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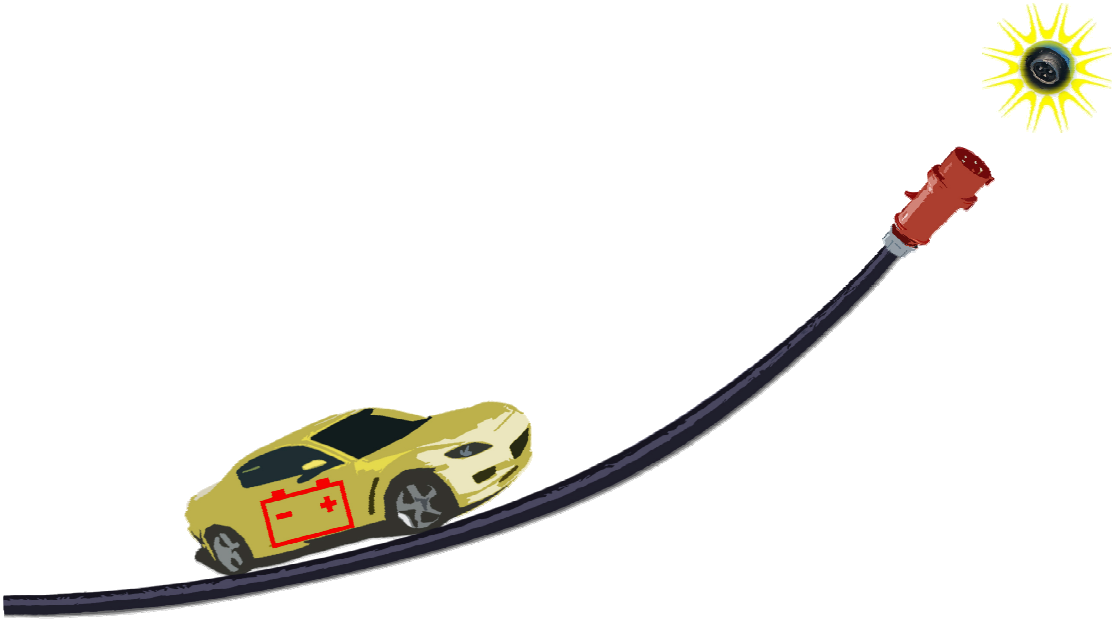
Current and future developments of batteries for electric cars - an analysis



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Current and future developments of batteries for electric cars - an analysis

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Summary

The reduction of fossil fuel use and greenhouse gas emissions from road transport gets wide attention. To achieve this, the use of electric vehicles is considered to be important. Battery Electric Vehicles (BEVs) do have a zero emission potential when the energy stored in the battery is produced from renewable energy sources. Nevertheless, batteries have to meet a large number of requirements to make battery electric vehicles competitive to present internal combustion engine vehicles (ICEVs).

This study aims to get insight into current and future battery technology developments, as well as into the extent to which different battery technologies can fulfill the requirements and influence the performance of BEVs in the short, medium and long term. Therefore, the central research question is:
"*How and in which time frame are battery chemistries, that are currently being developed, expected to fulfill battery requirements and to influence the performance and competitiveness of battery electric cars?"*
To answer this question, the research consisted of three parts. In the first part an overview was created of battery chemistries that are now available for BEV application or are currently under consideration in research, development and demonstration (RD&D) activities focusing on battery electric cars. From this inventory, a selection was made of five technologies that can were considered to be most promising in the short (<5 years), medium (5-20 years) and long term (>20 years).
In the second part the selected technologies were further examined and projections were made on the battery performance and cost in the short, medium and long term. Also, sustainability aspects (raw material availability and the environmental impact of the batteries) were assessed. In the third part driving cycle simulations were carried out to assess how the selected technologies and their development will influence the energetic, environmental and economic performance of battery electric cars.

The findings of this study indicate that for all five batteries selected, it remains a challenge to simultaneously achieve all requirements in the medium or even long term. Projections on lifetime, specific power, efficiency and costs are often lower than required and uncertain. Only lithium-ion batteries could possibly attain all conditions in the medium term. Furthermore, while lithium-based batteries have high specific energy potentials, batteries that do not contain lithium have better cost perspectives.

Furthermore, the results indicate that battery electric cars will be energetically and environmentally competitive to ICEVs, regardless of the specific battery technology applied. Nevertheless, low efficiencies of metal-air and lithium-sulfur batteries result in higher WTW energy consumption and emissions levels compared to Li-ion and ZEBRA batteries.
The use of future Li-ion batteries results in the lowest WTW energy consumption and WTW emissions, being at least 75 Wh/km and 61 gCO_{eq}/km below present ICEVs. ZEBRA batteries attain lowest total driving costs; 6,033-8,741 $/year compared to about 4,800 to 5,300 $/year for ICEVs.
If lithium-sulfur batteries can achieve the USABC requirements in the long term, especially with regard to costs and efficiency, the performance of the car can become better than or as good as for Li-ion and ZEBRA batteries. Low cost zinc air batteries can become preferable with regard to total driving costs, but it will be more difficult to attain competitive WTW energy consumption and emission levels. High efficiency lithium-air batteries could attain low energy consumption and emission levels, but their expected high costs make the battery economically undesirable.
Finally, recycling of batteries is needed to limit environmental impact as well as to restrict resource depletion and keep material prices low.

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List of abbreviations

BEV	Battery electric vehicle
BMS	Battery management system
CCS	Carbon capture and storage
CPI	Consumer Price Index
DoD	Depth of Discharge: percentage of maximum battery capacity that has been discharged
EMF	Electromotive force: battery cell voltage
GDP	Gross Domestic Product
GER	Gross Energy Requirement
FCEV	Fuel cell electric vehicle
HEV	Hybrid electric vehicle
ICEV	Internal combustion engine vehicle
LCA	Life Cycle Assessment
PHEV	Plug-in hybrid electric vehicle
RD&D	Research, development and demonstration
R&D	Research & development
SHE	Standard hydrogen electrode
SLI	Starting, lightning and ignition
SoC	State of Charge: present battery capacity as percentage of the maximum battery capacity
TTW	Tank to Wheel
WTT	Well to Tank
WTW	Well to Wheel

List of terminology

Anode	Electrode at which an oxidation reaction takes place (in this report the anode refers to the negative electrode, at which the oxidation reaction takes place during discharge)
Calendar life (years)	Period of time before a battery fails to meet specific performance criteria, whether in active or inactive use
Cathode	Electrode at which a reduction reaction takes place (in this report the cathode refers to the positive electrode, at which the reduction reaction takes place during discharge)
Cycle life (# discharge /recharge cycles)	Number of discharge/charge cycles a battery can experience before it fails to meet specific performance criteria
Electrode	Metal or alloy that undergoes a reduction or oxidation reaction
Electrode potential (Volts)	The propensity (natural tendency) of the electrode material to gain or lose electrons
Electrolyte	A medium that provides an internal circuit between the positive and negative electrode
Energy storage capacity (kWh)	Total energy (watt-hours) available when the battery is discharged

Electrode storage capacity (mAh/g)	see Theoretical specific capacity
Lifetime (years)	see Calendar life
Oxidation reaction	Reaction during which electrons are generated
Production volume (batteries per year)	Number of products produced per unit time
Production capacity (kWh/year)	Total capacity of products produced per unit time
Progress ratio	Parameter to express the rate at which costs decline with a doubling of the cumulative production
Reduction reaction	Reaction during which electrons are consumed
Specific energy (Wh/kg)	Total energy (watt-hours) available per unit mass
Specific power (W/kg)	The maximum available power per unit mass
Theoretical specific capacity (mAh/g)	Maximum amount of electric charge that can be stored in one unit mass of electrode material.
Traction battery	Battery that can provide motive power over a longer period
Utilization factor/rate	Share of (theoretical) specific energy that is maintained at cell or pack level after losses due to weight impact of inactive materials

1. Introduction

Currently, global environmental stress is caused by a growing demand on finite resources. Declined air quality and global warming are caused by the release and accumulation of greenhouse gasses from burning fossil fuels [World Commission on Environment and Development (WCED), 1987]. The transportation sector is a large consumer of fossil fuels and contributes extensively to greenhouse gas emissions. In the pre-2004 EU Member States (EU-15) 21 percent of total emissions originated from transport. The largest part of these emissions is represented by CO_2, caused by fuel combustion [European Environment Agency (EEA), 2008]. Furthermore, road transport is by far the largest contributor (93%) to transport related emissions.
The last two decades, passenger and freight kilometers increased and also the amount of passenger cars and trucks grew. On the other side, fuel efficiency improved and slowed down the increase of emissions from road transport [EEA, 2008]. An important development in the improvement of fuel efficiency is the introduction of Hybrid Electric Vehicles (HEVs). Hybrid vehicles combine an internal combustion engine with an electric motor. Energy generated by the engine or recovered during braking is stored in a battery and is used to provide supporting or even full electric motive power. However, electric power is restricted due to limited battery capacity [IEA, 2009].

A more significant reduction of emissions could be achieved by substitution of fossil fuels. Among other alternatives is electricity: full electric cars (energy provided by a battery or fuel cell) have a zero emission potential when electricity is produced with the use of for example renewable energy sources. Due to the higher energy efficiency of a battery system compared to a fuel cell, the tank to wheel (TTW) energy consumption of battery electric cars is lower than that of fuel cell cars [Van Acker, 2008; Kendall, 2008].
However, the well to wheel (WTW) energy efficiency and CO_2 emission reduction of battery electric vehicles (BEVs) might actually be lower than that of fuel cell electric vehicles (FCEVs) [Kromer & Heywood, 2007; Bandivadekar et al., 2008; Thomas, 2009]. Although decarbonization of electricity production is an important way to improve the WTW balance, also battery weight does affect the energy consumption of the car and the WTW energy performance. To limit the battery weight and energy consumption, relatively small batteries are currently applied that restrict the driving range of BEVs. Besides, these batteries show more limitations: recharge times are long [Thomas, 2009], the performance of the battery declines with time [Kalhammer et al., 2007] and costs of the batteries are high [Chan et al., 2009; Thomas, 2009]. In order to let consumer acceptance increase and stimulate the introduction of BEVs, it is essential that batteries meet certain requirements with regard to battery performance, costs and material use:

- Battery performance:
  - Energy storage capacity (kWh)
  - Specific energy (Wh/kg)
  - (maximum) specific power (W/kg)
  - Calendar and cycle life (years, # discharge /recharge cycles)
  - Charging time (min, hour)
  - Energy efficiency (%)
  - Operating temperature
- Costs:
  - Total and specific cost of battery system ($ and $/kWh)
- Material use:
  - Safety
  - Environmental impact
  - Scarcity

Table 1.1 shows which goals are defined for batteries to make battery electric cars competitive with internal combustion engine vehicles (ICEVs).

Table 1.1: Goals for batteries to make battery electric cars competitive with internal combustion engine cars [U.S. Advanced Battery Consortium (USABC), n.d.; Duvall & Alexander, 2005; Kalhammer et al., 2007].

	USABC Commercialization	USABC long term	Duvall & Alexander	Kalhammer et al.
Energy storage capacity (kWh)	40	40	25 to 40	25, 40 [(1)]
Specific energy (Wh/kg) - C/3 discharge rate	150	200	100 to 140	100, 160 [(1)]
Specific power (W/kg) – discharge, 80 % DOD/10 sec	300	400	300 to 400	200, 400 [(1)]
Cycle life (cycles) @ 80 DoD	1000	1000		1000 to 1500 [(2)]
Calendar life (yr)	10	10		10 to 15
Normal recharge time (h) (20 to 100% SoC)	4 to 6	3 to 6		
Fast recharge time (min)	<30 (20 to 70% SOC)	<15 (40 to 80% SOC)		
Operating temperature (°C)	-40 to +50	-40 to +85		
Cost ($/kWh) 40 kWh battery	<150 [(3)]	100 [(3)] (230-250 inflation adjusted [(4)])		<150 [(5)]
Cost ($) 40 kWh battery				<6000 [(5)]
Safety				Proven safety in tests (e.g. on abuse tolerance)

[(1)] Goals stated by Kalhammer et al. are derived from Deiml et al.; requirements are given for small and midsize BEVs, respectively, with weight, performance and accommodations comparable to similar size ICEVs; [(2)] 1000 and 1500 deep discharge – full recharge cycles for a 10 and 15 years lifetime respectively; [(3)] Cost at production rate of 25,000 batteries per year; [(4)] [Advanced Research Projects Agency –Energy (ARPA-E), 2009; Boston Consultancy Group (BCG), 2010]; [(5)] Cost at production rate of 25,000 batteries per year, derived from USABC goals.

Nowadays, mainly lithium-ion batteries are applied in electric cars (see table 1.2). Also, these batteries are widely considered to be the most promising technology in the next decades and many research and development activities take place to improve the performance of Li-ion batteries. However, the challenges that have to be overcome to simultaneously achieve all goals are numerous [IEA, 2009; Kromer and Heywood, 2007]. Especially expectations on the decrease of costs are ambiguous. It is not clear when or to what extent USABC goals can be achieved and the effect of learning is uncertain.
Yet, expectations on the specific energy of other innovative battery chemistries are very promising. Therefore, they might be able to address the problems mentioned above. Due to high specific energy the battery volume and weight will be much lower. Hence, it is probable that battery costs will

Table 1.2: Characteristics of some commercially available battery electric cars.

	Tesla Roadster (sports car)	Mitsubishi i MiEV (compact car)	Th!nk (2-seater) [9]
Energy storage capacity	55kWh [1] (Li-ion, consumer electronic design)	16 kWh [6] (Li-ion, EV design)	22 kWh (Li-ion) 23 kWh (ZEBRA)
Range	244 miles (just below 400km) [2]	100-150 km [6]	160 km
Maximum speed	125 mph (200 km/h) [3]	130 km/h [6]	110 km/h
Battery lifetime	7 years or 100,000 miles [3]	10 years / 150.000 km [7]	
Battery recharge time	3.5 hours [3]	7 hours, fast charge: 30 min [6]	7-8 hours
Battery cost	Retail price: $36,000 [1] Cost: 409 to 545 $/kWh [4]		
Vehicle price	€84,000 (excl. VAT) [5]	€48,000 [8]	

[1] [California Air Resources Board (ARB), 2009]; [2] Driving in normal conditions (mixed city and highway conditions in a range of temperatures) [Tesla Motors, 2010a]; [3] [Tesla Motors, 2010b]; [4] Estimation based on retail price [ARB, 2009]; [5] [Tesla Motors, 2010c]; [6] [Mitsubishi Motors, 2010]; [7] [Jacobs, 2009]; [8] [Vermeulen, 2010]; [9] [Think, 2010b]

decline by a need for less materials and that the WTW energy consumption and emissions of the car will improve substantially.
Nevertheless, literature that discusses the state of the art and prospects of automotive batteries does not or only slightly assess research and development activities that focus on these new battery chemistries. Therefore, the objective of my research is to examine the prospects of available and new battery technologies; the degree to which they might attain battery requirements and their effect on the performance of battery electric cars. Hence, the central research question is expressed as follows:

How and in which time frame are battery technologies, that are currently being developed, expected to fulfill battery requirements and to influence the performance and competitiveness of battery electric cars?

To answer this question, three sub questions are formulated:

1. *How do battery technologies that are currently considered in R&D activities compare on development stage and expectations on battery specifications and which battery technologies can be selected as a promising option in the near, medium and long term?*
2. *What pathways can be defined with regard to battery and cost developments of the selected battery technologies?*
3. *How do expectations on battery performance affect the energetic, environmental and economic performance of battery electric cars over time and how do these results compare to expectations for other vehicle technologies?*

2. Methodology

2.1 System definition

From the central research question and the related sub questions, the following choices are made:

a. Only batteries for application in battery electric cars are considered. This is because of the differences in requirements on batteries for dissimilar purposes, e.g. BEV, HEV and PHEV. Battery electric cars are defined as cars that only have electric propulsion power *and* energy; the batteries are recharged by electricity from the grid [Kalhammer et al., 2007].
b. My focus is on passenger cars, which have to be competitive with ICEVs in the future. Batteries for urban and neighborhood electric vehicles are not taken into consideration, as these vehicles have a limited range and usability. A compact 5-seater is used as a reference car. This class includes amongst others the VW Golf and Toyota Corolla [Van Vliet, 2010].

2.2 Approach overview

The research consists of three parts. In the first part an overview is created of battery chemistries that are now available for BEV application or are currently under consideration in research, development and demonstration (RD&D) activities focusing on battery electric cars. Also, information from literature is collected about the current stage of development and the extent to which the technologies (have the potential to) meet requirements on battery performance, costs and safety. Based on this concise inventory, a selection is made of five technologies that can be considered to be most promising in the short (<5 years), medium (5-20 years) and long term (>20 years).
In the second part the selected technologies are further examined and a more in depth analysis of how the selected technologies are expected to develop in time is made. Next, in the third part driving cycle simulations are carried out to assess how these technologies and their development will influence the energetic, environmental and economic performance of battery electric cars.
In the discussion, results from this part are compared with prospects for other vehicle technologies.
In sections 2.3 to 2.5 the methodologies and theories used for each part are further explained.

2.3 Inventory and comparison of battery technologies

Through literature review and web search an overview is made of all battery technologies that are now available for BEV application or are currently under consideration in research, development and demonstration activities focusing on battery electric cars. For these battery technologies data is collected about the current development stage, battery performance, costs and safety. The following battery development stages are defined by Matheys & Van Autenboer [n.d.]:

- Laboratory R&D
- Cell design and testing
- Module design
- Pilot production, module testing and pack design
- Pack field trial, manufacturing development
- Factory installation and start up
- Volume production

The technologies that are compared in this part are not all in the same development stage. Therefore, the availability of data varies. For example, in an early stage of development no reliable information will be available about production costs. As a result, the comparison could not be made

for each aspect individually. However, it was tried to identify the most important positive and negative features of each battery technology. Five battery types were selected such that their advantageous characteristics covered all considered battery aspects.

To be able to compare the different technologies on the potential of the battery to achieve a high specific energy value, the theoretical specific energy was used. The theoretical specific energy is the maximum energy available per unit mass (Wh/kg). This value is based on the cell voltage and the maximum amount of free charge that can be transferred from the negative to the positive electrode per unit of mass of active material in one battery cell (mAh/g). In practice, the battery's specific energy will be much lower and depends on the battery pack design and discharge conditions. Values of specific energy and specific power levels currently realized on battery cell, module or pack level are used to get some insight the in the present state of the art battery performance.

2.4 Projections on battery development and costs

Of the selected battery technologies, projections are made on how battery and cost developments will take place in time. This evaluation first of all concentrated on battery performance characteristics:

- Specific energy and specific power
- Calendar and cycle life (including battery deterioration)
- Charging time
- Efficiency
- Operating temperature
- Safety and reliability

To be able to make estimations about future battery development, information was gathered about state of the art battery characteristics, present proceedings in RD&D activities and current barriers and possibilities for improvement. This analysis was mainly based on papers and reports that cover detailed technical analyses, comparisons of technical concepts, descriptions of recent developments and roadmaps. Papers about recent research did help to understand what the focus of current RD&D activities is and thus which issues may be considered most important.
To complement, support and verify the information found experts were consulted. Their understanding of the field and their judgments were important to make statements about the future of the considered battery technologies. Where possible, experts were consulted through an interview (W. Robers, E. Kelder and F. Ooms). One expert was asked for his opinion by email (B. Scrosati).

Next, the following sustainability aspects were not considered in part one and are investigated in this part:

- Scarcity of materials: future prospects
- Environmental impact: environmental impact (including energy use) and the effect of recycling throughout the total life cycle of the batteries

Prospects on future availability of materials are based on reports that focus on the (expected) supply and demand of these resources. To assess the environmental impact, literature was used in which Life Cycle Assessments (LCAs) of batteries are discussed. Also, information was gathered about the gross energy requirement (GER) for the production of different materials, and the potential energy savings associated with recovery of these materials.

In addition to development prospects on the aspects mentioned above, projections on costs are made. The first method used was a literature review on projections made by others. Secondly, experience curves were composed. The theory behind experience curves and the basic conditions are discussed at the end of this section. Generally, these curves illustrate how production costs have developed in the past. Trough extrapolation it is possible to show how costs might develop in the future. A condition, however, is that there is sufficient data available. As batteries for battery electric cars are not produced yet on a large scale, this appeared to be a problem. The experience curves were mainly based on projected (cost) data. Nevertheless, they were used to get an idea of the potential bandwidth of the progress ratio.
Finally, a cost breakdown of the different batteries was made to assess the impact of various components on the total costs. Also, a comparison of raw material prices was made to identify the minimum cost of some batteries. For the innovative battery technologies, however, no reliable information was available about the cost breakdown. A comparison of raw material prices was made here to indicate what cost levels could be attained in the future.
To make all cost projections comparable, costs were adjusted to US $2010. The Consumer Price Index (CPI) from the U.S. Bureau of Labor Statistics (BLS) was used to correct for inflation and annual average exchange rates were used to modify other currencies to the U.S. dollar [BLS, 2010; Oanda, 2010]. For 2010, the CPI index for July and the exchange rate average from January 1 to August 28 were used. Unless stated different, all costs in this report are mentioned in US $2010.

Experience curves
An experience curve can be used to describe the production cost development of industrial products. The curve shows how costs decline when cumulative production increases. Often, this relationship between production cost and cumulative production can be represented by a linear curve when plotted in a double-logarithmic scale [Junginger et al., 2010]. The exponential equation that describes this curve and its logarithmic form are given below (equations 2.1 and 2.2).

$$C_{Cum} = C_0 Cum^m \qquad \textit{Equation 2.1}$$

$$\log C_{Cum} = \log C_0 + m \log Cum \qquad \textit{Equation 2.2}$$

(C_{Cum} = cost per unit, C_0 = cost of the first unit produced, Cum = cumulative (unit) production, m = experience index [Junginger et al., 2010])

The progress ratio and learning rate are two parameters that can be used to express the rate at which costs decline with a doubling of cumulative production. The progress ratio (equation 2.3) is equal to the slope of the experience curve; a progress ratio of 80% is equivalent to a learning rate of 20% (equation 2.4) and means that costs reduce by 20% when cumulative production doubles [Junginger et al., 2010].

$$PR = 2^m \qquad \textit{Equation 2.3}$$

$$LR = 1 - 2^m \qquad \textit{Equation 2.4}$$

(PR=progress ratio, LR=Learning rate, m = experience index [Junginger et al., 2010])

When using experience curves, costs should be expressed in real terms, i.e. corrected for inflation. This is done by using a national CPI or GDP (Gross Domestic Product) deflator [Junginger et al., 2010]. In addition, because prices are not only related to production costs but also depend on, for example, product demand and the stage of market introduction, prices are less appropriate to compose an experience curve.

The cost reduction can be caused by (a combination of) different factors. Amongst others, these are: learning by searching (innovations caused by RD&D), learning-by-doing (improved production process), upsizing (upscaling of product) and economies of scale (upscaling of production numbers). Besides, changing input prices can also (negatively) affect cost reductions.

2.5 Electric vehicle performance

Driving cycle simulations are used as the basis for an analysis of the energetic, environmental and economic performance of battery electric cars. To carry out these simulations, a computer simulation model was developed in Excel. In the model standardized cycles are used to simulate urban and highway driving. Here the New European Driving Cycle (NEDC) was used. This driving cycle consists of four repeated urban (ECE) driving cycles and one extra-urban (EUDC) cycle.

