



Life Cycle Assessment of Five Batteries for Electric Vehicles under Different Charging Regimes

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ABSTRACT (Aim, Method, Results)

Life Cycle Assessment (LCA) methodology is used in this study to assess the environmental impact of five candidate batteries for electric vehicles under different conditions of charging. The entire lifetime of a passenger electric vehicle is considered as the basis for all batteries.

Five different battery systems are considered. The four of them are electrically recharged - Lead-Acid, Nickel-Cadmium, Nickel-Metal hydride and Sodium-Nickel chloride – whereas one system comprises batteries that are recharged mechanically (Zinc-Air). One specific battery from these five systems is selected. The results are representative of these particular batteries and not of the battery systems to which they belong.

The study includes three scenarios, the basic scenario and two fast charging scenarios. The difference between the scenarios is in the phase of the battery's use and involves the charging regimes. Consequently, the other stages of the battery's life are identical in all three scenarios. The basic scenario implies normal overnight charging is used during the entire lifetime of an electric vehicle. In the first fast charging scenario, fast charging is combined with normal charging. The second fast charging scenario involves the exclusive use of fast charging. In both fast charging scenarios the user's behaviour is considered. In this study, it is believed that it is the violation of fast charging rules, set by the battery manufacturer rather than the fast charging technique, that will be critical for the cycle life of the battery.

Due to low energy efficiency of the batteries and losses in the charging procedure, the use of energy for operating the electric vehicle seems to be a major contributor to the total environmental impact of the system. Significant resource constraints may prevent mass production of certain batteries or lead to increased prices of others. Use of fast charging increases the number of batteries used during the lifetime of the electric vehicle. It appears though, that it makes little difference if fast charging is used partially or exclusively. The use of recycled materials will reduce the size of the impact.

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**LIFE CYCLE ASSESSMENT
OF FIVE BATTERIES FOR ELECTRIC VEHICLES
UNDER DIFFERENT CHARGING REGIMES**

By Michail Rantik

**CHALMERS UNIVERSITY OF TECHNOLOGY
DEPARTMENT OF TRANSPORTATION AND LOGISTICS**

SUMMARY

The purpose of this study is to assess the environmental impact of five candidate batteries for electric vehicles under different conditions of charging, considering the entire lifetime of a passenger electric vehicle as the basis for all batteries. In order to achieve this goal the Life Cycle Assessment (LCA) methodology is used.

The life cycle of a battery starts with the collection of the raw materials and ends with the deposit of the battery components that cannot be used anymore. The production of primary and auxiliary materials, the manufacturing, the use and the recycling of the battery are the intermediate stages in the battery's life. Each one of these stages bears a certain environmental burden. Transportation, involved between the several stages, bears an additional environmental burden. These burdens are highly changeable since several factors may, positively or negatively, affect their magnitude. Performing an LCA implies the collection, evaluation and, finally, use of information concerning all these stages which are derived from both the manufacturers and the literature.

Five different battery systems are considered. The four of them are electrically recharged - Lead-Acid, Nickel-Cadmium, Nickel-Metal hydride and Sodium-Nickel chloride – whereas one system comprises batteries that are recharged mechanically (Zinc-Air). One specific battery from these five systems is selected. The results are representative of these particular batteries and not of the battery systems to which they belong.

The study includes three scenarios, the basic scenario and two fast charging scenarios. The difference between the scenarios is in the phase of the battery's use and has to do with the charging regimes. Consequently, the other stages of the battery's life are identical in all three scenarios. According to the basic scenario, normal overnight charging is used during the entire lifetime of an electric vehicle. With regard to the first fast charging scenario, fast charging is combined with normal charging. Finally the second fast charging scenario involves the exclusive use of fast charging. In both the fast charging scenarios the user's behavior is considered. In this study, it is believed that it is the violation of fast charging rules, set by the battery manufacturer rather than the fast charging technique, that will be critical for the cycle life of the battery.

With respect to the uncertainties involved, the following conclusions can be made: Due to low energy efficiency of the batteries and losses in the charging procedure, the use of energy for operating the electric vehicle seems to be a major problem. Significant resource constraints may prevent the mass production of certain batteries or lead to increased prices of others. The environmental performance of the batteries differs in accordance with the impact considered. Use of fast charging increases the number of batteries used during the lifetime of the electric vehicle (but this cannot be taken for granted). Consequently, the environmental impact is higher under fast charging regimes. It appears though, that it makes little difference if fast charging is used partially or exclusively. The use of recycled materials may reduce the size of the impact.

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List of Acronyms

Ah	Ampere-hours
CC	Constant Current (method of charging)
CC/CV/CC	Constant Current/Constant Voltage/Constant Current (method of charging)
CFC	Chlorofluorocarbon
CV	Constant Voltage (method of charging)
DOD	Depth Of Discharge
ELU	Environmental Load Unit
EPS	Environmental Priority in Product Design (valuation method)
ET	Environmental Themes (valuation method)
EV	Electric Vehicle
FNC	Fiber Nickel-Cadmium battery
FU	Functional Unit
GJ	10^9 Joule
HEV	Hybrid Electric Vehicle
ICEV	Internal Combustion Engine Vehicle
LCA	Life Cycle Assessment
MJ	10^6 Joule
Na-NiCl ₂	Sodium-Nickel Chloride (ZEBRA) battery
Ni-Cd	Nickel-Cadmium battery
Ni-MH(AB ₂)	Nickel-Metal Hydride battery with AB ₂ metallic alloy based on Ti, Zr
Ni-MH(AB ₅)	Nickel-Metal Hydride battery with AB ₅ rare-earth alloy based on LaNi ₅
SOC	State Of Charge
ton-km	ton-kilometer
Wh	Watt-hours
Zn-Air	Zinc-Air battery

1 INTRODUCTION

1.1 SCOPE AND OBJECTIVES OF THE STUDY

Increased environmental awareness has, for the last thirty years, made the negative consequences of the automobile widely known. Internal combustion engines that have been the basis of the automobility since the beginning of the century are associated with emissions of pollutants which have been recognized through the years, as more or less dangerous for the human health and the environment. As a consequence, the internal combustion engine vehicle (ICEV) has been the center of an intense criticism. The increasing reaction forced the automobile manufactures to strive for a reduction of vehicle emissions. The genesis of the catalytic converter associated with inspection and maintenance programs paved the way for less polluted vehicles.

However, environmental problems, especially in urban areas, forced authorities to set stringent emission standards and this gave rise to a stronger interest for the so called zero emission vehicles, like the electric vehicle (EV) and the hybrid electric vehicle (HEV). Consequently all the big automobile manufacturers developed and keep on developing as well as improving, EVs and HEVs responding to the public requirements for cleaner vehicles.

If the main problem of the ICEV is identified after the engine, in the EV is definitely before the engine. It is well known that the main drawback of the EV has been the battery, or in other words, the energy storage system. Comparing with the fuel tank of an ICEV, the battery takes up more space, is heavier, contains less energy and is recharged in a much longer time than the time a fuel tank is refilled, and thus making the EV slow, inflexible and unattractive comparing with an ICEV.

Considering the low energy content of present batteries, ideas about rapidly recharging the battery are brought up and in some cases realization takes place on an experimental basis. However, there is a lot of uncertainty within the battery industry about whether fast charging is beneficial or detrimental for the battery since charging and discharging mechanisms are complex. Furthermore, factors such as state of charge (SOC) of the battery, in combination with the user's behavior with regard to fast charging may result in shorter battery cycle life. An additional issue is the tremendous amounts of energy that will be needed to rapidly charge EV fleets, equivalent to ICEV fleets of today.

Considering the above, this study deals with the environmental impact of five batteries for EVs taking into consideration normal and fast charging regimes as well as a combination of them. First, the Life Cycle Assessment (LCA) methodology will be used in order to identify these stages of the battery's cycle life that bear the heavier environmental load. Next, the

performed LCA will be modified with the focus set on the part of the battery's use, where partial or exclusive fast charging will be taken into consideration.

1.2 STRUCTURE OF THE REPORT

In Chapter 2 the basic principles of operation of a battery and a brief description of the batteries considered in this study are given. In addition the main stages of a battery's life cycle are briefly presented.

Chapter 3 deals with the LCA methodology and how it is adapted to the examined batteries. The functional unit is identified and the basic scenario is described. The resource utilization of each battery is presented in the inventory analysis and the environmental impact is assessed.

In Chapter 4 the characteristics of a fast charging technique and some critical parameters with regard to its use are given. Two scenarios where fast charging is involved are described. Finally the environmental impact is assessed and a comparison between these two scenarios and the basic scenario is given.

Chapter 5 comprises the conclusions of the study as well as some proposals for further research.

2 BATTERY CONCEPTS AND LIFE CYCLE

2.1 BASIC PRINCIPLES OF A BATTERY

Battery is a multiple of electrochemical cells of the same chemistry. Electrochemical energy storage in a cell is based on the conversion of chemical energy into electrical energy and vice versa. Each battery is characterized by a chemical reaction, which includes the exchange of electrical charges between ions. Electrical energy is gained through two separate electrode reactions; one electrode releases ions, the other electron absorbs them and current flows through the connected device (Rand et al., 1998).

The operation of a cell is schematically presented in the following Figure 2.1.

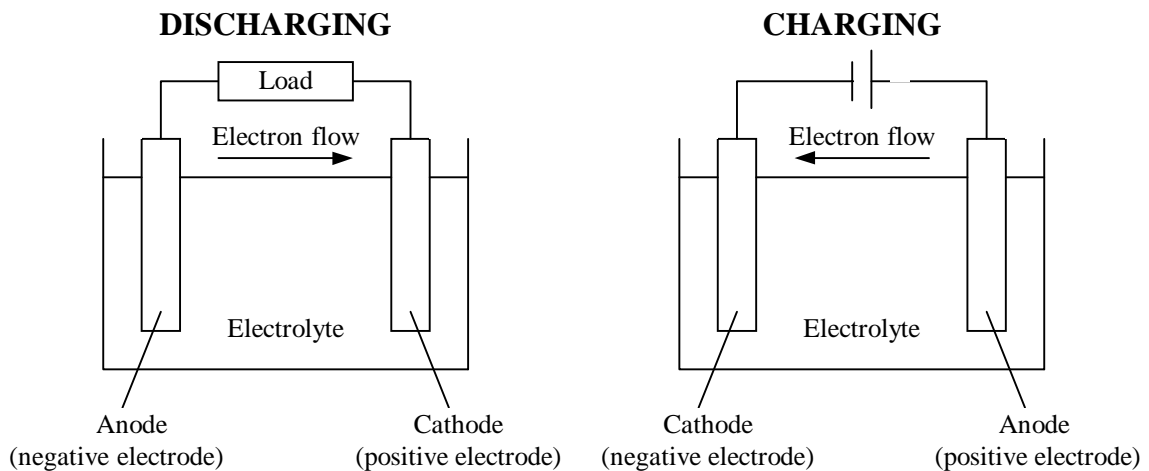


Figure 2.1 Cell operation during charging and discharging (Rand et al., 1998).

The basic components of a cell are the *positive electrode*, the *negative electrode* and the *electrolyte*. The electrodes consists of active materials that take part in the electrochemical reactions. During discharging the negative electrode (e.g. a metal or an alloy) is called *anode* and is capable of being oxidized while the positive electrode (e.g. an oxide or a sulfide) is called *cathode* and is reduced. During charging the positive electrode is oxidized and turns then into the anode whereas the negative electrode is reduced and is turned into the cathode. The electrolyte must be a non-conductor for electrons in order to avoid self-discharge of the cell (Rand et al., 1998).

Other components of a cell are the *current-collectors* or *terminals* which conduct current to and from the electrodes and the *separators* which prevent a short-circuit by ensuring that the electrodes do not come into contact with each other.

A battery consists of one or more cells that are electrically connected in series. The voltage of the battery is the individual cell voltage multiplied by the number of the connected cells. When the battery is fully charged and in no-load condition, this voltage is called *open-circuit voltage* and is higher than the typical voltage during discharging (*working voltage*). The battery voltage at which the discharge is terminated is called *end or cutoff voltage*.

Batteries can be either *primary* or *secondary*. Primary batteries are capable of being recharged electrically and are discarded after discharging. Batteries that can be recharged electrically are termed secondary.

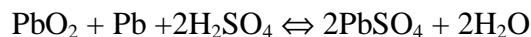
2.2 ELECTRIC VEHICLE BATTERIES

The following five traction batteries are studied:

- Lead-Acid
- Nickel-Cadmium
- Nickel-Metal hydride
- Sodium-Nickel chloride
- Zinc-Air

2.2.1 The Lead-Acid battery

In a Lead-Acid battery, lead oxide is used as the active material of the positive electrode and metallic lead in a sponge form as the active material of the negative electrode. In the traditional ‘flooded’ design the electrodes (or plates) are immersed in an electrolyte which consists of a concentrated aqueous solution of H_2SO_4 (~35% wt.). Thin sheets of porous insulators (‘separators’) are used to isolate the positive and negative plates from each other. The active material of both electrodes is converted to lead sulfate during discharge of the battery. The overall reaction is:



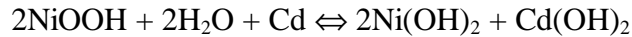
At electrolyte concentrations typically used in traction batteries (specific gravity 1.25-1.30) the open circuit voltage is around 2.1 V at room temperature (Rand et al., 1998).

Although the basic electrochemistry of the system remains the same, Lead-Acid batteries can differ widely in design, choice of component materials and details of manufacture.

2.2.2 The Nickel-Cadmium battery

The Nickel-Cadmium (Ni-Cd) battery comprises a nickel hydroxy-oxide (NiOOH) positive electrode and a metallic cadmium negative. The electrolyte is a concentrated solution of potassium hydroxide (typically 240 g/l). The electrolyte contains also lithium hydroxide (50 g/l) which exerts a stabilizing effect on the capacity of the nickel electrode during charge-

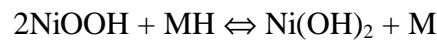
discharge cycling. Sheets of polypropylene can be used as separators between the positive and the negative electrode. The overall reaction is:



In the fully charged stage the open-circuit voltage of the battery is 1.3 V, while on discharge, the voltage has an average value of 1.2 V (Rand et al., 1998).

2.2.3 The Nickel-Metal hydride battery

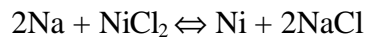
Nickel hydroxy-oxide (NiOOH) is also the active material of the positive electrode in the Nickel-Metal hydride (Ni-MH) battery. Hydrogen absorbed in a metal alloy (metal hydride) is used for the negative active material. Two types of metallic alloys are used, namely, the AB₅ class of alloys based on lanthanum and nickel and the AB₂ class of alloys consisting of titanium and zirconium. An aqueous solution of potassium hydroxide is used as electrolyte which may also contains an LiOH additive. The overall reaction is:



The cell has an open-circuit voltage in the range of 1.25 to 1.35V while the nominal voltage is 1.2 V (Rand et al., 1998).

2.2.4 The Sodium-Nickel chloride battery

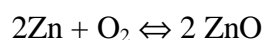
The Sodium-Nickel chloride (Na-NiCl₂) battery is based on nickel chloride as positive electrode and sodium as negative electrode. The reaction that takes place within the cell is fully reversible:



Both electrodes are separated by a sodium ion-conducting electrolyte the ceramic β''alumina, which is solid. Since the positive electrode, kept in a nickel matrix to assure the electronic conductivity, is also solid, a second electrolyte in a liquid form is needed to make the ceramic and the positive electrode work together electrochemically. Molten sodium tetra-chloro-alumina (NaAlCl₄) is used as a second electrolyte, serving as a sodium ion-conductor during normal operation. At 300°C the cell shows an open circuit voltage of 2,58 V (Rand et al., 1998), (AEG ZEBRA, 1997).

