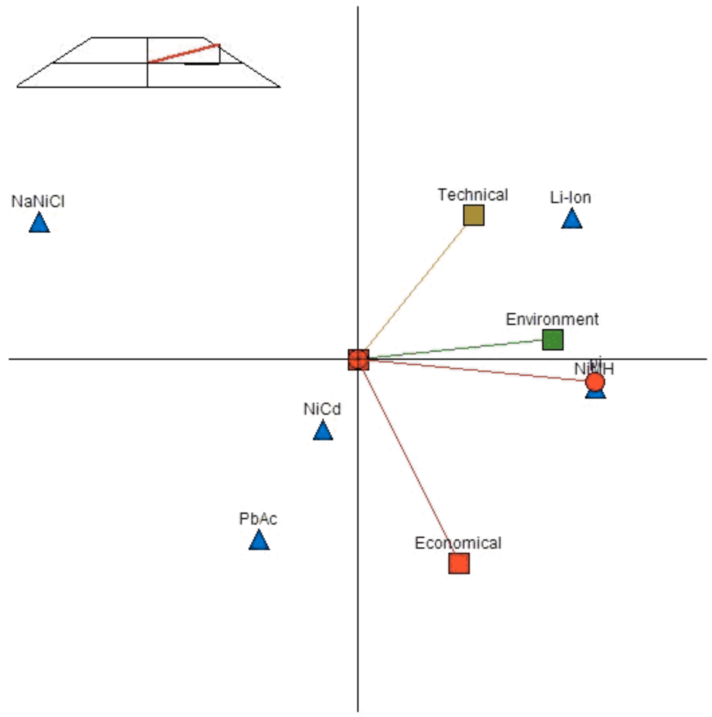


Figure 16: GAIA Plane for HEV 2005.

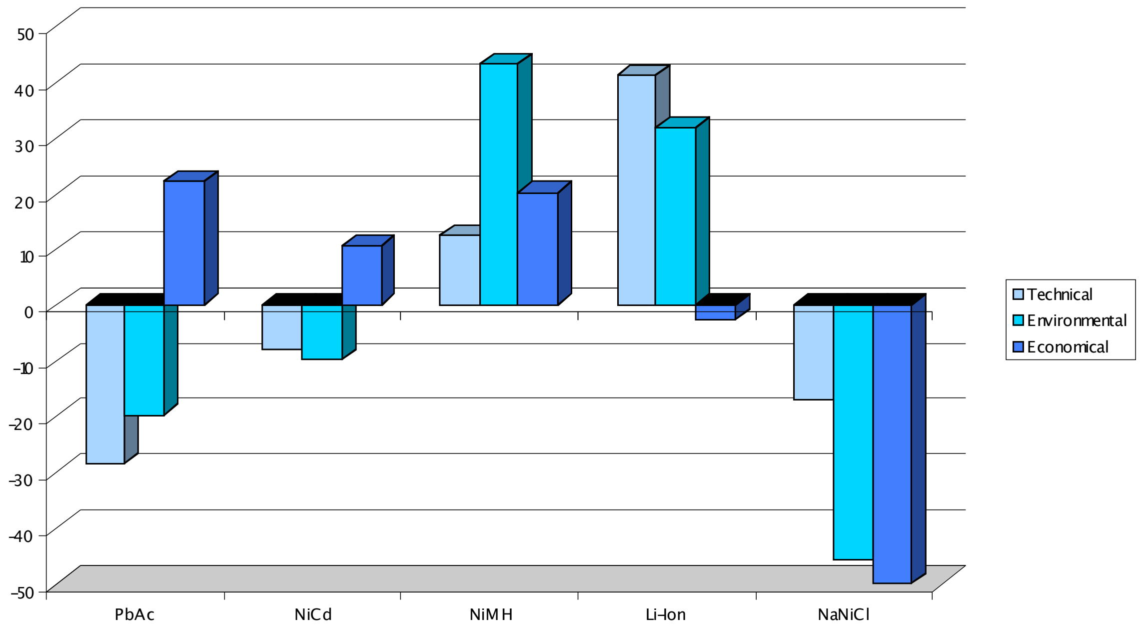


Figure 17: Action Profile for HEV 2005.

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.

