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SUBAT: An assessment of sustainable battery technology

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Abstract

The SUBAT-project evaluates the opportunity to keep nickel–cadmium traction batteries for electric vehicles on the exemption list of European Directive 2000/53 on End-of-Life Vehicles. The aim of the SUBAT-project is to deliver a complete assessment of commercially available and forthcoming battery technologies for battery-electric, hybrid or fuel cell vehicles. This assessment includes a technical, an economical and an environmental study of the different battery technologies, including the nickel–cadmium technology. In a general perspective, the impacts of the different battery technologies should be analysed individually to allow the comparison of the different chemistries (lead–acid, nickel–cadmium, nickel-metal hydride, lithium-ion, sodium–nickel chloride, . . .) and to enable the definition of the most environmentally friendly battery technology for electrically propelled vehicles.

The project officially ran from 2004-01-01 to 2005-03-31. This paper summarizes the outcome of the project at the time of the submission of the paper, i.e. January 2005.

Keywords: Batteries; Electric vehicle; LCA; Environment

1. Introduction

In urban traffic, due to their beneficial effect on environment, electric vehicles are an important factor for improvement of traffic and more particularly for a healthier living environment [1]. This is the case independently of the electricity production mix and is even more beneficial when using renewable energy sources [2]. When analysing electric vehicles, the battery is often considered to be the main environmental concern, be it pertinent or not. Anyhow, the environmental impact of the battery should be assessed. To this effect, the SUBAT project [3] has been performed in the context of the European Sixth Framework Programme. The main aim of SUBAT is to assess different types of traction batteries from a technological, ecological and economical point of view.

Because the main environmental impact can lie in different life stages for different products, an overall approach is a must when wanting to obtain an appropriate assessment. The most adapted approach to compare the overall environmental burden of the different battery technologies is the life cycle analysis.

The first step of the analysis was to study the available technologies for battery and hybrid electric vehicle appliances.

Afterwards, a model for the different battery types has been developed and introduced in the Simapro® 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.

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The final step is the compilation of these results to obtain an overall environmental score for each battery type. The attribution of these scores is only possible after normalisation and weighting of the intermediate results. The overall scores of the different batteries have been calculated, and the different battery technologies can be ranked according to their environmental performances. The main difficulty encountered while performing this study was the gathering of appropriate, comparable and accurate data.

Finally, to demonstrate the robustness of the results, a sensitivity analysis has been performed.

2. Technical assessment

2.1. Overview of battery types

2.1.1. Lead–acid

Lead–acid represents the oldest and best known electrochemical couple. For vehicle use, it strongly dominates the market of SLI batteries, and is also the most widely used battery for industrial electric vehicles such as fork lift trucks and the like. The main advantage of the lead–acid battery is its low cost compared to other battery types.

For electric road vehicles however, lead–acid presents a considerable drawback due to its low specific energy of typically 30 Wh kg^{-1}. Advanced battery designs allowing a higher specific energy have been proposed. However, in general these have a much shorter life. Lead–acid is thus less suitable for advanced high-performance battery-electric vehicles, although it will most likely be used for many years to come in low-speed vehicles such as “neighbourhood electric vehicles”, milk floats, etc.

Lead–acid batteries can be manufactured focusing on high power output, particularly the so-called spiral wound types. Such batteries have been proposed in a number of hybrid vehicle designs.

2.1.2. Alkaline batteries

A second family of batteries are nickel-based and use an alkaline solution as electrolyte. For the considered application fields, this family consists of nickel–cadmium, nickel metal hydride and nickel–zinc.

2.1.2.1. Nickel–cadmium. The nickel–cadmium battery presents interesting options for traction purposes: a specific energy nearly twice as high as the lead–acid batteries (50 Wh kg^{-1} compared to 30 Wh kg^{-1}), availability of fast charging, good specific power (batteries can be designed specifically for high-power applications) and a good cycle life. Nickel–cadmium batteries equip most of the electric road vehicles currently being manufactured and used in Europe. Their main drawback is their high purchase cost. The environmental concerns about the presence of cadmium in this battery are extensively covered in Work Package 2 of the SUBAT project.