2.2.5 The Zinc-Air battery

Electric Fuel Limited (EFL) is a leading developer of Zinc-Air (Zn-Air) batteries for electric vehicles. The EFL system is based on a discharge-only battery pack which is made up of modules of 44 or 66 cells connected in series. Each cell contains a central static anode bed of zinc particles slurried in potassium hydroxide solution. Atmospheric oxygen available in a continuous supply is the positive material. The overall reaction is as follows:



The cell has an open-circuit voltage of 1.6 V but the operating value is in the region of 1.1 to 1.3 V due to overpotential losses in the air electrode (Rand et al., 1998).

Some additional characteristics of the batteries are given in the following Table 2.1, where *specific energy* is the energy output of a battery per unit weight, *cycle life* is the number of charge-discharge cycles that can be obtained from a battery before it fails to meet selected performance criteria and *energy efficiency* is the fraction of the energy used in charging the battery that is delivered on discharge (Rand et al., 1998).

Battery	+	-	Specific energy (Wh/kg)	Open-Circuit Voltage (V)	Cycle Life	Energy efficiency (%)
Lead-Acid	PbO ₂	Pb	35 – 50	2.1	500 – 1000	>80
Ni-Cd	NiOOH	Cd	40 – 60	1.3	800	75
Ni-MH	NiOOH	H ₂	75 – 95	1.25 – 1.35	750 – 1200	70
Na-NiCl ₂	NiCl ₂	Na	80 – 120	2.58 (at 300°C)	1000	80
Zn-Air	O ₂	Zn	100 – 220	1.6	600	60

Table 2.1 Characteristics of the selected batteries for electric vehicles (Rand et al, 1998).

2.3 MAIN STAGES OF A BATTERY LIFE CYCLE

Figure 2.2 presents the main parts of the battery life cycle in a ‘from cradle to grave’ approach. A more analytical decomposition of the main functions of an EV battery is presented in Schlüter et al. (1996).

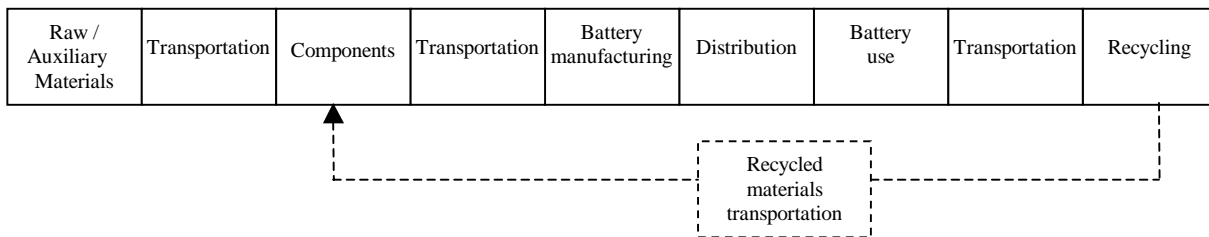


Figure 2.2 The pipeline of the battery’s cycle life.

The cycle life starts with the production of raw materials. The production of raw materials includes the exploitation as well as the extraction of primary raw materials. Production of raw materials can also include the efforts to find ores or minerals in the ground, which are not considered in this study.

Primary raw materials are further processed to form the components used in the assembly of the battery. For this purpose they are transported to the location of components suppliers. The main components of the battery are the anode, the cathode, the electrolyte and the separator but auxiliary components such as the container, the terminals and others are also considered.

Auxiliary materials and components are thereafter transported to the battery manufactures where further processing takes place before the final assembly of the battery.

The battery is delivered to the final user - owner of the EV - through mediators such as retailers. Due to the fact that transportation from manufactures to mediators and from mediators to users is embraced by high complexity, it is assumed that the battery is transported by truck from the manufacturer straight to the final user and an average distance is also assumed.

The owner of the EV uses the battery for as long as it delivers the appropriate capacity. The battery use stage includes the charge and discharge of the battery. After the battery has completed its lifetime, it is transported to a recycling facility through the mediators who normally collect the disposable batteries. In this case also transportation is a complex issue and an average distance from the user to the recycling plant is assumed. Some of the battery's materials are recycled and transported to component suppliers.

Due to the fact that some of the batteries considered still are at a stage of development, no recycling routes have been formed yet. For those batteries the recycling stage includes only the recovery of components (e.g. steel parts easily obtained after dismantling the battery) for which recycling routes already exist.

3 LIFE CYCLE ASSESSMENT FOR FIVE BATTERIES OF ELECTRIC VEHICLES

3.1 INTRODUCTION

In this chapter LCA is applied for the basic scenario. The selected batteries are evaluated according to information obtained from manufacturers and the literature.

3.2 LCA METHODOLOGY

LCA consists of four generally accepted parts according to the Society for Environmental Toxicology and Chemistry (SETAC) guidelines. These four parts are schematically presented in Figure 3.1.

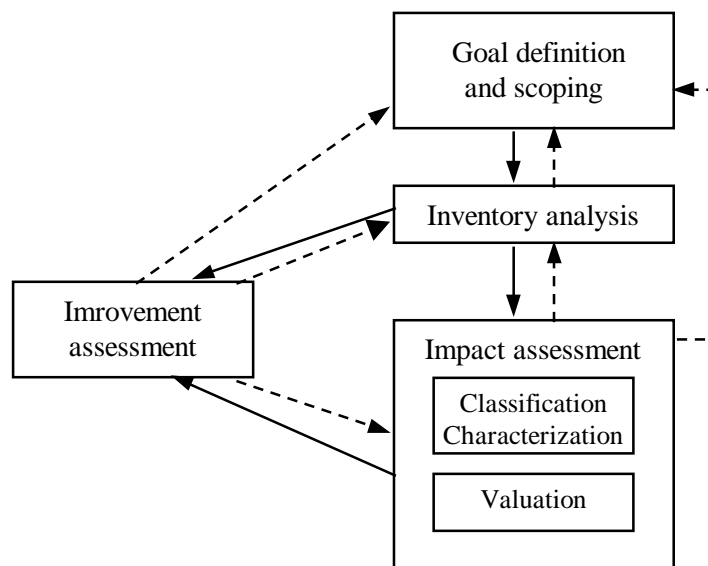


Figure 3.1 Methodological framework of LCA (Tillman, 1995).

3.2.1 Goal definition and scoping

In the goal definition and scoping part, the purpose of the study and the basic assumptions are described and the functional unit is defined.

In the present study the goal is to find out *which of the five batteries used in EV applications is the less harmful for the environment if the whole life cycle of the battery is to be considered.*

The reason for carrying out the present LCA is to identify what environmental load is borne by the individual parts or functions of the life cycle of the five considered batteries. An additional reason is to assess the environmental load if fast charging is partially or fully used during the entire life of these batteries. The study is carried out owing to the interest of the Swedish Transport and Communication Research Board (KFB) that has funded it. The purpose is to update the LCA made by Schlüter et al. (1996) and take additional features into consideration.

In order to carry out the LCA a common basis for all the five batteries is needed. The basis will be the function of the EV as it has been described in Schlüter et al. (1996). In other words, the batteries are evaluated according to operation characteristics of an EV such as its weight, its energy utilization, its annual driving distance and its lifetime. All these four characteristics and especially the energy utilization differ significantly from vehicle to vehicle. The main specific scenario is the same as in Schlüter et al. (1996):

A 1300 kg full-sized passenger vehicle (weight without battery) with an energy utilization of 120 Wh per ton-km (60 km/h for a drivetrain efficiency of 77%), an estimated ten-year lifetime and an annual driving range of 20,000 km is considered. Ambient temperature is assumed to be 25°C.

In addition, the vehicle range per cycle is assumed according to the respective specific energy of each battery (Schlüter et al., 1996). Consequently the Lead-Acid battery with 35 Wh/kg energy density is assumed to give a vehicle range per cycle equal to 80 km whereas the Zn-Air with 200 Wh/kg energy density may yield a 300 km range per cycle.

Battery weight	Lead-Acid	Ni-Cd	Ni-MH	Na-NiCl₂	Zn-Air
Recharging	electrical	electrical	electrical	electrical	mechanical
Energy density (Wh/kg)	35	57	75	86	200
Vehicle range per cycle (km)	80	100	125	150	300
Energy consumption (Wh/kgkm)	0,12	0,12	0,12	0,12	0,12
Vehicle weight without battery (kg)	1300	1300	1300	1300	1300
Battery weight (kg)	491	346	325	344	285
Total vehicle weight (kg)	1791	1646	1625	1644	1585
Battery energy (Wh)	17197	19760	24375	29594	57073
Vehicle lifetime (years)	10	10	10	10	10
Annual driving range (km)	20000	20000	20000	20000	20000
Total range during lifetime (km)	200000	200000	200000	200000	200000
Total number of driving cycles	2500	2000	1600	1333	667
Battery cycle life (80% DOD)	700	2000	600	1000	400
Total number of batteries per PV	3.6	1	2.7	1.3	1.7
Additional batteries per battery	-	-	-	-	1.2
Integer number of batteries	4	1	3	2	2
Total primary battery weight	491	347	325	344	285
Total secondary battery weight	1473	-	650	344	285

Table 3.1 Number and weight of batteries used under the main specific scenario.

The *functional unit* is the same as in Schlüter et al. (1996); *ten electric passenger vehicle years with specified driving range per cycle and year.*

The battery weight m_b is calculated according to the following formulae:

$$m_b = \frac{m_{car}}{\frac{e_b}{c_{car} P x_{cycle}} - 1}$$

Where: m_{car} is the vehicle weight without battery in kg;
 e_b is the specific energy density in Wh/kg;
 x_{cycle} is the driving range per cycle in km;
 c_{car} is the energy consumption of the vehicle in Wh/kgkm.

It has to be mentioned that the assumptions made are found to be close to reality. Data derived from tests of EVs under real conditions (DAUG, 1996) showed that for instance, a VW Golf A3 weighing 1000 kg, equipped with a 300 kg Ni-Cd battery with energy density 47 Wh/kg and having a mean energy use of 0.252 Wh/kgkm had a measured average range per cycle equal to 49 km. Incorporating this data to the above formulae used in the assumptions the range per cycle obtained is equal to 43 km.

Data for the production and recycling of all the batteries considered were not available. Data for the Lead-Acid battery are derived from Tudor (1998) and from Kertes (1996) and they are rather accurate. Data for the Ni-Cd battery were found in Schlüter et al., (1996) and Gaines et al. (1996). It is based on studies carried out in the US and contains a certain

degree of uncertainty. Attempts to obtain better information were unsuccessful since manufactures such as SAFT regard data as proprietary. Data for Ni-MH are also derived from Schlüter et al. (1996) based on American studies. SAFT in France has begun a pilot production of the battery but again data were not provided. Data for the Na-NiCl₂ battery were supplied from AEG ZEBRA. Data for the production of the battery are not included and no recycling route exists to date. Data for the Zn-Air battery are obtained from Schlüter et al. (1996). Electric Fuel did not provide further information. Therefore data for the production, regeneration and recycling of the battery are not included.

3.3 INVENTORY ANALYSIS

3.3.1 Raw and auxiliary materials

Lead-Acid

A flooded tubular Lead-Acid battery manufactured in England by Chloride Motive Power, is considered. The battery has an energy density equal to 35 Wh/kg, and a cycle life of 700 cycles (80% DOD) (Table3.1).

The proportions of materials are assumed to be similar to the Tudor battery EV500 and are presented in the following Table 3.2 (Kertes, 1996), (Tudor, 1998).

MATERIALS Lead-Acid	Primary	Secondary
Antimony (Sb)	0.71	0.71
Arsenic (As)	0.03	0.03
Copper (Cu)	0.01	0.01
Glass	0.20	
Lead (Pb)	60.96	30.48
Oxygen (O ₂)	2.26	
Polyethylene	1.83	1.83
Polypropylene	6.72	
Sulfuric acid (H ₂ SO ₄)	10.33	10.33
Water (unsalted)	16.93	16.93
Glass (secondary)		0.20
Lead (secondary)		30.48
Polypropylene (second.)		6.72

Table 3.2 Materials of Lead-Acid battery (Kertes, 1996).

Lead is by far the most used material in the battery followed by water and sulfuric acid, which form the electrolyte. Data about the production of the materials used in the manufacturing of the battery are derived from Schlüter et al. (1996) and Sunèr (1996). It is assumed that the first battery mounted on a new EV (primary battery), is manufactured from primary materials while in the next batteries (secondary), some materials are derived from recycling.

Nickel-Cadmium

A vented fiber Ni-Cd (FNC) battery made by an American manufacturer is considered (Gaines et al., 1996). The battery has an energy density of 57 Wh/kg and the proportions of the materials included (Gaines et al., 1996), (Schlüter et al., 1996) are presented in Table 3.3. These proportions match quite well with the equivalent of a similar battery made by DAUG-HOPPECKE in Germany (Patyk et al, 1996).

MATERIALS Ni-Cd	Primary	Secondary
Cadmium	24.60	
Cobalt	1.40	1.40
Copper	2.05	2.05
Lithium hydroxide	0.70	0.70
Nickel	20.20	
Nickel hydroxide	17.40	17.40
Polypropylene	3.10	3.10
Potassium hydroxide	5.22	5.22
Steel (low alloy)	11.70	11.70
Steel (unalloyed)	2.05	2.05
Water (unsalted)	11.48	11.48
Other inorganic substances	0.10	0.10
Cadmium (secondary)		24.60
Nickel (secondary)		20.20

Table 3.3 Materials of Ni-Cd battery (Gaines et al., 1996), (Schlüter et al., 1996).

Data about the production of the materials used in the manufacturing of the battery are derived from Schlüter et al. (1996), Gaines et al. (1996) and Sunèr (1996).

Nickel-Metal hydride

The proportions of the materials used in the two types AB₂ and AB₅ of the Ni-MH battery are presented in Table 3.4 based on Schlüter et al. (1996).

MATERIALS Ni-MH(AB ₂)	Primary	Secondary	MATERIALS Ni-MH(AB ₅)	Primary	Secondary
Aluminium	0.37	0.37	Aluminium	0.29	0.29
Chromium	2.14	2.14	Cerium	0.20	0.20
Nickel	24.01		Cobalt	1.67	1.67
Polypropylene	5.00		Lanthanum	3.21	3.21
Potassium hydroxide	3.00	3.00	Manganese	0.78	
Steel (low alloy)	43.50	43.50	Neodymium	0.15	0.15
Titanium	0.79		Nickel	29.22	
Vanadium	7.11	7.11	Polypropylene	5.00	
Water (unsalted)	6.00	6.00	Potassium hydroxide	3.00	3.00
Zirconium	2.50	2.50	Praseodymium	1.40	1.40
Oxygen	4.31	4.31	Steel (low alloy)	43.50	43.50
Hydrogen	0.27	0.27	Hydrogen	0.27	0.27
Leveling agents	1.00	1.00	Oxygen	4.31	4.31
			Water (unsalted)	6.00	6.00
			Leveling agents	1.00	1.00
Nickel (secondary)		24.01	Manganese (secondary)		0.78
Polypropylene (secondary)		5.00	Nickel (secondary)		29.22
Titanium (secondary)		0.79	Polypropylene (secondary)		5.00

Table 3.4 Materials of Ni-MH, AB₂ and AB₅ type, battery (Schlüter et al., 1996).

Sodium-Nickel chloride

The Zebra battery Z12 made by AEG is considered and the proportions of materials used are as in the following Table 3.5 (Böhm, 1997).

MATERIALS Na-NiCl ₂	Primary	Secondary
Aluminium	1.12	1.12
Aluminium oxide	2.19	2.19
Beta-alumina	13.14	13.14
Copper	0.24	0.24
Iron	2.19	2.19
Mica	6.08	6.08
Mild steel (low alloy)	14.76	14.76
Nickel	18.25	
Sodium aluminium chloride (NaAlCl ₄)	11.68	11.68
Sodium chloride (NaCl)	9.49	9.49
Stainless steel	11.66	11.66
Silica (SiO ₂)	4.56	
Others	4.64	4.64
Nickel (secondary)		18.25
Silicon dioxide (secondary)		4.56

Table 3.5 Materials of Na-NiCl₂ battery (Böhm, 1997).