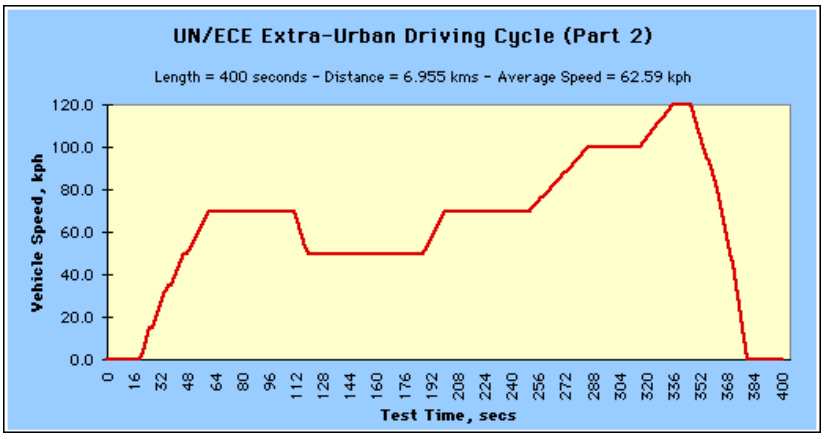


*Figure 2.1: S*tandardized driving cycle for extra-urban driving [U.S. Environmental Protection Agency (EPA), 2010]

For a certain period of time the vehicle's velocity is prescribed, see figure 2.1. Then, for each moment in the cycle the motive force that is required at the wheels can be calculated by using equation 2.5 [Berry, 2010; Chan & Chau, 2001]. The motive force is the force required to overcome the road load and to achieve a certain acceleration. The road load is defined by the rolling resistance, aerodynamic drag and climbing forces. In the prescribed cycles, driving under a slope is not included (α=0). The power required at the wheels can be calculated by Equation 2.6 [Campanari et al., 2009]. Then, the power to be supplied by the battery can be calculated with the use of drive train efficiencies (figure 2.2) and taking into account extra power for auxiliary equipment (equation 2.7). During deceleration, power from regenerative braking is recovered to recharge the battery (equation 2.8). The average TWT energy consumption (average energy supplied by battery) of the driving cycle can be calculated by using equation 2.9.

$$F_m = F_L + F_a = F_r + F_d + F_c + F_a = mgC_R + 0.5\rho C_D A_F v^2 + mg\sin\alpha + m\delta a \qquad \textit{Equation 2.5}$$

$$P_{wheels} = F_m \cdot v \qquad \textit{Equation 2.6}$$

$$P_{el.supply} = P_{aux} + \frac{P_{wheels}}{(\eta_{trans} \cdot \eta_{motor} \cdot \eta_{controller})} \qquad (P_{wheels} > 0) \qquad \textit{Equation 2.7}$$

$$P_{el.recover} = P_{wheels} \cdot (\eta_{trans} \cdot \eta_{motor} \cdot \eta_{controller}) - P_{aux} \qquad (P_{wheels} < 0) \qquad \textit{Equation 2.8}$$

$$E_{avg} = \frac{\int Pdt}{s_{total}} \qquad \textit{Equation 2.9}$$

(F_M = motive force; F_L = road load; F_a = force required for acceleration; F_r = rolling resistance force; F_d = aerodynamic drag force; F_c = climbing force; m = vehicle mass (kg); a = vehicle acceleration (m/s^2); g = gravitational acceleration (m/s^2); C_R = coefficient of rolling resistance; ρ = density of air (kg/m^3);C_D = aerodynamic drag coefficient; A_F = frontal area (m^2); α = angle of the road (degrees); δ = mass correction factor; v = vehicle velocity (m/s); P_{wheels} = power required at the wheels (W); $P_{el.supply}$ = power supplied by the battery (W); $P_{el.recover}$ = power recovered by the battery (W); P_{aux} = electric auxiliary equipment power (W); η = energy efficiency; E_{avg} = average energy supply by battery (Wh/km); s_{total} = total driving distance (km))

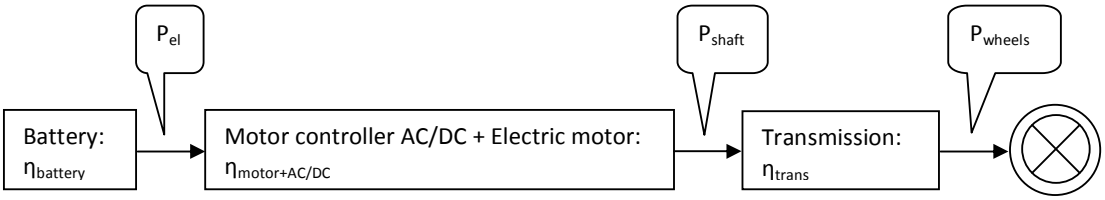


Figure 2.2: Main elements and power flow inside a vehicle [Campanari et al., 2009]

To simulate the energy supply of the battery, a standard car (VW Golf) was defined. Values of coefficients and other parameters that are used in equations 2.5, 2.7 and 2.8 are derived from literature that model comparable passenger cars, e.g. Ogden et al. [1999] and Van Vliet [2010]. Only battery specific values (e.g. battery efficiencies) are derived from results of the previous parts of this research.
Data on the prescribed velocity of different driving cycles is freely available, for example via the website of the United States Environmental Protection Agency (EPA). The vehicle velocity is given for each time step of one second. Formulas to calculate the power required at each time step were taken from Campanari et al., [2009].

As it is aimed to show how different battery technologies influence the performance of BEVs, the energy consumption will be calculated over an array of driving ranges (100, 200, …, 600km). Thus, for each distance selected the required weight of the battery has to be calculated. As battery weight is an input as well as an output parameter of the driving cycle simulation, an iterative process is applied to find the correct value (when input and output are equal). This iterative process is shown in figure 2.3. Depending on the maximum power and total energy needed to achieve a certain range, the battery weight is defined by the specific energy or specific power of the battery. The values of these two parameters are taken from the prospects and outlook for battery technologies from the second part of this research.

When the specific energy is decisive, the TTW energy consumption resulting from the driving cycle simulation is used to calculate the required battery storage capacity (equation 10a). Then, the battery weight is a function of the battery capacity and specific energy (equation 10b). When the specific power is decisive, the battery weight depends on the maximum power required (equation 11a). In this case the battery capacity is defined by the battery weight and specific energy (equation 11b).

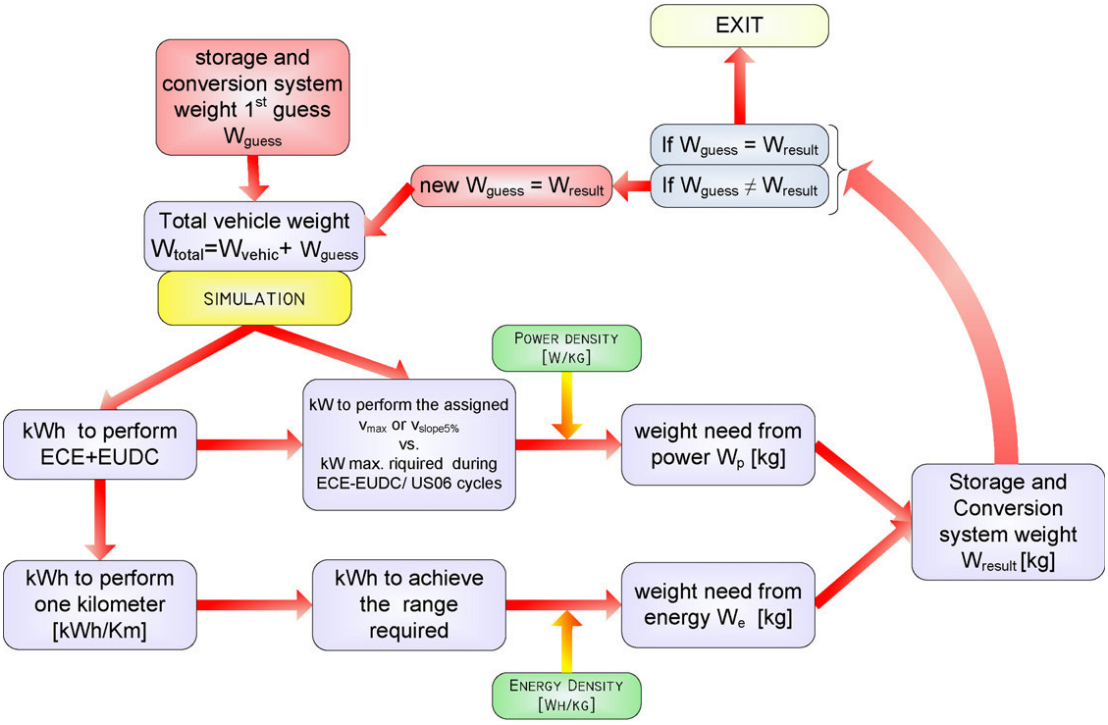


Figure 2.3: Conceptual scheme of an iterative calculation procedure for driving cycle simulation [Campanari et al., 2009]

$$C_{battery} = \frac{E_{avg} \cdot d}{DoD \cdot \eta_{battery}}$$ (specific energy is decisive for battery weight) *Equation 2.10a*

And: $$M_{battery} = \frac{C_{battery}}{E_{spec}}$$ *Equation 2.10b*

$$M_{battery} = \frac{P_{peak\,max}}{P_{spec} \cdot \eta_{battery}}$$ (specific power is decisive for battery weight) *Equation 2.11a*

and: $$C_{battery} = M_{battery} \cdot E_{spec}$$ *Equation 2.11b*

$C_{battery}$ = battery storage capacity (Wh); d = driving range (km), DoD=Depth of discharge (%), $M_{battery}$ = battery weight (kg); E_{spec}=specific energy of battery (Wh/kg), $P_{peak\,max}$ = maximum peak power (W); P_{spec} = specific power (W/kg)

WTW energetic, environmental and economic performance

When the correct battery capacity and weight are found, the WTW energy consumption (Wh/km), WTW emissions (gCO_2eq/km) and total driving cost ($/km) are calculated (equations 2.12 to 2.14, 2.15 and 2.16 respectively).

Here, recent and values for prices, efficiencies and the emission factor of electricity production and distribution are used. Battery specific data were again derived from earlier results of this research. Finally, a sensitivity analysis was carried out. By adjusting input parameters it was determined what their impact is on WTW energetic, environmental and economic performance.

$$E_{cons.battery} = \frac{E_{avg}}{\eta_{battery}}$$ *Equation 2.12*

$$E_{elec.prod} = \frac{E_{cons.battery}}{\eta_{elec.distr} \cdot \eta_{bat.charger}}$$ *Equation 2.13*

$$E_{WTW} = \frac{E_{elec.prod}}{(\eta_{elec.prod} \cdot \eta_{extr/distr.raw\,mat})}$$ *Equation 2.14*

$$EM_{WTW} = E_{elec.prod} \cdot EF_{elec}$$ *Equation 2.15*

$$C_{drive} = C_{fuel} + C_{car} = \frac{E_{cons.battery}}{C_{elec}} + \frac{\alpha_{car} \cdot I_{car} + \alpha_{battery} \cdot I_{battery}}{s_a} + C_{MRT}$$ *Equation 2.16*

The capital recovery factor is calculated by:

$$\alpha = \frac{r}{1-(1+r)^{-1}}$$ *Equation 2.17*

($E_{cons.battery}$= energy supply to battery (Wh/km); $E_{elec.prod}$ = electricity production demand (Wh/km); E_{WTW} = WTW primary energy consumption; $\eta_{bat.charger}$ = energy efficiency battery charger; $\eta_{elec.prod}$ = energy efficiency electricity production; $\eta_{elec.distr}$ = energy efficiency electricity distribution; $\eta_{extr/distr.raw\,mat}$ = energy efficiency of raw material extraction and distribution; EM_{WTW} = WTW emission (from electricity production) (gCO_2eq/km); EF_{elec} = electricity emission factor (gCO_2eq/Wh); C_{drive} = total driving cost; C_{fuel} = cost of electricity use ($/km); C_{car} = cost of car ($/km); C_{elec} = electricity price ($/Wh); α = capital recovery factor (yr^{-1}); I_{car} = investment cost of car ($); $I_{battery}$ = investment cost of battery ($); s_a = annual driving distance (km/yr); C_{MRT} = maintenance, repair and tire costs ($/km); r = discount rate; L = lifetime of the car or battery (yr))

3. Part one: Overview and selection battery technologies

3.1 Overview

3.1.1 Introduction

In literature, a large number of rechargeable battery types can be found that are considered to be applicable as traction batteries (see appendix I). Lead acid and nickel cadmium batteries are well known and widely used for various purposes. However, the specific energy of these batteries is low,

Table 3.1: Possible BEV battery technologies, theoretical specific energy and development stage

	Theoretical specific energy (Wh/kg)	Development stage
NiMH	>200 [1]	Commercial production for HEVs
Lithium batteries		
Lithium ion	>300 [2] / ~600 [3]	Commercial production for BEV
Lithium Metal Polymer	~500 [4] / 890 [5]	Commercial production for BEV expected from 2010 [9]
Lithium Sulfur	2,500 [6]	Demonstration/pack field trial in unmanned aerial vehicles, not in BEVs [10]
Metal air		
Li-air	11,000 [12]	Laboratory R&D
Al-air	8,000 [12]	Laboratory R&D
Zn-air	1,200 [6]	Commercial production for small electronic applications expected in 2010 [11]
Fe-air	1,883 [12]	Laboratory R&D
Silicon-air	8,470 [7]	Laboratory R&D
High temperature		
ZEBRA	787 [8]	Commercial production for BEV
NaS	750 [8]	Commercial production for stationary applications, not for BEV
Other innovative technologies		
Conversion batteries		Laboratory R&D
Organic lithium battery		Laboratory R&D
Ambient temperature Na-ion		Laboratory R&D
Mg-ion		Laboratory R&D
Nickel-lithium		Laboratory R&D
Lithium copper		Laboratory R&D
All-electron battery		Laboratory R&D

[1] Depends on composition of metal-hydride alloy [Thackeray, 2004]; [2] [Thackeray, 2004]; [3] Depending on chemistry: choice and composition of active materials [Cairns, 2004]; [4] depending on chemistry: cathode capacity and voltage [Scrosati et al., 2001]; [5] based on vanadium oxide cathode [Cairns, 2004; Thackeray, 2004]; [6] [Cairns, 2004]; [7] [Cohn et al., 2009]; [8] [Cairns, 2004; Thackeray, 2004]; [9] [Green Car Congress, 2009a]; [10] [Sion Power, 2007; Sion Power, 2010]; [11] [Bullis, 2009b]; [12] [Blurton and Sammells, 1979].

around 30 to 50 Wh/kg [Husain, 2003; Cairns, 2004], and application in electric cars would result in very large and heavy batteries.

Table 3.1 shows which batteries are nowadays considered to be a (possible) viable option for battery electric cars. In the table also the theoretical specific energies and current development stage of these battery types are given. For comparison, the specific energy of gasoline is 13,000 Wh/kg [BCG, 2010]. Even when taking into account efficiency losses in ICEVs, the TTW specific energy is 1,700 to 2500 Wh/kg [Green Car Congress, 2010a; Kendall, 2008; Srinivasan, 2009]. A discussion regarding state of the art or potential performance of the battery technologies from table 3.1 can be found in the next paragraphs. This is followed by a summary and a selection of some batteries that will be further dealt with in chapter 4.

3.1.2 Lithium-ion

Lithium batteries are nowadays most widely considered because of the low electronegativity and low equivalent weight of lithium [Patil, 2008]. The largest part of rechargeable lithium batteries available today are lithium ion batteries. These batteries have a liquid, nonaqueous, organic electrolyte and electrodes that intercalate lithium, i.e. the electrode materials are a host structure for lithium ions [Cairns, 2004; U.S. Department of Energy (DOE), 2007]. The anode consists of lithiated graphite (LiC_6). The most common cathode materials are lithium metal oxides.

Performance

Table 3.2 shows the battery performance of Li-ion packs. With regard to battery performance, specific energy is most behind the USABC goals and restricts the battery capacity in most existing BEVs. The theoretical specific energy of lithium ion battery cells with a graphite anode lies about 600 Wh/kg [Cairns, 2004]. However, practical values in commercial batteries are well below the theoretic ones; on cell level the specific energy is approximately 140-170 Wh/kg, at battery pack level the current specific energy is up to 40% lower and ranges between 80 and 125 Wh/kg [Kalhammer, 2007; BCG, 2010]. The actual performance depends on choices related to for example materials and electrode design [Howard and Spotnitz, 2007]. The specific power of Li-ion batteries is low relative to Nickel-Metal-Hydride (NiMH) batteries (see section 3.1.3). Still, the specific power of the batteries mainly meets the USABC goals.

The recharge time is considerably improved as fast charging is possible for Li-ion batteries in the latest BEV models. Also, cycle life and lifetime seem to be in line with the defined targets. On the other hand, the operating temperature is an issue as the power ability declines seriously at low temperatures and fast battery degradation takes place at high temperatures [ARPA-E, 2009; Cars21, 2010].

Safety

Safety is an important issue for Li-ion batteries. Present problems are for example instability at high voltages, flammability and risks for the environment and human health [Scrosati and Garch, 2010]. The safety of a battery depends on its actual design and is related to choices of electrode and electrolyte materials [Scrosati and Garch, 2010].

One example of enhanced safety by improved battery design is the substitution of the liquid electrolyte by a gel-type polymer electrolyte, resulting in a so called lithium-ion polymer (Li-ion polymer) battery [Scrosati and Garch, 2010]. Another example is the replacement of lithium cobalt oxide ($LiCoO_2$) as cathode material. Lithium cobalt oxide is broadly applied in commercial batteries for consumer electronics. However, for electric vehicle applications this material has some limitations with regard to safety and toxicity [DOE, 2007; Cairns, 2004]. Therefore, other materials like nickel, manganese and aluminum are considered to (partly) replace cobalt.

Table 3.2: Performance of Li-ion batteries (battery pack)

	Cathode material	Storage capacity (kWh)	Specific energy (Wh/kg)	Specific peak power (W/kg)	Cycle life (#cycles at 80% DoD)	Life time (yr)	Recharge time	Cycle Efficiency (%)
Th!nk (EnerDel) [(11)]		22						
Tesla Roadster [(1)]	$LiCoO_2$	55	125	444		7	3.5 h	
iMiEV [(2)] (Lithium Energy Japan)		16				10	7h / 30 min	
Leaf [(3)] (AESC)	$LiMn_2O_4$	24					8h / 30 min	
JCS [(4)]	$Li(NiCoAl)O_2$	24	90	210	>3200	>12		
GAIA [(4)]	$Li(NiCoAl)O_2$	22	115	250	~1000			
LitCel [(4)]	$LiMnO_2$	20	118	912	~1000			
Kokam [(4)]	$Li(NiCoMn)O_2$	30	110	490	~3000	>10		
Valence [(5)]	$LiFeMgPO_4$		79-91		1500-2500		2.5 h	
[(6)]								92
[(7)]		35/50	120					
[(8)]			125	400	1000			90
[(9)]			80-120					
[(10)]		20	75-120		1000-3000		3-6 h	90

[(1)] [ARB, 2009; Tesla Motors, 2010b; Campanari et al., 2009; Kalhammer et al., 2007]; [(2)] [Mitsubishi Motors, 2010; Jacobs, 2009]; [(3)] [Nissan, n.d. a; Nissan, n.d. b]; [(4)] [Kalhammer et al., 2007; page 29]; [(5)] [Valance, 2009]; [(6)] [Campanari et al., 2009]; [(7)] [Kalhammer et al., 2007]; [(8)] [Matheys and Van Autenboer, 2005]; [(9)] [BCG, 2010]; [(10)] [Challenge Bibendum, 2007]; [(11)] [Think, 2010b].

Costs

Current costs of Li-ion batteries do largely exceed cost targets, table 3.3. Moreover, these costs are based on nominal capacity; the actual useable capacity can be significantly lower. On the other hand, present costs are based on low volume battery production. Expansion of production volumes can result in significant cost reduction. Also, improvements in battery design can lead to lower costs [D. Galves, personal communication, August 30, 2010].

Table 3.3: Current costs of Li-ion battery packs and cells

	Battery pack ($2010/kWh)	Cell ($2010/kWh)	Source
	1013		IEA, 2008
	813-1219		ARB, 2009
	1267		Van Vliet, 2010
	990-1220	650-790	BCG, 2010
	759-1013		Anderson, 2009 (2008 cost values)
	1013-2025		BERR & DfT, 2008
	711-1524		Hensley et al., 2009
Nissan Leaf	726		W. Robers, personal communication, October 1, 2010
Western Europe		850-992	Roland Berger, 2009
China		>25% lower compared to Western Europe costs	Roland Berger, 2009
Tesla Roadster (consumer electronic batteries, estimated costs)	416-545		ARB, 2009
Batteries for consumer electronics	250-400		BCG, 2010

3.1.3 Nickel-Metal-Hydride

Nickel-metal-hydride (NiMH) batteries are based on the release and absorption of hydrogen (OH^-) by a nickel oxide anode and a metal hydride cathode [Husain, 2003]. Many present-day hybrid cars use nickel-metal-hydride (NiMH) batteries. For these vehicles, specific energy and power requirements are satisfied well by NiMH batteries. However, compared to HEVs the battery performance requirements are quite different for BEVs and a substantially higher specific energy is needed. Modern NiMH batteries do not satisfy this requirement, see table 3.4.

Table 3.4: Performance of NiMH batteries

	Storage capacity (kWh)	Specific energy (Wh/kg)	Specific peak power (W/kg)	Recharge time	Cycle life (# cycles)	Eff. (%)	Operating temperature (°C)	Cost ($/kWh)
System level [(1)]	20	50-70	1000-1500	3-6 hours	2000	75	-10 to +50	1000
EV HEV [(2)]		68 50	150 (80% DoD) 750 (50% DoD)					
System level [(3)]		30-80	250-1000		1500			

[(1)] [Challenge Bibendum, 2007]; [(2)] [Thackeray, 2004]; [(3)] [Woodbank Communications, 2009]

Besides, in the past NiMH batteries were also considered to be a good interim solution for BEVs, as lithium ion batteries showed important safety problems [Van Vliet, 2010; Taniguchi et al., 2001]. But, these problems can significantly be reduced as discussed above.
Finally, the cost of NiMH batteries is around $1000/kWh, which is comparable to the cost of Li-ion batteries. However, the share of nickel in NiMH batteries is very high; 7-8 kg/kWh is needed [Challenge Bibendum, 2007]. Therefore, future NiMH battery cost reductions might be limited by a high nickel price [Advanced Automotive Batteries (AAB), 2007; Van Vliet, 2010].
Taking these considerations into account, nickel-metal-hydride batteries cannot be seen as a serious candidate for large scale application in battery electric cars. On the contrary, NiMH batteries are expected to be replaced by Li-ion ones in HEVs [Green Car Congress, 2004; AAB, 2007; Howell, 2009].