2.1.2.2. Nickel-metal hydride. The nickel-metal hydride battery has comparable performances to the nickel–cadmium; it uses special alloys instead of cadmium however. These batteries, in a power-optimized version, are now fitted to commercialized hybrid vehicles such as the Toyota Prius. Nickel-metal hydride batteries optimized for energy content and specifically designed for battery-electric vehicles, or for hybrid vehicles with a considerable emission-free range, have been developed but are not very widely available in Europe.

2.1.2.3. Nickel–zinc. The nickel–zinc battery presents superior properties as to its specific energy (due to its higher cell voltage compared with other alkaline couples), but is hampered by short cycle life due to dendrite formation. At this moment, research is being performed towards improved nickel–zinc batteries; this research however is still focusing on the cell and module level and no full batteries for electrically propelled vehicle applications are available today.

2.1.3. Lithium batteries

With its potential for high specific energy (up to 2000 Wh kg^{-1}) and specific power values, the lithium battery has been hailed as a promising battery solution for the future. The lithium technology can be concretised in several versions, the most interesting for traction purposes being the lithium-ion and the lithium–polymer batteries. Lithium batteries have been fitted in several prototype vehicles.

Although the lithium batteries are now on the brink of series production, further optimisation as to life, system safety and stability and production cost is still being performed, and today, the lithium systems cannot be considered as a commercially available product yet.

2.1.4. High-temperature batteries

Amongst the batteries with molten electrodes and a high operating temperature (around 300 °C), the sodium–nickel–chloride battery (widely known under its brand name Zebra) presents interesting opportunities for electrically propelled vehicles due to its high specific energy around 100 Wh kg^{-1}. These batteries have been successfully implemented in several electric vehicle designs.

The thermal management of the high-temperature system is integrated with the battery and presents no specific operational or safety problems; during prolonged standstill periods (exceeding 24 h) however, the battery has to be heated (typically using 100 W power) to preserve the operating temperature. This issue makes this battery more particularly suitable for intensively used vehicles in fleet applications (without long standstill periods).

2.1.5. Metal–air batteries

Metal–air batteries, such as zinc–air and aluminium–air, are not strictly secondary rechargeable electric batteries, but can rather be considered as fuel cells, which are “recharged” with new metal electrodes. This procedure is also known

Table 1
Specific power and energy of battery types

	$Wh\,kg^{-1}$	$W\,kg^{-1}$
Pb	30–25	80–300
NiCd	50–60	200–500
NiMH	60–70	200–1500
NiZn	70–80	200
NaNiCl	125	150
Li	60–150	80–2000
Zn–air	200–300	70
ZnBr	80	100

as “mechanical” recharging. These systems present a high specific energy; the specific power is rather low however. Although they have been implemented in a number of experimental fleets, the logistic burden of physically replacing electrodes (and recycling the spent ones) is a major drawback to their generalised use.

2.1.6. *Redox batteries*

Redox batteries, such as zinc–bromine, are complex electrochemical systems with circulating electrolytes. The heart of the system can be considered as a reversible fuel cell stack. Although this presents promising values for the energy density, the complexity of the system and the needs for ancillary equipment have been major drawbacks for further consideration of these couples.

2.2. *Comparison of battery types*

Table 1 gives an overview of the key technical performance factors (specific energy in $Wh\,kg^{-1}$ and specific power in $W\,kg^{-1}$) of several battery types.

In order to compare the different battery types on the level of their performances, one can make use of the so-called Ragone chart (Fig. 1), 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 foremostly need energy) and hybrid vehicles (which foremostly need power).

In this framework, one should note that the 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.

3. Methodology

3.1. *Generalities*

Life cycle assessment (LCA) allows the practitioner to study the environmental aspects and the potential impacts of a product throughout its life from raw material acquisition through production, use and disposal. The so-called “cradle-to-grave” approach makes LCA unique and useful.