It is assumed that recycled nickel and silicon dioxide are used in the manufacturing of the secondary batteries while information about the production of the materials are derived from Schlüter et al. (1996) and Sunèr (1996).

Zinc-Air

Material data for the Zn-Air battery are derived from Schlüter et al. (1996) based on estimations (Table 3.6). Electric Fuel that has developed the battery was contacted but information concerning the battery is regarded as proprietary.

MATERIALS Zn-Air	Primary	Secondary
Carbon	19.53	19.53
Copper	2.05	2.05
Nickel	19.43	19.43
Polypropylene	3.50	
Polytetrafluoroethylene	2.40	2.40
Potassium hydroxide	6.00	6.00
Steel (low alloy)	11.70	11.70
Steel (unalloyed)	2.05	2.05
Water (unsalted)	12.00	12.00
Zinc	21.00	
Other inorganic substances	0.34	0.34
Polypropylene (secondary)		3.50
Zinc (secondary)		21.00

Table 3.6 Materials of Zn-Air battery (Schlüter et al., 1996).

Schlüter et al. (1996) and Sunèr (1996) are again used as sources for information about the production of the materials used in the manufacturing of the battery.

3.3.2 Manufacturing

Lead-Acid

In the tubular batteries the positive plate has a tubular rather than flat form. The positive plate consists of a row of tubes which contain coaxial lead alloy rods (known as “spines”). Tubular batteries are predominantly in motive-power applications.

Highly purified lead is the basic material with which the production of the Lead-Acid battery starts. Primary lead is usually used for the production of alloys, which are converted into lead oxides. The lead oxides will yield lead dioxide used for the positive active material and sponge lead for the negative active material (Rand et al.,1997).

The production of battery is briefly described by the following steps (Rand et al.,1997):

- *Production of grids;*
- *Lead oxide production;*
- *Paste production and pasting;*
- *Drying;*

- *Curing;*
- *Formation.*

Information regarding energy and emissions associated with each one of these six manufacturing stages was difficult to be found. According to Tudor (1998), a total amount of 14,579 ton of lead was used in the 1997-production of all the different types of batteries that the company produces. Assuming that only the EV battery is produced and given the percentage by weight of lead in this battery (60.96%), the annual production of batteries would be 23,916 ton. For this amount of lead used at Tudor, emissions to water were reported to 115 kg while emissions to air amounted to 29.7 kg. Energy utilization during 1997 was 64 m³ oil EO1, 71 ton Liquefied Petroleum Gas (LPG) and 31,846 MWh electricity. After processing this information the following Table 3.7 is derived:

Energy for the Manufacturing of Lead-Acid battery (MJ/kg battery)	
Oil	0.102
Electricity	4.793
LPG	0.137
Heat	1.671
Emissions from Manufacturing of Lead-Acid (kg/kg battery)	
Lead (air)	1.242E-06
Lead (water)	4.808E-06

Table 3.7 Energy and emissions associated with the manufacturing of the Lead-Acid battery (based on Tudor (1998)).

Nickel-Cadmium

The two basic stages in the production of the FNC battery are the Processing and the Formation and data about emissions (Table 3.8) are derived from Schlüter et al. (1996). No energy data are reported.

Emissions from Manufacturing of Ni-Cd battery (kg/kg battery)	Processing	Formation
Cadmium (air)	1.102E-05	5.510E-06
Cobalt (air)	0.722E-06	0.361E-06
Nickel (air)	1.596E-05	7.980E-06
Cadmium (water)	1.596E-05	7.980E-06
Cobalt (water)	1.026E-06	0.513E-06
Nickel (water)	2.280E-05	1.140E-05

Table 3.8 Emissions from the manufacturing of the Ni-Cd battery (Schlüter et al. 1996).

Nickel-Metal hydride

NiMe-hydride in Mönsterås has a pilot production of Ni-MH(AB₅) small cells. Information regarding energy and emissions associated with the manufacturing of these cells was found in Törnblom (1996). These data have been processed in order to match the production of an EV battery and are presented in Table 3.9:

Energy for the Manufacturing of Ni-MH(AB₅) battery (MJ/kg battery)	
Electricity	1.960
LPG	8.350
Emissions from Manufacturing of Ni-MH(AB₅) battery (kg/kg battery)	
Aluminium (air/water/ground)	2.223E-04
Nickel (air/water/ground)	0.008
Cobalt (air/water/ground)	0.001
Other metals (air/water/ground)	0.047
Plastics (air/water/ground)	0.003

Table 3.9 Emissions from the manufacturing of the Ni-MH(AB₅) battery (based on Törnblom (1996)).

No data for the production of the Ni-MH(AB₂) were found. Since the metal hydride used in the AB₂ type is different than the one used in AB₅ the above data cannot be used.

Sodium-Nickel chloride

AEG has a pilot production of the Na-NiCl₂ battery but information about the emissions and the energy utilization was not provided.

Zinc-Air

No emissions and energy data regarding the production of the Zn-Air battery were provided so the manufacturing stage of the battery's cycle life is not considered.

3.3.3 Use

The environmental implications of the use of batteries are associated mostly with the charging of the battery and the amount of energy utilized during the charging process. A crucial parameter in order to estimate the amount of energy that has to be transferred to the battery is the energy (or Wh) efficiency of the battery.

In cyclic applications heat is generated mainly due to the internal resistance of the battery (R) and the equivalent resistance of the activation and concentration overpotentials at the electrodes (η). The total Joule effect can be partitioned into (Chang, 1993):

$$IP(V-V_o) = I^2PR + IP\eta$$

where: I is the current;
V is the cell voltage;
V_o is the open-circuit voltage.

Due to the low internal resistance of the most cells the ohmic heating (I^2PR) is relatively small compared with the non-ohmic heating ($IP\eta$) when normal charging is applied and the current is low. Under a fast charging regime with high current values the ohmic heating dominates in the initial period of charging but again the non-ohmic heating is mainly responsible for the energy losses and the rise of temperature within the battery (Chang, 1993).

The energy efficiency of a battery is estimated by taking into account the losses due to the total Joule effect (determined by the voltaic efficiency of the battery) and the losses due to parasitic processes such as the electrolysis of water in batteries that use aqueous electrolytes (determined by the coulombic efficiency). The product of the voltaic efficiency and the coulombic efficiency is the energy efficiency of the battery.

Energy is also wasted due to the fact that the battery is self-discharged. In Lead-Acid batteries self-discharging is mainly caused by hydrogen evolution in the negative electrode. Typical values are 1-2% per 24 hours (Rand et al., 1997). Ni-Cd batteries are self-discharged because of decomposition of the charged nickel hydroxide and the loss of capacity fluctuates between 1 and 10% per 24 hours (DAUG, 1996). Self discharge in Ni-MH batteries is caused by the slow decomposition of both the positive and the negative electrodes due to their intrinsic instability and also due to reaction of any hydrogen in the cell with the nickel electrode. It may amount to 50% of capacity within 10 days and 20°C (Berndt, 1997) but manufacturers, such as Ovonic, have reported lower values, in the area of 1% per 24 hours. Na-NiCl₂ batteries are not self-discharged. The energy losses due to self-discharge E_{sd} is roughly estimated by the following equation:

$$E_{sd} = a_{sd}PE_{bat}$$

Where: a_{sd} is the 24-hour self-discharge coefficient ;
 E_{bat} is the nominal Wh capacity of the battery.

The FNC batteries require daily an additional amount of 0.5 kWh in order to keep their charge. An additional amount of charge that may reach the 10% of their nominal capacity is also required for reasons of maintenance. (DAUG, 1996). The frequency of this additional charging depends heavily on the use of the electric vehicle and the behavior of the user.

Na-NiCl₂ batteries function in temperatures of around 300°C and therefore require an amount of energy to be converted into heat. A part of this amount can be obtained from the losses on the internal resistance R, while the rest is derived either from the utility grid while the vehicle is connected or from the battery. About 5 kWh is needed daily to heat a 30 kWh Na-NiCl₂ (DAUG, 1996). The heat generated on the internal resistance can be used to keep the battery in a high temperature but after a level, specified by the energy needs of the vehicle, this heat is perceived as loss.

All the energy losses are taken into account according to Table 3.10.

Electrically recharged batteries	Net of losses in the utility grid to the socket¹	Charger Efficiency²	Energy efficiency³	Self-discharge per 24h⁴	Losses due to heating⁵	Gain from regenerating braking⁶	Total Energy Efficiency
	(a)	(b)	(c)	(d)	(e)	(f)	(g) ⁷
Lead-Acid	9%	85%	80%	1%	-	8%	66%
Ni-Cd	9%	85%	80%	5%	-	8%	63%
Ni-MH	9%	85%	70%	2%	-	8%	57%
Na-NiCl ₂	9%	85%	97%	-	17%	8%	67%
Mechanically recharged batteries	Net of losses in the utility grid to the regeneration	Multi-MW power converters efficiency	Power consumption regeneration operation	Regeneration efficiency	Self-discharge per 24h	Losses due to distribution	Total Energy Efficiency
	(h)	(i)	(j)	(k)	(l)	(m)	(n) ⁹
Zn-Air ⁸	6%	98%	95%	57%	3%	3%	47%

¹ Estimated according to 'Livscykelanalys för elnätet' Svenska Kraftnät, Vattenfall, Göteborg Energi

² Estimated based on DAUG (1996) and Schlüter et al. (1996)

^{3,4} Estimated based on DAUG (1996), Schlüter et al. (1996) and Rand et al (1997)

⁵ According to DAUG (1996) and AEG ZEBRA (1997)

⁶ Average from DAUG (1996)

⁷ $g = (1-a)*b*c*(1-d)*(1-e)*(1+f)$

⁸ Source: (Schlüter et al. 1996)

⁹ $n = (1-h)*i*j*k*(1-l)*(1-m)$

Table 3.10 Total energy efficiency for the batteries in question.

The total energy efficiency will be assessed by assuming average values for the several losses, as the Table 3.10 shows. Under the present scenario it is deemed that each battery is charged from 20 to 100% SOC and discharged from 100 to 20% SOC, according to the specifications provided by the manufacturers. In other words, normal, Level 2, EV charging (Sims et al., 1997) is performed and no capacity loss or cycle life reduction are considered.

3.3.4 Recycling

Lead-Acid

Recycling of Lead-Acid batteries is done by the blust-furnace process. According to this process the more or less smashed batteries together with coke and smelting additives are filled into the furnace without previous separation of the components. The crude lead obtained has to be refined by subsequent metallurgical processes.

Lead-Acid batteries are recycled in Sweden by Boliden Bergsöe and the following data (Table 3.11) are derived after processing data from Kertes (1996).

Energy for the Recycling of Lead-Acid Battery (MJ/kg)	
Electricity	0.875
LPG	1.954
Heat	-1.568
Emissions from Recycling of Lead-Acid Battery (kg/kg)	
Particulates (air)	1.69E-05
Lead (air)	5.15E-06
Cadmium (air)	3.05E-08
Copper (air)	5.76E-08
Zinc (air)	1.92E-07
Arsenic (air)	1.53E-08
Nitrogen oxides (air)	0.24E-03
Sulfur dioxide (air)	2.25E-03
COD (water)	9.52E-05
Antimony (water)	3.64E-07
Mercury (water)	1.84E-10
Nickel (water)	2.33E-08
Lead (water)	7.63E-08
Cadmium (water)	5.08E-09
Copper (water)	6.78E-09
Zinc (water)	3.05E-08

Table 3.11 Energy and emission data from the recycling of Lead-Acid batteries (Kertes, 1996).

Nickel-Cadmium

Recycling of Ni-Cd batteries is made in Sweden (Saft-Nife) with the thermal oxidation process and information is derived from Schlüter et al. (1996).

Energy for the Recycling of the Ni-Cd Battery (MJ/kg)	
Electricity	4.068
Furnace gas	-0.790
Emissions from Recycling of the Ni-Cd Battery (kg/kg)	
Cadmium (air)	7.029E-07
Nickel (air)	1.213E-07
Cadmium (water)	0.005E-07
Nickel (water)	0.024E-07
By-products from Recycling of the Ni-Cd Battery (kg/kg)	
Cadmium (secondary)	0.246
Ferronickel (secondary)	0.703

Table 3.12 Energy and emission data from the recycling of Ni-Cd batteries (Schlüter et al., 1996).

Nickel-Metal hydride

The pyrometallurgical process is supposed to be used for the recycling of Ni-MH batteries and data (Table 3.13) are derived from Schlüter et al. (1996). This process does not recover valuable elements such as titanium. Removing the electrodes from the case would allow nickel recovery with little or no iron contamination. Recycled nickel can be used back to battery materials but the fact that spent metal-hydride electrodes are highly oxidized makes the procedure difficult (Gaines et al., 1996).

Material Resources for the Recycling of the Ni-MH Batteries		
(kg/kg)		
	AB₂	AB₅
Iron (ore)	0.252	0.062
Iron silicate	0.025	0.006
Water	0.244	0.244
Aluminium	0.068	
Lime	0.037	0.037
Oxygen	0.019	0.026
Silica	0.018	0.019
Other inorganic substances	0.020	0.015
Energy for Recycling of the Ni-MH Batteries		
(MJ/kg)		
Coke	1.193	1.193
Electricity	5.400	5.400
Emissions from Recycling of the Ni-MH Batteries		
(kg/kg)		
Slag (solid)	0.236	0.156
Toxic chemicals (solid)	0.030	0.030
By-products from Recycling of the Ni-MH Batteries		
(kg/kg)		
Chromium (secondary)	0.017	
Ferronickel (secondary)	0.471	0.422
Nickel (secondary)	0.010	
Polypropylene (secondary)	0.049	0.049
Steel/Iron (secondary)	0.285	0.285
Vanadium (secondary)	0.057	

Table 3.13 Energy and emission data from the recycling of Ni-MH batteries (Schlüter et al., 1996).

Sodium-Nickel Chloride

A recycling route for the Zebra battery does not exist. Investigations have shown that the recycling will involve the thermal processing of the whole cell at high temperatures in order to use the high amount of nickel contained in the battery. The cells will be thermally treated together with other nickel-containing waste materials and ores (Böhm, 1997).

The slag of the thermal process contains the other materials of the cell and can be used in construction applications. Chlorine will be contained in both the slag and the exhaust gases. The chlorine will be removed from the exhaust gases in a washing process.

Since such a recycling path does not exist no emissions and energy data are available.

Zinc-Air

No information about any possible recycling route of the Zn-Air battery is available and therefore the recycling of this battery is not treated in this study.

3.3.5 Transportation

Transportation is a complex issue especially concerning the parts from production to use and from use to recycling where the distribution of the batteries follows random schedules depending on the user's location (for simplification reasons no mediators are considered as it was mentioned in §2.3). Therefore, a transportation scenario is to use road transport and a mean distance of 500 km from the production plant to the final user and from the final user to the recycling facility, assuming that is representative of the worst case (comparing with maritime and rail transport). With regard to materials production transportation is not always included. However, no mean distances were used since in the most cases the points of origin and destination were unknown.

3.4 IMPACT ASSESSMENT

3.4.1 Classification and Characterization

The environmental loads identified in the inventory analysis are sorted with regard to relevant impact categories. The categories considered are:

- resources utilization;
- global warming;
- acidification;
- eutrophication;
- carcinogenic.

Regarding the resources utilization a distinction between material resources and energy is made.

Carbon dioxide, methane, dinitrogen oxide and chlorofluorocarbons (CFCs) are the main contributors to global warming.