3.1.4 High temperature batteries

High temperature or sodium-beta batteries are based on sodium ion transport between the cathode and anode. There are two variants of the sodium-beta battery: the sodium sulfur (NaS) and ZEBRA battery. Both batteries have an anode that consists of molten sodium and a ceramic sodium aluminum oxide electrolyte with a complex crystal structure which is called a beta-alumina-oxide (β"-Al_2O_3) solid electrolyte [Husain, 2003]. The operating temperature is between 300 and 350ºC [Lu et al., 2010].
The NaS battery has a molten sulfur cathode, the ZEBRA battery is has a transition metal halide cathode. The metal is either nickel or iron. The use of nickel chloride (Sodium-Nickel-Chloride or NaNiCl battery) is the most common option [Lu et al., 2010]. Besides, this cathode is applied in a liquid secondary electrolyte in order to ensure good electrochemical contact between the solid electrolyte and cathode.
ZEBRA batteries are already applied in BEVs. The NaNiCl battery from FZ SoNicK SA (formerly MES-DEA) can currently be used in BEVs from THINK.

Performance
Table 3.5 shows the performance of high temperature batteries. The theoretical specific energy is just above that of Li-ion batteries. However, in practice the specific energy is comparable. The specific power is significantly lower compared to Li-ion batteries and is below the (long term) USABC requirements.
Because of the high internal operating temperature of sodium-beta batteries, their operation is independent of ambient temperatures. However, the internal temperature has to be kept high in order to prevent solidification of the molten parts. Thus, when the car is not in use it must be plugged in to keep the temperature high [THINK, 2010a]. Therefore, application of these (ZEBRA) batteries only seems to be an option if the car is used regularly (e.g. for commercial and public transport vehicles) [THINK, 2010a].

Costs
From a cost perspective these batteries are very interesting: prices of sodium(-chloride) and sulfur are very low. The current cost of ZEBRA batteries is stated to be 600 $/kWh (630 $2010/kWh), which is significantly below Li-ion costs [BERR & DfT, 2008; Kalhammer et al., 2007].

Safety
Safety is an important issue for NaS batteries. When the electrolyte breaks, the two molten electrode materials come in direct contact with each other and a strong reaction will take place, which can cause fire and explosion. This is partially due to the fact that the boiling point of sulfur (440 C) is close to the operating temperature of the battery [Lu et al., 2010]. Because of this safety problem, sodium

sulfur batteries are not considered interesting for EV purposes. However, they are commercially available for stationary applications.
The ZEBRA battery is preferred with regard to safety: when the solid electrolyte breaks the battery can be further operated at a lower voltage while the capacity remains unchanged [Lu et al., 2010].

Table 3.5: Performance of the ZEBRA battery

	Storage capacity (kWh)	Specific energy (Wh/kg)	Specific peak power (W/kg)	Recharge time	Cycle life (#cycles at 80% DoD)	Life (yr)	Eff. (%)	Internal temperature (°C)	Operating temperature (°C)
NaS [(1)]		110	150		1000			350	
ZEBRA									
MES-DEA (Th!nk) [(2)]	23	115	180	11 hours (0-80% DoD: 7 hours)	1000	15	90	260-360	Due to internal working temperature, performance is guaranteed regardless of ambient temperature
system level [(3)]	20	100-120	180	10-12 hours			90		No limitation due to hot battery
system level [(4)]					1000				
system level [(5)]		100-135	90-200			15			
system level [(6)]					>1450	11			

[(1)] [Woodbank Communications, 2009]; [(2)] [THINK, 2010a; THINK, 2010b; FZ SoNicK, 2010; Kalhammer et al.,2007]; [(3)] [Challenge Bibendum, 2007]; [(4)] [BERR & DfT, 2008]; [(5)] [ARPA-E, 2009]; [(6)] [DOE, 2007]

3.1.5 Lithium Metal Polymer

While Li-ion batteries are based on lithium insertion into the crystal structure of the electrodes, also other lithium battery concepts exist in which one or both of these electrodes is not an intercalation material. One example is the Lithium Metal Polymer (LMP) battery. In this battery, metallic lithium is applied instead of a lithium intercalation anode material. This means that on charge lithium ions migrate to the negative electrode and undergo a reduction reaction by which metallic lithium is formed [Chan & Chau, 2001].
However, the use of metallic lithium is accompanied with some big safety issues. The safety can be enhanced significantly by applying a polymer electrolyte instead of a liquid electrolyte [Scrosati and Garche, 2010]. In theory also other solid state (like ceramic and glass) electrolytes can be used [Fergus, 2010b].
Metallic lithium has a very high storage capacity, which does positively influence the specific energy of the battery. From the discussion below, nevertheless, it seems that this advantage cannot be realized yet in present LMP batteries.

Performance
The first application of lithium metal polymer batteries in commercial EVs is planned to start this year, see table 3.6 for performance characteristics. The specific energy and especially the specific power of this battery are lower than for most Li-ion batteries. Because of the low specific peak power the battery is combined with supercapacitors which do store energy generated from braking. This energy is used to improve the cars' acceleration and driving range (>250 km) [Bluecar, 2010c].
The supplier of the car states that the lifetime is approximately 200,000 km [Bluecar, 2010a], which is more than the total range of current electric cars with Li-ion batteries (table 1.2). However, assuming a driving range of 250 km between charging results in a cycle life of 800 cycles, which is lower than for Li-ion batteries and below USABC goals.
Finally, another present disadvantage of LMP batteries is the operating temperature, which is between 60 and 80°C. This elevated temperature is desired to enhance the ionic conductivity of the polymer electrolyte. Thus, preheating of the electric drive system is needed before the car can be used [Bluecar, 2010b].

Table 3.6: Performance of the LMP battery

	Storage capacity (kWh)	Specific energy (Wh/kg)	Specific peak power (W/kg)	Recharge time	Life time (km)	Internal temperature (°C)	Operating temperature (°C)
Bluecar [(1)]	30	100	150[(2)]		200,000	60-80	-20 to +60
[(3)]	20	100-120	200-250	6-10 h			No limitation (hot battery)

[(1)] [Bluecar, 2010a]; [(2)] derived from peak power output and battery pack weight; [(3)] [Challenge Bibendum, 2007]

Costs
No information was found on the costs of LMP batteries. As metallic lithium is the most expensive form of lithium [Bullis, 2009a] it is not expected that costs will below those of Li-ion batteries.

3.1.6 Lithium Sulfur

Like the LMP battery, a lithium sulfur (Li-S) battery is strongly related to the Li-ion battery. But, instead of an intercalation cathode a sulfur cathode is applied in which sulfur is typically paired with carbon [Bullis, 2009a]. During discharge, sulfur reacts with lithium ions and lithium-polysulfides are formed. The advantage over Li-ion batteries is the higher number of lithium ions that can be hosted by one sulfur atom compared to lithium ion host atoms in common intercalation materials. Therefore, the theoretical capacity of lithium sulfur batteries is higher [Bullis, 2009a].

Performance
Lithium sulfur batteries are not commercialized yet. However, pilot operation of batteries developed by Sion Power in an unmanned aerial flight showed good performance. The battery cells are stated to have a specific energy of 350 Wh/kg [Sion Power, 2010]. Also, it is believed that Li-S batteries have the potential of high power capability [DOE, 2007]. However, the cycle life is limited yet [Sion Power, n.d.].

Safety
Originally, metallic lithium is used as anode material in lithium sulfur batteries. However, recently a non metallic lithium sulfur battery was developed to overcome the safety issues related to lithium metal [McKenna, 2010].

Costs
As Li-S batteries are still in the development stage, it is not clear yet what the costs of these batteries will be. At a workshop of the Advanced Research Projects Agency – Energy (ARPA-E), part of the U.S. Department of Energy (DOE), an estimation was made that there is a high potential to attain costs as low as 250 $/kWh [ARPA-E, 2009].

3.1.7 Metal-air

In metal-air batteries oxygen form ambient air acts as cathode material. Metals like zinc, aluminum, iron and lithium can be applied as anode material. Because oxygen is external to the battery, the weight is reduced significantly and the specific energy increased drastically, see table 3.1 [Tahil, 2007a]. Originally, a water based (alkaline) electrolyte is used. Oxygen from ambient air forms hydroxyl ions in contact with the electrolyte. These ions move through the electrolyte to the anode were the metal is oxidized and electrons are released [Hamilton, 2009].

Metal air energy systems can be either a rechargeable battery or a fuel cell: the battery is recharged in the same way as other rechargeable batteries, in a fuel cell one or more parts of the cell are physically replaced. One method is to mechanically exchange the oxidized metal anode, another is to replace the electrolyte in which metal anode particles are mixed [Tahil, 2007a; Neburchilov et al., 2010].

Zinc-Air
In 1979, Blurton and Sammells did expect that zinc-air rechargeable batteries had the greatest potential for EV application. This might still be true, as this is one of the few metal air technologies that can still be found in literature considering EV application. Primary zinc-air batteries do already exist and have a specific energy up to 300 Wh/kg [Frost & Sullivan, 2009; DOE, 2007]. Although zinc-air batteries are in potential electrically rechargeable [DOE, 2007; Blurton and Sammells, 1979], secondary batteries have not been commercialized until now. But, ReVolt has developed rechargeable zinc-air batteries and expects to introduce them on the market this year for use in hearing aids. For the coming years applications will be restricted to consumer electronics, electric vehicles are a longer term goal [Bullis, 2009b]. Finally, zinc-air batteries have a very low cost potential; it is believed that costs of $100/kWh or lower could be reached [ARPA-E, 2009]

Lithium-Air
Originally, lithium-air batteries were not considered to be electrically rechargeable. Also, Blurton and Sammells (1979) did not expect practical application of these batteries. Nevertheless, research on Li-air batteries is widely conducted today; this system is considered to be possibly able to approach the energy density of current liquid hydrocarbon fuels [DOE, 2007]. Also, rechargeable Li-air batteries are being developed now [DOE, 2007]. These batteries have the potential to achieve a specific energy of 500 Wh/kg or higher [Tarascon, 2010; ANL, 2009].
Research and development activities can be found in a large number of universities and other research institutes. Also, research activities are employed by commercial companies like IBM Research (in partnership with U.S. national labs) and PolyPlus Battery [Bourzac, 2009]. Nonetheless, commercial application is still considered to be a long term ambition [Scrosati and Garche, 2010].

As lithium reacts violently with water, an alkaline electrolyte cannot be used. Therefore, instead of forming hydroxyl ions, oxygen reacts with lithium ions to form Li_2O_2. A catalyst is needed to facilitate this reaction. Despite the absence of an aqueous electrolyte, protective membranes are needed to exclude water but let in oxygen [Bourzac, 2009].

Iron-Air and Aluminum-Air
Despite large interest in earlier decades, iron-air and aluminum-air batteries are not widely considered anymore for EV application. Because important technological problems prevented commercialization, interest has moved to other high potential battery technologies like Li-S and Li-air [DOE, 2007].

Commercialization of Al-air batteries has not been possible until now mainly due to hydrogen evolution caused by aluminum corrosion. This highly reduces the efficiency of the battery [Tang et al., 2004; Wang et al., 2010]. Besides, Al-air batteries are not electrically rechargeable, mechanical replacement of the oxidized aluminum anode is needed [DOE, 2007; Blurton and Sammells, 1979]. Iron-air batteries suffered from low energy efficiency and low cycle life ["University of Southern California", n.d.]

Silicon-air
Silicon is a so called metalloid or semi-metal and behaves as a semi-conductor. Because of its theoretical specific energy, the silicon-air couple is considered to be attractive for battery purposes [Cohn et al., 2009]. The use of silicon in a 'metal'-air battery is interesting because of its abundance, non-toxicity and safety [Cohn et al., 2009; Cohn and Ein-Eli, 2010]. The development of the silicon-air battery is in a very early stage, but Cohn et al. [2009] do regard it as a very promising technology that could outperform other metal-air battery types.

3.1.8 Other innovative technologies

Next to the battery technologies discussed above, also other battery technologies were found in literature. However, these technologies seem only to be investigated by a limited number of researchers and are often in a very early stage of development.

Conversion batteries
Current Li-ion batteries are based on the mechanism of lithium insertion into the cathode's transition metal matrix. For example, the insertion of lithium ions into a metal-oxide matrix results in lithium-metal-oxide. In conversion batteries, conversion instead of insertion takes place. This means that a new lithium-oxide matrix is formed in which metallic particles are embedded [Scrosati and Garche, 2010; Armand and Tarascon, 2008]. The two mechanisms can be written as the following equations:

$xLi + MX_y \leftrightarrow Li_xMX_y$ *Insertion mechanism*
$xLi + MX_y \leftrightarrow Li_xX_y + M$ *Conversion mechanism*

Where X is for example oxide, sulfide, nitride, phosphate [Scrosati and Garche, 2010]

The energy density of the battery can be improved significantly by the conversion mechanism. This is because of the larger amount of lithium ions that can be taken by the electrode material. An important drawback, however, is the poor energy efficiency of the conversion mechanism [Armand and Tarascon, 2008]. Also, lifetime is a problem [Scrosati and Garche, 2010]. Nevertheless, Tarascon [2010] has the personal expectation that conversion cathodes could be available from 2015. Then, the specific energy of these batteries will exceed 250 Wh/kg [Tarascon, 2010].

Organic lithium battery
With regard to the abundance of materials currently used in batteries and the environmental impact of battery life-cycles, the use of materials from organic sources is very attractive [Tarascon, 2010]. These materials can for example be fabricated by or in living cells (e.g. with the use of a virus of

bacterium) or produced from organic matter like natural sugars [Armand and Tarascon, 2008]. The use of organic materials decreases the consumption of non-renewable resources, waste production and energy consumption through battery production and recovery [Chen et al., 2008]. But, battery performance (thermal stability, specific power density) has to be improved to make organic lithium batteries commercially applicable [Armand and Tarascon, 2008]. Organic electrode materials are currently being tested in laboratory setting [Chen et al., 2009]. Tarascon [2010] expects that such cathode materials will not be available before 2020. At that time, batteries with these cathodes will have a specific energy comparable with current values for Li-ion batteries [Tarascon, 2010].

Ambient temperature sodium-ion
Sodium-ion (Na-ion) batteries are based on sodium ion transport between the anode and cathode. Thus, also the high temperature batteries discussed earlier are sodium-ion batteries. As discussed for ZEBRA batteries, sodium-ion batteries can be very interesting with regard to costs and safety. But, the high operating temperature of current batteries limits the use in BEVs. Therefore, research is focused on developing sodium-ion batteries that operate at room temperature [Tarascon, 2010; Lu et al., 2010]. Although a disadvantage compared to Li-ion will be specific energy, the abundance and low cost of sodium can be reason for sodium-ion batteries to play a role in the future [Tarascon, 2010].

Magnesium-ion
Magnesium-ion (Mg-ion) batteries are based on transport of magnesium ions between the electrodes [Peng and Chen, 2009]. Magnesium is attractive because of its high storage capacity and the small size of its ions, which enhances transportation through electrode and electrolyte. Furthermore, costs, toxicity and safety of Mg-ion batteries are considered to be good [Peng and Chen, 2009].
The US based company Pellion Technology, a spin-out of MIT University, has the aim to develop the first commercial magnesium-ion battery. This battery might have a higher specific energy than current L-ion batteries and should be applicable in (hybrid) electric vehicles [“Pellion Technologies, Inc.”, n.d.].

Nickel lithium
Last year researchers from Japan developed a nickel-lithium battery. This battery consists of a metallic lithium anode and a nickel hydroxide cathode. The purpose was to combine the high cell voltage of Li-ion batteries and the high cell capacity of NiMH batteries [Li et al., 2009]. In the battery cell two different electrolytes (hybrid electrolyte) are used which are divided by a glass ceramic film. The researchers calculated the specific energy of the nickel-lithium battery to be 935 Wh/kg, compared to 414 Wh/kg for the Li-ion battery used as reference. They also expect that the battery has a higher power potential and is safer than Li-ion batteries with a lithium-cobalt-oxide cathode [Li et al., 2009].

Lithium copper
In this battery type, a metallic copper cathode is applied. Like in the nickel lithium battery, a hybrid electrolyte is applied: during discharge, lithium ions move from the lithium anode through an organic electrolyte, solid electrolyte separator and an aqueous electrolyte to the copper cathode [National Institute of Advanced Industrial Science and Technology (AIST), 2009]. The lithium copper battery is similar to the nickel lithium one very innovative and in the first stages of development.

All-electron battery
Researchers of Stanford University (US) are looking at a battery concept in which electrons are used instead of ions to store energy [“Stanford University”, n.d.; “ahpcrc projects”, n.d.]. Their

experiments have shown that such an all-electron battery might have a higher specific energy, specific power and lifetime than conventional batteries [“ahpcrc projects”, n.d.]. The project at Stanford University seems to be focused on military purposes, but is also funded by the US government with the aim to promote the development of new generation battery technologies for PHEVs and BEVs [“Stanford University”, n.d.; “ahpcrc projects”, n.d.].

3.2 Selection

Summary

In the previous section a large number of battery technologies was discussed. Of these, only a few are nowadays used in electric cars; Li-ion, NiMH and ZEBRA batteries. Also, application of lithium metal polymer batteries will take place in a very short term. In figure 3.1 it is showed how these four battery technologies compare to each other with regard to (theoretical) specific energy, specific power and cost. Furthermore, in table 3.7 an overview is given of positive and negative characteristics of each battery type.

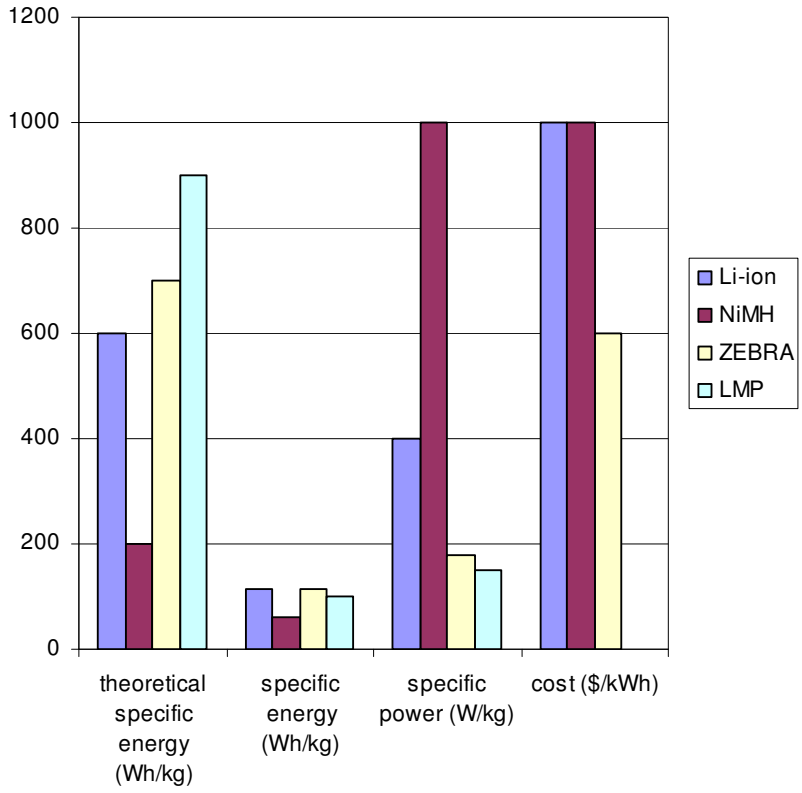


Figure 3.1: Comparison of four commercial battery technologies on present performance and cost characteristics

Table 3.7: Present positive and negative aspects of all battery technologies discussed in section 3.1

		Specific energy	Specific power	Eff.	Cycle life	Life-time	Tempe-rature	Costs	Safety
Present commercial batteries	*NiMH*	-	++	-	+			-	**+**
	Li-ion	+	+	+	+	+/-	-	-	**-**
	LMP	+	-		-	+	- [2]	-	**-** [4]
	ZEBRA	+	-	+	+/-	+	-- [2]	+/-	**+**
	NaS	+	-		+/-	+	-- [2]		**--**
Potential high energy batteries	*Li-S*	++	+/-		-			+	**-** [4]
	Zn-air	++	-					++	
	Li-air	++	-						**-** [4]
	Al-air	++	-	--	- [1]				
	Fe-air	++	-	-	-				
Other Innovative battery technologies	*Conversion*	+							
	Organic lithium	-	-				- [3]		
	Ambient temperature Na-ion	-					+ [2]	+	**+**
	Mg-ion	+						+	**+**
	Ni-Li	+	+						
	Li-Cu								
	All electron (potentially)	**+**	**+**			**+**			

Explanatory statements: [1] Not electrically rechargeable; [2] internal temperature; [3] thermal stability; [4] metallic lithium.

Lithium-ion batteries significantly represent the largest share of commercial batteries for BEV purposes. These batteries provide compact cars with a range of around 150 km. However, improvement of the technology is needed to enhance the specific energy and operating temperature. Also, safety and costs are important issues. Fortunately, there is room to improve the Li-ion technology. As a result, Li-ion batteries are widely considered to dominate the market in the next decades.
ZEBRA batteries are also applied, but their high operation temperature restricts their implementation. Besides, both their specific energy and specific power have to be improved. Costs are below Li-ion batteries, but still substantially higher than demanded.
Nickel-metal-hydride batteries are widely used in hybrid vehicles, but their performance makes them much less attractive for BEV purposes; as the theoretical specific energy is relatively low, the required specific energy level cannot be met.
The use of metallic lithium in LMP batteries should have a positive effect on the specific energy, but the batteries that are to be used in electric cars show no great performance advantages (yet) compared to Li-ion batteries. Even, their specific power lags behind. Also, the cycle life does not or only slightly meet the requirements. Finally, sodium sulfur batteries are also commercially available, but do not appear to be suitable for BEVs because of fundamental safety issues.

Not only Li-ion, but also other lithium based battery technologies do get much attention in research and development activities. Lithium Sulfur and lithium-air batteries (table 3.7) are founded on the use of materials that have a highly positive influence on the specific energy. However, the use of metallic lithium results in operational problems, especially with regard to safety.

Of other metal-air concepts (table 3.7), zinc-air batteries get most attention. Besides, their stage of development is significantly ahead of other types. Aluminum-air and iron-air technologies were widely considered in the past, but interest seems to be declined as interest in and expectations of other battery types grew.
Yet, as these high energy battery technologies are still in development, less information is available about their performance. Apart from specific energy, it is uncertain what levels can be attained with regard to specific power, efficiency, cycle life and lifetime.

Finally, there is a significant number of other innovative technologies that show some very attractive features (table 3.7). They might not all be able to compete with lithium batteries in terms of specific energy, but aspects with regard to costs, safety and environmental impact are interesting.
In fact, conversion and organic batteries are strongly related to present Li-ion batteries. Therefore, Li-ion batteries might profit from the developments of these new battery types.
Also, battery types based on sodium ion technology seem to be an attractive option. Possibly, ZEBRA batteries could take advantage of the development of ambient temperature sodium-ion batteries.
Regarding the remaining innovative battery technologies, their development is in a very early stage and research activities are carried out by only a small group of researchers. Therefore, making statements about their prospects depends on too many uncertainties.