LCA is one of the most efficient tools to compare the complete environmental burden of different products. This can be explained by the fact that different products may have burdens in different parts of their life cycle. For example, one product may use less resources compared to another product during the use phase, but this may be at the cost of more resources used in its production phase [4].

The life cycle assessment of a product will never be completely exhaustive; as a consequence, one can choose to which degree of detail to model the assessed life cycle. However, it should be clear that, this choice is determining the degree of precision and correctness of a study to a certain extent.

This study has been performed according to the four ISO standards specifically designed for LCA applications (ISO 14040-14043) [5].

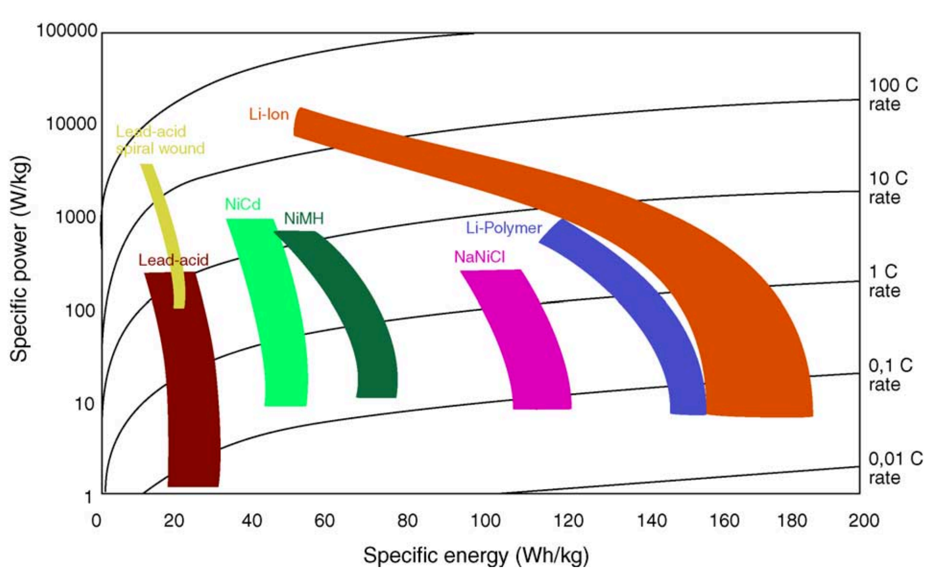

Fig. 1. Ragone chart, with Section 2.2.

3.2. Assumptions

As several products have to be compared, an appropriate functional unit has to be defined. As the different batteries have various life times, the total lifetime of the battery is not a suitable option. Many different functional units were analyzed, but in the end, it was decided to choose a functional unit corresponding to a battery enabling the car to cover a determined range, with one charge. This "one-charge range" was chosen to be 60 km when driving up to 80% depth-of-discharge. Besides this parameter, it was decided to compare the environmental impacts for a lifetime range of the car being 180,000 km, corresponding to 3000 charge–discharge cycles (80% depth-of-discharge). Depending on the technology, the required number of batteries needed for the functional unit has been determined. The considered battery originates from a car with a net weight of 888kg (excluding the battery, including the 75 kg driver). The system boundaries were defined. Concerning the assessed time period, the current state of the technology was considered. The related other life cycles (trucks, industrial buildings, electric power plants, roads, etc.) have not been considered. Self-discharge was not included for any of the assessed technologies because of the great dependence of this parameter on the way of using the vehicle. Neither was the maintenance of the batteries because of the presumption this impact is relatively small. Regarding electricity consumption, the European (EU-25) electricity production mix has been considered. It has been considered that the recycled materials have the same quality as the original data. A collection rate of 100% was assumed and a recycling rate of 95% was used for the recuperated materials (except for the lead–acid recycling technology, which exists since much longer and which is very mature, where the lead metal recycling rate is 98.3%). It was assumed that the electrolyte is neutralized before disposal (except for the lead–acid technology where 90% is recuperated and 10% is neutralized before disposal). 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 phase of the battery;
- the recycling of discarded batteries;
- the final disposal or incineration.