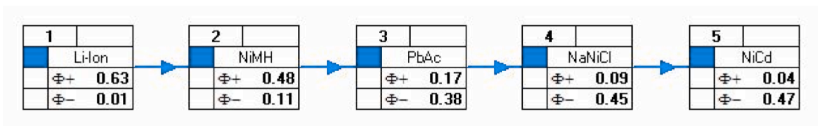


Figure 18: Partial Ranking PROMETHEE I for HEV 2012.

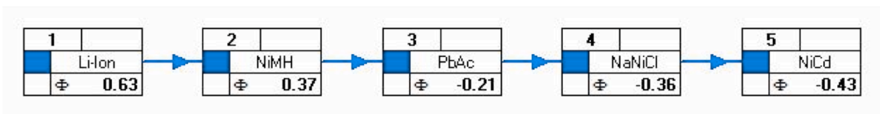


Figure 19: Complete Ranking PROMETHEE II for HEV 2012.

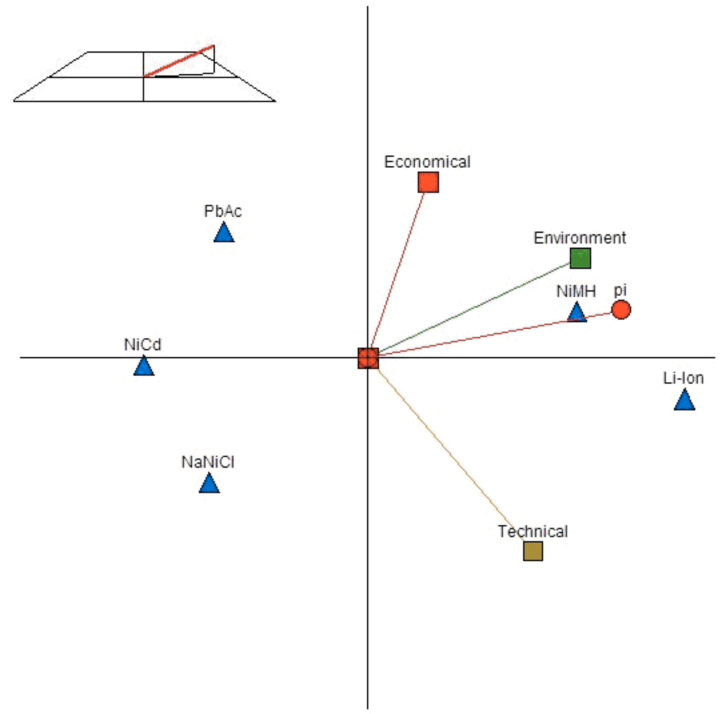


Figure 20: GAIA Plane for HEV 2012.

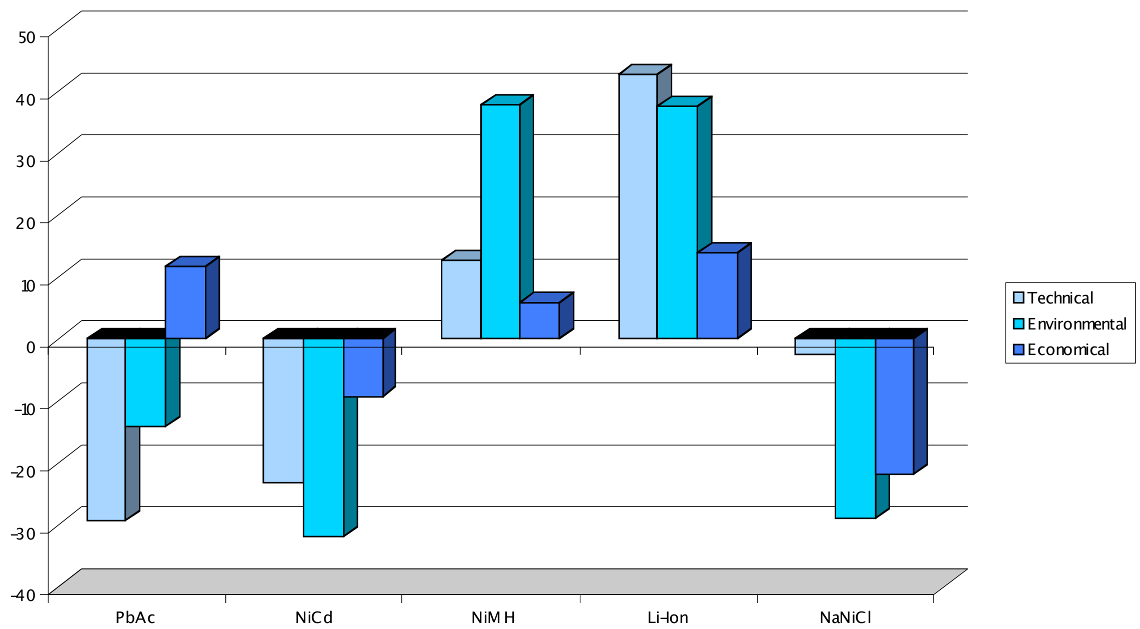


Figure 21: Action Profile for HEV 2012.