Selection
Based on the considerations summarized above, the following battery technologies are selected for a more in depth analysis:

- **Li-ion**: This is clearly the most promising option in the short term and is also widely expected to maintain its position in the market in the medium and possibly even long term. The specific power of Li-ion batteries is an attractive property. Also, various other performance characteristics (cycle life, recharge time and efficiency) seem to meet the requirements to a large extend. On the other hand, specific energy, safety and costs need to be enhanced. Therefore, the question is how and to what extend these batteries can improve in time.
- **ZEBRA**: ZEBRA batteries are already in use, but applications are limited. Nevertheless, ZEBRA batteries show advantages over Li-ion with regard to costs, safety and lifetime. On the other hand, both the specific energy and specific power have to be enhanced. The analysis has to show if and how the required improvements can be made.
- **Lithium Sulfur**: Li-S batteries are still in development, but could be an interesting option in the medium term. The technology is promising with regard to specific energy and costs, but the cycle life is an important issue. The analysis will be focused on what developments are needed to make commercialization for BEV purposes possible, and to what extend battery requirements can be attained.
- **Metal-air**: Both zinc-air and lithium-air batteries will be considered. Li-air batteries are still in the initial stages of development and application in battery electric cars can be expected in the medium or long term. Zinc-air batteries are in a more advanced development stage and could be available for BEV purposes in the medium term. Both batteries are very interesting with regard to their specific energy. Lithium-air batteries could even approach the energy density of current liquid hydrocarbon fuels. Besides, the zinc-air technology does have good cost perspectives. On the other hand, the specific power of metal-air batteries could be a barrier for application in BEVs. Also, there a much uncertainties yet on the potential performance of metal-air batteries. It will be asked what most important barriers do prevent the step to a next development stage, when commercialization could start and to what extend metal-air batteries can outperform other battery technologies.

4. Part two: projections and uncertainties

4.1 Performance projections

In appendix II an extensive discussion can be found about current topics in battery research and development activities. Also, projections found on the performance of Li-ion, ZEBRA, Li-S and metal-air batteries are discussed. The next four sections will shortly review what topics are considered to be most important in the development of the different batteries. Also, it will be discussed what projections were found and how well-founded they are.

4.1.1 Li-ion

Table 4.1: Importance of improvement of Li-ion battery performance characteristics and projections on future enhancement.

	Importance of improvement	Projections	Comments	Source
Specific energy (Wh/kg)	Central research topic	250	2025 (6%/year improvement)	ARPA-E, 2009 In accordance with: ARB, 2009; E. Kelder, personal communication, 2010; Rozenkranz in: Cars21, 2010
		140	2020	Winter in: Miller, 2009
		150	2035 (2%/year improvement)	Bandivadekar et al., 2008
Specific power (W/kg)	Low	-	-	-
Cycle life (# cycles)	Low	1000-3000	Present at 80% DoD	Kalhammer et al., 2007
		>2000	Demonstrated at 70-80% DoD	Anderman, 2010
Lifetime (years)	High	unclear	Difficult to control and extend lifetime	Kelder, personal communication, 2010; Anderman, 2010
Recharge time (min/hours)	Mediate	15-30 min	Faster is possible, but too expensive for consumers	W. Robers, personal communication, 2010
Operating temperature (°C)	Mediate to high	-	-	-
Efficiency (%)	Low	-	-	-
Safety	Absolute condition	-	Safety may demand sacrifices in battery performance and cost	ARPA-E, 2009; E. Kelder, personal communication, 2010; Anderman, 2010

The amount of (scientific) literature about lithium-ion battery research topics is extensive, but in most cases not specially focused on batteries for BEV purposes. As a result, no projections are found

in most documents. The projections that were found, are based on present performance levels (cycle life), historic developments (specific energy) and personal perceptions of experts (specific energy, lifetime and recharge time).

The specific energy is an important topic in research and development. It is aimed to substantially increase this parameter by improvements at both cell and pack level. The different projections in table 4.1 show that improvements in specific energy are highly dependent on how fast technological breakthroughts can be realized. A high yearly improvement rate is expected by the majority [ARPA-E, 2009; ARB, 2009; E. Kelder, personal communication, 2010; Rozenkranz in: Cars21, 2010]. However, it is very difficult to forecast technological developments for ten or more years from now [B. Scrosati, personal communaication, September 8, 2010].
Besides, a higher specific energy is not considered to be a key requirement. Safety, however, is an absolute condition for battery commercialization [E. Kelder, personal communication, July 7, 2010; ARPA-E, 2009; Anderman, 2010]. At present, a number of Li-ion chemistries exist, which all have their pros and cons [BCG, 2010; Lache et al., 2009]. Therefore, it is needed to find compromises with regard to performance, costs and safety. This means that safety enhancements may even demand sacrifices in battery performance (a.o. specific energy) and cost [E. Kelder, personal communication, July 7, 2010; ARPA-E, 2009; Anderman, 2010].

Also, lifetime is considered to be a central aspect. However, there is little information about what is practically achievable and real-life validation is needed [Kelder, personal communication, 2010; Cars21, 2010]. Besides, it is difficult to control and extend the lifetime as it depends on various operational conditions [Anderman, 2010]. An important parameter is temperature; battery degradation takes place at high temperatures and affects the life time and cycle life of the battery. Futhermore, power declines at low temperatures. Present battery chemistries have to be improved to prevent this [ARPA-E, 2009], but it is highly uncertain how this will affect the operational temperature.

With regard to cycle life, present levels (table 3.2) do already comply to USABC goals [Kalhammer, 2007, Anderman, 2010]. Nevertheless, little knowledge is available about how and to what extend the cycle life could be enhanced in the future [E. Kelder, personal communication, 2010].
Also present specific power levels do already meet the USABC requirements (section 3.1.2). Thus, there is little need for R&D to focus on this topic. No projections were found on if and how the specific power may improve.
However, the power rate is of importance for a fast recharge time. With specific battery chemistries recharge times of five minutes will be possible. However, such batteries are only considered to be economically feasible for commercial purposes [W. Robers, personal communication, 2010]. It is expected that recharge times will be in the range of 15 to 30 minutes.

Finally, no goals are stated by the USABC with regard to battery efficiency. Nevertheless, it is an important parameter. For Li-ion batteries, the charge-dicharge efficiency is about 90% (section 3.1.2). In literature, no statements were found that research is focused on improving this level.

4.1.2 ZEBRA

The number of literature sources on ZEBRA batteries is small compared to Li-ion batteries. Especially recent and (independent) scientific literature is limited. The few projections found were mainly from reports of the U.S. government (DOE, 2007, ARPA-E, 2009; Kalhammer et al., 2007]. However, their data is primarily based on information from FZSoNick SA (MES-DEA), manufacturer of ZEBRA batteries.

Table 4.2: Importance of improvement of ZEBRA battery performance characteristics and projections on future enhancement.

	Importance of improvement	Projections	Comments	Source
Specific energy (Wh/kg)	High	200	Cell level (±160 at pack level)	DOE, 2007
		300	Upper limit	ARPA-E, 2009
		155-200	2025 (2% and 4% improvement rate respectively)	Based on Li-ion improvement rates
Specific power (W/kg)	Very High	400	Cell level (estimated 280 at pack level)	DOE, 2007
		1500	Upper limit	ARPA-E, 2009
Cycle life (# cycles)	Low	1000	Present at 80% DoD	Kalhammer et al., 2007
		>1450	Demonstrated	DOE, 2007
		6000	Upper limit at 100% DoD	ARPA-E, 2009
Lifetime (years)	Low	15 years		
Recharge time (min/hours)	Mediate	-	Fast (partial) recharge not possible yet; improvement of power/energy ratio needed	ARPA-E, 2009
Operating temperature (°C)	Mediate	Ambient temperature after 2020	Radical redesign needed	Tarascon, 2010; Lu et al., 2010
Efficiency (%)	Low	-	-	-
Safety	Low	-	-	-

In contrast with Li-ion batteries, safety and lifetime are no key issues for ZEBRA batteries (table 4.2). Actually, the performance on these aspects is very good (section 3.1.4). Also the present cycle life and efficiency of ZEBRA batteries is good. In literature, no statements were found that research is focused on improving the levels of safety, lifetime, cycle life and efficiency.
On the other hand, both specific energy and specific power are important topics. Substantial redesign of the cells could result in a specific energy and specific power of 200 Wh/kg and 400 W/kg at cell level [DOE, 2007]. Consequently, at pack level the performance will still be too low.
At a high improvement rate of 4%, the specific energy could reach the 200 Wh/kg goal in 2025. However, attaining the required power/energy ratio at the same time would need a specific power improvement rate of 5.5%. This does not seem to be very realistic. Besides, improving the power/energy ratio is regarded to be a key requirement [ARPA-E, 2009]. Therefore, it may be expected that research will mainly focus on the enhancement of the power rate and not of the specific energy.
Improving the power rate is also important to make fast recharge possible [ARPA-E, 2009]. Yet, no statements were found on what charge rates could be achieved, and in what time frame.

Finally, lowering the operating temperature of the ZEBRA battery is considered to be an important goal [ARPA-E, 2009]. At a present operational temperature of 300 °C, a heat conductivity of 0.006 W/mK and a yearly driving distance of 14,000 km the battery will not be in operation for 8,343 hours/year. This means that 14 MWh_e/year is needed to keep the battery's temperature high [Galloway and Dustmann, 2003; Van Vliet, 2010]. However, ambient temperature operation would

require radical changes in battery design and chemistry [Lu et al., 2010]. Nevertheless, Tarascon [2010] expects that room temperature sodium-ion batteries can be commercialized after 2020.

4.1.3 Li-S

In scientific literature, the development of lithium-sulfur batteries is discussed extensively [Zhu et al., 2005; Zhang et al., 2009]. However, as for Li-ion batteries, little projections were found in these papers. The figures in table 4.3 are demonstrated performance levels in laboratory and field tests and development goals. These development objectives are mainly defined by the company Sion Power [ARPA-E, 2009; Green Car Congress, 2010b].

Table 4.3: Importance of improvement of lithium-sulfur battery performance characteristics and projections on future levels.

	Importance of improvement	Projections	Comments	Source
Specific energy (Wh/kg)	High	350	Demonstrated at cell level	Sion Power, 2010; Mikhaylik et al., 2008
		550, 600	Cell level, (BEV) goals Sion Power for 2012 and 2016	ARPA-E, 2009; Green Car Congress, 2010b
		550-650	Target at cell level	Nazar, 2009
Specific power (W/kg)	High	100-200	Demonstrated	Mikhaylik et al., 2008]
		>600		Kalhammer et al., 2007
		>400		ARPA-E, 2009
		Up to 2000	At 250 Wh/kg, specific energy declines with increasing specific power	Mikhaylik et al., 2008
Cycle life (# cycles)	Very high	100	Present	Kalhammer et al., 2007
		>500	Demonstrated	Cairns, 2009
		500, 1000	(BEV) Goals Sion Power for 2012 and 2016 (100% DoD)	ARPA-E, 2009; Green Car Congress, 2010b
Lifetime (years)	Unknown	-	-	-
Recharge time (min/hours)	Low	<3 hours		Sion Power, n.d.
Operating temperature (°C)	Low to Mediate	100 Wh/kg at -60°, but thermal runaway at high temperatures	Demonstrated	ARPA-E, 2009; Sion Power, n.d.
Efficiency (%)	Unknown	-	-	-
Safety	High			

For lithium-sulfur batteries, the key issue in R&D activities is increasing the cycle life [Aurbach et al., 2009; Nazar, 2009; Sion Power, n.d.]. Sion Power has the aim to produce cells with cycle lives of 500

and 1000 cycles in 2012 and 2016 [ARPA-E, 2009; Green Car Congress, 2010b]. This would mean that batteries with a satisfying cycle life could be commercialized from approximately 2020.
Means to improve the cycle life do also positively affect the specific energy of Li-S batteries. Nevertheless, the development goals of Sion Power for BEV purpose batteries are significantly above present demonstrated performance levels. Besides, the specific energy goals are given at cell level; the utilization rate at pack level is unknown. Depending on this rate, goals of 550 to 650 Wh/kg at cell level may result in a specific energy at pack level between 330 and 520 Wh/kg.

The demonstrated levels of specific power do vary between different sources. However, it is clear that the specific energy will decline at higher power levels. Therefore, a trade-off has to be made between these two variables. Data from Sion Power [Mikhaylik et al., 2008] suggest that the specific power will be relatively low at the targeted levels of specific energy.

Another important issue in the development of Li-S batteries is safety. The use of metallic lithium does significantly affect the safety. Several technological solutions are proposed in literature, but cannot totally solve the problems. A more effective solution could be replacing metallic lithium with silicon [Yang et al., 2010]. However, this will reduce the (theoretical) specific energy of the battery. Another safety issue is thermal runaway at high temperatures. On the other hand, performance at very low temperature is relatively good compared to Li-ion batteries [Sion Power, n.d.].

Also, stated recharge times (less than 3 hours) are low compared to present Li-ion and ZEBRA batteries. However, it is not known if fast charge is or will be possible.
Finally, with regard to efficiency and lifetime, no information was found on present or projected performance levels. Also, no statements were found whether these are important topics in research and development. This suggests that efficiency and lifetime are not considered to be key subjects. Still, it remains highly uncertain what their level will be in commercial batteries.

4.1.4 Metal-air

Similar to lithium-sulfur batteries, an extensive amount of scientific literature can be found about research on lithium-air batteries. Also for zinc-air batteries scientific papers can be found, but information was mainly collected from other sources [ARPA-E, 2009; Bullis, 2009a].
It is believed that commercialization of metal-air batteries could start from or after 2020 [James Miners in: Cars21, 2010; Tarascon, 2010; ANL, 2009]. Yet, the development of the two battery technologies is in very different stages. Lithium-air batteries are in initial stages of development [Kraytsberg and Ein-Eli, 2010]. Essential technological developments are required and their feasibility (for consumer electronics) has to be proven yet [ARB, 2009]. Therefore, potential future performance levels are very uncertain. Rechargeable Zn-air batteries, however, are stated to be commercially available on a very short term for small electronic applications like hearing aids [Bullis 2009b]. On the other hand, demonstrated performance levels and development goals are only based on information from the company ReVolt [Bullis, 2009b; ARPA-E, 2009].

The differences in development stage are illustrated by the discrepancy in present and projected battery performance levels (tables 4.4 and 4.5). Demonstrated specific energies are stated to be 300 to 400 Wh/kg for Zn-air cells and not higher than 263 Wh/kg for Li-air cells [ARPA-E, 2009; Zhang et al., 2010; Kraytsberg and Ein-Eli, 2010]. Nevertheless, the projections for Li-air cells exceed those for Zn-air cells. At pack level, expectations of the specific energy of Li-air batteries ranges from 500 to more than 1000 Wh/kg [Girishkumar in: Green Car Congress, 2010a; Kumar et al., 2010; Tarascon, 2010; ANL, 2009]. Depending on the design (standard or flow battery) and utilization factor

Table 4.4: Importance of improvement of zinc-air battery performance characteristics and projections on future levels.

	Importance of improvement	Projections	Comments	Source
Specific energy (Wh/kg)	Mediate	480 to 600	Cell level (40-50% of theoretical level)	Girishkumar in: Green Car Congress, 2010a
		400	Tested at cell level	ARPA-E, 2009
		300	Zinc-flow, tested at cell level	ARPA-E, 2009
Specific power (W/kg)	Very High	-	-	-
Cycle life (# cycles)		500	Demonstrated in laboratory	ARPA-E, 2009
		2,000-10,000	Zinc-flow goals (DoD unknown)	Bullis, 2009a
Lifetime (years)	Unknown	-	-	-
Recharge time (min/hours)	Unknown	-	-	-
Operating temperature (°C)	Unknown	-	-	-
Efficiency (%)	Very high	65-70	Present	ARPA-E, 2009
		80	Future target	ARPA-E, 2009
Safety	Low	Low risk No volatile materials		Tahil, 2007a Bullis, 2009a

Table 4.5: Importance of improvement of lithium-air battery performance characteristics and projections on future levels.

	Importance of improvement	Projections	Comments	Source
Specific energy (Wh/kg)	Mediate	263	Highest attained in laboratory tests at cell level	Zhang et al., 2010; Kraytsberg and Ein-Eli, 2010
		1700 (850)	Cell level (pack level at 50% utilization rate)	Girishkumar in: Green Car Congress, 2010a
		1000 to 3000	Cell level	Kumar et al., 2010
		500	Pack level at commercialization	Tarascon, 2010
		5 to 10 times higher compared to Li-ion		ANL, 2009
Specific power (W/kg)	Very High	0.46 mW/g	Attained in laboratory tests at cell level	Kraytsberg and Ein-Eli, 2010
Cycle life (# cycles)	Very high	-	-	-
Lifetime (years)	Unknown	-	-	-
Recharge time (min/hours)	Unknown	-	-	-
Operating temperature (°C)	Unknown	-	-	-
Efficiency (%)	Very high	60-70	Present	Green Car Congress, 2010a
		85-90	Future	Bullis, 2010
Safety	Very High			

(appendix II), it is assumed that the specific energy of Zn-air batteries could range between approximately 150 and 420 Wh/kg [Girishkumar in: Green Car Congress, 2010a; ARPA-E, 2009].
On the other hand, projections for Li-air batteries are far below theoretical values; the formation of reaction products that contain oxygen and the impact of non-active materials significantly reduce the actual specific energy [ARPA-E, 2009; Green car Congress, 2010a].The reaction products in Li-air batteries do also cause clogging of the porous cathode and limit the discharge capacity and cycle life. However, no information is available about what is achievable. It seems highly uncertain if the cycle life requirements can be met.
Zn-air batteries do also encounter some physical and chemical processes that reduce the cycle life. However, problems seem to be much less crucial. 500 cycles are already demonstrated [ARPA-E, 2009]. Also, expectations on the cycle life of a zinc-air flow battery are very high [Bullis, 2009b].

Next to cycle life, also expectations on the specific power of Li-air batteries are not very optimistic. The low electric current density is considered to be an important issue. It is uncertain what specific power levels could be attained in the future. Also for zinc-air batteries the specific power is considered to be an important issue [ARPA-E, 2009]. Yet, again the potential power level is uncertain. Also the efficiency of metal-air systems is low. But, it is believed that present levels can be increased [ARPA-E, 2009; Green Car Congress, 2010a; Bullis, 2010].

It is believed that metal-air batteries may have an advantage with regard to safety; because oxygen is outside the system, the energy for reactions is not stored in the battery. However, metallic lithium does affect the safety of the Li-air battery. It is necessary to prevent lithium to come into contact and react aggressively with water [Green Car Congress, 2010a; Frost & Sullivan, 2009]. In contrast, the safety of zinc-air batteries is believed to be very good [Tahil, 2007a; Bullis, 2009b].

Finally, it remains unknown what the potential performance levels are for lifetime, recharge time and operating temperature. This holds for both Zn-air and Li-air batteries.

4.1.5 Summary performance projections

Based on the findings discussed in section 4.1 performance projections are made for the short, medium and long term. These projections are shown in tables 4.6 to 4.8. If no data was found at all on a certain performance characteristic, *'unknown'* is filled in. Especially for Li-air batteries, this is often the case.

Table 4.6: Short term (2015) battery performance projections based on literature review and expert consultation

	Specific energy (Wh/kg)	Specific power (W/kg)	Efficiency (%)	Cycle life (# cycles)	Lifetime (years)	Operating temperature	safety
Li-ion	120-150	400 or more	90	1,000-3,000 (80% DoD)	7	Limited	Good, but attention still needed
ZEBRA	115-130	230 max	90	1,000 (80% DoD)	15	300-350 °C	good
Li-S	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Zn-air	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Li-air	n/a	n/a	n/a	n/a	n/a	n/a	n/a

Table *4.7*: Medium term (2025) battery performance projections based on literature review and expert consultation

	Specific energy (Wh/kg)	Specific power (W/kg)	Efficiency (%)	Cycle life (# cycles)	Lifetime (years)	Operating temperature	safety
Li-ion	150-250	500 or more	92	1,000-3,000 (80% DoD)	7-10 (uncertain)	Improved, but uncertain	Good
ZEBRA	130-160	320 max	90	1,000-1,500 (80% DoD)	15	Below 350 °C, possibly approaching ambient temperature	Good
Li-S	300-400	200-300	unknown	500-1,000 (100% DoD)	unknown	low temperature good (to -60°), high temperature limited	Uncertain, possibly good [(2)]
Zn-air	150-300 [(1)]	unknown	70 max	2,000 max (DoD unknown)	unknown	unknown	Good
Li-air	500	unknown	70 max	Unknown	unknown	unknown	Key issue

[(1)] Depending on design: flow vs. standard zinc-air battery; [(2)] depending on use or not of metallic lithium

Table 4.8: Long term (beyond 2025) battery performance projections based on literature review and expert consultation

	Specific energy (Wh/kg)	Specific power (W/kg)	Efficiency (%)	Cycle life (# cycles)	Lifetime (years)	Operating temperature	safety
Li-ion	250	500 or more	95	1,000-3,000 (80% DoD)	10 or more (uncertain)	unknown	Good
ZEBRA	200 max	400 max	95	1,500 (80% DoD)	15	ambient temperature	Good
Li-S	500 max	300 or more (uncertain)	unknown	1,000 or more (100% DoD)	unknown	Both high and low temperature good	Uncertain, possibly good [(2)]
Zn-air	200-400 [(1)]	unknown	80	2,000 or more (DoD unknown)	unknown	unknown	Good
Li-air	500-1,000	unknown	85	1,000 (uncertain, DoD unknown)	unknown	unknown	uncertain

[(1)] Depending on design: flow vs. standard zinc-air battery; [(2)] depending on use or not of metallic lithium

4.2 Battery cost projections

4.2.1 Overview data

In table 4.9 an overview is given of the battery cost projections derived from literature review and an assessment of progress ratios and battery cost breakdowns. In appendix III, detailed background information is given on these figures. Below, a short clarification is given for each battery technology.

Table 4.9: Overview of battery costs projections from literature review and the assessment of progress ratios and battery cost breakdowns

Battery technology	Literature ($/kWh)		Learning ($/kWh)		Lower cost limit based on cost breakdown ($/kWh)	Cost of active cell materials ($/kWh)
Li-ion	366-508 (Medium term, 2020) [1,2]	200-300 (Long term, 2030) [1,3]	211-611 (Medium term, 2020) [4]		305 [5]	55-87 [6]
ZEBRA	86-210 [7,8]		166-320 (Medium term, 2020) [9]	374 (short term, 2015) [10]	86-149 [11]	
Li-S	250 (long term potential) [12]					34-123 [13]
Zn-air	<100 (long term potential) [12]					35 [12]
Li-air						88-152 [13]

[1] [IEA, 2008; IEA, 2009; ARB, 2009; Matheys and Van Autenboer, n.d.; Bandivadekar et al., 2008; Kromer and Heywood, 2007; Anderman, 2010; Offer et al., 2010; BERR & DfT, 2008; BCG, 2010; Lache et al., 2008]; [2] Deviating projections by Van Vliet [2010] and Lache et al. [2009]: ~800 $/kWh and 249 $/kWh respectively; [3] Deviating projection by BERR & DfT [2008]: 97 $/kWh; [4] four scenarios, based on present costs of 800 and 1200 $/kWh (section 3.1.2), cumulative production of 7.1 million batteries in 2020 [BCG, 2009; Green Car Congress, 2010d; Lache et al., 2008], and progress ratios of 83% and 91% (derived from Nagelhout and Ros [2009], Toyota [2009], Kalhammer et al. [2007], Institute of Information Technology (IIT) [2005] and Kamath [2009]); [5] [Lache et al., 2009; BCG, 2010; Howard and Spotnitz, 2007; Roland Berger, 2009]; [6] [Lache et al., 2009; Howard and Spotnitz, 2007; Roland Berger, 2009]; [7] [Galloway and Dustmann, 2003; Solartaxi, n.d.; Kalhammer et al., 2007]; [8] Lower value estimation from manufacturer [Galloway and Dustmann, 2003], higher value based on information from manufacturer [Kalhammer et al., 2007]; [9] two scenarios, based on present cost of 630 $/kWh (section 3.1.2), cumulative production of 7.1 million batteries in 2020 [BCG, 2009; Green Car Congress, 2010d; Lache et al., 2008], and progress ratios of 83% and 91% (derived from Nagelhout and Ros [2009], Toyota [2009], Kalhammer et al. [2007], IIT [2005] and Kamath [2009]); [10] based on cost and production volume projections from FZ SoNicK SA [Kalhammer et al., 2007; Cebi, 2010]; [11] [Galloway and Dustmann, 2003; MetalPrices, 2010]; [12] [ARPA-E, 2009]; [13] [Lache et al., 2009; MetalPrices, 2010].