A schematized overview of the life cycle of a battery is shown in Fig. 2.

3.3. Impact assessment

The inventory analysis has been performed using information available in the literature, information obtained by intensively interrogating the worldwide industry and information obtained through commercially available databases. Starting from the data obtained by these means, a process tree of each stage of the life of the functional unit was drawn and these subsystems were linked to each other using mass balances.

When considering the use phase of the batteries, it can be subdivided in three parts. First of all, the use phase was studied for an ideal battery (mass = 0 kg, energy efficiency of the battery = 100%). In other words, this is the energy used to move the car (excluding the battery). In a second step, the influences of the varying masses and energy efficiencies of the different battery technologies have been taken into account. Obviously, the energy consumption of the car will vary slightly, depending on the value of the mass of the battery. These differences in energy consumption have been simulated and calculated using the Vehicle Simulation Program (VSP) [6].

LCA-practitioners have different life cycle impact assessment methods at their disposal. The methodologies often differ and the choosing of one of the methods remains an important decision [7].

In this study, the chosen LCA method is Eco-indicator 99 (hierarchist perspective), which was chosen for it is a standard and widespread methodology [8–10].

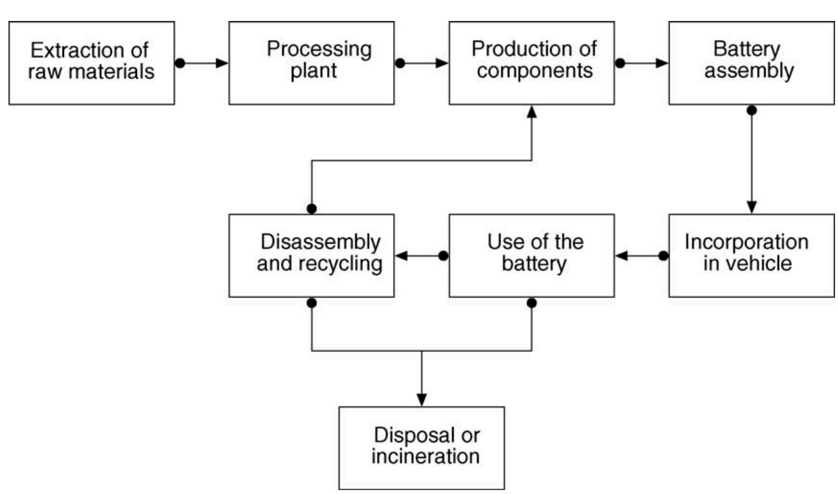

Fig. 2. The schematized life cycle of a battery, with Section 3.2.

Table 2
Battery properties

	$E_{density}$ ($Wh\,kg^{-1}$)	Number of cycles	Energy efficiency (%)	Losses due to heating
Pb-acid	40	500	82.5	
NiCd	60	1350	72.5	
NiMH	70	1350	70.0	
Li-ion	125	1000	90.0	
NaNiCl	125	1000	92.5	7.2%

The main goal of this study is to define which type of traction battery is the most appropriate for electric vehicle applications from an environmental point of view. This analysis is performed considering the complete battery life cycle. Taking the overwhelming number of calculations needed to perform an LCA into account, the use of an appropriate software package is unavoidable.

A number of battery technologies have been selected on the basis of technical and commercial interest, and have been analysed quantitatively: lead–acid, nickel–cadmium, nickel-metal hydride, sodium–nickel chloride and lithium-ion. Some important data, used to compare the battery technologies, are summarized in Table 2.

The results obtained by using SimaPro® and eco-indicator 99, are given in Eco-indicator points. Actually, one eco-indicator point is equivalent to one thousandth of the yearly environmental impact of an average European inhabitant. However, to allow an easy comparison of the environmental rating of the different battery technologies, the results were all compared to the environmental impact of the lead–acid battery, which was taken as a reference.

4. Results

4.1. Environmental impact assessment

When considering the life cycle of the batteries, it appeared that the energy losses in the battery and the energy losses due to the additional mass of the battery have a very significant impact on the environment (Table 3 and Fig. 3). 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.