Acidification is mainly due to airborne emissions of nitrogen oxides, sulfur oxide, and sulfur dioxide, ammonia, hydrogen chloride and hydrogen fluoride.

Eutrophication is caused from waterborne emissions of ammonia, phosphates and from chemical oxygen demand whereas also ammonia and nitrogen oxides into the air also contribute.

Carcinogenic emissions are discharges into the air of arsenic, benzoapyren, benzol, chromium, nickel and polycyclic aromatic hydrocarbons.

3.4.2 Valuation

The environmental impacts are assessed according to two valuation methods, namely the Environmental Priority Strategies in product design (EPS) and the Environmental Themes for Sweden based on a normalization (ET). Each one of these methods addresses a number of identified, important environmental issues and gives a score for each of these environmental issues. The emissions identified in the inventory analysis are converted into contributions to an impact category by multiplying with an equivalent factor. Environmental load indexes for these two methods are taken from Eriksson et al. (1996).

3.5 RESULTS AND DISCUSSION

3.5.1 Results in values

Results concerning the energy utilization, the material resources and the emissions of CO₂, SO₂ and NO_x are presented in the following paragraphs. It has to be pointed out that emissions from the production of the electricity and the fuels used in the production of raw materials and components, in the final production, in the recycling process of the battery as well as in the associated transports are not considered. However, emissions from the production of the electricity utilized while using the battery will be estimated.

With regard to emissions related to the use of battery, the Swedish mix of electricity production (Figure 3.2) is used. This mix corresponds to the electricity that is provided to Swedish State Railways.

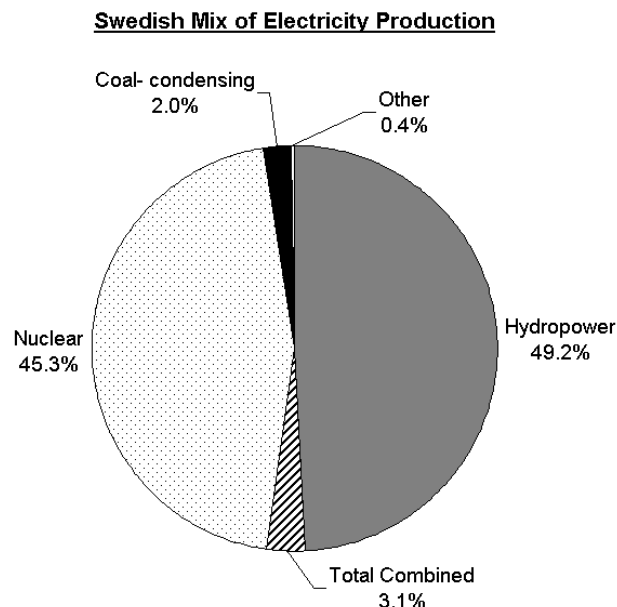


Figure 3.2 Swedish mix of electricity production (@NTM, 1998).

Emission factors concerning the electricity production are taken from @NTM (1998). The emission factors of each energy source have been multiplied with the share of the source (Figure 3.2) and an average emission factor related to the source is derived. By aggregating the average emission factors the total emission factors are obtained.

	CO ₂	NO _x	SO ₂	CO	Particles	HC
	[g/kWh el]	[g/kWh el]	[g/kWh el]	[g/kWh el]	[g/kWh el]	[g/kWh el]
Hydropower [49.2%]	0.0333314	0.0001295	0.0000537	0.0008862	0.0000145	0.0001216
Nuclear [45.3%]	0.0326218	0.0000997	0.0000956	0.0000152	0.0000117	0.0000236
Coal – condensing [2%]	17.0656200	0.0441558	0.0489294	0.0000108	0.0020487	0.0000889
Other (Wind-Gasturbine-Oil condensing) [0.4%]	3.0768643	0.0069069	0.0020809	0.0023836	0.0001637	0.0001745
Total Combined [3.1%]	3.0633498	0.0072377	0.0045943	0.0033820	0.0004989	0.0000246
Total (g/kWh el)	23.2717873	0.0585296	0.0557538	0.0066778	0.0027375	0.0004333
Total (kg/MJ el)	0.0064644	0.0000163	0.0000155	0.0000019	0.0000008	0.0000001

Table 3.14 Emission factors from electricity production (based on @NTM, (1998)).

Energy utilization

Figure 3.3 presents the distribution of the energy used within the entire lifetime of an EV equipped with Lead-Acid and Ni-MH(AB₅) batteries (only for these two batteries information about the entire cycle life exists).

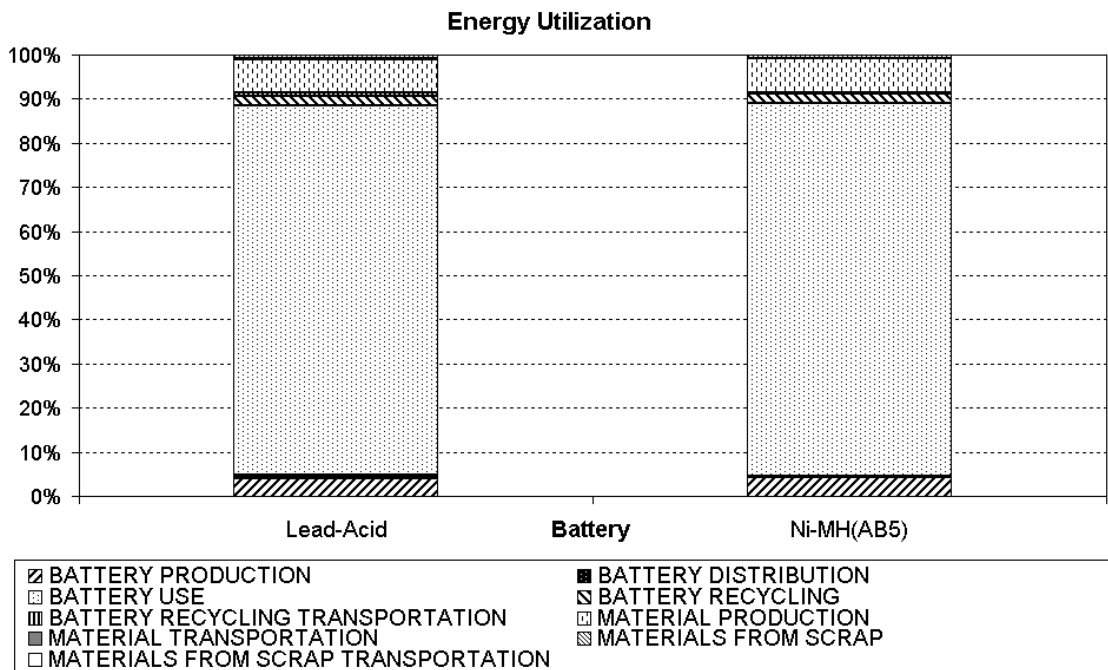


Figure 3.3 Energy utilization associated with the cycle life of Lead-Acid and Ni-MH(AB₅) batteries within the complete lifetime of an EV, corresponding to 200,000 km.

It is obvious that both batteries have similar energy distribution profiles. Due to the fact that Lead-Acid batteries are significantly heavier than Ni-MH batteries the transportation parts of the Lead-Acid batteries account for higher energy utilization than the ones of Ni-MH batteries creating slight differences between the two profiles.

The same energy distribution profile should be expected for other batteries. Figure 3.4 presents the energy distribution profiles for the batteries Lead-Acid, Ni-Cd, Ni-MH(AB₂) and Ni-MH(AB₅) without considering the production stage (data not available for Ni-Cd and Ni-MH(AB₂)). The material production stage of the Ni-Cd battery has a high energy requirement due to the use of energy-intensive materials (one should consider that only one Ni-Cd is used during the entire life of the EV (Table 3.1), in contrast with four Lead-Acid and three Ni-MH batteries).

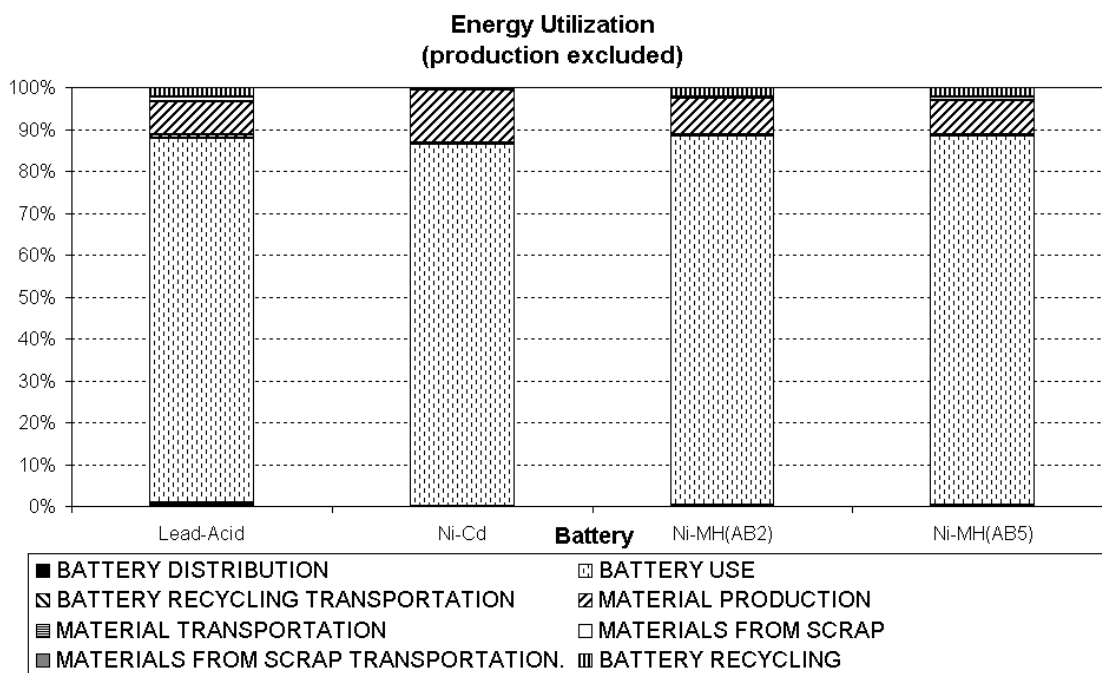


Figure 3.4 Energy utilization excluding the production stage, for the Lead-Acid, Ni-Cd and Ni-MH(AB₂ and AB₅) batteries. Energy utilization for the recycling of Ni-Cd batteries is not included.

Figure 3.5 presents the energy utilization in GJ for all the considered batteries. The conclusion that the energy distribution profile is similar for all the examined batteries is further reinforced in this figure, where results for Na-NiCl₂ and Zn-Air batteries also are presented. In addition, one could observe that all the batteries tend to have similar energy needs during the entire life of the EV. It can be claimed that the energy needs of an EV battery during the complete lifetime of the EV will fluctuate around 240 GJ .

From Figures 3.3, 3.4, 3.5 it can be seen that the use of battery is the part where the most - almost 85% - of the energy is utilized. One could assume that the main reason for that is the rather low total energy efficiency (Table 3.1). It has to be mentioned that making batteries with high energy efficiency is not enough. Even if the Lead-Acid battery of Table 3.1 had an

energy efficiency of 95% the total energy efficiency would not be higher than 80% and the energy losses would be again significant. Therefore, reducing losses in the electric utility power supply, improving charger efficiency and making better use of the regenerative braking may be equally important. That is to say, that apart from the battery industry, the power supply industry, the charger manufacturers as well as the automotive industry should join forces in order to make EVs that will operate reliably and efficiently.

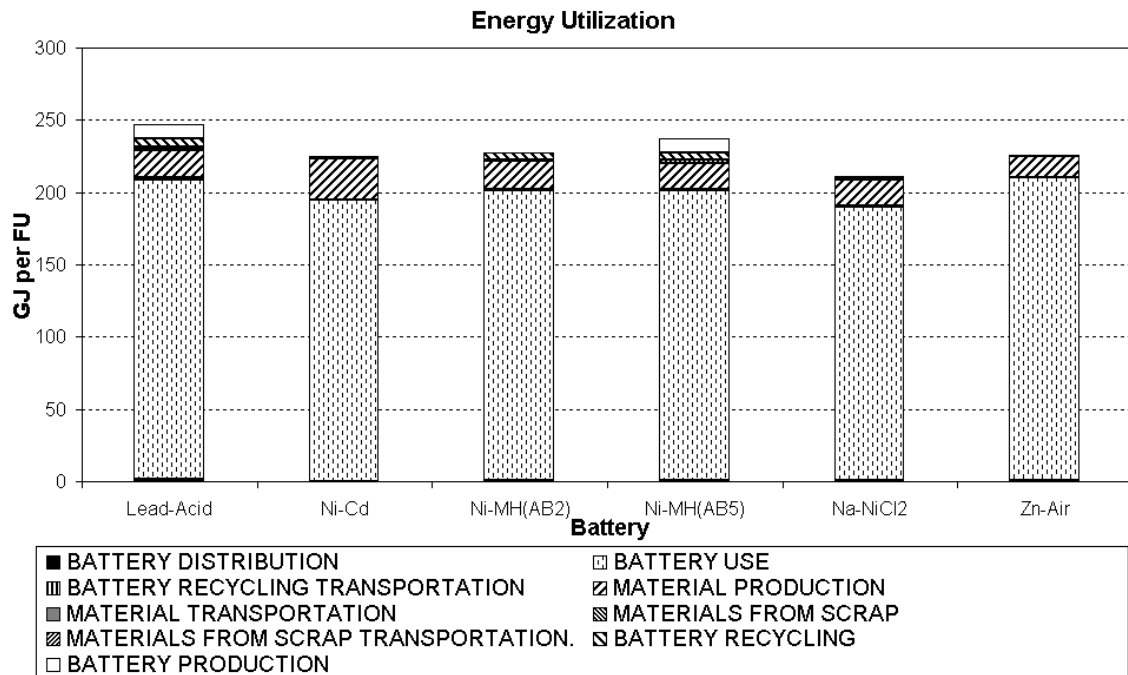
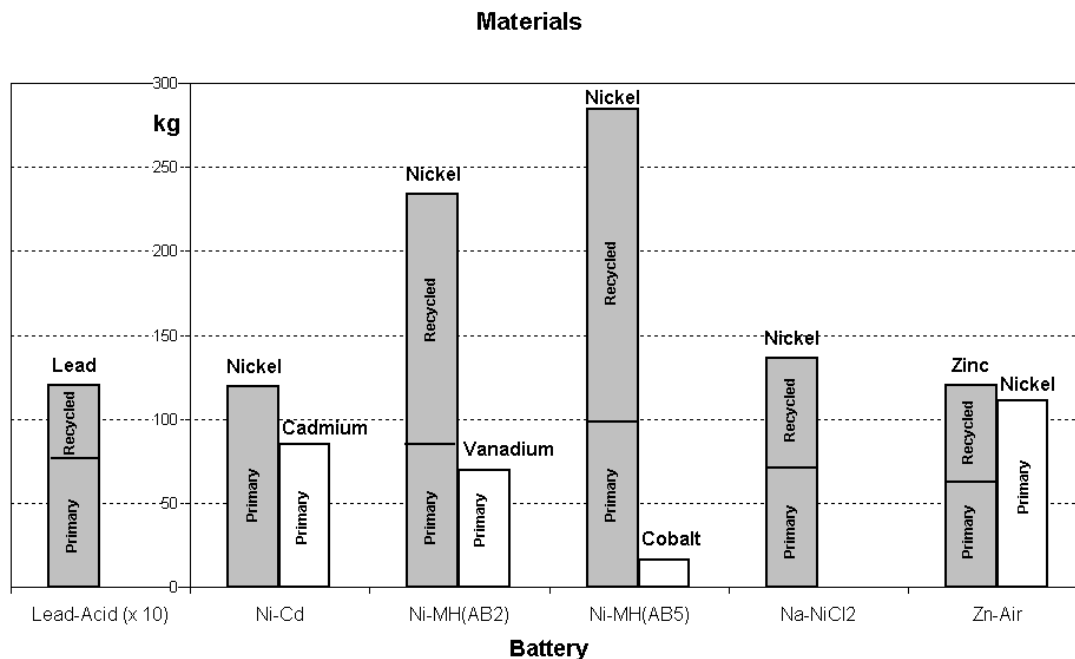


Figure 3.5 Energy utilization (all forms included) associated with the cycle life of the corresponding batteries during the entire lifetime of an EV. Production is reckoned only for the Lead-Acid and the Ni-MH(AB₅) batteries while recycling is taken into account for the Lead-Acid, Ni-Cd, Ni-MH(AB₂) and Ni-MH(AB₅) batteries. (FU: ten electric-passenger-vehicle years with specified driving range per cycle and year, corresponding to 200,000 km).