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.

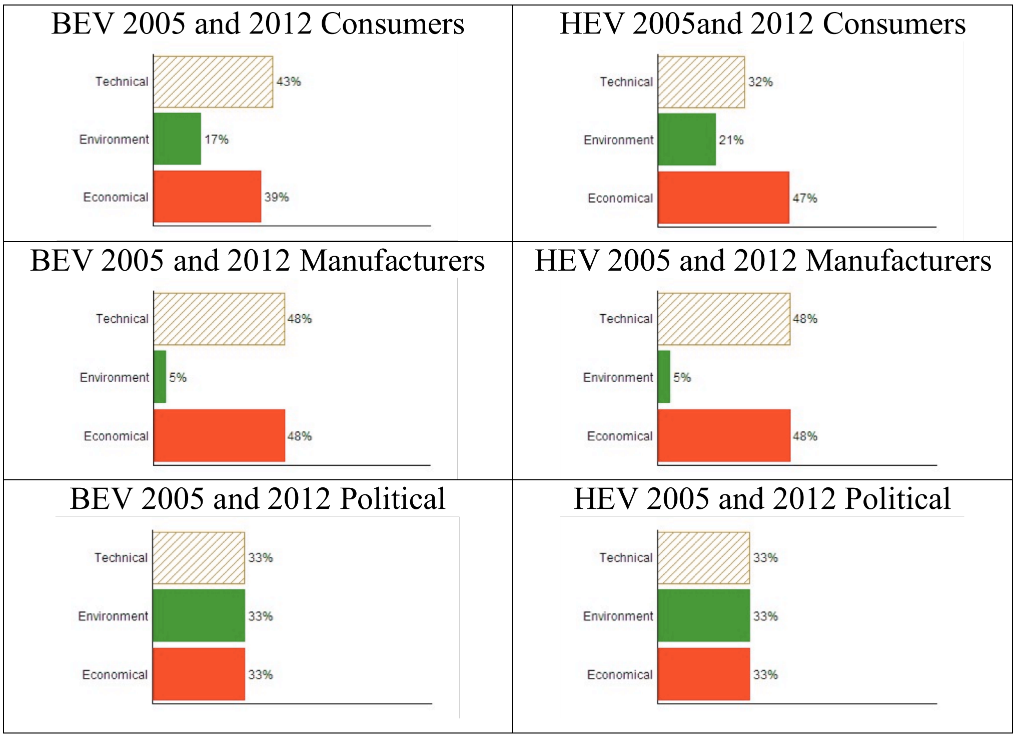


Figure 22: Importance allocated to the technical, environmental and economical criteria for the different stakeholders.

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 economical and technical categories are identical. The weighting of the different criteria within each category is identical for the manufacturer perspective and for the political perspective.

V.3.3. Results.

The output of the MCA regarding the consumer perspective and the car manufacturer perspective is presented in this section. The input data describing the battery characteristics of the political perspective are independent of the perspectives and have been kept identical for these perspectives. The input data can be seen in the previous section of the report (§V.2). The results of the political scenario are shown as well to enable the reader to compare and discuss the outputs of the different perspectives in an easy way. The partial ranking PROMETHEE I is the only graphical output shown in this section. The other graphs (PROMETHEE II, GAIA plane, Actions Profiles) can be found in appendix 1.

It should be mentioned that the results presented in this chapter are valid taking the specific boundary conditions related to each WP into account and are presented and discussed in this context.

V.3.3.1. BEV 2005.

The PROMETHEE I graphical output for the different perspectives for BEV in 2005 are shown in Figure 23.