Li-ion

A large number of cost projections for lithium-ion batteries was found in various sources. These projections were made by academics as well as governmental and consultancy agencies. According to most projections, costs can reduce to 366-508 $/kWh in 2020 and to 200-300 $/kWh in 2030. A few deviating estimations were found that were relatively pessimistic [Van Vliet, 2010] or optimistic [BERR & DfT, 2008; Lache et al., 2009]. Also, costs below 250$/kWh are only projected by a few sources [Kalhammer et al., 2007; Offer, 2010; BERR & DfT, 2008]. Therefore, it is more probable that costs will reduce to 250 to 300 $/kWh in the long term.

This is in accordance with the results from assessing the cost breakdown of Li-ion batteries. Information about the cost of different components of Li-ion batteries and battery cells at low and high production volume was compared. Also, costs of active materials were considered. Based on this information it is assumed that battery costs can reduce to approximately 300 $/kWh. However, this projection is based on only four different sources, of which three are consultancy firms. Besides, the cost breakdowns showed that low priced raw materials have to be used to achieve costs of 300 $/kWh or lower. Also, wide variation over time in material prices (especially with regard to nickel and cobalt) can influence battery costs substantially.
The Boston Consultancy Group [2010] even states that a major breakthrough in chemistry is needed to attain fundamentally higher specific energy without significant increase in cost of materials or production process. Only in such a case a cost target of $250/kWh could be achieved [BCG, 2010].

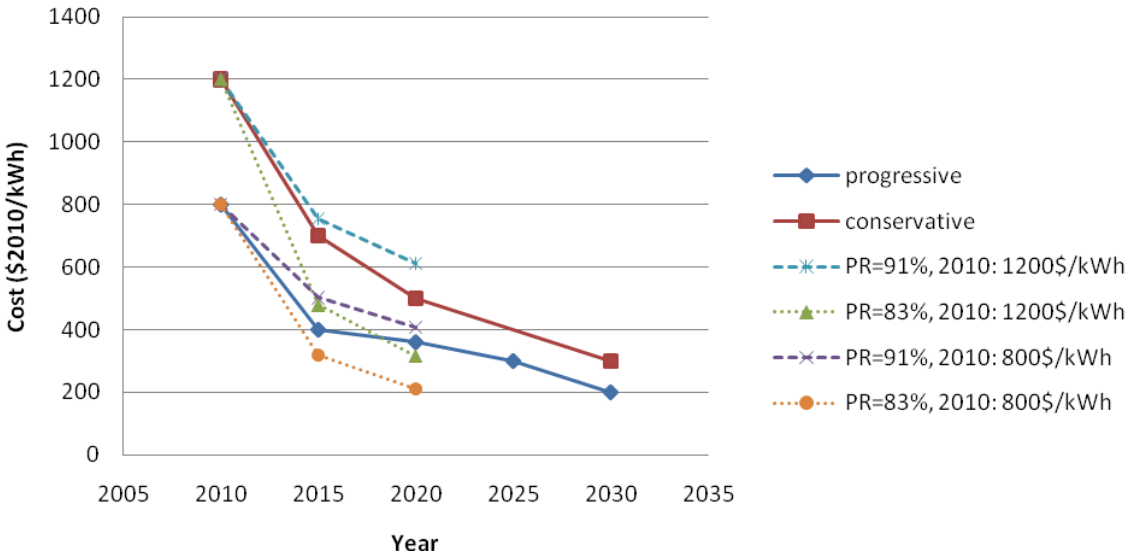


Figure 4.1: Comparison scenarios derived from literature and from market/experience curve approach

In figure 4.1, two battery cost scenarios based on projections from literature are compared to the projections based on experience curves and BEV market forecasts. From this comparison, it seems that a progress ratio of 83% is quite opportunistic. In this case, costs would reduce drastically in especially the next five years. Also, for a present cost of 800 as well as of 1200 $/kWh, costs would be below that of the progressive scenario in 2020.
On the other hand, a progress ratio of 91% shows slow cost decline compared to both scenarios. In reality, the progress ratio might be somewhere in between the values used.
Finally, the two scenarios in figure 4.1 show substantial cost reduction in the next five years. This may confirm the assumption that global BEV sales, and thus battery production volumes, will increase considerably within a few years [Lache et al., 2009].

ZEBRA

According to literature, it seems likely that ZEBRA batteries can reach a cost level of 200 $/kWh. Even when no new production facilities will be build, costs can decline to 300 $/kWh or lower as a result of production expansion and learning within the present battery plant of FZ SoNicK SA. Galloway and Dustmann [2003] state that battery costs can potentially reduce to about 86 $2010/kWh at large volume production. However, using the progress ratio of 84.6% from appendix IV results in a required production capacity of more than 75 GWh per year (a production volume of approximately 3.6 million batteries per year). This is far from reality yet, but possible if these

batteries will be used at large scale in the future. However, even when assuming the most positive projections for BEV sales from appendix III this volume can only be reached in 2020 if the majority of the batteries will be based on ZEBRA technology. Therefore, it is very plausible that costs can only approach 100 $/kWh in a much longer term.
Besides, such cost levels can only be reached when raw material prices are low. In appendix III it was showed that prices of nickel have varied from 9 to 55 $/kg in the last five years. At a high nickel price, costs of cell materials could even become higher than costs of Li-ion cell materials.

However, with regard to ZEBRA batteries, cost projections are based on very little sources. Besides, all data from these sources is based on information from same manufacturer (FZ SoNicK SA, formerly MES-DEA). Therefore, the projections should be considered uncertain.

Li-S and metal-air

For lithium-sulfur and metal-air batteries, very little information was found on cost perspectives. Only for Li-S and Zn-air batteries an indication of long term cost potentials was found; 250 $/kWh and 100 $/kWh respectively. Therefore, prices of anode and cathode materials were used to get an impression of how battery costs may relate to Li-ion costs.
The material prices show that anode and cathode costs of Li-S and Zn-air batteries can potentially be lower compared to Li-ion. However, costs of Li-S materials do largely depend on the price of metallic lithium. The replacement of metallic lithium for silicon is a good cost effective option. For Li-air batteries, the wide price range of metallic lithium results in an uncertain cost perspective. However, it is clear that costs will not be below Li-ion costs.
In practice, however, battery costs will not only depend on electrode material prices, but also on the amount of materials needed and on other cost components. Unfortunately, too little information is available to make reasonable assumptions on the total battery costs.

4.2.2 Summary cost projections

Based on the projections found trough the different review and assessment methods, aggregated cost projections are made for the short, medium and long term. These are shown in table 4.10. For Li-S and metal-air batteries, medium term costs will be high because commercialization will be in its initial stages. Therefore, only projections are made for the long term. The long term projections reflect what is considered to be attainable eventually. Nevertheless, especially for Li-air batteries this ultimate level is very uncertain.

Table 4.10: Battery cost projections based on literature review and assessment of progress ratios and battery cost breakdowns

	Cost Li-ion ($/kWh)	Cost ZEBRA ($/kWh)	Cost Li-S ($/kWh)	Cost Zn-air ($/kWh)	Cost Li-air ($/kWh)
Short term (2015)	400-600	350-400	-	-	-
Medium term (2025)	300-400	200-300	Highly uncertain [(1)]	Highly uncertain [(1)]	Highly uncertain [(1)]
Long term (beyond 2025)	250-300	100-200	250-500	100-300	350-700

[(1)] At initial stages of commercialization, costs are much higher than ultimately achievable cost levels.

4.3 Sustainability prospects

4.3.1 Prospects material availability

Projections on material availability for EV batteries show that there are substantial uncertainties. Andersson and Råde [2001] did assess the requirement and availability of metals for batteries, taking into account the intensity of metal use in batteries (a.o. cobalt, lithium, nickel), losses in recycling and manufacturing and available resources. They showed that the results do highly depend on the assumptions concerning these variables. The use of pessimistic and optimistic assumptions results in a maximum of 200 million to 12 billion battery electric vehicles with a (17 kWh) Li-ion battery respectively. With (18-19 kWh) ZEBRA batteries a number of 350 million to 7.2 billion BEVs could be attained.
The cathode material of lithium batteries is of importance; it is considered that Li-ion batteries containing manganese can be provided in larger amounts than nickel containing ones. The former will be constrained by lithium availability, the latter one by lithium or nickel constraints. Cobalt based Li-ion battery numbers are much lower, constrained by the availability of cobalt (32 to 670 million BEVs). Tahil [2007b], Angerer [2009] and Gaines and Nelson [2010] do confirm that the abundance of cobalt could be a limiting factor.

Furthermore, the lithium availability will constrain lithium metal batteries more than lithium ion batteries, because of the higher intensity of lithium used [Andersson and Råde, 2001]. On the other hand, a large share of lithium in the battery does not take part in the chemical reaction. Therefore, a decrease of the lithium intensity will positively influence the maximum number of metallic lithium batteries.
This also accounts for NaNiCl batteries that will be constrained by the availability of nickel. The relatively high potential to decrease the nickel intensity can positively influence the availability of this metal for ZEBRA batteries [Andersson and Råde, 2001].

Tahil also states that a fast increase in lithium demand from the battery/automotive industry could become restrained by limited production levels. If production levels would rise, reserves depletion could take place at fast rates [Tahil, 2007b]. On the other hand, Angerer [2009], from the German Fraunhofer institute, and Gaines and Nelson [2010], from Argonne National Laboratory, state that even at high growth rates of EV production enough lithium will be available for the next decades. However, Angerer, Andersson and Råde and Gaines and Nelson do all emphasize that recycling of lithium (and other metals) is essential to ensure material availability. For example, Dewulf et al. [2010] show that using recovered cobalt and nickel for Li-ion battery cathode material results in a 51% saving of natural resources.

With regard to Li-S and metal-air battery technologies, no literature was found about the demand for materials and the availability of raw materials. Therefore, based on data for other batteries, assumptions are made on the demand of these materials. These values can be found in table 4.11.

Table 4.11: Total demand for raw materials for a cumulative number of 1.6 billion EVs in 2050 (with 25 kWh batteries that all contain the same chemistry) and present other demand, world reserves and reserve base.

		Demand (kg/kWh)	Demand EVs 2050 (1,000 tonne)	Other demand 2009 [7] (1,000 tonne)	World reserves [7] (1,000 tonne)	World reserve base [10] (1,000 tonne)
Li-ion	Lithium	0.150 [1]	6,000	14	9,900	11,000
	Nickel ($LiNiO_2$)	1.2 [2]	48,000	1,430	71,000	150,000
	Cobalt ($LiCoO_2$)	1.2 [2]	48,000	62	6,600	13,000
	Manganese ($LiMnO_4$)	1.2 [4]	48,000	10	540	5,200,000
	Phosphate ($LiFePO_4$)	0.8 [4]	32,000	158	16,000	n/a
	Aluminum ($Li(NiCoAl)O_2$)	0.04 [4]	1,600	37	n/a	n/a
	Iron/steel ($LiFePO_4$)	0.4 [4]	16,000	1,200	77,000	n/a
ZEBRA	Nickel	2.4 [2]	96,000	1,430	71,000	150,000
Li-S	Lithium (metallic)	0.52 [3]	20,800	14	9,900	11,000
	Sulfur	1.2 [5]	48,000	70	n/a	5,000,000 [9]
Zn-air	Zinc	0.26 [6]	10,400	11	200	1,900,000 [9]
Li-air	Lithium (metallic)	0.52 [3]	20,800	14	9,900	11,000

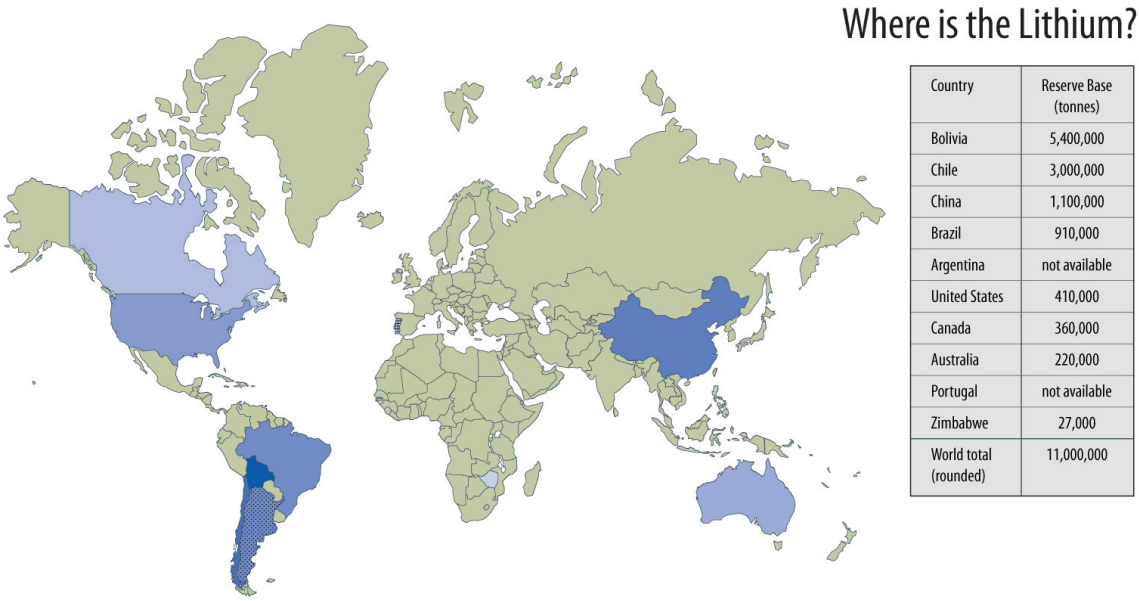
[1] [Angerer, 2009; Andersson and Råde, 2001]; [2] [Andersson and Råde, 2001]; [3] based on Li-metal/Vanadium battery [Andersson and Råde, 2001]; [4] based on the proportion of cumulative demand of this material and of nickel, derived from table V in Gaines and Nelson [2010]; [5] no data available, assumption based on high cathode metal demand values for Li-ion batteries; [6] no data available, assumption based on lithium metal demand in Li-air battery and corrected for lithium excess. [7] [U.S. Geological Survey (USGS), 2010b]; [8] U.S. capacity [Gaines and Nelson, 2010]; [9] world resources [USGS, 2010b]; [10] [Gaines and Nelson, 2010].

Furthermore, the IEA developed a scenario to meet the IPCC CO_2 reduction goals. In this scenario the cumulative amount of electric vehicles produced by 2050 would be 1.6 billion [Gaines and Nelson, 2010]. This also includes (plug-in) hybrids. In table 4.11 a battery capacity of 25 kWh is assumed to calculate the total material demand until 2050, when all batteries contain the same chemistry. Also, the present use of materials (other than for batteries), world reserves and the world reserve base are shown.

The results for Li-ion and ZEBRA batteries are in line with the information from Andersson and Råde [2001], Gaines and Nelson [2010], Angerer [2009] and Tahil [2007]. If all Li-ion batteries would be based on cobalt, material availability would be a considerable problem. Also, nickel reserves could constrain the production of ZEBRA batteries. The world reserves of lithium would be sufficient. The reserves of manganese and phosphate would not meet the demand. On the other hand, their world reserve base is stated to be very high [Gaines and Nelson, 2010].
Considering lithium-sulfur and metal-air batteries, the higher demand for lithium compared to Li-ion batteries is constrained by lithium reserves. Also, the demand for zinc largely exceeds world reserves.

For sulfur, no data on world reserves was found. Nevertheless, world resources of both sulfur and zinc are stated to be very high [USGS, 2010b].
Also, it is not likely that all batteries will contain the same chemistry. Yet, the high demand numbers compared to the present demand for the various materials confirm the need of recycling.

Apart from the availability of resources, (low cost) material availability is influenced by demand from other sectors and the concentration of production locations [Andersson and Råde, 2001; Tahil, 2007b]. The first issue especially accounts for nickel, table 4.11 [Andersson and Råde, 2001]. With regard to the latter, most lithium resources are located in South American countries, see figure 4.2 [Gaines and Nelson, 2010; Tahil, 2007b]. This could disrupt the supply of lithium, depending on monopolistic behavior and geopolitical relations [Angerer, 2009; Andersson and Råde, 2001].



Country	Reserve Base (tonnes)
Bolivia	5,400,000
Chile	3,000,000
China	1,100,000
Brazil	910,000
Argentina	not available
United States	410,000
Canada	360,000
Australia	220,000
Portugal	not available
Zimbabwe	27,000
World total (rounded)	11,000,000

Figure 4.2: Locations of known lithium reserves [Gaines and Nelson, 2010]

Nevertheless, present lithium reserves may be limited but lithium can also be found in large quantities at other locations. Currently, lithium (purified lithium carbonate) is recovered by solar evaporation from lithium chloride, which exists in salt water lakes (brines). Lithium could also be extracted from sea water, but this requires a very complicated and expensive process [Tarascon, 2010].For other materials no indications were found that their availability could be affected by demand from other sectors or by the concentration of production locations [Gaines, 2010; Tahil, 2007].

4.3.2 Environmental impact

The environmental impact of batteries depends on the use of energy and materials during the total life cycle of the battery and on related wastes and emissions emitted to the environment [Notter et al., 2010a]. A widely used way to assess the environmental impact of a product is a Life Cycle Assessment (LCA). LCAs considering batteries were found of Van den Bosche et al. [2006] and Notter et al. [2010a].

Van den Bossche et al. [2006] performed a life cycle assessment for several battery technologies, amongst which NaNiCl and Li-ion batteries (table 4.12). Their results showed that in the production

phase, the environmental impact of these two battery types was comparable. However, due to recycling, the impact of ZEBRA batteries was more reduced than that of Li-ion batteries. On the other hand, this was partly counteracted by energy demand to heat the battery during operation [Van den Bossche et al., 2006].

Table 4.12: Environmental impact of batteries designed for range of 60 km, car lifetime 180,000 km (corresponding to 3,000 cycles) [Van den Bossche et al., 2006]

Eco-indicator points (EI 99 H)				
	Production	**Additional use**	**Recycling**	**Total**
Li-ion (125 Wh/kg)	361	89	-172	278
ZEBRA (125 Wh/kg)	368	122	-256	234

Notter et al. [2010a] did assess a lithium-ion battery with a lithium-manganese-oxide cathode and compared the results to a reference gasoline ICEV (figure 4.3). They show that the battery causes significant increase of the environmental impact (Ecoindicator 99 H/A) in the production phase of the car. However, the battery plays a minor role when taking the total life cycle of the vehicle into account. The battery counts for 15% of the total environmental impact [Notter at al., 2010a]. For both vehicles, the impact of the operational phase is highest. But, the share of this phase on the total impact is significantly higher for the ICEV [Notter et al., 2010a].

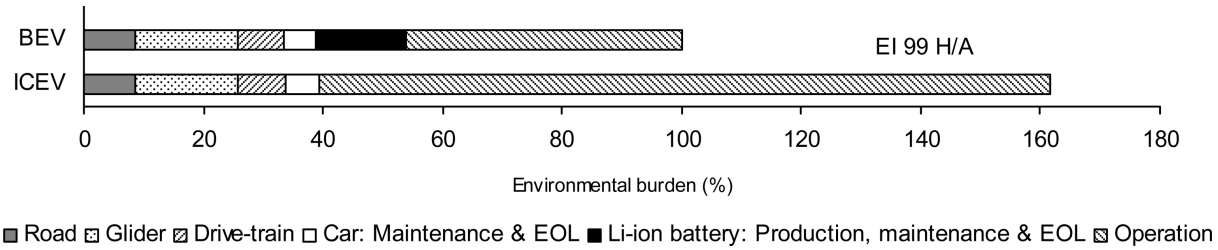


Figure 4.3: Shares of environmental impact correlating to an ICEV and a BEV (ICEV value in % of BEV, BEV is set as 100%), li-ion battery designed for a range of 200 km and a car lifetime 150,000 km (corresponding to 750 cycles) [Notter et al., 2010a]

However, when looking at the impact of the Li-ion battery itself (table 4.13) the dominant component is the copper current collector at the anode side (43%), followed by the cathode components and the battery pack. Other components play a minor role [Notter et al., 2010a; Notter et al., 2010b]. Also the impact of lithium is small, mainly because of its low content in the battery (0.007 kg per kg battery) and because of the simple and low energy demanding process of lithium carbonate extraction from brines [Notter et al., 2010a].
A comparison with the use of $Li(MnNiCo)O_2$ and $LiFePO_4$ as active cathode materials showed that the presence of nickel and cobalt increases the environmental impact of the battery, while substitution with lithium-iron-phosphate results in a small impact reduction [Notter et al., 2010a].

Table 4.13: Environmental impact of 1 kg Li-ion battery (one battery was designed for a range of 200 km and a car lifetime 150,000 km, corresponding to 750 cycles) [Notter et al., 2010b]

1 kg Li-ion, 114 Wh/kg	Eco-indicator points (EI 99 H/A)	Percentage (%)
Raw materials	**0.034**	**4.27**
Cathode	**0.131**	**16.4**
$LiMnO_4$	0.0448	5.59
Aluminum (current collector)	0.082	10.3
Anode	**0.403**	**50.3**
Graphite	0.0296	3.7
Copper (current collector)	0.346	43.2
Separator	**0.017**	**2.12**
Electrolyte	**0.048 +**	**5.99 +**
Single cell	**0.638**	**79.7**
Battery pack	**0.162 +**	**20.3 +**
Total	**0.801**	**100**

For other battery technologies, no LCAs seem to be conducted. However, based on the results of Notter et al. it might be concluded that also for other battery types the current collector at the anode is of importance. Therefore, metallic lithium batteries may have an advantage if the lithium metal anode is also used as current collector itself (as suggested in the ARPA-E report [ARPA-E, 2009]). Furthermore, zinc and sulfur are regarded as being non-toxic [ReVolt, 2009; Cairns, 2009; Zhang et al., 2009]. Their influence on the environmental impact of the battery will depend on the extraction and production process of these materials.
An interesting advantage of zinc-air batteries is stated by Tahil [2007a] to be the need to remove CO_2 from inlet ambient air to prevent precipitation of carbonate in the cathode. In this way CO_2 is removed from the atmosphere and CO_2 levels could be reduced. This does also apply to lithium-air battery systems [Green Car Congress, 2009b]. However, it is unclear what the effective CO_2 reduction will be.

Energy consumption
In supporting information to the paper of Notter et al. the results from the LCA are split into the three Eco-indicator damage categories [Notter et al., 2010b]. This shows that fossil fuel demand has a share of 22% in the environmental impact. In table 4.14 an overview is given of the non-renewable cumulated energy demand for the most important components. The highest energy demand is required for the production of the electrode materials (incl. current collectors) out of raw materials, drying of electrodes and for production of electronic components of the battery management system. The extraction of raw materials demands low or moderate energy consumption.