Furthermore, the total energy efficiency is one but not the only reason. The specific energy is another important factor. This can be concluded from the comparison of the Lead-Acid and the Na-NiCl₂ batteries (Figure 3.5), regarding only the energy utilization. Na-NiCl₂ has only slightly higher total efficiency than the Lead-Acid battery (67% and 66% respectively). However, in the case of Lead-Acid battery about 10% more energy has to be used. This can be explained from the fact that the Na-NiCl₂ battery has a much greater specific energy. High specific energy means a lighter battery - and therefore a lighter vehicle and a lower rolling resistance -, a longer driving range per cycle and finally lower energy utilization. Batteries with high specific energy are a must but the fact that a high specific energy is usually associated with shorter cycle life (Schlüter et al., 1996) has to be taken into consideration.

Material resources

The utilization of materials of possible future scarcity, which are used in the manufacturing of the examined batteries, is illustrated in Figure 3.6. Taking into account the *reserves*, in other words the identified resources that can be mined economically at prevailing prices (Andersson, 1998), Table 3.15 presents the number of EVs equipped with the corresponding battery that can be manufactured. Use of only primary materials and use of recycled materials (values in brackets in Table 3.15) are taken into account but a brand-new



EV is always equipped with a battery made only by primary materials (§3.3.1). This is the reason why no recycling is taken into account regarding nickel and cadmium for the Ni-Cd battery, where one battery can last for the entire lifetime of the EV (Table 3.1).

Figure 3.6 Materials of the examined batteries, which are expected to meet resource constraints (in kg per FU; FU: ten electric-passenger-vehicle years with specified driving range per cycle and year, corresponding to 200,000 km).

Considering the present-day passenger car population (about 500 millions) and forecasts showing that this population may be as high as 1 billion within 25 years (@Calstart, 1996), it stands to reason that there is no battery that can be produced in equivalent numbers. Consequently mass production of EVs should not be based on a sole battery, even if this battery has a very high performance. It seems therefore, that parallel development of different batteries is a necessity. In addition, due to the fact that nickel is used in a large number of batteries, the large-scale production of one nickel-based battery is likely to be preventive for the mass production of another nickel-based battery. Consequently, success of more than one nickel-based battery technologies may raise significantly the price of nickel

and finally the price of the batteries. The subject of resource constraints is analytically treated in Andersson (1998).

	Lead	Nickel	Cadmium	Vanadium	Cobalt	Zinc	Number of EVs per battery (millions)
Reserves (10⁶t)	68 ^a	47 ^a	0.54 ^a	10 ^a	4 ^a	180 ^b	
Recoverable Reserves^c (10⁶t)	54.40	58.75	0.43	8.00	32.80	144.00	
Lead-Acid	45.41 ^d (72.65) ^e						45.41 (72.65)
Ni-Cd		315.21	0.34				0.34
Ni-MH(AB₂)		160.62 (481.85)		473.17			160.62 (473.17)
Ni-MH(AB₅)		131.97 (395.94)			491.34		131.97 (395.94)
Na-NiCl₂		276.41 (513.45)					276.41 (513.45)
Zn-Air		339.13				1201.36 (2402.80)	339.13

^a Source: (Andersson, 1998)

^b Estimated according to cadmium reserves; cadmium is a by-product of zinc (cadmium-to-zinc ratio equal to 3:1000 (Schlüter et al., 1996)

^c Recoverable reserves are assumed to be 80% of the (extractable) reserves (Andersson, 1998)

^d Recycling is not taken into consideration

^e For number in brackets recycling is considered according to the proportions given in the Tables in §3.3.1; a new EV is always equipped with a battery made by primary materials

Table 3.15 Number of EVs (in millions), equipped with the corresponding battery, that can be produced using all the recoverable reserves of materials meeting resource constraints.

CO₂ Emissions

Figure 3.7 presents the total CO₂ emissions related to the cycle life of the particular battery during the entire lifetime of an EV. The use of battery is the most crucial stage of all the batteries. The highest emissions are attributed to Ni-MH battery mainly due to the production of the materials used in the battery. The high utilization of iron, associated with high CO₂ emissions is the reason for the high emissions of the Ni-MH battery. The production of materials, particularly iron and aluminum, is also the reason behind the high emissions of Na-NiCl₂ batteries. On the other hand, the high emissions attributed to the Lead-Acid battery are related to the transportation stages (significantly higher ton-kms in comparison with the other batteries). Here, the use of rail transport may soften the impact of Lead-Acid battery. Ni-Cd battery appears to yield the lowest CO₂ emissions. Only one battery is used during the lifetime of the EV and relatively low CO₂ emissions are discharged during the production of the materials used in Ni-Cd batteries.

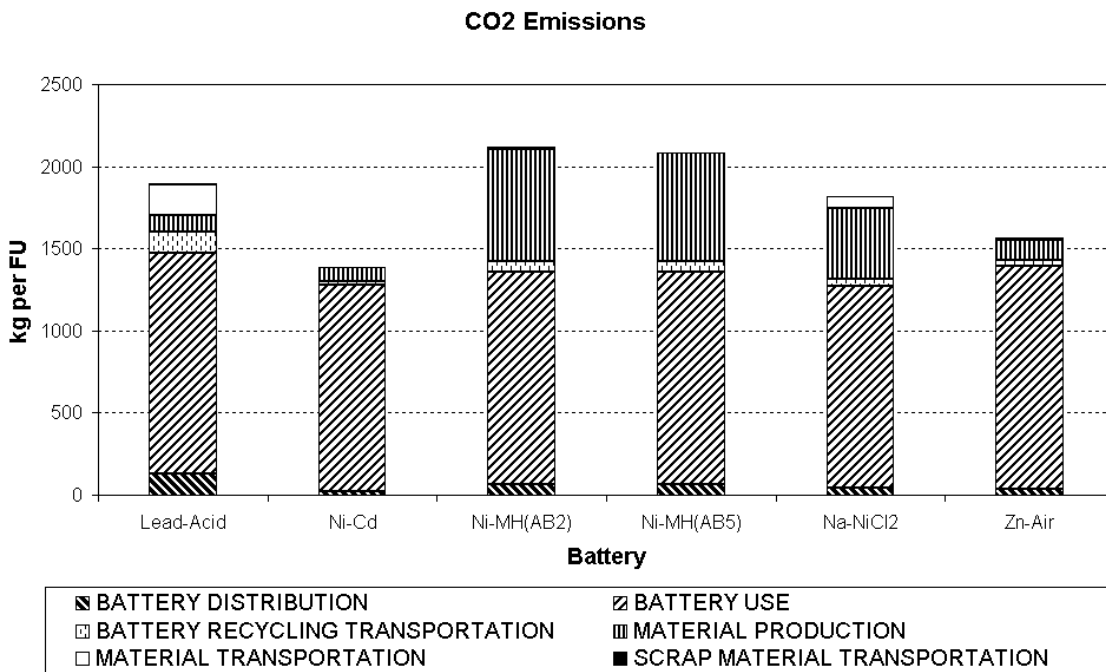


Figure 3.7 CO₂ emissions associated with the cycle life of the corresponding batteries, during the entire lifetime of an EV (FU: ten electric-passenger-vehicle years with specified driving range per cycle and year, corresponding to 200,000 km).

NOx Emissions

Figure 3.8 illustrates the emissions of NO_x. Battery use is the stage that contributes the most. Lead-Acid battery appears to have the highest emissions mainly due to the high ton-kms associated with the transportation of the battery and its materials. Transportation yields significant NO_x emissions in the case of Ni-MH and Na-NiCl₂ batteries as well. The lowest emissions are attributed to the Ni-Cd battery and, as in the case of CO₂ emissions, the fact that only one battery is considered results in a low number of ton-kms and justifies the battery's better performance.

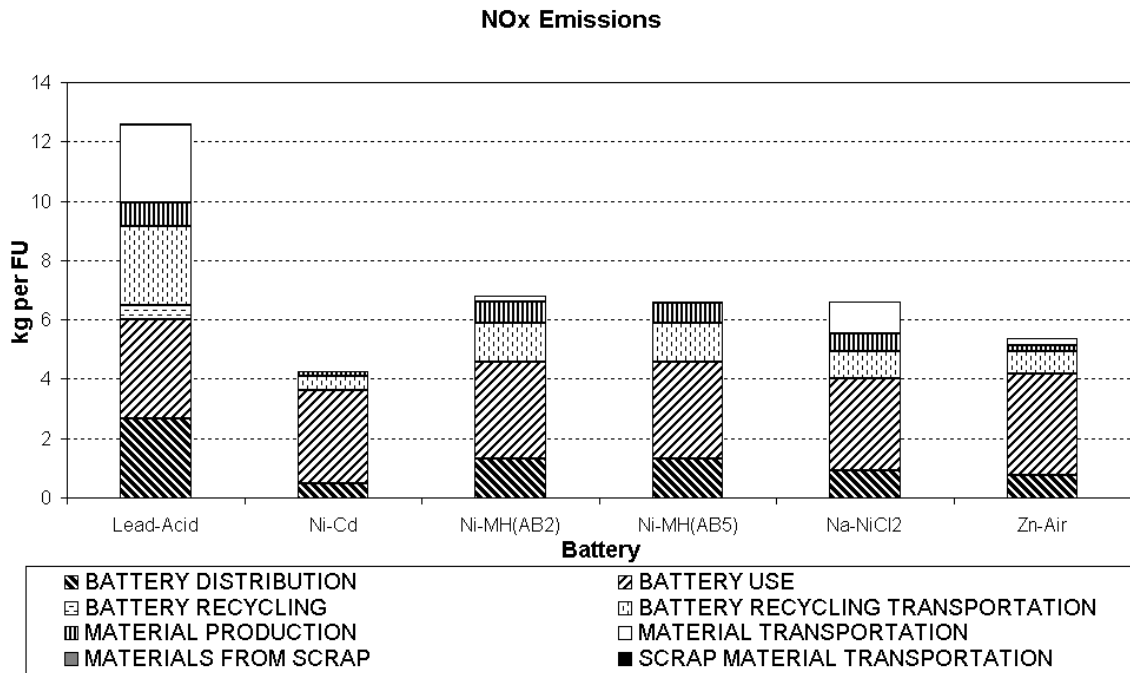


Figure 3.8 NO_x emissions associated with the cycle life of the corresponding batteries, during the entire lifetime of an EV (FU: ten electric-passenger-vehicle years with specified driving range per cycle and year, corresponding to 200,000 km).

SO₂ Emissions

Regarding SO₂ emissions (Figure 3.8), with the exception of the Lead-Acid battery, the stage that contributes the most is undoubtedly the material production. Nickel is largely used in the manufacturing of all batteries, exclusive of Lead-Acid (Figure 3.6). The extraction of primary nickel is associated with high emissions of sulfur dioxide – 2 kg SO₂ are emitted for the mining of 1 kg nickel (Schlüter et al., 1996). Nevertheless, these values are representative of the conditions of certain mines. Ni-Cd and Zn-Air batteries are associated with great needs of primary nickel (per FU) and consequently with high SO₂ emissions. On the other hand, even if the total amount of nickel (per FU) used in Ni-MH and Na-NiCl₂ batteries (Figure 3.6) is higher than in Ni-Cd and Zn-Air, the use of recycled nickel gives these batteries a better performance. Relatively high SO₂ emissions are associated with the transportation of the Lead-Acid battery due to its heavy weight but the recycling part also contributes significantly.

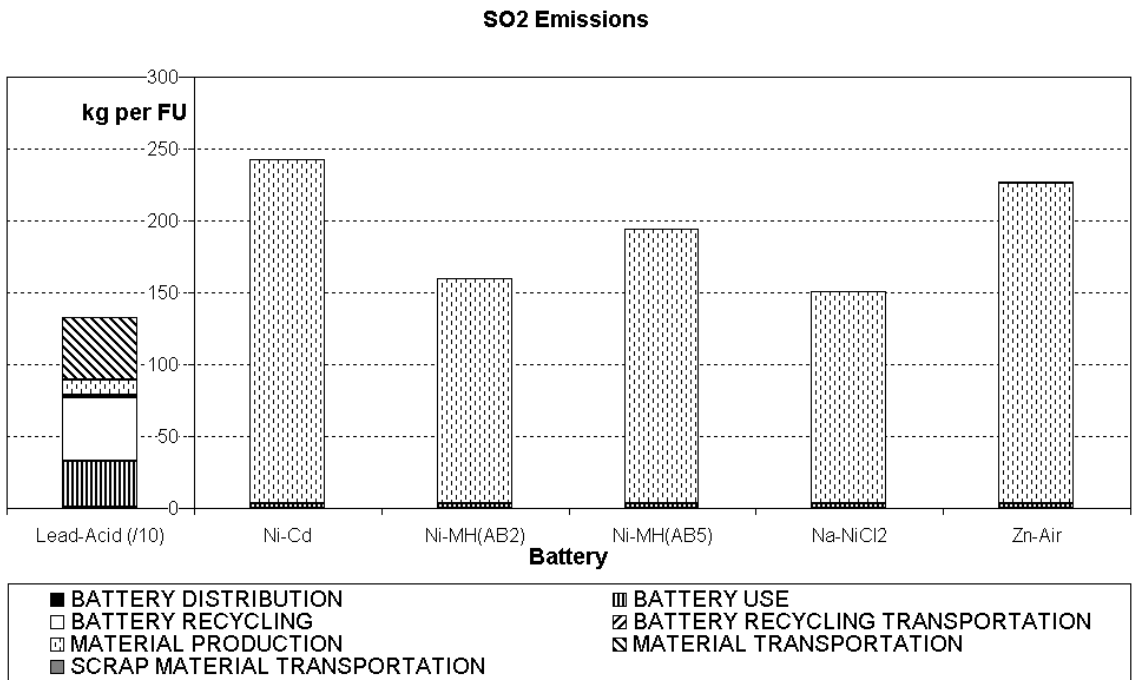


Figure 3.9 SO₂ emissions associated with the cycle life of the corresponding batteries, during the entire lifetime of an EV (FU: ten electric-passenger-vehicle years with specified driving range per cycle and year, corresponding to 200,000 km).

3.5.2 Valuation

Global Warming

Since emissions of CH₄, CFCs and N₂O are almost insignificant, the environmental load of the batteries with regard to global warming depends heavily on CO₂ emissions. The similar profiles of Figures 3.7, and 3.10 are leading to this conclusion. According to both valuation methods Ni-MH has the highest environmental load and Ni-Cd the lowest.