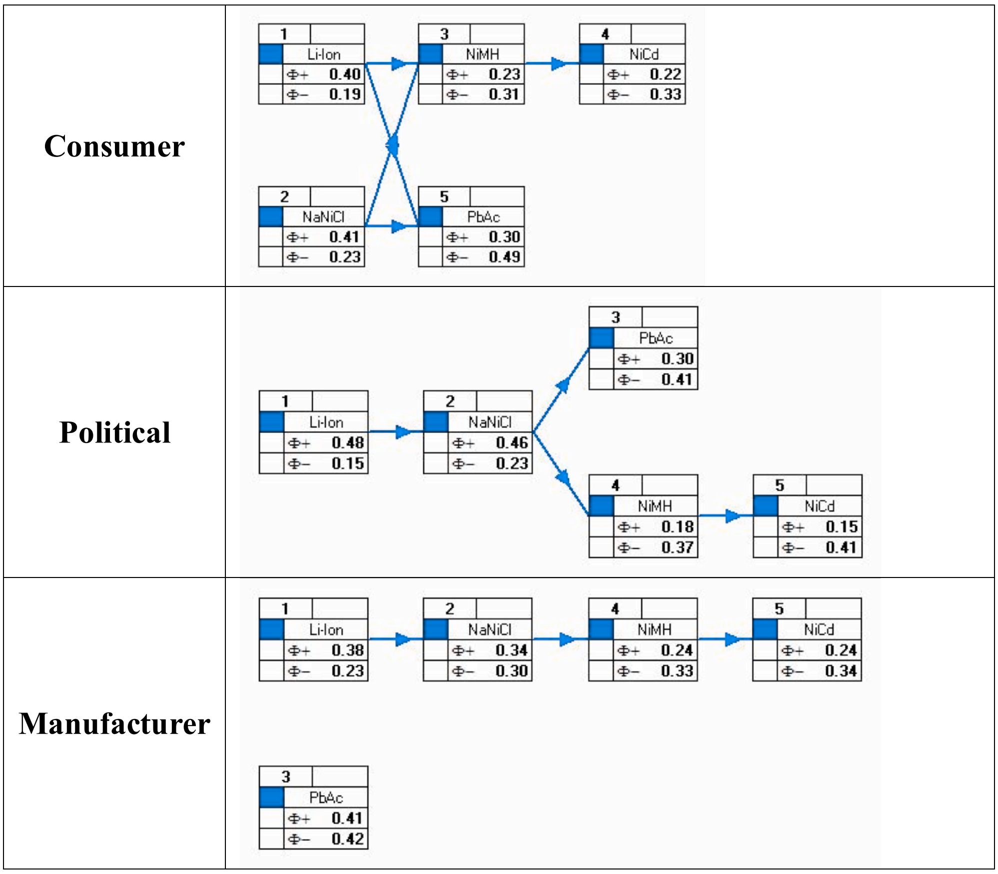


Figure 23: PROMETHEE I results for different perspectives for BEV 2005

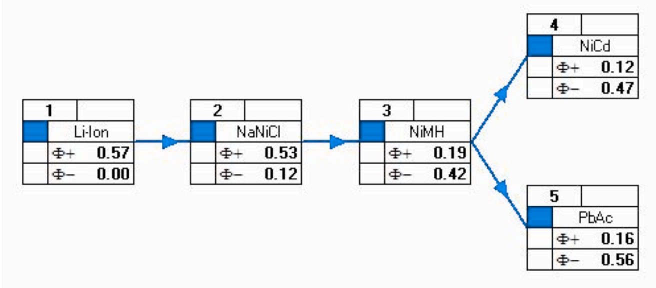
The PROMETHEE I method couldn't classify lead-acid in the manufacturer perspective, as lead-acid is strongly preferred to the other technologies and the other technologies are strongly preferred over lead-acid for other criteria as well. In the PROMETHEE II method the lead-acid ranks between sodium-nickel 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.

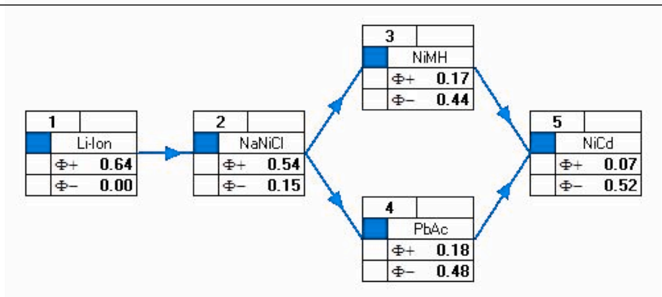
V.3.3.2. BEV 2012.

The PROMETHEE I graphical output for the different perspectives for BEV in 2012 are shown in Figure 24.