Table 3
Environmental scores (eco-indicator points) of the life stages of the assessed battery technologies

	Production	Additional use (including mass and battery efficiency)	Recycling	Total
Lead–acid	1091	221	−809	503
Nickel–cadmium	861	303	−620	544
Nickel-metal hydride	945	323	−777	491
Lithium-ion	361	89	−172	278
Sodium–nickel chloride	368	122	−256	234

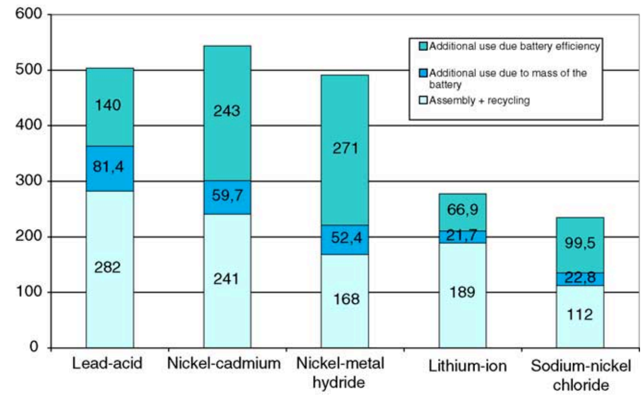

Fig. 3. Environmental impact of the assessed technologies, including the losses due to the battery during the use phase, with Section 4.1.

When looking at the rest of the environmental impact of the battery (excluding the use phase completely), it appears that the lead–acid battery has got the highest impact, followed by nickel–cadmium, lithium-ion, nickel–metal hydride and sodium–nickel chloride.

Additionally, it is noticeable that the recycling phase allows to compensate the environmental impacts of the production phase to a great extent.

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

4.2. Sensitivity analysis

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

The sensitivity analysis assessed the effects of the assumptions (concerning average battery composition, energy consumption, etc.) and of possible variations in the collected data on the results. This analysis was performed by varying the assumed parameters. These implemented variations included calculations, using different relative sizes of the components of the battery (10% more weight of one component, compensated by an equivalent decrease of another component). The proportional masses of the electrodes, electrolytes and cases have thus been altered. Also, the recycling rates and recycling efficiencies have been modified as well as the required amounts of energy to produce and recycle the different types of batteries.

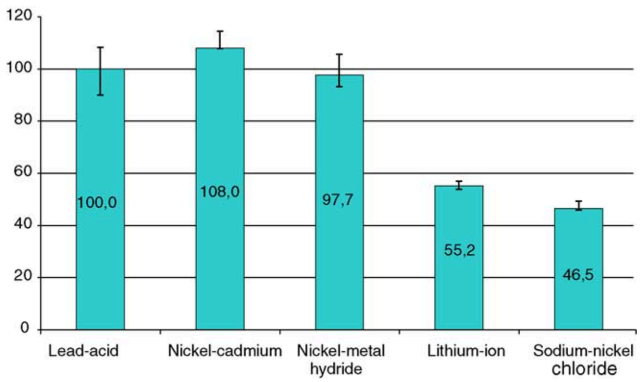

Fig. 4. Graphical overview of the relative environmental scores (including the sensitivity analysis), with Section 4.2.

Fig. 3 summarizes the relative environmental scores as well as the results of the sensitivity analysis. It should be mentioned that Fig. 3 only includes the results originating from production, recycling and the energy losses due to the battery mass and to the battery efficiency, but not the energy use in the hypothesis of an ideal battery, as this parameter does not vary from one battery technology to another. Additionally, this energy use is imputable to the use of the vehicle and not to the battery itself. The bars in Fig. 4 represent the relative environmental impacts of every battery type, considering the lead–acid as a reference. The overall environmental score of the lead–acid battery has been set to 100. The error bars represent the intervals containing all the results obtained during the sensitivity analysis.

Fig. 4 demonstrates that the assumptions 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.