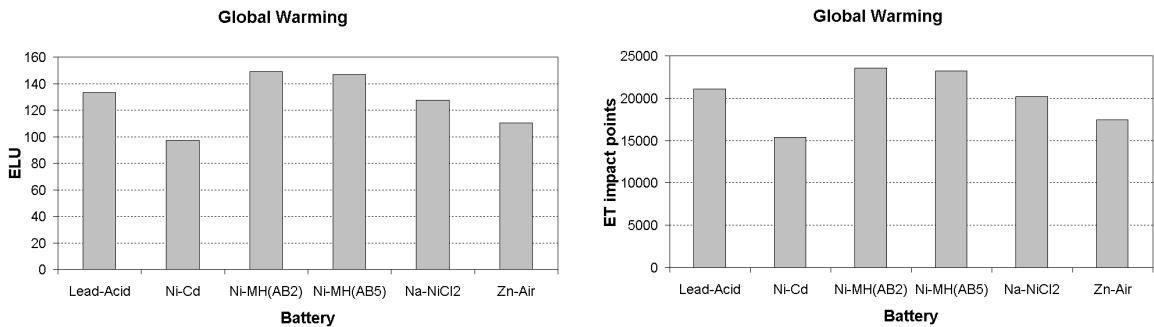


Figure 3.10 EPS score (ELU) and ET score with regard to global warming.

Acidification

SO₂ emissions and minor NO_x emissions determine the performance of the batteries regarding acidification since the emissions of other relevant pollutants are insignificant. Again it stands to reason that the profiles of Figures 3.11 and 3.9 are similar, leading to the conclusion that the impact to acidification depends foremost on SO₂ emissions and the production of nickel, for all the batteries exclusive of Lead-Acid. Lead-Acid battery is associated with very low SO₂ emissions but the high NO_x emissions (Figure 3.8) increase the battery's score.

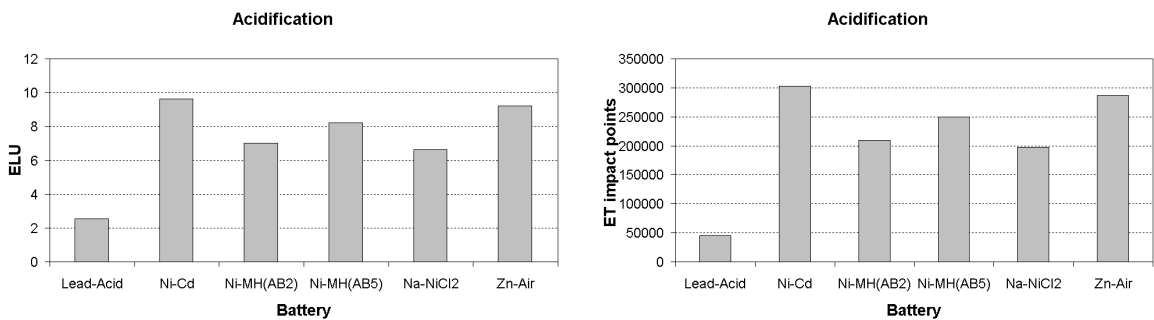
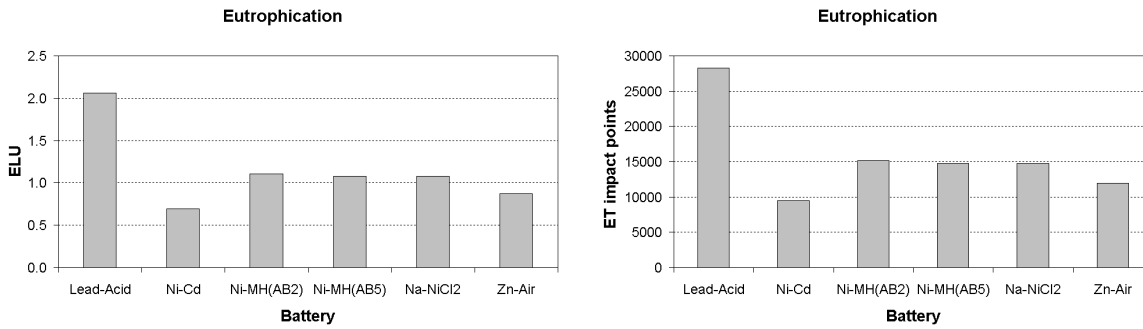


Figure 3.11 EPS score (ELU) and ET score with regard to acidification.

Eutrophication

NO_x emissions play the most important role concerning the impact to eutrophication. This can be concluded from the comparison of Figures 3.12 with the Figure 3.8. It goes without saying that Lead-Acid battery has the highest environmental load followed by Ni-MH and Na-NiCl₂, which appear to have similar scores.



Na-NiCl₂, which appear to have similar scores.

Figure 3.12 EPS score (ELU) and ET score with regard to eutrophication.

Carcinogenic

Production of lead, largely used in the manufacturing of the Lead-Acid battery, is associated with significant emissions of arsenic and this is the reason why the certain battery has by far the highest environmental load with regard to carcinogenic impact. Arsenic emissions are insignificant in the case of other batteries with the exception of Zn-Air that appears to have the second highest environmental load which, however, is significantly lower than the load of Lead-Acid. The production of zinc is also associated with emissions of arsenic.

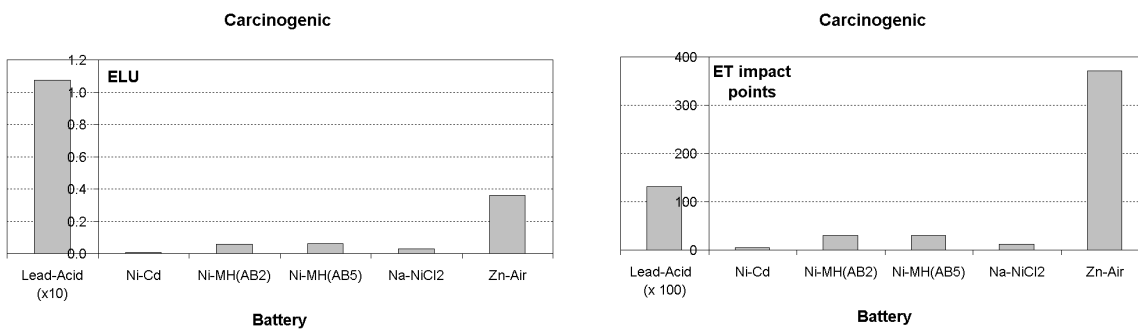


Figure 3.13 EPS score (ELU) and ET score with regard to carcinogenic impact.

3.5.3 Discussion

Due to the relatively moderate energy efficiency of the considered batteries as well as other losses (mains, charging stations), the stage of the cycle life of the battery that bears the heavier environmental load is the area of use. Improving the energy efficiency and the

specific energy of the battery must be a priority for the battery manufacturers. Moreover, other industries involved in the manufacturing and operation of the EV such as the automotive industry, the charger manufacturers and the power supply industry should also contribute by improving the efficiency of their products.

Resource constraints seem to be a major problem for the mass production of the considered batteries. There is no battery that could be mass-produced in numbers equivalent to the car population of today. The Ni-Cd cannot be manufactured in more than 300,000 units due to the scarcity of cadmium. One should also consider that nickel is largely used in four battery systems (Ni-Cd, Ni-MH, Na-NiCl₂, Zn-Air). A possible success of all or some of them associated with failure of other no-nickel battery technologies, could result in increased needs of nickel, leading to high nickel prices and consequently to high battery prices.

With regard to environmental impact, Lead-Acid is associated with emissions that contribute to eutrophication and increase the carcinogenic potential whereas its contribution to global warming is also significant. Due to the high cycle life and the fact that only one battery is used during the EV lifetime, Ni-Cd appears to have worse performance, than the other batteries, only when it comes to acidification. Ni-MH and Na-NiCl₂ have a bad picture concerning the global warming but their performance with regard to acidification cannot be characterized as good. Finally, the high acidification potential is a drawback for the Zn-Air battery, which also showed a relatively high eutrophication score.

4 FAST CHARGING OPTIONS

4.1 INTRODUCTION

Fast charging is regarded as the basis for the commercialization of the EV and as the necessary boost for new applications. Under a fast charging regime, charging the EV battery may take almost as long as refueling an ICEV. The kilometer performances, which can be attained on this basis, may write off the advantages of the fuel-based vehicles. The user will be given the ability to use the EV as primary means of transport, the same way as he or she uses an ICEV, and without having to count the distance that the battery's capacity of the EV can afford between charges.

Under these conditions the EV society will have to face two major issues:

1. The impact of fast charging on electricity generation, given that fast charging of a significant number of EVs will take place in hours of peak electrical demand and considering the much higher rate of power that is transferred with fast charging, comparing with normal charging.
2. Mechanisms that affect negatively the cycle life of the battery and come into force when the battery is overcharged, undercharged or deep-discharged. Therefore, charging must always be controlled and any deviation from adequate charging schedules will result in capacity loss and reduction of the battery cycle life. Within this framework, it is claimed in this study that it is not the fast charging technique that may wear out the battery, but the way in which the user may charge and discharge the battery, having in mind the possibility or convenience of fast charging. When comparing the EV with the ICEV it is the user who, in both cases, decides how much energy has to be transferred to the vehicle and when. In the case of the ICEV, it is again the user who will decide the end of this energy transfer, while in the case of the EV, it is the on-board computer that will control the battery. However, adequate fast charging, according to the on-board computer, may take significantly longer than the refilling of the fuel tank and due to the high power rate it may be rather expensive. Therefore, it should be expected that charging rules incorporated into the on-board computer will often be violated since users for economical or time reasons, may require the same degree of freedom in transferring energy to the vehicle as they have today.

Research has been devoted to both these issues and the scientific community is striving to solve problems like, e.g., how many new power stations are needed to accommodate a certain number of EVs, if they have to be charged quickly during daytime, or how a certain battery reacts to a particular fast charging algorithm. The aim of this chapter is, with regard to environmental impact, to try to reveal the possible surprises that might hide behind the fast charging curtain.

4.2 FAST CHARGING

4.2.1 Charging fast

Fast charging is expected to have consequences on battery's life. However, there is a certain degree of confusion on whether or rather under what conditions, fast charging is damaging the battery. Before proceeding with the analysis of the consequences of fast charging on the function of the batteries, some aspects of charging will be given.

In general, three functions are necessary to perform to allow power to flow from the mains to the EV (Sims et al., 1997):

- Since the EV electrical system is based on direct current, the alternating current provided by the mains must be changed, or rectified, to direct current;
- The supply voltage must be constantly higher than the primary EV electrical system voltage, during the entire charging period;
- The power source must be physically connected to the EV.

Fast charging has been defined as the Level 3 EV charging (Sims et al., 1997) according to which charging will be taking place at retail fast charge stations and more than 50% of the battery's capacity will be returned within 10 to 15 minutes. For a 60 kWh battery for instance, 400 A at 400 V will be required to achieve a 50% recharge in less than 15 minutes. Normally a 50% recharge is returned slower if the battery is to be charged up to 100% SOC instead of being charged up to 80% or 70% SOC (Hawker Energy, 1998). Nevertheless, this fact is not taken into consideration. Fast charging will most likely take place during daytime and likely at periods of peak electrical demand.

With regard to the charging schedule, fast charging implies the use of a special algorithm. An algorithm such as the CC/CV/CC (constant current/constant voltage/constant current) may be used (Hawker Energy, 1998). With such an algorithm the charger starts in a constant current (CC) mode until the battery terminal voltage reaches a specific value. Then the charger switches to a constant voltage (CV) mode and it continues like that for a time interval specified by the manufacturer. By the end of this interval the charger switches to a constant current mode until just before the end of charge, when constant voltage is applied again. It has to be mentioned that in the beginning of charging, the battery has high charge acceptance efficiency and the CC charger rapidly replaces a large portion of the discharged capacity, depending on the SOC of the battery. The charger must switch to a CV mode when the battery voltage reaches a peak, in order to avoid overcharging of the battery. Under the CV mode the charge current is regulated continuously.

4.2.2 Critical parameters in a fast charging regime

As negative effects of charging have been reported the rise of temperature, the gassing and the 'memory effect'. Temperature rises in the battery due to the total Joule effect which takes place more intensively under fast charging due to the high currents employed (§ 3.3.3). Gas evolution is the result of water decomposition taking place vigorously when charging at high current limits. Finally 'memory effect' (or memory accumulation) is a

problem mainly for Ni-Cd and to a lesser degree for Lead-Acid, and Ni-MH batteries¹. When a battery is not fully discharged before charging, the battery ‘remembers’ the size of the discharge, resulting in a temporary voltage drop. After that, it will only be charged up to the level where it was last discharged (@Power Warehouse, 1998). Under a fast charging regime the importance of the memory effect will rise due to the fact that the battery will be charged from several SOCs.

Nevertheless, methods and techniques already exist, or are under development, to successfully tackle these effects. Rise in temperature is coped with by ventilation of the battery and removal of the excess heat. Ventilation and in addition proper periodic maintenance and watering are solutions to problems raised due to gas evolution. Furthermore, appropriate battery management is used to identify those blocks of the battery pack, needing maintenance or replacing. Finally, memory effect has been significantly restricted even in the case of Ni-Cd batteries, where cells without memory effect have been developed (Cornu, 1994). In addition ‘clever’ chargers that fully discharge the batteries before charging them can be manufactured today.

In the present study, it is believed that commercialization of the EV can not take place, if the above mentioned degradation mechanisms are still in action. Therefore it is taken for granted that under a fast charging regime, battery deterioration due to such effects will not be the case.

On the other hand, critical mechanisms directly associated with the way of charging and discharging the batteries (§4.1) and which can affect a battery’s cycle life are taken into consideration. It is believed in this study, that it is easier for the battery industry to find solutions for the above mentioned problems (e.g. gassing) than for problems raised due to undercharging and deep discharging. In addition the importance of these problems will rise in significance when fast charging is fully or partially performed.

The most damaging case for a battery is the deep discharge, in other words the extension of discharging after the limit that has been specified by the manufacturer (usually 80% DOD) (Rand et al. 1998). Furthermore, in cyclic applications and particularly if fast charging can be performed, undercharging is likely to happen often, leading to a premature failure of the battery. On the other hand, discharging from 100% SOC to depths of discharge, lower than the DOD specified by the manufacturer, is beneficial for the battery’s cycle life and that will also be discussed here. It has to be mentioned that overcharging is another critical issue which, however, is not considered here since it is assumed that the on-board computer will always prevent cases of overcharging.

Bearing in mind that fast charging stations will be similar to today’s gas stations, the behavior of the EV user may be equivalent to that of an ICEV user. This means that the user may interfere with the procedure of charging (the same way it does today while fueling an ICEV), as it was discussed in §4.1, and the above mentioned parameters may indicate a much greater importance than in normal charging.

¹ Such an effect has not been reported for other battery systems. Therefore, it is unknown if other battery systems suffer from the ‘memory effect’.

Undercharge

Generally in a cyclic application, incomplete charge or in other words charge up to a lower level than 100% SOC is damaging for the battery. It has been reported that a Lead-Acid battery with a cycle life of 500 cycles failed in less than 30 cycles due to undercharge (Hawker Energy, 1998). Hawker suggests that a good way to avoid capacity loss due to undercharge is to fully recharge the battery periodically with low current limit. No information about the relation between undercharging and cycle life is available. It is a complex issue and it is likely that it does not affect the cycle life of other batteries. Nevertheless, it was decided to take it into consideration, as it is something that will very often take place under a fast charging regime. It is assumed that every time a battery is undercharged its cycle life is reduced linearly.

Deep discharge

Loss of capacity and earlier degradation are the consequences of deep discharge which is produced when the battery is discharged beyond the end-of-discharge voltage specified by the manufacturer. It is a problem mainly for Lead-Acid batteries where the structure of the active material is permanently lost due to sulfating mainly in the bottom of the electrodes (Tudor, 1998). It is therefore recommended to discharge the battery until 80% DOD. In Ni-Cd deep-discharging it is not so critical but it may cause short-circuits due to formation of cadmium dendrites at the positive electrode (Berndt, 1997). When Ni-MH batteries are deep-discharged the consequence might be oxidation of the hydrogen-storing alloy (Berndt, 1997). Na-NiCl₂ batteries do not suffer from deep-discharge since the liquid electrolyte develops a protective reaction and the battery can have a full cycle life despite excess discharge of a few Ah (AEG ZEBRA, 1997). For Lead-Acid, Ni-Cd and Ni-MH batteries the effects of deep-discharge will be assessed with the assumption that every time the battery is discharged below 80% DOD, its cycle life reduces linearly by a certain rate.