Consumer



Political



Manufacturer

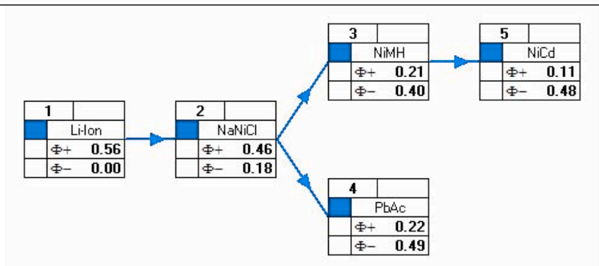


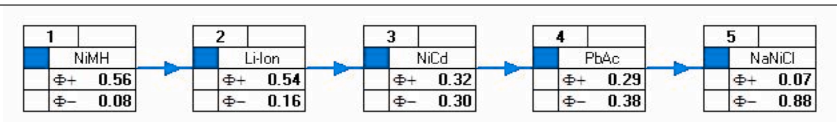
Figure 24: PROMETHEE I results for different perspectives for BEV 2012

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



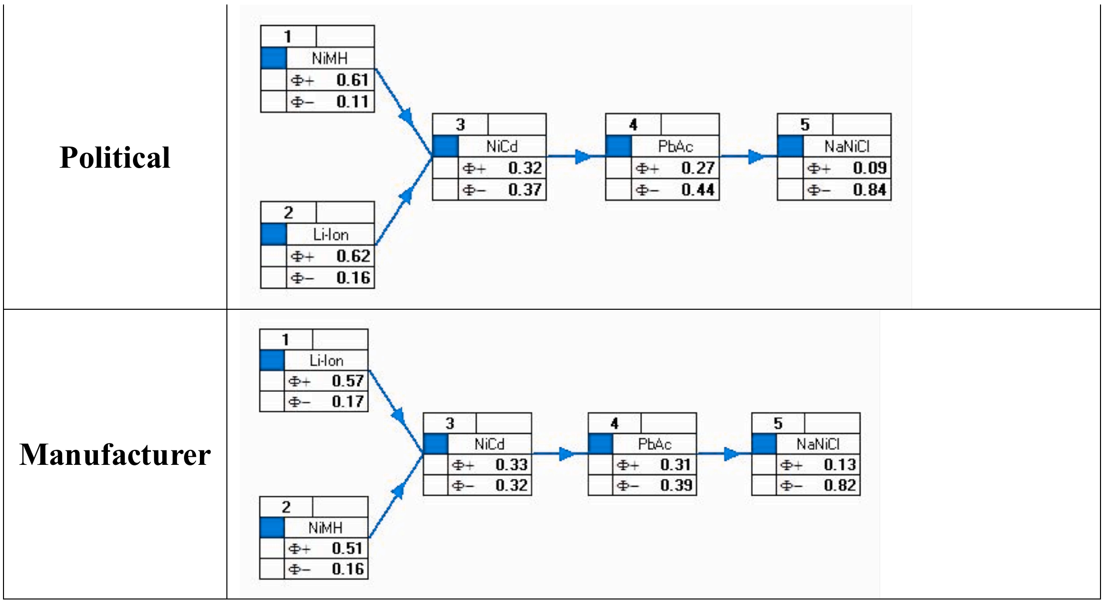


Figure 25: PROMETHEE I results for different perspectives for HEV 2005

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.