Earlier in this section, it was already stated that recycling would result in increased material availability and reduced environmental impact of the battery. Concerning the latter, recycling could also result in reduced energy consumption. Table 4.15 shows for a number of materials if they are being recycled nowadays and how recycling does affect the gross energy requirement for these materials. Comparison of tables 4.14 and 4.15 shows that recycling of aluminum is very important to limit the energy consumption of battery production. Also, the energy requirement of copper, cobalt and zinc is reduced significantly by recycling. This is confirmed by Dewulf et al. [2010], who show that using recovered cobalt and nickel for Li-ion batteries results in a 45% reduced consumption of fossil resources.

Table 4.14: Environmental burden of the production of 1 kg Li-ion battery; non-renewable cumulated energy demand (CED) [Notter et al., 2010b]

1 kg Li-ion, 114 Wh/kg	Cumulated energy demand (CED, MJ-equivalents)	Percentage (%)
Cathode	**31.4**	**30.1**
$LiMnO_4$	13	12.5
Extraction raw material MnO_3	5.41	5.2
Extraction raw material Li_2CO_3	1.85	1.88
Aluminum (current collector)	16.8	16.1
Anode	**19.6**	**18.8**
Graphite	10.6	10.2
Copper (current collector)	5.24	5.03
Electrolyte	**11.08**	**10.64**
Extraction raw materials PCl_5 and LiF	2.03	2.05
Separator	**4.69**	**4.51**
BMS – printed wiring board	**13.7**	**13.1**
Single cell	**76.5**	**73.5**
Battery pack	**27.6**	**26.5**
Total	**104**	**100**

Table 4.15: Gross Energy Requirement, recycling and energy savings through recycling for battery raw materials.

	GER extraction (MJ/kg) [(1)]	Energy savings through recycling [(3)]	Recycling? [(2)]	GER incl. present recycling level (MJ/kg)	GER 100% recycling (MJ/kg)
aluminum	211	92-97%	35%	139-143	6-17
lithium			Insignificant, but increasing through the recycling of lithium batteries		
copper	33-64	84-88%	35%	23-45	4-10
cobalt			24%		
sulfur			no		
manganese			Incidentally		
nickel	114-194	90%	42%	70-121	11-19
sodium chloride			no		
silicon			Insignificant		
zinc	36-48	60-72%	54%	22-32	10-19

[(1)] [Norgate et al., 2007]; [(2)] U.S. 2009 statistics [USGS, 2010b]; [(3)] [Powell, 1983; British Metals Recycling Association (BMRA), n.d.]

Other materials like sulfur, manganese and silicon are not recycled yet. The present level of recycling of lithium is low, but increases through the recycling of lithium batteries [USGS, 2010b]. Unfortunately, it is not known what the Gross Energy Requirement of these materials is, and how it can be reduced by recycling. Furthermore, the results from Notter et al. [2010b] show that raw material production is not the most energy consuming part in present Li-ion battery production. Processes to produce electrodes and current collectors out of raw materials are more energy consuming. An important reason is the need to assemble the battery in a water free environment. Therefore, drying of the electrodes is needed, but requires a lot of energy [E. Kelder, personal

communication, July 7, 2010]. In non lithium based batteries, which do not contain materials that react aggressively with water, drying may not be needed. However, no information is found on this.

Finally, also the method of materials recovery does have impact on the amount of energy savings. Presently, valuable metals like nickel and cobalt are recovered by a smelting process. This takes place at high temperatures, and not all materials contained in the input are recovered for reuse in batteries [Gaines and Nelson, 2010]. Another method to recover battery-grade materials, however, is the use of various physical and chemical separation processes. In this way, all active materials can be recovered and made suitable for reuse in batteries [Gaines and Nelson, 2010]. Also, this process does require little energy. Thus, most of the energy needed to produce battery grade materials from raw materials is saved. However, this technique has been demonstrated but is not applied on large scale yet [Gaines and Nelson, 2010].

5. Part three: Data input driving cycle simulation

Battery performance and cost parameters

Tables 5.1 and 5.2 give an overview of the battery performance and cost parameters that will be used in the driving cycle simulation and the related sensitivity analysis. With regard to future Li-ion and ZEBRA batteries, the parameter values are chosen to represent projections for the medium term (around 2025). The values for the sensitivity analysis are related to short term (2015) and long term (from 2030) projections. Besides, they can be seen as more progressive and conservative projections for the medium term. However, note that not for all parameters a projection in time is available. Here, average values from chapter 4 are used. Higher and lower values found are used in the sensitivity analysis.

Concerning Li-S and metal-air batteries, the projections found for performance and cost parameters were principally not related to a specific point in time. The figures found for the performance are assumed to be applicable to batteries in the first stages of commercialization (medium term for Li-S and Zn-air, medium/long term for Li-air). The sensitivity range shows the uncertainty here. The costs are a longer term projection; like costs of Li-ion batteries, costs will be very high at the start of commercialization and will decline as a function of cumulative production levels. However, this is not predictable. The chosen range depicts what could be achievable at mass commercialization.

Table 5.1: Base case battery performance of Li-ion and ZEBRA batteries (based on sections 3.1.2 and 3.1.4)

	Specific energy (Wh/kg)	Specific power (W/kg)	Charge/ discharge Efficiency (%)	DoD (%)	Cost ($2010/kWh)	Cycle life	Life time (yr)
Li-ion	110	400	90	80	1000	1,000	8
ZEBRA	115	180	90	80	630	1,000	15

Table 5.2: Future battery performance of five battery technologies, at pack level (based on sections 4.1 to 4.6). Between brackets: bandwidth for sensitivity analysis. Shaded cells: values were assumed, as no projections were found on these performance characteristics.

	Specific energy (Wh/kg)	Specific power (W/kg)	Charge/ discharge Efficiency (%)	DoD (%)	Cost ($2010 /kWh)	Cycle life (# cycles)	Life time (yr)
Li-ion	200 (150-250)	500 (400-600)	92 (90-95)	80 (70-90)	300 (250-350)	2,000 (1,000-3,000)	10 (7-15)
ZEBRA	160 (130-200)	280 (250-320)	90 (90-95)	80 (70-90)	250 (100-350)	1,000 (1,000-1,500)	15
Li-S	400 (300-500)	300 (200-400)	80 (70-90)	100 (90)	375 (250-500)	1,000 (500-1,000)	7 (5-10)
Zn-air	250 (150- 350)	300	70 (65-80)	80 (70-90)	225 (100-350)	2,000 (1,000-3,000)	7 (5-10)
Li-air	500 (500-1,000)	300	70 (60-85)	80 (70-90)	500 (300-700)	1,000 (500-1,000)	7 (5-10)

Other parameters

In tables 5.3 to 5.5 all other parameters used in the driving cycle simulation are given. Table 5.3 gives the parameters that are not depended of the car used, table 5.4 shows all non-battery related parameters related to the reference car chosen. Finally, table 5.5 gives the parameters related to electricity supply.

Table 5.3: Car independent parameters

parameter	unit	value
g	m/s2	9.81
ρ, air density	kg/m3	1.2

Table 5.4: Reference car parameters

parameter	unit	value	source
coefficient of rolling resistance		0.01	Van Vliet, 2010
aerodynamic drag coefficient		0.32	Van Vliet, 2010
frontal area	m2	2.10	Van Vliet, 2010
delta (inertia)		1	Campanari et al., 2009
weight (excl battery)	kg	1120	Van Vliet, 2010
overweight (% of battery weight)		0.15	Campanari et al., 2009
efficiency motor		0.92	Campanari et al., 2009
efficiency controller		0.97	Campanari et al., 2009
efficiency transmission		0.98	Campanari et al., 2010
Power auxiliary	W	400	Ogden et al., 1999
annual driving distance	km	14,000	Van Vliet, 2010
discount rate	%	10	Van Vliet, 2010
vehicle lifetime (depreciation period)	year	10	Van Vliet, 2010
capital recovery factor	/year	0.199	
cost platform	$2010	20,717	Van Vliet, 2010
cost drivetrain	$2010	5,894	Van Vliet, 2010
Cost maintenance, repair and tires	$2010/km	0.057	Van Vliet, 2010

Table 5.5: Electricity supply parameters

parameter	unit	value	source
energy eff. extraction and transport raw materials		0.95	Campanari et al., 2010
energy eff. production		0.43	Campanari et al., 2010
energy eff. distribution EU average		0.928	Van Vliet, 2010
energy efficiency charger		0.9	Campanari et al., 2010
WTT emission factor electricity UCTE European Electricity mix	gCO_2eq/kWh	593	Gauch et al., 2009
	gCO_2eq/Wh	0.593	
Electricity price	$/kWh	0.110	Van Vliet, 2010: 83 Euro/MWh (NL)
	$/Wh	1.1E-04	

6. Part three: Results driving cycle simulation

The results are presented in four sections. First of all, battery weight and cost are discussed. This is followed by the energetic performance of the car and the related emissions. Finally, the total driving costs are shown. All these values are calculated for driving ranges of 100, 200, 300, 400, 500 and 600 km. In the different sections it will be discussed how these ranges influence the results for each simulated battery technology.

6.1 Battery

In figure 6.1 it is showed what weight is required for each battery technology to deliver the required power and energy at the simulated driving ranges. With increasing range, the results do diverge more and more. At 100 km, Li-ion and future ZEBRA batteries do have the lowest weight. However, from 200 km, the weight of present Li-ion and ZEBRA batteries is clearly higher compared to all future batteries. Also, from 300 km, the weight of future Li-ion, ZEBRA and zinc-air batteries diverges from the low weight lithium-sulfur and lithium-air batteries. For the latter two batteries, the weight remains constant until a range of 400 km and only increases relatively slow at higher ranges. The constant weight is caused by the fact that the specific power is decisive over the specific energy. At low ranges, this phenomenon does to a lesser extend also affect the results of the other batteries (except present Li-ion). This will be further discussed in the next chapter. The Li-S battery weight is lower compared to the Li-air battery, because of its higher charge/discharge efficiency and (when the specific energy is decisive) its higher depth of discharge.

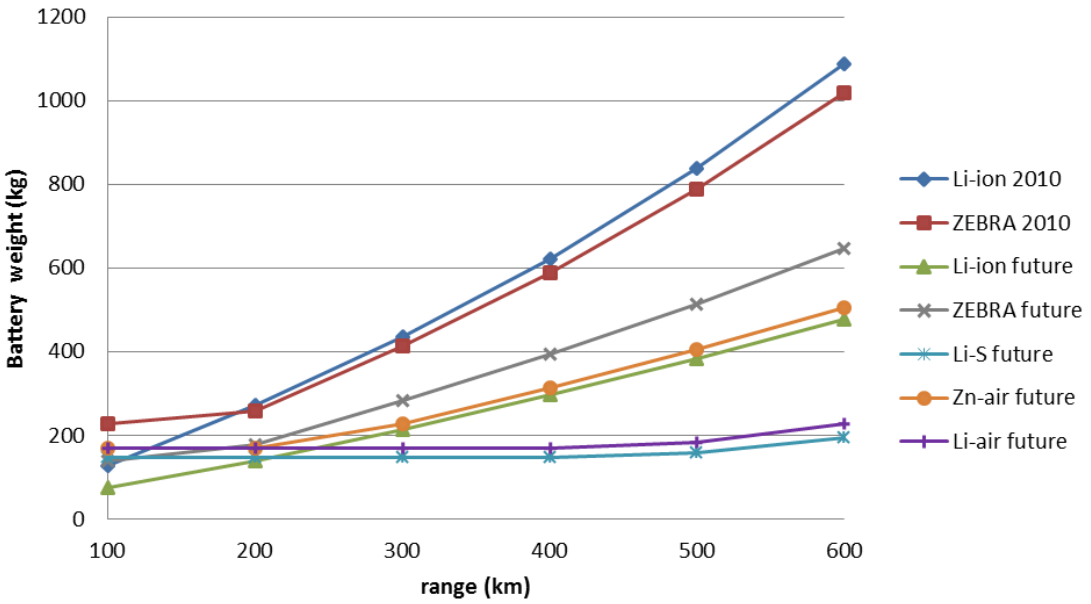


Figure 6.1: Battery weight as a function of the driving range

In figure 6.2 the battery costs are showed. Compared to figure 6.1, very different results are found. Although the li-air battery had a very low weight at higher ranges compared to other batteries, its high costs per kilowatt-hour make this battery very expensive compared to all other future bateries. Only the costs of present Li-ion and ZEBRA batteries do exceed Li-air costs from approximately 300

and 400 km respectively. The costs of future Li-ion, ZEBRA and zinc-air batteries are relatively comparable. Also, future ZEBRA batteries do have the lowest costs at ranges of 200 km and higher. At 100 km future Li-ion battery costs are about 1,100 US$ lower compared to ZEBRA costs.
Finally, Li-S batteries have relatively high costs at lower ranges, but converge to future Li-ion and Zn-air batteries at 500 and 600 km.

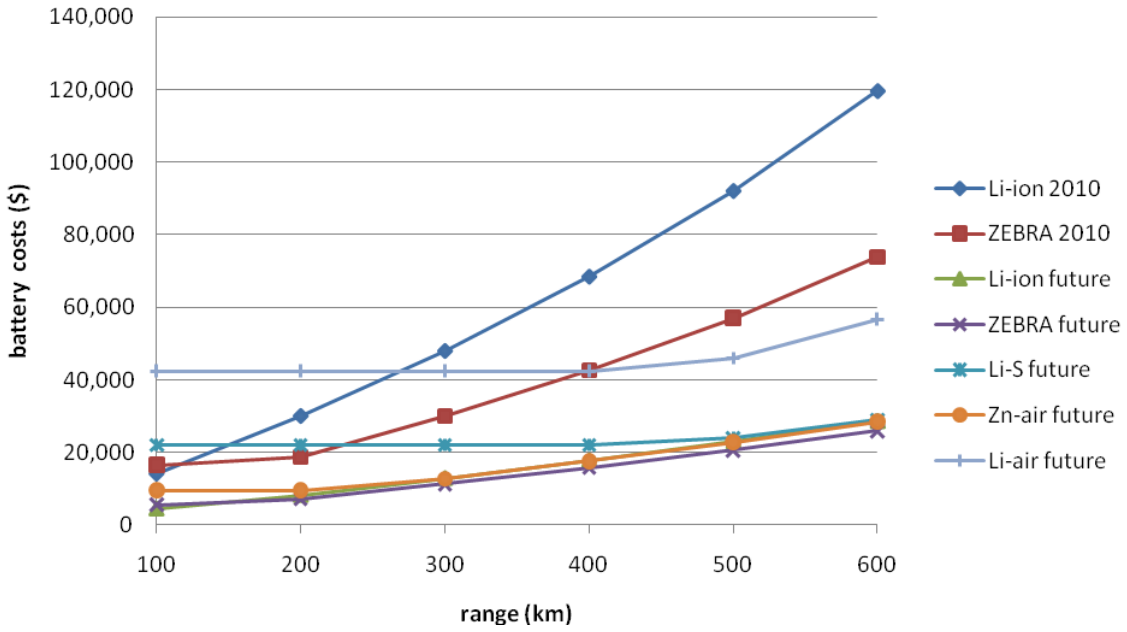


Figure 6.2: Battery cost as a function of the driving range

6.2 Energetic performance

Figure 6.3 shows the amount of energy supplied by the battery to the drive train. As the energy consumption of the drive train is directly related to the total mass of the car it is also closely related to the battery weight. Therefore, it is not surprising that figure 6.3 shows large resemblance with figure 6.1. Again, the results at 100 km are relatively close to each other, but diverge at higher ranges. Above 200 km, Li-air and Li-S batteries show the lowest energy supply. The use of present Li-ion and ZEBRA batteries results in significant higher energy consumption values. The energetic performance of BEVs with future ZEBRA, Li-ion and zinc-air batteries is in between those two extremes.

Figure 6.4 shows the WTW energy consumption of the battery electric car. In fact, the values are a result of multiplying the energy supplied by a factor that is directly defined by the battery efficiency, and the efficiencies in the electricity supply chain. The latter efficiencies are equal for all batteries. Yet, the low energy efficiency of metal-air (and to a lesser extend Li-S) batteries negatively affects the WTW energy consumption. Thus, the low battery to wheel energy consumption (energy supplied by battery) is largely counterbalanced by the low efficiency. As a result, the WTW energy consumption is highest at all ranges for the zinc-air battery, followed by the Li-air battery. Only at 500 km or more, the use of (high weight) present Li-ion and ZEBRA batteries results in a higher energy consumption compared to the Li-air battery.
Because of their high efficiency, future Li-ion and ZEBRA batteries mainly have the lowest impact on the WTW energy consumption of the electric car. Only after more than 400 km the Li-S battery

passes the future ZEBRA battery and closely approaches the future Li-ion battery at 600 km. However, note that energy needed to heat the ZEBRA battery (when not in operation) is not included. At the present temperature of 300 °C the WTW energy consumption would increase with 2,640 Wh/km. At 100 °C the additional energy use would reduce to 760 Wh/km, but this is still considerable higher than the consumption levels in figure 6.4.

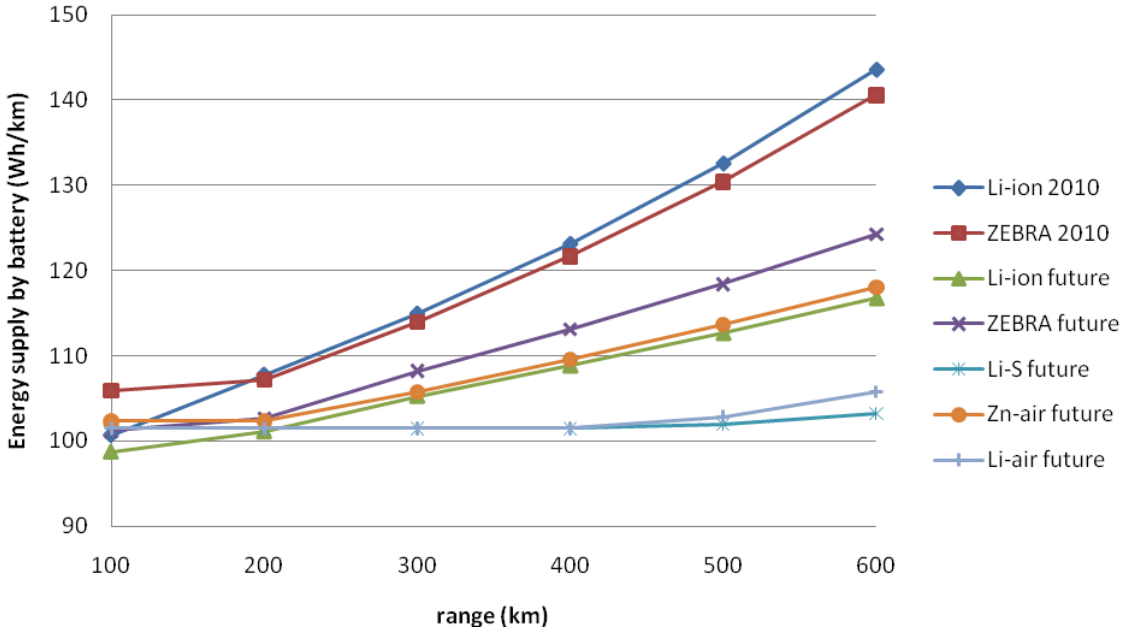


Figure 6.3: Energy consumption of the drive train (energy delivered by the battery) as a function of the driving range

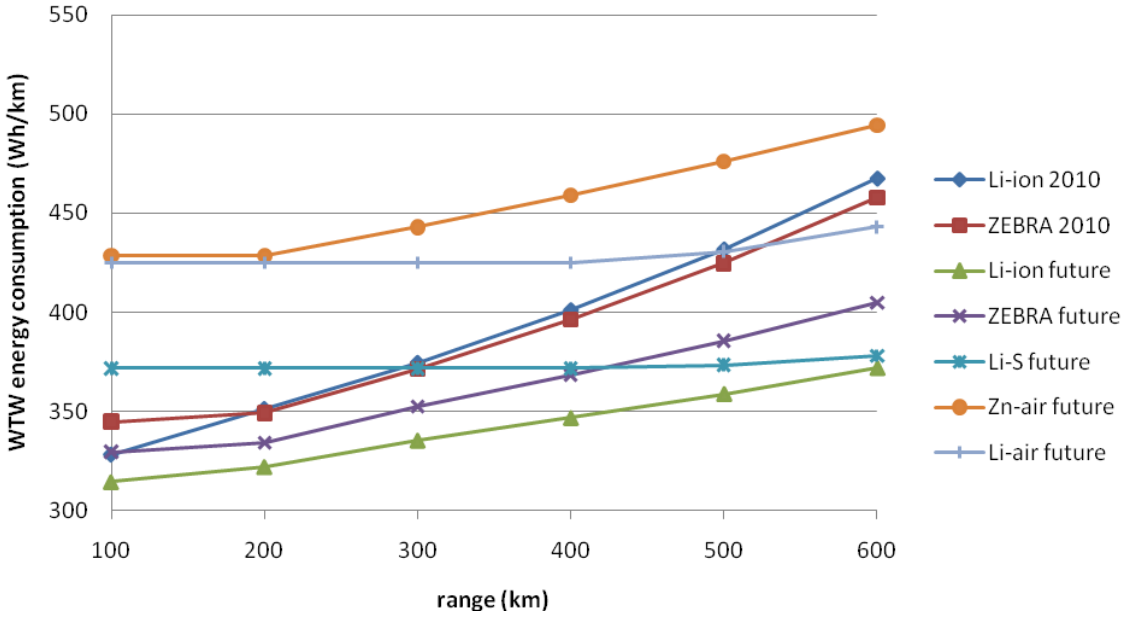


Figure 6.4: WTW energy consumption of battery electric car as a function of the driving range. Energy consumption for heating of the ZEBRA batteries (when not in operation) is not included.

6.3 Emissions

In figure 6.5 the direct CO_2 emissions of the battery electric car are showed. Here, the results do correspond to the outcomes of the WTW energy consumption. Because of their efficiency, future Li-ion and ZEBRA batteries are favorable at most ranges. Only after more than 400 km, the Li-S battery it favored over the future ZEBRA battery. The use of low-efficiency metal-air batteries does result in high emissions. Also, present Li-ion and ZEBRA batteries are only an option at low driving ranges. This is because of the impact of their high weight on the car's energy consumption and thus emissions.