Low level of discharge

Discharging the battery from 100% SOC to depths of discharge lower than 80% is usually beneficial for the battery because the battery can have a longer cycle life as it is illustrated in the Figure 4.1.

It is supposed that the ability to fast-charge the battery will lead to more frequent charges but with less capacity. The latter can also be supported by the fact that the user may prefer to spend the shortest time possible in charging the battery at a charging station and therefore permit only small capacities to be delivered to the battery.

The following curve (Figure 4.1) is representative of Lead-Acid batteries. Similar curves for other batteries were not found. There is though evidence that the cycle life of Ni-MH batteries varies also exponentially with the DOD (Niklasson, 1997). This curve will be used to assess the effects of a low discharge level for all the considered batteries. The curve is approximately represented by the following equation:

$$\text{Cycles} = 19843Pe^{(-0.06168P \text{ DOD})}$$

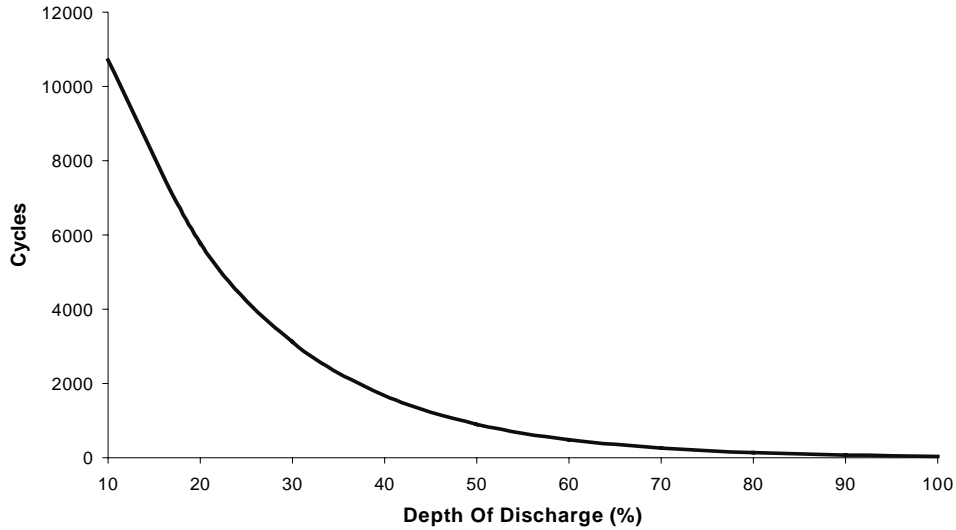


Figure 4.1 Cycle life versus DOD (based of a figure provided by Elcat, 1998).

Figure 4.2 presents possible charging-discharging routines. It cannot be claimed that these routines are representative of the operation of an EV which nevertheless differs widely according to the purpose of the EV.

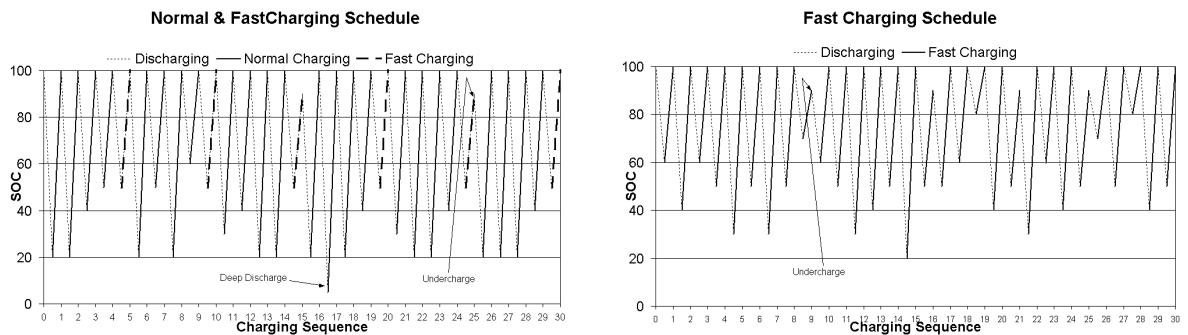


Figure 4.2 Charging sequences for combination of normal and fast charging and exclusive fast charging (assumed, based on information from Asakura (1997) and DAUG (1998)).

Deciding the reduction rate

Since no information is available concerning the impact of undercharge and deep-discharge on the cycle life of the considered batteries (curves like the one in Figure 4.1 were not found), a sensitivity analysis is performed. For simplification reasons it is assumed that the cycle life is reduced linearly and with the same rate for all the batteries, every time undercharge or deep-discharge occurs. Most likely this is not true, but the complexity of the mechanisms and lack of information, do not permit of a better approach. Several reduction rates are chosen and using the charging schedules presented in Figure 4.2 the number of

cycles as well as the number of batteries used in the entire life of an EV (200,000 km) are calculated and presented in Table 4.1.

Battery	Rate of reduction of cycle life	Fast & Normal Charging		Fast Charging	
		Number of cycles	Number of batteries	Number of cycles	Number of batteries
Lead-Acid	2%	580	6	853	5
	5%	372	9	461	9
	10%	241	13	279	15
Ni-Cd	2%	986	3	1216	3
	5%	565	5	613	6
	10%	337	8	350	9
Ni-MH	2%	526	4	800	4
	5%	346	6	443	6
	10%	227	9	266	10
Na-NiCl ₂	2%	841	2	973	3
	5%	541	3	515	5
	10%	356	5	302	7

Table 4.1 Cycle life and number of batteries according to different rates of reduction due to undercharge or deep-discharge.

From Table 4.1 it is obvious that a 10% reduction of the cycle life would turn fast charging unacceptable. The number of batteries that have to be used during the entire life of an EV would at least triple, in comparison with normal charging. It stands to reason that such a scenario is not realistic. On the other hand, a 2% reduction of cycle life seems too good to be true. The number of batteries does increase but not significantly, with the exception of Ni-Cd battery². It can be claimed that a scenario of 2% reduction may not show clearly the trends in the environmental performance of the batteries since it is very close to a normal charging scenario. As a more realistic approach emerges therefore a 5% reduction and is the one that is taken into consideration.

4.2.3 Energy losses while fast charging

Energy losses are mainly assessed in the same way as in §3.3.3. Regarding the part of charging, the higher current applied will result in higher amounts of heat being generated due to the total Joule effect. The energy efficiency of the battery is therefore expected to be lower. When comparing with normal charging and assuming similar discharge currents, the much higher charging current will result in lower voltaic efficiency and consequently in lower energy efficiency. In addition, the heat generated is destructive for the battery (probably with the exception of Na-NiCl₂ batteries where the excess heat is not a *de facto* loss) and must be removed by ventilating the battery and the utilization of an additional amount of energy. Since no information was available, it was assumed that the energy efficiency of the batteries, while fast charging, is 10% lower compared with normal charging. It is also assumed that the charger efficiency is 5% lower.

² A linear reduction of the cycle life is more critical for the Ni-Cd battery than for the other batteries, due to the significantly higher number of cycles that this battery can afford.

Assuming that 50% of the nominal capacity have to be returned to the battery within 15 minutes then the average current required (2PC₅) is given in the following Table 4.1. A comparison with normal overnight charging with 0.1PC₅ current is presented in order to form a conception of how higher current limits may be used in a fast charging regime.

	Nominal Capacity (Wh)	Voltage (V)	Ah capacity (5-h rate) (Ah)	Charge Current (normal charging) (A)	Charge current (fast charging) (A)
Lead-Acid	17000	70	250	25	500
Ni-Cd	20000	200	100	10	200
Ni-MH	25000	250	100	10	200
Na-NiCl ₂	30000	250	120	12	240

Table 4.2 Hypothetical current limits for charging the batteries with normal and fast charging.

Electrically recharged batteries	Net of losses in the utility grid to the socket ¹	Charger Efficiency ²	Energy efficiency ³	Self-discharge per 24h ⁴	Losses due to heating ⁵	Gain from regenerating braking ⁶	Total Energy Efficiency
	(a)	(b)	(c)	(d)	(e)	(f)	(g) ⁷
Lead-Acid	9%	80%	70%	1%	-	8%	54%
Ni-Cd	9%	80%	70%	5%	-	8%	52%
Ni-MH	9%	80%	60%	2%	-	8%	46%
Na-NiCl ₂	9%	80%	87%	-	17%	8%	57%
Mechanically recharged batteries	Net of losses in the utility grid to the regeneration	Multi-MW power converters efficiency	Power consumption regeneration operation	Regeneration efficiency	Self-discharge losses	Losses due to distribution	Total Energy Efficiency
	(h)	(i)	(j)	(k)	(l)	(m)	(n) ⁹
Zn-Air ⁸	6%	98%	95%	57%	3%	3%	47%

¹ Estimated according to 'Livscykelanalys för elnätet' Svenska Kraftnät, Vattenfall, Göteborg Energi

² Assumed

³ Assumed

^{4,5} According to DAUG (1996) and AEG ZEBRA (1997)

⁶ Average from DAUG (1996)

⁷ $g = (1-a) \cdot b \cdot c \cdot (1-d) \cdot (1-e) \cdot (1+f)$

⁸ Source: (Schlüter et al. 1996)

⁹ $n = (1-h) \cdot i \cdot j \cdot k \cdot (1-l) \cdot (1-m)$

Table 4.3 Total energy efficiency for the batteries in question while fast charging.

4.3 LCA MODIFICATION WITH RESPECT TO FAST CHARGING OPTIONS

4.3.1 Fast charging scenarios

Considering the above, two fast charging scenarios are drawn:

Scenario 1: Normal and fast charging

Fast charging is combined with normal overnight charging according to specific routine (Figure 4.2). Tests under real conditions, showed that the share of energy used for fast charging in total energy used for charging did not exceed the 20% (DAUG, 1996) and this proportion is taken into account. The on-board computer controls charging, but external interference is also possible. When normal charging is applied the battery is charged from several depths of discharge up to always 100% SOC. When fast charging is performed, 50% of its capacity can be returned within 15 minutes. While fast charging, the user may stop the charging abruptly, before the completion of charging (100% SOC) once in a while (Figure 4.2), and every time this undercharge occurs, the cycle life of the battery is reduced linearly by a certain proportion (5%). In addition, deep discharge is also taken into consideration assuming again that the battery is deep-discharged once in a while, and every time this happens the lifetime of the battery reduces again linearly by a certain ratio (5%). The remaining cycle life is assessed with the help of Figure 4.1. All the energy losses (mains, charger, and battery) as well as recuperated braking energy are considered as in §4.2.3 (Table 4.3) and the ambient temperature is assumed to be 25°C.

Scenario 2: Fast Charging

A more advanced fast charging regime is assumed and the batteries can be fast-charged continuously from several depths of discharge up to 100% SOC. As a consequence normal charging is not employed at all. The on-board computer controls continuously the battery but user interference is again possible and therefore undercharge cases may occur. It is supposed that the ability to charge quickly the battery will reduce and even eliminate deep discharge cases. As a possible consequence, undercharge occurs more often due to the fact that the shorter driving distance per charge and the elimination of deep discharge will result in a more frequent interruption of charging than in scenario 1. (A user in a hurry, may prefer to interrupt the charging process instead of deep-discharging the battery when the battery capacity is not enough for the distance that has to be driven). When the battery is undercharged, its cycle life is reduced linearly by the same proportion (5%) as in scenario 1. Energy losses, recuperated braking energy and ambient temperature are as in scenario 1.

Results from the two scenarios are presented in Table 4.1.

With respect to the assumptions made, the use of fast charging affects the cycle life of the battery negatively, regardless if it is used partially (in combination with normal charging) or exclusively. Due to the battery's degradation the average kilometer distance per charge is lower compared with normal charging.

Charging Scenario	Number of charges-discharges per battery	Energy utilisation per battery (losses included) [kWh]		Average km driven per charge	Integer number of batteries per EV lifetime (200,000 km)
		Normal	Fast		
Lead-Acid					
Normal	700	16000		80	4
Normal & Fast	372	5518	1092	66	9
Fast	461		7038	51	9
Ni-Cd					
Normal	2000	54000		100	1
Normal & Fast	565	10031	1997	83	5
Fast	613		11227	63	6
Ni-MH					
Normal	600	20592		125	3
Normal & Fast	346	8402	1697	103	6
Fast	443		11304	79	6
Na-NiCl₂					
Normal	1000	40461		150	2
Normal & Fast	541	13701	2634	124	3
Fast	515		13013	95	5
Zn-Air					
Normal	400	29100		300	2

Table 4.4 Comparison of the three charging options.

4.3.2 LCA results and comparison with normal charging

Figure 4.2 presents the comparison between the three charging scenarios with regard to energy utilization. Under a normal/fast charging regime, the higher number of batteries used, and consequently the higher ton-kms of transport, as well as the greater energy losses while using the EV, cause an increase of the total energy used. This increase is almost 15% regarding Lead-Acid and Ni-MH batteries and 20% in the case of Ni-Cd batteries. The increase is greater if only fast charging is applied and with regard to Ni-Cd batteries it may reach 40%.

Considering the Na-NiCl₂ battery a slight decrease (2%) in the amount of the energy used, when normal charging and fast charging are combined, is observed, despite the use of one more battery. This can be explained from the fact that the battery does not suffer from deep discharge and consequently high kilometer performances may be achieved occasionally without degradation of the cycle life. When comparing with normal charging, the lower total energy utilization while using the EV outweighs the increase in energy due to one more battery and the associated transports.

It stands to reason that Zn-Air become advantageous with regard to energy utilization if only fast charging is considered.

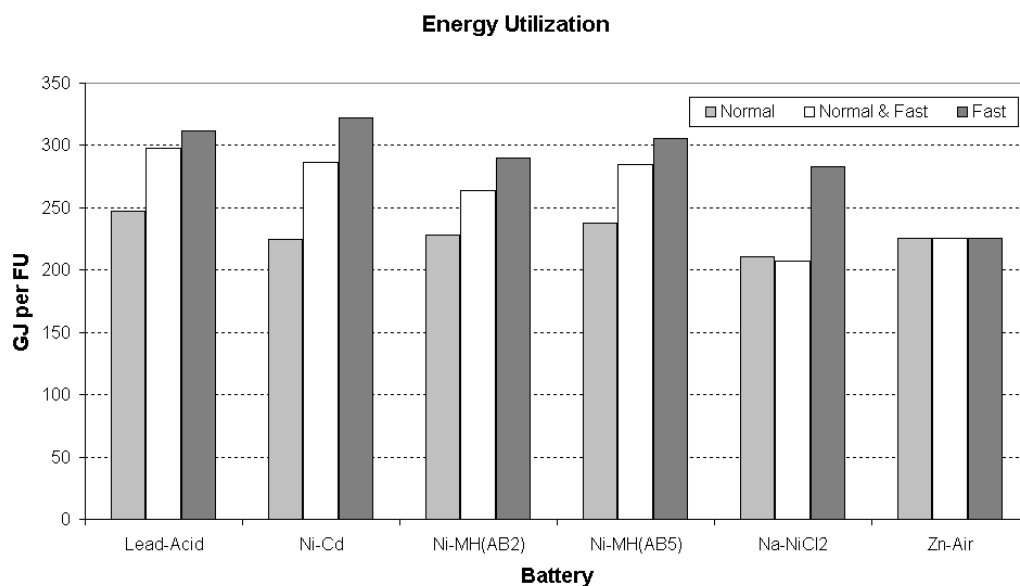


Figure 4.3 Energy utilization under different charging regimes. Production is reckoned only for the Lead-Acid and the Ni-MH(AB₅) batteries while recycling is taken into account for the Lead-Acid, Ni-Cd, Ni-MH(AB₂) and Ni-MH(AB₅) batteries. (FU: ten electric-passenger-vehicle years with specified driving range per cycle and year, corresponding to 200,000 km).