Finally, other values have been assumed for the typical range on one charge (50 or 70 km instead of 60 km). The results of the changes in the "one-charge range" are discussed separately from the other results of the sensitivity analysis,

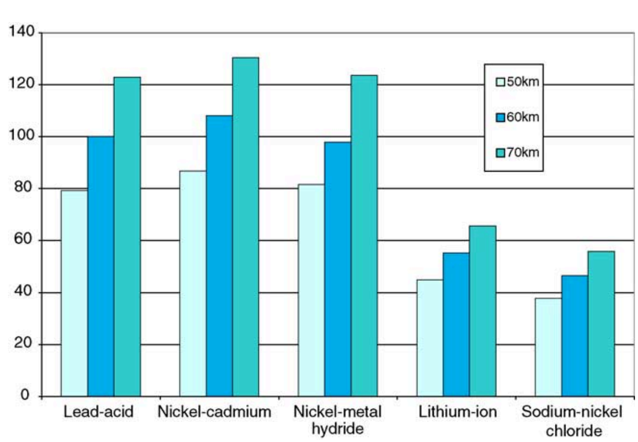

Fig. 5. Environmental burden when the "one-charge range" is modified to 50 or 70 km, with paragraph 4.2.

because they imply the creation of new and different functional units. Such changes can typically be caused by the use of vehicles for different purposes or in other target environments (e.g. urban versus suburban use).

When looking at the environmental impacts of the batteries having 50 and 70 km "one-charge ranges", the results in Fig. 5 are obtained. These results are still based on the same reference as Fig. 4 (lead–acid with a 60 km range = 100). It is noticeable that the absolute environmental impacts are different from the ones obtained using the 60 km range. But the main trends and thus the conclusions, stay the same within each of the assessed "same-range batteries".

5. Conclusions

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

When excluding the energy losses during the use phase (due to the battery efficiencies and the additional masses of the batteries), the following environmental ranking is obtained (decreasing environmental impact): lead–acid, nickel–cadmium, lithium-ion, nickel-metal hydride, sodium–nickel chloride.

Looking at the global results, the following environmental ranking is obtained (decreasing environmental impact): nickel–cadmium, lead–acid, nickel–metal hydride lithium-ion and sodium–nickel chloride. Globally three battery technologies (lead–acid, nickel–cadmium and nickel-metal hydride) appear to have very comparable impacts on the environment. It can thus be stated that, taking the sensitivity analysis into account, these technologies have a higher environmental impact than the lithium-ion and the sodium–nickel chloride technology.

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

Specifically considering the case of nickel–cadmium batteries, it should be mentioned that cadmium is a fatal by-product of zinc production. This means that for every produced ton of zinc, approximately 3 kg of cadmium are produced, simply because an amount of cadmium is present in nearly all zinc ores. The amount of cadmium produced worldwide is thus inflexible since it depends on the zinc production. This cadmium production should be dealt with in a sensible way. Disposing of the cadmium in nature would be unacceptable from an environmental point of view and would furthermore be waste of a limited and valuable resource. Useful, safe and environmentally friendly applications of cadmium shall thus be sought. Large traction batteries can offer an ideal example of such an application: they are safe during use (not releasing any cadmium in the environment) and they can be easily collected and recycled, establishing a closed system for the cadmium, which is kept isolated from the environment.

As for the proposed phase-out of nickel–cadmium batteries through the European directive, one can assume that such a phase-out is not feasible because no car manufacturer has yet launched a marketable battery vehicle using an alternative technology. Additionally, it can be assumed that, before the end of 2005, alternative technologies will either not be available in the quantities needed to meet the market or still will be at a development stage.

It is also important to allow the different market segments to select the technology that fits their particular needs the best way and, therefore, it is necessary to maintain the availability of the largest possible choice.

A re-examination of the situation in about 5 years seems therefore reasonable. A shorter term will continue to hamper the market due to the generated uncertainties for the availability of replacement batteries and, indirectly have a negative impact on the development of hybrid and fuel cell vehicles that are partly based on technology progress induced by research on pure electric vehicles.

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.

Acknowledgment

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