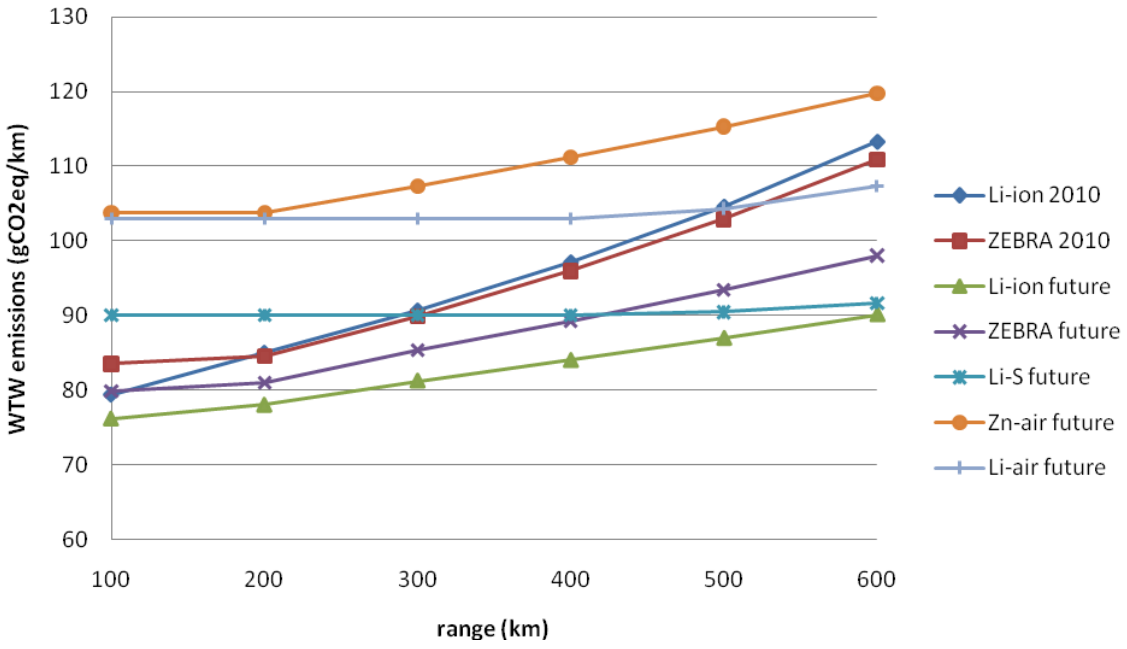


Figure 6.5: WTW emissions of the battery electric car as a function of the driving range. Energy consumption for heating of the ZEBRA batteries (when not in operation) is not included.

6.4 Total driving cost

In figure 6.6 the total driving costs of the battery electric car are showed. In the calculation are included the battery cost and lifetime, the electricity price, costs for maintenance, repair and tires (MRT) and the cost and depreciation period of the vehicle's platform and drive train. The costs for MRT and the vehicle's platform and drivetrain are equal for all simulated BEVs. Therefore, the differences in driving costs are a result of the variance in battery cost and lifetime and the electricity consumption of the car.

The total driving costs related to present Li-ion and ZEBRA batteries are negatively affected by both the high battery costs and high energy consumption (due to high battery weight). However, for future Li-ion and ZEBRA batteries, the energy consumption and battery costs are reduced significantly. As a result, the related total driving costs are the lowest amongst all simulated batteries. The total driving costs of ZEBRA batteries are below those of Li-ion batteries because of their longer life time.

The high energy consumption of the BEVs with metal-air batteries does negatively affect the results. However, the low cost of zinc-air batteries counteracts this. Therefore, the total driving costs for Zn-air batteries are significantly lower compare to Li-air batteries. Lithium-sulfur batteries have relatively high driving costs at low ranges, but closely approach zinc-air batteries at high ranges.

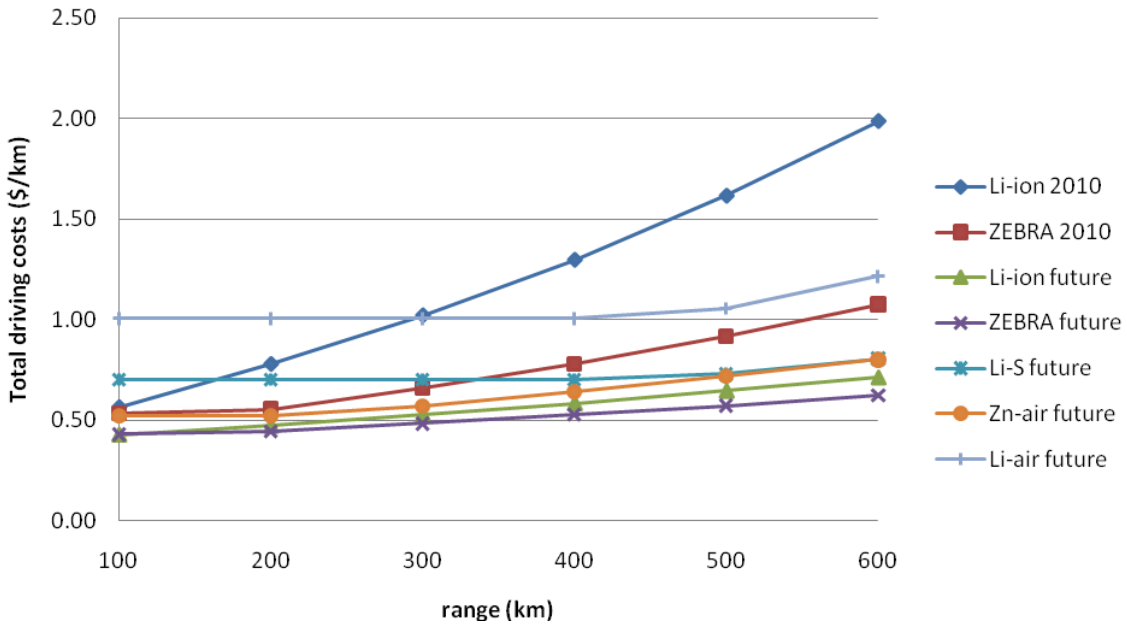


Figure 6.6: Total driving costs of the battery electric car, considering a number of present and future battery technologies

6.5 Cycle life

The impact of the cycle life was not included in the driving cycle simulation. However, it is important that the cycle life is high enough to ensure that the battery can operate satisfactory during its total lifetime. The annual driving distance of the simulated BEV is assumed to be 14,000 km [Van Vliet, 2010]. In table 6.1 the cycle life and lifetime of each simulated battery it is given. Based on these numbers and the annual driving distance, it is calculated what the minimum range between two full charges should be.

Table 6.1: cycle life and lifetime of the simulated batteries, and the minimum range required between two full charges

	cycle life (# discharge/charge cycles)	life time (year)	Minimum range (km)
Li-ion 2010	1000	8	112
ZEBRA 2010 & future	1000	15	210
Li-ion future	2000	10	70
Li-S	1000	7	98
Zn-air	2000	7	49
Li-air	1000	7	98

ZEBRA batteries have a very high lifetime, but no higher cycle life compared to other batteries. Therefore, the driving range of a ZEBRA based BEV should be more than 200 km. For future Li-ion batteries, the minimum range is lower compared to present ones, because the cycle life is expected to increase at a higher rate than the lifetime. For Li-S and metal-air batteries, the lifetime is assumed to be relatively short. Hence, a low driving range of 100 km would already be satisfactory. When the actual range is higher than the minimum range, satisfactory operation of the battery will be limited by its lifetime and not by the cycle life.

7. Sensitivity analysis

7.1 Specific power

The results of the driving cycle simulation showed that for a range up to 400 km the battery size of Li-air and Li-S batteries (and up to lower ranges also of the other batteries) is constant. This is caused by the fact that the battery's weight was not defined by the specific energy, but by its specific power (the weight required to deliver the energy needed for a certain range was lower than the weight required to deliver the required maximum power). As the maximum power required does not depend on the range of the car, the size of the battery does not change as long as the specific power is decisive over the specific energy. In other words, the battery is over-dimensioned to be able to deliver the required power; the range of the car is larger than suggested by the graphs in chapter 6. Table 7.1 shows until which range the specific power is decisive for each battery. For future Li-ion , ZEBRA and Li-S batteries, the same table also shows how this range changes with the specific power level.
For Li-ion and ZEBRA batteries, the range until which the specific power is decisive is relatively low. Also when the specific power is lowered, this range does not exceed 183 km: present BEVs have ranges of about 160 km. Therefore, over-dimensioning has not to be considered a main problem. However, for Li-S and metal-air batteries this is not the case. For these batteries, figures 7.1 to 7.3 show what levels of specific power are required at certain ranges to make the specific energy decisive in defining the battery's weight.

Table 7.1: Range up to which the specific power is decisive over the specific energy of the battery in defining the battery's weight.

Battery	Li-ion 2010	ZEBRA 2010	Li-ion future		ZEBRA future		Li-S		Zn-air	Li-air
Range (km)	77	179		111		159		464	232	464
Sensitivity range specific power (W/kg)	-	-	400 (80%)	600 (120%)	250 (89%)	320 (114%)	200 (67%)	400 (133%)	-	-
Impact on range (km)	-	-	139 (125%)	93 (83%)	183 (115%)	143 (89%)	699 (150%)	348 (75%)	-	-

The impact on the weight of the batteries is substantial, especially for metal-air batteries. Figures 7.1 and 7.3 show that the battery weight of Li-S and Li-air batteries will be significantly lower compared to future Li-ion batteries. The latter does not account for zinc-air batteries. This is because their relatively low specific energy compared to Li-S and Li-air batteries (250 Wh/kg vs. 400 and 500 Wh/kg) and their low cycle efficiency.
On the other hand, the specific power required is high. It is uncertain what levels can ultimately be attained by Li-S and metal-air batteries. Of all batteries simulated, only present or future Li-ion batteries can achieve power levels of 400 W/kg or more. Therefore, it is very unrealistic that specific power levels of 695 W/kg or more can be attained by Li-S and metal-air batteries. Thus, these batteries may only be interesting for use in BEVs with driving ranges of a few hundred kilometers.

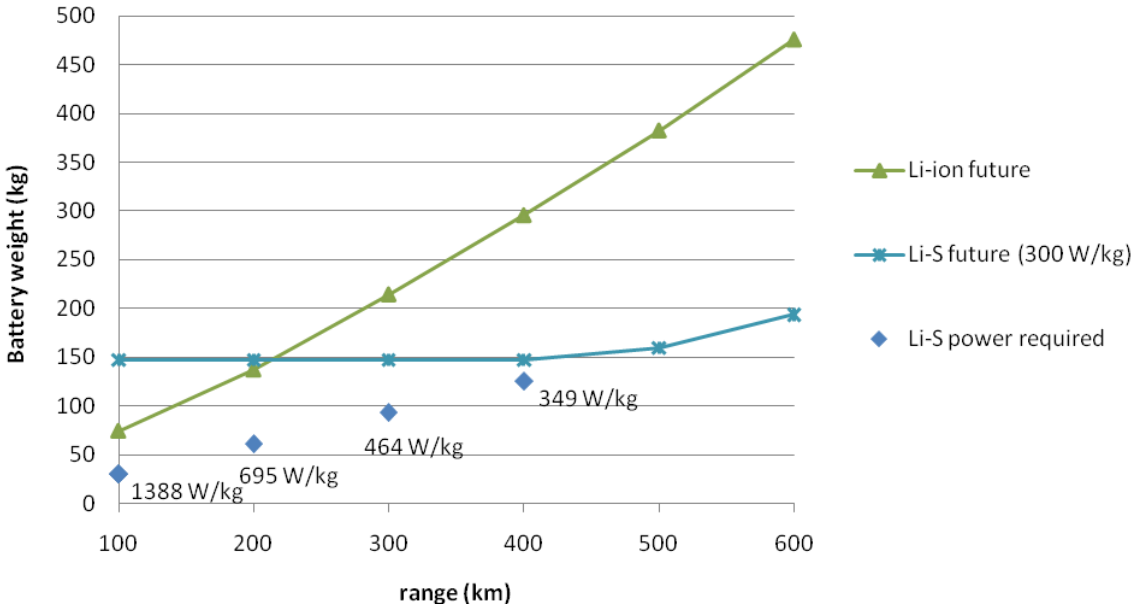


Figure 7.1: Specific power levels that should be attained for a Li-S battery to make the specific energy decisive in defining the battery's weight and impact of the specific power on the battery weight

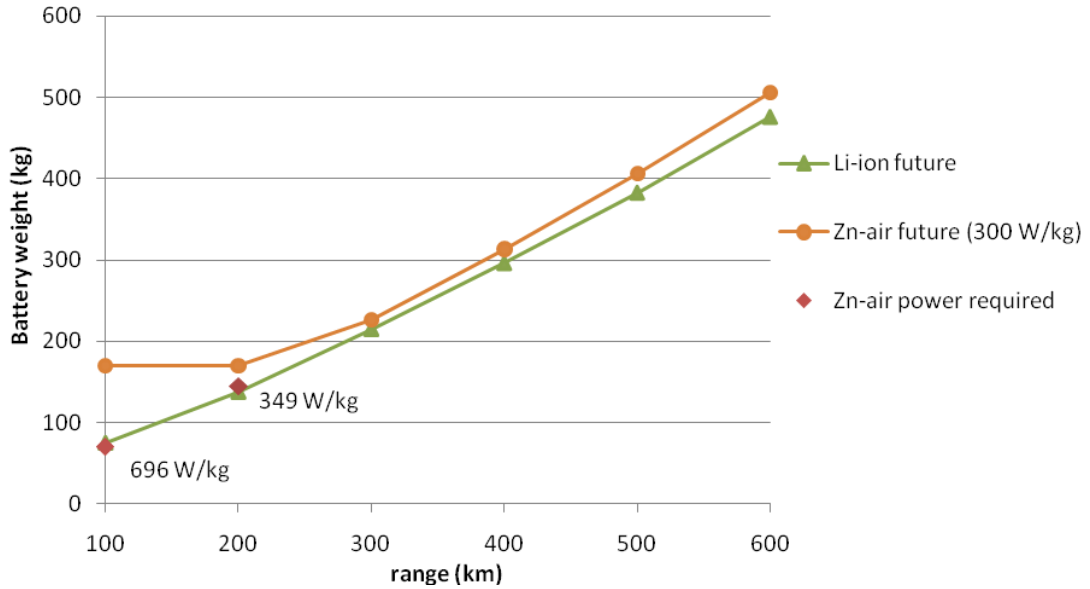


Figure 7.2: Specific power levels that should be attained for a Zn-air battery to make the specific energy decisive in defining the battery's weight and impact of the specific power on the battery weight

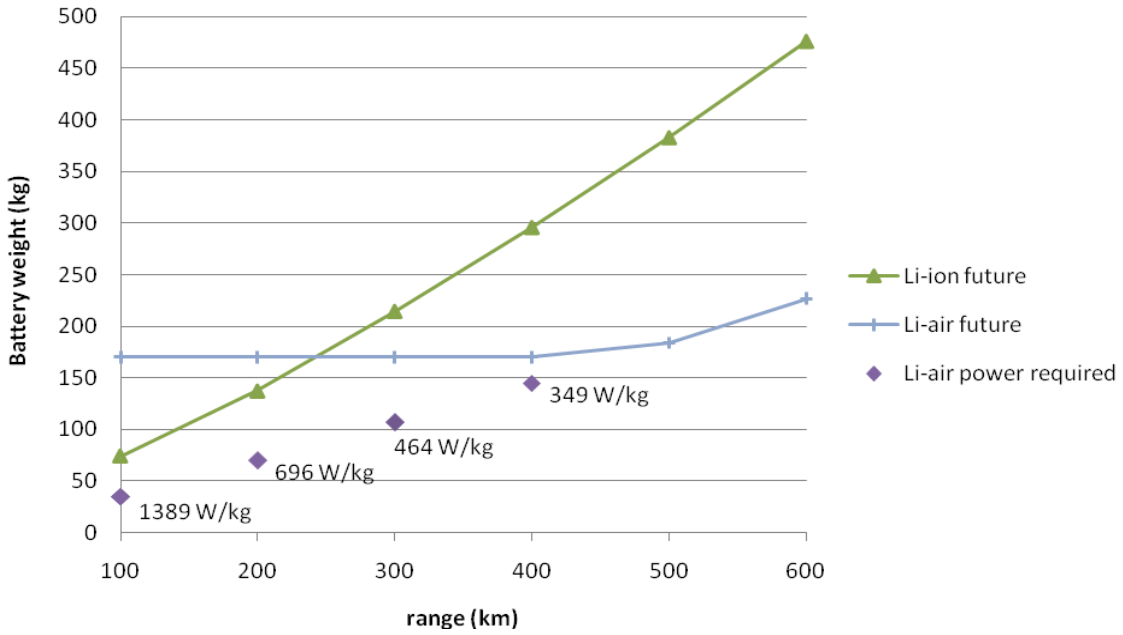


Figure 7.3: Specific power levels that should be attained for a Li-air battery to make the specific energy decisive in defining the battery's weight and impact of the specific power on the battery weight

Furthermore, figures 7.4 to 7.7 show that the availability of the required specific power levels do positively affect battery costs, WTW energy consumption, emissions and total driving costs of the car. However, it is also seen that future Li-ion batteries still show better results for most parameters. With regard to battery costs, Zn-air costs do just fall below Li-ion costs. Also, Li-S costs do approach Li-ion battery costs closely. However, because of their lower efficiency, the difference for the WTW energy consumption and the direct emissions is larger again. Only the results for Li-S batteries do converge to the Li-ion results at high ranges.

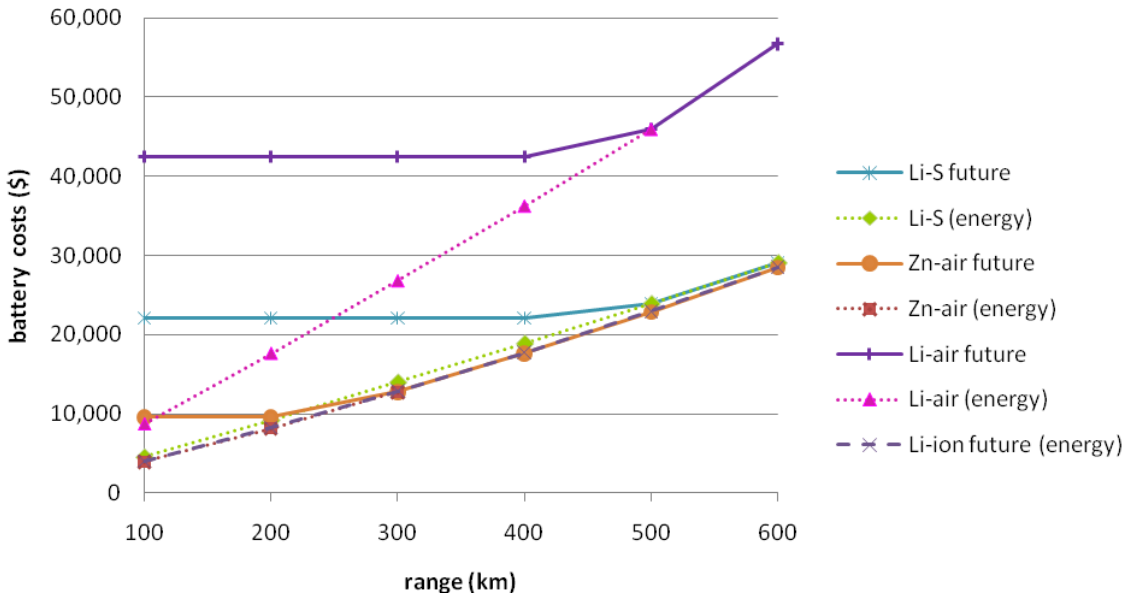


Figure 7.4: Impact on the battery weight if the specific power is high enough to make the specific energy decisive in defining the battery's weight

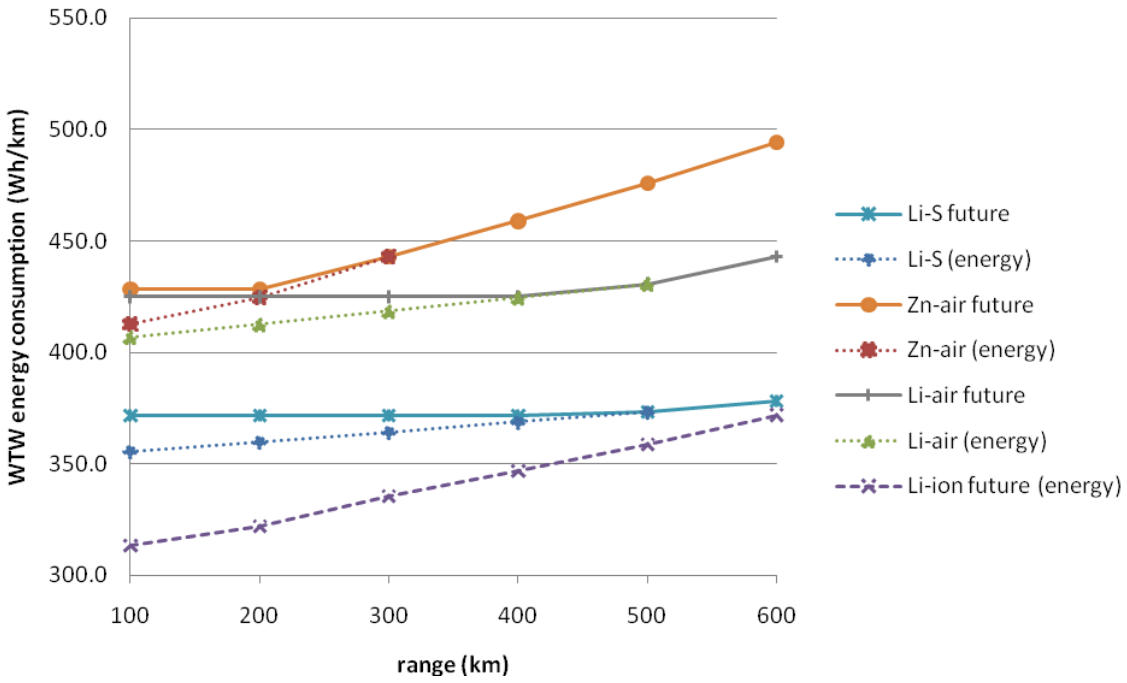


Figure 7.5: Impact on the WWT energy consumption if the specific power is high enough to make the specific energy decisive in defining the battery's weight impact

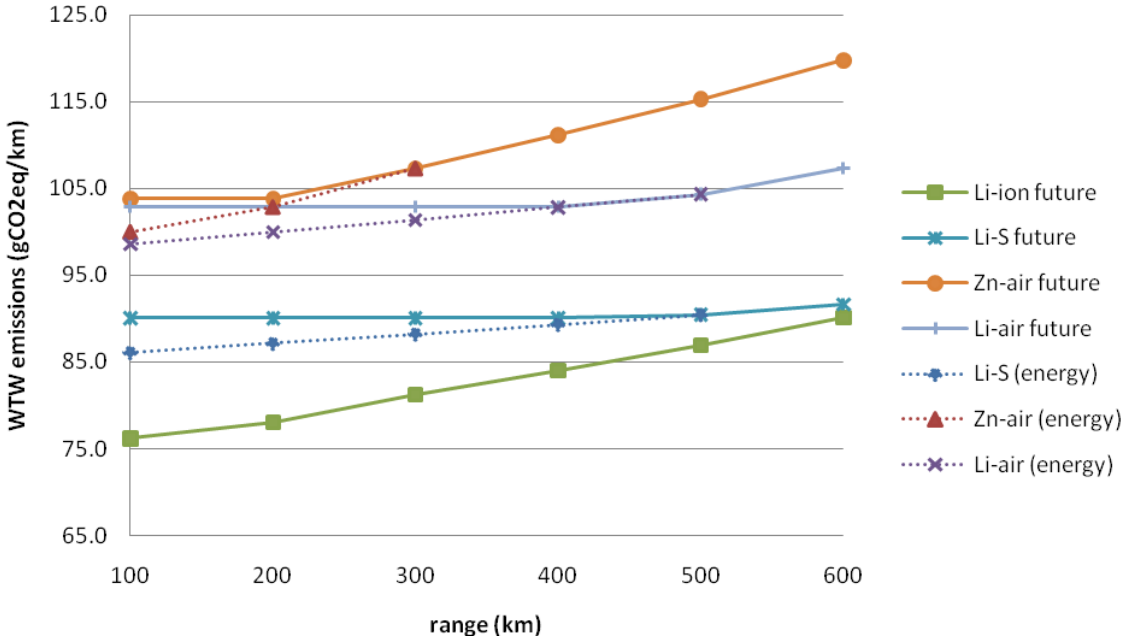


Figure 7.6: Impact on the WWT emissions if the specific power is high enough to make the specific energy decisive in defining the battery's weight impact

Although the energy consumption for Zn-air batteries is considerably higher compared to future Li-ion batteries, the difference in total driving costs is much less significant. But, the driving costs diverge at higher ranges. This is also true for Li-S batteries. Finally, because of both considerable higher battery costs and higher energy consumption, the use of Li-air batteries results in significant higher driving costs.