With regard to acidification (Figure 4.4), the comparison of the scores related to the different scenarios leads to the conclusion that fast charging does not alter the picture. With the exception of Ni-Cd and Lead-Acid batteries, the use of fast charging does not increase significantly the EPS score of the batteries and this is due to the use of secondary materials (particularly nickel). In the case of Ni-Cd battery the significantly higher EPS score is explained as in §3.5: the much higher number of battery units used and the use of primary nickel in the production of nickel hydroxide are the reasons for the bad performance of this battery. The beneficial consequences of using secondary materials can be observed by considering the Ni-MH and Na-NiCl₂ batteries where the nickel used is derived from recycling. Finally, the ELU of the Lead-Acid battery is increased mainly due to the higher NO_x emissions associated with the transportation parts and the greater number of ton-kms due to the fact that five more batteries are used in comparison with normal charging.

With regard to global warming (Figure 4.5), eutrophication (Figure 4.6) and carcinogenic impact (Figure 4.7) similar trends as in the case of energy utilization can be observed for all the batteries exclusive of Na-NiCl₂. It stands to reason that as fast charging leads to the use of more batteries during the lifetime of the EV, the EPS scores increase. Nevertheless, where use of recycled materials is involved, the increase in environmental impact is restricted. While, for instance, the number of Ni-MH batteries is doubled, the global warming and eutrophication scores do not increase more than 50%. On the other hand, considering that the carcinogenic impact is related to materials that are not recycled, it can be seen that the EPS score of all batteries is increased directly proportionally to the number of batteries.

Regarding the Na-NiCl₂ battery the different trends compared with energy utilization (while the energy utilization is slightly decreased, the environmental impact is slightly increased when normal and fast charging are combined), can be explained from the raised CO₂, SO₂ and NO_x emissions within the several parts of transport due to higher number of batteries and the consequent higher ton-kms. Exclusive use of fast charging causes the global warming and eutrophication scores to vigorously rise.

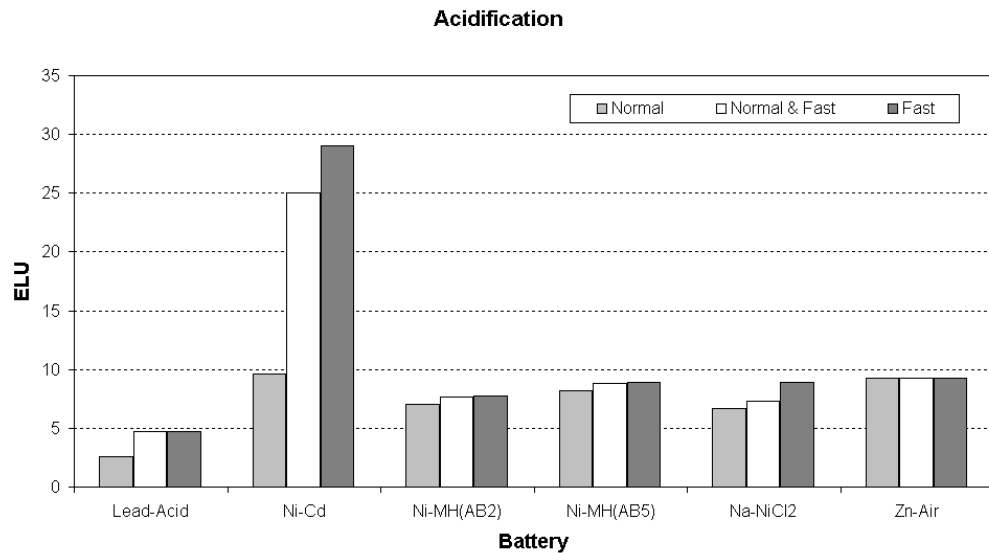


Figure 4.4 Acidification score (ELU), calculated with the EPS method, relative to the considered batteries, under different charging regimes.

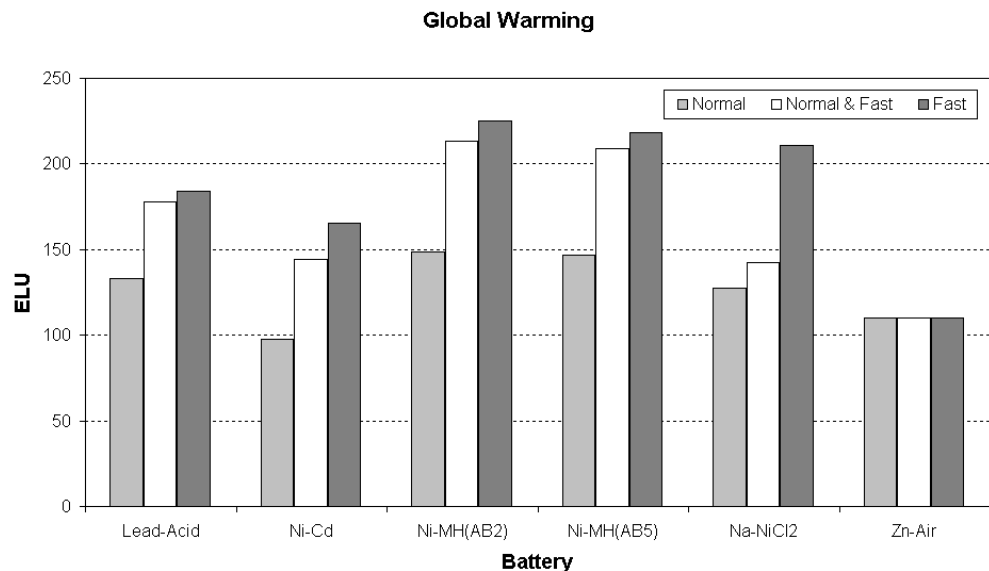


Figure 4.5 Global warming score (ELU), calculated with the EPS method, relative to the considered batteries under different charging regimes.

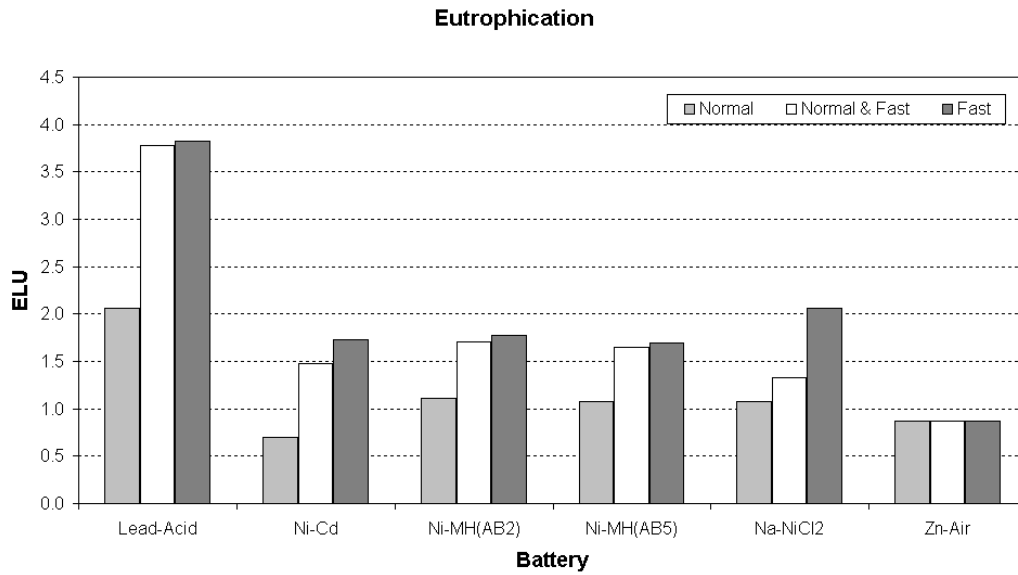


Figure 4.6 Eutrophication score (ELU), calculated with the EPS method, relative to the considered batteries under different charging regimes.

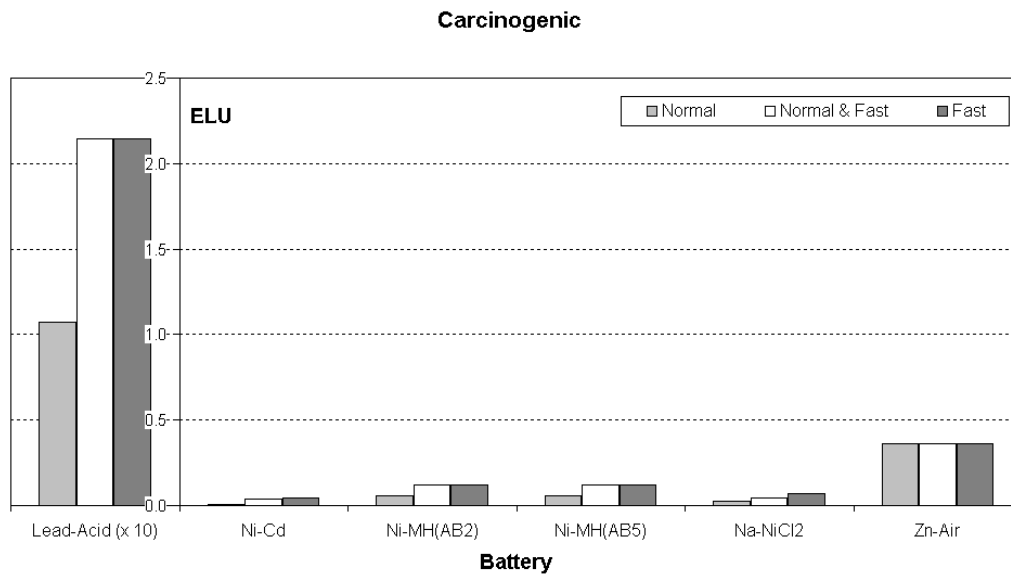


Figure 4.7 Carcinogenic impact score (ELU), calculated with the EPS method, relative to the considered batteries under different charging regimes.

4.3.3 Discussion

A central point in this chapter is that fast charging technique does not deteriorate the battery's cycle life, but mechanisms that negatively affect the battery may come into force when the EV user has the possibility to fast-charge the battery. Such mechanisms are activated when the battery is undercharged or deep-discharged and these cases may arrive more often if the user recharges the battery the same way he or she refills the fuel tank of an ICEV today.

Average charging-discharging routines, equivalent to those in Figure 4.2, representative of real conditions, have to be specified and statistical information, concerning the battery's state (by measuring specific parameters such as temperature, electrolyte and electrode condition etc.) in relation to these routines, should be collected. Therefore, a device equivalent to an airplane's 'black box' on-board the EV may be needed in order to continuously record information relevant to charging-discharging algorithms and the corresponding condition of the battery.

With respect to the assumptions made, it is expected that the use of partial or exclusive fast charging will negatively affect the cycle life of the battery. Consequently, more batteries will have to be used during the entire lifetime of an EV, compared with normal charging, resulting in an increase in both energy utilization and environmental impact. An interesting remark is that the increase in environmental impact is greater than the increase in energy utilization.

Regarding the environmental performance of the batteries, it can be claimed that it makes little difference if fast charging is used partially or exclusively. This statement is true for all batteries exclusive of the Na-NiCl₂ battery where the normal/fast charging sequence corresponds to an environmental profile similar to normal charging. The fact that this battery does not suffer from deep-discharging is beneficial for its environmental performance under normal/fast charging regime leading to the conclusion that solutions to prevent batteries from deep-discharge and undercharge must be found.

5 CONCLUSIONS

5.1 INTRODUCTION

The purpose of the present study is not to provide the reader with solid results. Partly due to lack of information and partly due to the fact that complex mechanisms are involved in the operation of the batteries, it is not feasible to arrive at concrete conclusions.

Within this framework, the purpose of the study has been to show some of the hot spots associated with the environmental performance of five candidate batteries for EVs. It also proposes a way to take fast charging into consideration based on the idea that a battery may suffer capacity loss not because fast charging is detrimental, but due to deviations from proper charging caused by the option and performing of fast charging.

5.2 CONCLUSIONS FROM LIFE CYCLE ASSESSMENT AND USE OF NORMAL CHARGING

The stage of the cycle life of the battery that bears the heavier environmental load is the area of use. The moderate energy efficiency of the considered batteries associated with other losses (mains, charging stations) results in a significant amount of wasted energy. Improving the energy efficiency and the specific energy of the battery must be a priority for the battery manufacturers, who in addition should cooperate strongly with other actors such as the automotive industry, the charger manufacturers and the power supply industry.

Significant resource constraints were identified for materials used in the considered batteries. There is no battery that could be mass-produced in numbers equivalent to the car population of today. The extreme case is this of Ni-Cd, which can be manufactured in only 300,000 units due to the scarcity of cadmium. Moreover, nickel is largely used in four battery technologies and all of them have strong prospects of succeeding. A possible success of all or some of them associated with failure of other battery technologies, could result in increased needs of nickel, leading to high nickel prices and consequently to high battery prices.

A characterization such as ‘the best’ regarding the environmental performance cannot be attributed to any battery. Ni-Cd appears to have a bad performance with regard to acidification. Lead-Acid is associated with emissions that contribute to eutrophication and increase the carcinogenic potential. Ni-MH and Na-NiCl₂ have a bad picture regarding the global warming. Finally, the high acidification potential is a drawback for the Zn-Air battery.

5.3 CONCLUSIONS FROM LIFE CYCLE ASSESSMENT AND USE OF FAST CHARGING

A central point in this study is that fast charging if it is properly performed, does not damage the battery. Mechanisms activated when a battery is charged rapidly and are detrimental for the cycle life of the battery (i.e temperature rise, gassing etc) can be also come into force when normal charging is performed. Therefore, the focus of the study has been shifted to critical deviations from proper charging, such as deep-discharge and undercharge, which are likely to take place more often when a user has a choice to fast-charge the battery.

In this respect and according to the analysis in chapter 4, partial or exclusive fast charging may lead to an increase of the number of batteries used within the entire lifetime of the EV. In addition, the shorter vehicle range per cycle and the higher energy losses raise the energy utilization. The environmental impact is higher due to the increase of the number of batteries used within the lifetime of an EV, but this can radically change if recycled materials are used. Combination of fast and normal charging increases the energy utilization compared with normal charging (with the exception of Na-NiCl₂), but the increase is higher if only fast charging is performed. On the other hand, regarding the increase in the environmental impact (excluding again the Na-NiCl₂ battery) it does little difference if fast charging is used partially or exclusively.

5.4 PROPOSALS FOR CONTINUATION

A better quality of information for all the individual phases of the cycle life of the considered batteries is required. Particularly the quality of information concerning the phases of the material production, the manufacturing and the recycling of the batteries has to be improved. Suppliers are located in several places around the world and the acquisition of environmental information is a particularly difficult task. Moreover, due to intense competition, the battery manufactures are rather reluctant in providing information about their products.

More accurate information is needed with regard to the consequences of charging in the cycle life and the performance of the battery. There is a lot of uncertainty associated with the mechanisms that deteriorate the performance of a battery and are activated when a battery is deep-discharged or undercharged. These mechanisms differ widely from battery to battery and even for batteries within the same system.

More accurate information regarding the charging schedules is also needed. Proper charging and discharging, will probably be a prerequisite for the commercialization of the EV. Statistical data about the amount of energy that is transferred during charging and withdrawn during discharging, in relation with the condition of the battery, has to be collected. The process of information derived from a device, equivalent to an airplane's 'black box', which will continuously record details relevant to battery's condition (e.g. temperature, electrolyte state etc), can probably lead to useful conclusions.

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