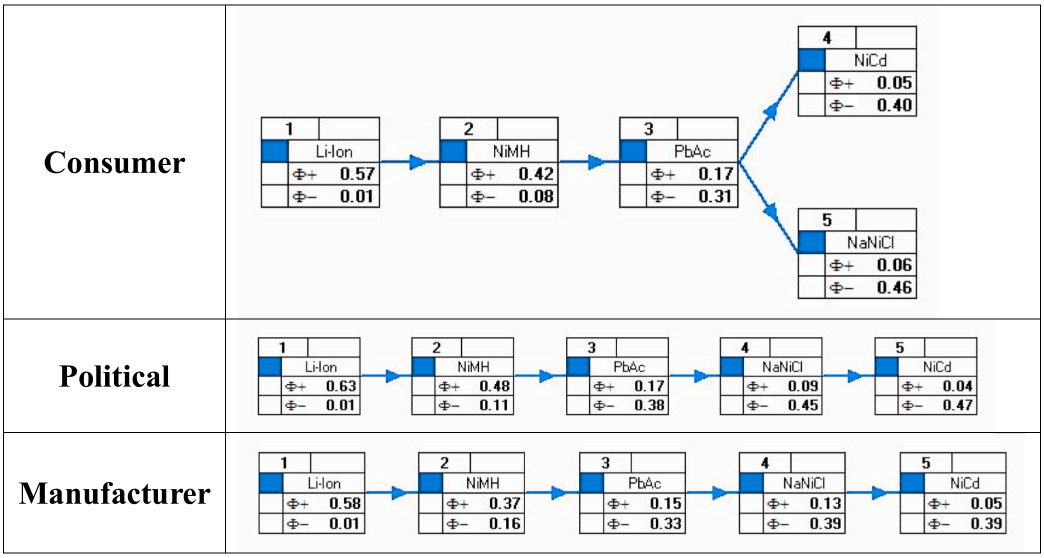


Figure 26: PROMETHEE I results for different perspectives for HEV 2012

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** ~~40~~	250	**700** ~~500~~	83	*512*	*8576*	100	100
NiCd	**40** ~~60~~	200	**2000** ~~1350~~	73	*607*	*12350*	100	100
NiMH	**55** ~~70~~	**250** ~~350~~	**2000** ~~1350~~	70	*494*	*14016*	60	100
Li-ion	**110** ~~125~~	400	**3000** ~~1000~~	**93** ~~90~~	*164*	*8489*	60	100
NaNiCl	**100** ~~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.

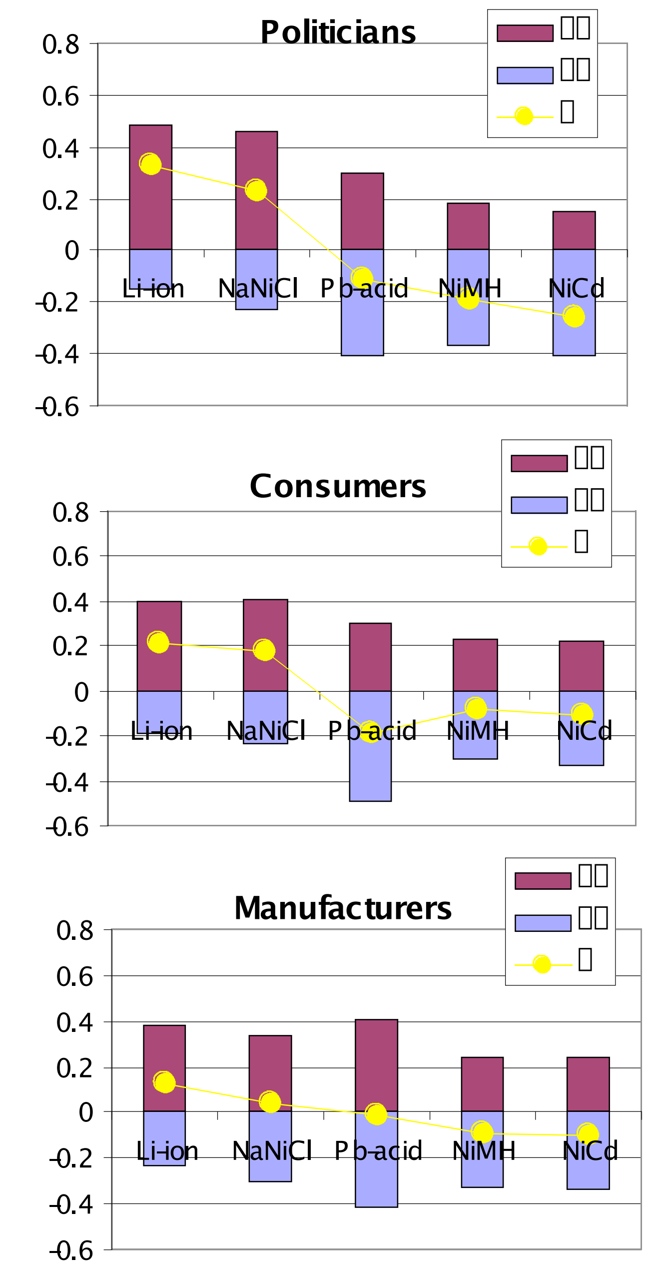


Figure 27: Graphical overview of the results for BEV batteries (in 2005) based on the Subat data.

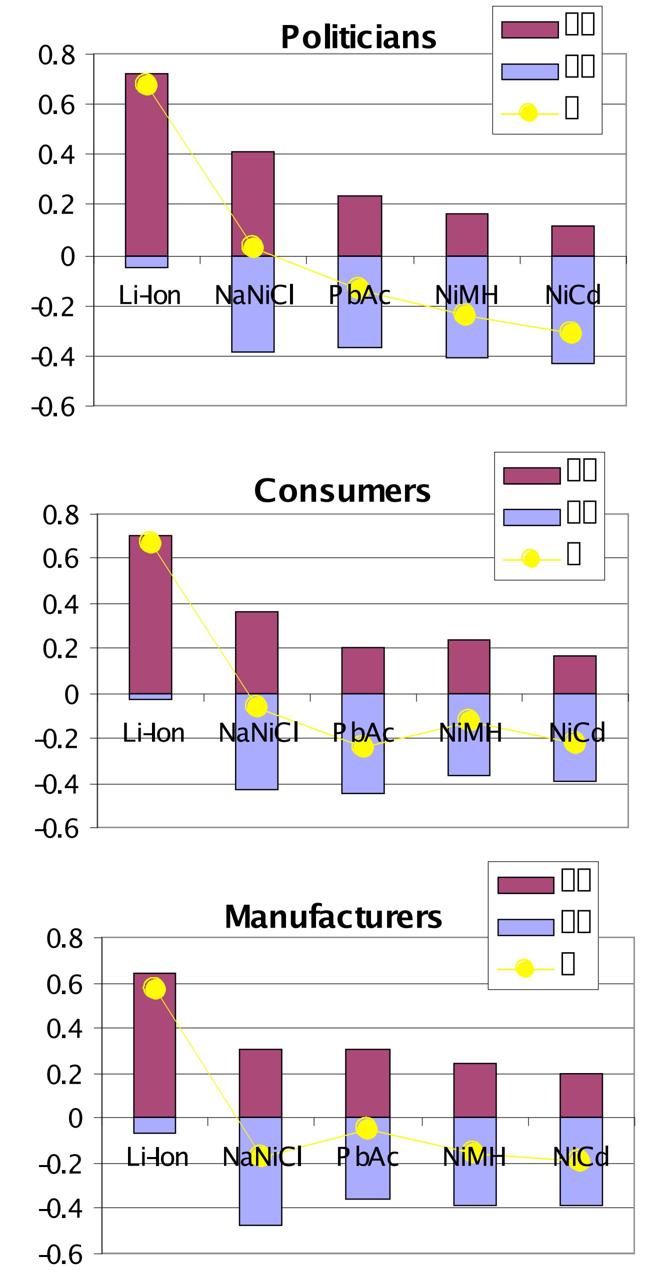


Figure 28: Graphical representation of the results for BEV batteries (in 2005) based on the Eurobat data.

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 influence on the price and thus on the market penetration of these applications.

The price of the battery is largely influenced by the market prices of its composing metals as well as by the production-scale. The Li-ion technology is the most promising technology when it comes to the increase of the production scale, as the others have already reached a large-scale production.

Considering only the economical aspect, the NiCd technology remains the only usable technology for BEV in the short term, the other prices remaining too high for an industrial application.

The number of replacements as well as the quantity of batteries required to obtain a battery capable of delivering a certain payload determines the price/cost. As a consequence, the price/cost of a battery is not just equivalent to the price/cost per kWh or per kW, but is linked to the performances of the specific battery technology (number of cycles, specific energy, specific power, etc.).

- Overall comments

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 and of road transportation in general.

As a consequence, the will to improve the environmental friendliness of transportation (by improving the environmental friendliness of batteries for electric vehicles) should not discourage the electric vehicle manufacturers. And some time should be provided to the vehicle manufacturers to adapt their production modes and to integrate some more environmentally sound battery technologies in their vehicles. During the discussion the consortium had with various stakeholders, this cannot be performed within about 5 years.

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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 capacity 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 energy content E (kWh), this is the amount of energy the battery can store like the capacity dependent on the discharge current;

d. The specific energy, (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 energy density, expressed in watt-hours per litre (Wh/l). This is a measurement for the battery volume in function of the energy content.

f. The specific power, (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 internal resistance, (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 energetical efficiency is the ratio of the discharged energy (Wh) and the energy necessary to bring the battery back to its initial state of charge:

The ampere-hour efficiency, 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 charge factor, (%). 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 cycle life 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).