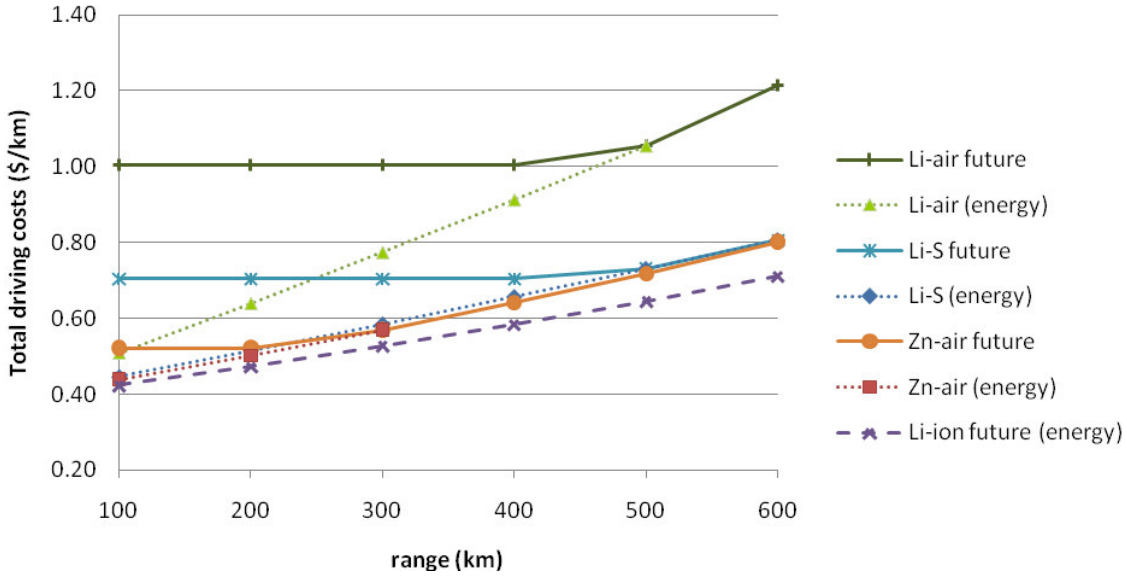


Figure 7.7: Impact on the total driving costs if the specific power is high enough to make the specific energy decisive in defining the battery's weight impact

7.2 Cycle life

In figure 7.8 it is shown how the cycle life and lifetime of the battery affect the minimum range that is required to limit satisfactory operation of the battery by its lifetime and not by the cycle life. For Li-S and Li-air batteries, it is uncertain if high cycle lives can be reached. However, their lifetime is

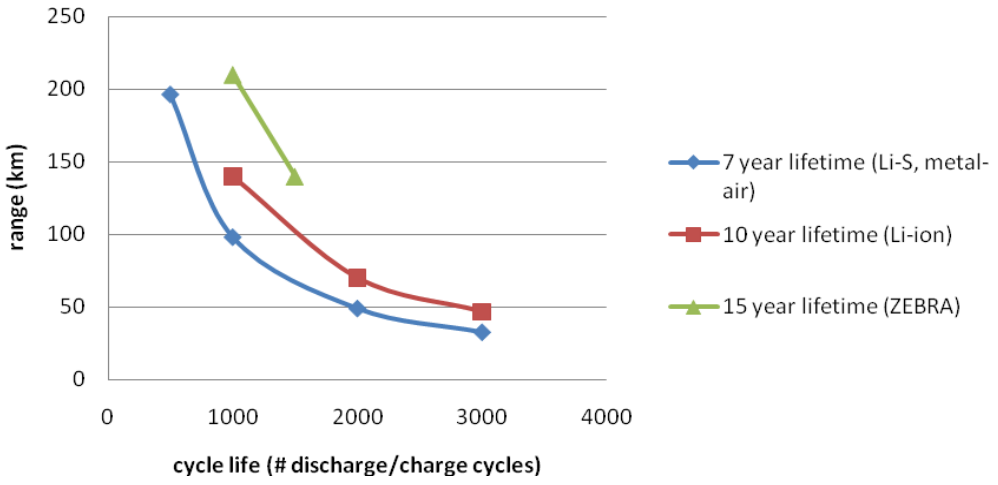


Figure 7.8: Minimum range required between two full charges as function of cycle life and lifetime.

expected to be relative short. Therefore, a low cycle life does not have to be a big problem. Even at 500 cycles, only a minimum range of 196 km is needed between two complete charges. Zn-air batteries were projected to have a comparable lifetime, but a higher cycle life. Thus, the cycle life of these batteries is not expected to limit the operational lifetime of the battery.
The ZEBRA battery has a very high lifetime. Therefore, a high cycle life is essential to reduce the minimum range. Li-ion batteries have a lifetime of 10 years and projected cycle lives of 1000 cycles or more. As a result, it is not expected that their cycle life will affect the operational lifetime of the battery.

7.3 Other variables

For all five future batteries, a sensitivity analysis was conducted to assess the impact of the specific energy, depth of discharge, efficiency, battery costs ($/kWh) and lifetime on battery weight, energy supplied, WTW energy consumption, emissions, battery costs ($) and total driving costs. To minimize the chance of the specific power being decisive over the specific energy, the sensitivity analysis was carried out at a driving range of 600 km. Only at the higher specific energy value of the Li-air battery, this phenomenon still took place.
For all the batteries simulated, the same dependencies between in- and output parameters existed. Therefore, the collective outcomes of the sensitivity analysis are discussed first. Subsequently, it is discussed if and how the variation of the input parameters does affect the results from chapter 6.

7.3.1 Collective outcomes

As an example for the collective outcomes, table 7.2 shows the outcomes of the sensitivity analysis for zinc-air batteries. Tables for all future battery technologies can be found in appendix V.
Because of their direct relation, a change in the specific energy has large impact on the battery's weight. As the energy consumption of the drive train does not only depend on the battery weight, the impact on the energy consumption and emissions of the car is less significant. Also, the cost of the battery is not considerably affected compared to the battery weight. This can be explained by the fact that the battery cost depends on its storage capacity, which is related to the energy supplied to the drive train. As the battery cost is only one component of the total driving costs, these do even chance to a smaller degree.
Also the efficiency and depth of discharge of the battery do influence the battery's weight considerably. Besides, these parameters do define what share of the total battery storage capacity is actually used effectively. Therefore, the efficiency and depth of discharge do affect the storage capacity, and thus the battery cost, significantly. The energy supplied by the battery to the drive train is affected less significant. But, the efficiency of the battery does have a direct effect on the TTW and WTT energy consumption and WTW emissions of the car. The impact of the depth of discharge on the energy consumption and emissions of the car is smaller.
The specific battery costs ($/kWh) do directly affect the total battery cost. The total driving costs are not only dependent on the battery cost. However, the significant change of the total battery cost does also have considerable impact on the total driving costs.
Finally, the lifetime of the battery does directly affect the annual depreciation cost of the battery. As the total driving costs are not only defined by the depreciation cost of the battery, the impact of the battery's lifetime on the total costs is weakened. Yet, the total driving costs are clearly affected by an adjustment of the battery's lifetime.

Table 7.2: Sensitivity of simulation model output parameters to changes in Zn-air characteristics (at a range of 600 km)

	Percentage of original value	battery weight	energy supplied	WTW energy consumption	WTW emissions	battery cost	total driving costs
Specific energy	60%	197%	118%	118%	118%	118%	110%
	140%	67%	94%	94%	94%	94%	97%
Depth of Discharge	88%	118%	103%	103%	103%	118%	110%
	113%	87%	97%	97%	97%	87%	93%
Efficiency	93%	110%	102%	110%	110%	110%	105%
	114%	85%	97%	85%	85%	85%	92%
Battery costs ($/kg)	44%					44%	71%
	156%					156%	129%
Lifetime	71%						115%
	143%						89%

7.3.2 Impact on simulation results

Figure 7.9 shows how the adjustment of the batteries' specific energy, depth of discharge and efficiency does affect the WTW energy consumption. Figures for the WTW emissions and total driving costs can be found in appendix V.
The effects on the WTW energy consumption and emissions are similar. In chapter 6, the zinc-air battery had the worst effect on these BEV performance characteristics. Only when its efficiency is improved from 70% to 80%, it can pass the lithium-air battery. The Li-air battery itself can even become the best option when its efficiency is 85% instead of 70%. On the other hand, a lower efficiency can mean that this battery becomes the worst option. The efficiency is also of importance for the Li-S battery. At an efficiency of 90% instead of 80%, it passes the Li-ion battery and will even be a better option than a high efficiency Li-air battery.
For the Li-ion and ZEBRA battery, the efficiencies are already high. Thus, there is less room for improvement. Nevertheless, by an improvement from 90% to 95%, the WTW energy consumption and emissions of a ZEBRA-based BEV could equal the performance of the Li-S battery.

Except for the specific energy of the Zn-air battery, the specific energy and depth of discharge have considerably less effect on the level of WTW energy consumption and emissions. But, note that for the Li-air battery the specific power becomes decisive over the specific energy. Therefore, the significant increase of the specific energy (from 500 to 1000 Wh/kg) has only little impact.

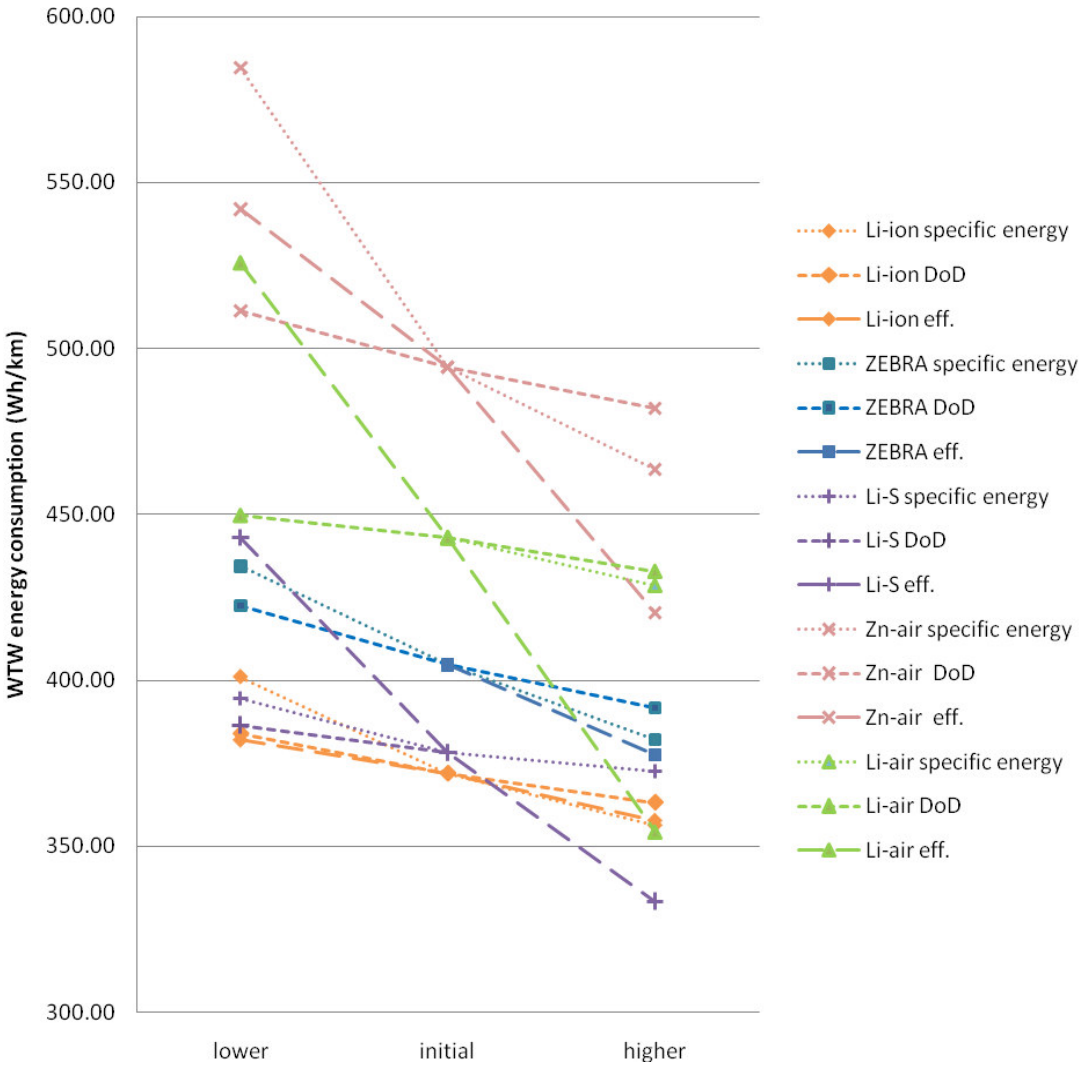


Figure 7.9: Change of WTW energy consumption (at a range of 600 km) due to adaption of the battery's specific energy, depth of discharge or efficiency (to the lower or higher value defined for the sensitivity analysis).

The total driving costs are not only affected by the specific energy, depth of discharge and efficiency of the battery, but also by its costs and lifetime. The battery costs can significantly change the total driving costs. Nevertheless, even when the costs of the Li-air battery are 300 $/kWh instead of 500 $/kWh, the total costs will approach but not pass Zn-air or Li-S batteries (of 225 and 375 $/kWh respectively) . On the other hand, lower costs of Zn-air and Li-S batteries can make these batteries more interesting than Li-ion batteries. At a very low cost of 100 $/kWh, the zinc-air battery could even become the best option with regard to total driving costs. But, if ZEBRA batteries would also achieve 100 $/kWh, their total driving costs could reduce to 0.46 compared to 0.57 $/km for low cost zinc-air batteries.

8. Discussion

8.1 Comparison literature

For the simulation, most parameter values for components other than the battery were taken from Van Vliet [2010]. Therefore, it is interesting to compare the outcomes of the simulation to his findings. Also, data from other sources can be used for comparison (table 8.1).

Table 8.1: TTW and WTW energy consumption and emissions: comparison of results from driving cycle simulation to data from Van Vliet [2010] and Notter et al. [2010a] and of the Nissan Leaf ['elektrische auto Nissan Leaf', 2010]

Vehicle	Range (km)	TTW energy consumption (Wh/km)	WTW energy consumption (Wh/km)	TTW emissions (gCO_2eq/km)	WTW emissions (gCO_2eq/km)	source
Simulation BEV Li-ion 2010	100-300 600	112-128 160	328-374 468	-	79-91 113	
Simulation Best BEV (Li-ion future)	100-300 600	107-114 127	314-335 372	-	76-81 90	
Simulation Worst (Zn-air)	100-300 600	146-151 169	429-443 494	-	104-107 120	
BEV 2010	250 ±34	127 ±35		-	0-166	Van Vliet, 2010
BEV 2015	250 ±34	124 ±32		-	0-163	Van Vliet, 2010
BEV	200	170		-		Notter et al., 2010a
BEV	100-600	200-300	700-1,000		150-210 [3]	Campanari et al., 2009
BEV (Nissan Leaf)	160	150		-		[1]
ICEV (VW Golf, diesel)		492	558 ±111	131	156 ±5	Van Vliet, 2010
ICEV (VW Golf, gasoline)		528	608 ±153	140	163 ±6	Van Vliet, 2010
ICEV (VW Golf, gasoline)		462 [2]		120 [3]	n.a.	Notter et al., 2010a
FCEV		194 ±39	289 ±58	-	0-131 [3]	Van Vliet, 2010

[1] ['elektrische auto Nissan Leaf', 2010]; [2] assuming 32 MJ_{LHV}/liter gasoline; [3] gCO_2/km

For the simulation, the electricity consumption related to the present Li-ion battery is 120-128 Wh/km at 200-300 km. As could be expected, this is comparable to the present BEV from Van Vliet. Compared to the Nissan Leaf ['elektrische auto Nissan Leaf', 2010] and results from Notter et al.

[2010a] and Campanari et al. [2009], the TTW energy consumption from the simulation is lower. However, note that the numbers from Campanari et al. are very high compared to all other sources. The comparison to Van Vliet also shows that the application of future Li-ion batteries (in the medium term) does result in a lower TTW energy consumption compared to present and short term BEVs (with Li-ion battery). The advantage compared to present ICEVs, and also a FCEV to a lesser extent, is even significantly larger. Also the WTW energy consumption is below that of ICEVs, but higher or comparable to the FCEV.
On the other hand, application of a zinc-air battery resulted in considerably higher TTW energy consumption levels, which are higher compared to Van Vliet but still lower compared to the Nissan Leaf, Notter et al. and Campanari et al. The WTW energy consumption related to this battery is comparable to high performance ICEVs.

With regard to emissions the comparison is less straightforward; the results from Van Vliet (table 8.1) show that the WTW emissions of BEVs can have lower WTW emissions compared to ICEVs, but this depends on the electricity mix. Assuming emissions for electricity of 593 gCO_2eq/kWh_e, the WTW emissions will be below ICEVs for all batteries considered.

The driving costs other than for the battery were all taken from Van Vliet (without Value Added Tax (VAT)). Nevertheless, the total driving costs from the simulation are higher compared to Van Vliet for a present Li-ion battery; at a range of 250 km the total costs are 12,557 $/yr and approximately 10,700 respectively (table 8.2). The most important reason is the battery lifetime used, which was assumed to be 8 years in the simulation and 10 years by Van Vliet [2010].

Table 8.2: Total driving cost: comparison of results from driving cycle simulation to data from Van Vliet [2010].

Vehicle	Range (km)	Total driving cost ($/km) [(1)]	Total driving cost, no VAT ($/year) [(1)]	Source
Simulation BEV Li-ion 2010	250	0.90	12,557 [(2)]	
Simulation Best (ZEBRA future)	200-300	0.45-0.49	6,237-6,792 [(2)]	
Simulation Worst (Li-air/Li-ion 2010)	200-300	1.00-1.02	14,069-14,300 [(2)]	
BEV 2010	250 ±34		± 10,700 [(3)]	Van Vliet, 2010
BEV 2015	250 ±34		± 9,600 [(3)]	Van Vliet, 2010
ICEV (VW Golf, diesel)			± 5,300 [(3)]	Van Vliet, 2010
ICEV (VW Golf, gasoline)			± 4,800 [(3)]	Van Vliet, 2010

[(1)] 14,000 km/year [Van Vliet, 2010]; [(2)] based on production costs, no VAT included; [(3)] Based on total cost of ownership, minus 19% VAT, depreciation period of 10 years for all car components (including the battery for BEV) and 10% discount rate [Van Vliet, 2010]

As the lifetime of the car was assumed to be 10 years, the battery has to be replaced during the lifetime of the car. If it is expected that the second battery can be sold at the end of the car's lifetime, and the depreciation period and cost of the battery have not changed, the total yearly driving costs will not change after the replacement of the battery. However, if the depreciation period is set equal to the remaining lifetime of the car, the total costs will increase. Replacement of the present Li-ion

battery and a depreciation period of two years for the second battery, would result in costs of 27,575 $/year in the ninth and tenth year of the car's life (at a range of 250 km).
The same line of reasoning is true for future lithium-sulfur and metal-air batteries, which were assumed to have a lifetime of 7 years. On the other hand, future Li-ion and ZEBRA batteries were projected to have a lifetime of 10 and 15 years respectively, and no battery replacement is needed.

Because of the long lifetime and relatively low cost of the future ZEBRA battery, costs can be reduced most when using this battery. The costs are 1,885 to 19,062 $/year lower at 100 to 600 km compared to current BEV costs. On the other hand, table 8.2 shows that the costs are still projected to be higher than for ICEVs. At a range of 100 km, BEV costs are approximately 700 and 1200 $/year higher compared to costs for diesel and gasoline ICEVs respectively. At 600 km, the divergence increases to about 3,400 and 4,000 $/year. When ZEBRA costs would reduce to 100 $/kWh in the long term, total driving costs could drop to 5600 $/year (at 100-200 km) and closely approach diesel ICEV costs. But, total BEV costs do increase with the driving distance to 6,700 $/year at 600 km.
Finally, Van Vliet did also asses FCEVs. The results for these cars are not directly comparable to the simulation results, as another discount rate was used. However, Van Vliet [2010] shows that future FCEVs will cost 5294 ±369 €/year compared to 4445 and 4214 €/year for present diesel and gasoline cars. This suggests that the future costs of FCEVs and best performing BEVs may be very close.

8.2 Data uncertainty

The simulation input values for the battery parameters were all based on an in depth review of literature and other information sources and the consultation of experts. Nevertheless, the uncertainty of performance and cost projections made is significant. The uncertainty analysis shows that this can have significant impact on the results. There are various reasons for these uncertainties.

First, subsequent reports of the Deutsche Bank [Lache et al., 2009; Lache et al., 2010] and the California Air Resources Board [Kalhammer et al., 2007; ARB, 2009] show that developments are going very fast. However, expectations on how fast these developments will take place do vary considerably. For Li-ion batteries, the largest amount of information was available. Nonetheless, a large deviation of projections on costs and performance was found. One reason is that improvements of different battery characteristics do depend on each other. For example, the specific energy can only be enhanced when safety is guaranteed. Besides, future developments do largely depend on factors like government policies, governmental and private investments and consumer acceptation and demand. Such factors are not predictable.

Secondly, the number and credibility of information sources did fluctuate. More scientific literature was collected for lithium based batteries [Scrosati and Garche, 2010; Fergus, 2010a, 2010b; Howard and Spotnitz, 2007; Zhang et al., 2009; Yang et al., 2009; Kraytsberg and Ein-Eli, 2010] than for ZEBRA [Dustmann, 2004; Lu et al., 2010] and zinc-air batteries [Neburchilov et al., 2010]. However, this literature was useful to define what the most important current research topics are, but did not give much information about future performance and cost expectations. For all batteries, such projections were often based on manufacturer consultations.
For Li-ion batteries, the amount of manufacturers is extensive and projections could be based on information from different sources [Kalhammer et al., 2007, ARB, 2009; BCG, 2010; Lache et al., 2009]. However, for zinc-air, ZEBRA and Li-S batteries references did only lead to only one manufacturer of each technology. Therefore, projections were mainly based on development goals of this company.
Concerning Li-air batteries, various commercial companies do conduct research on this technology but they do give very little information. Statements about the specific energy of Li-air batteries were

found in various sources [Girishkumar in: Green Car Congress, 2010a; Tarascon, 2010; Kumar et al., 2010], but no or only one discussion on other performance characteristics was found [Kraytsberg and Ein-Eli, 2010; Green Car Congress, 2010a].
Besides, data on the performance of batteries was not always focused on BEV purposes. For example, for Li-S and metal-air batteries information was found on recently attained performance levels. However, these levels were mainly achieved during research which was not especially focused on developing batteries for use in BEVs [Sion Power, 2010; Kumar et al., 2010; Kraytsberg and Ein-Eli, 2010].

Finally, very little data was found about learning or experience curves for batteries. Based on information from various sources, different progress ratios were distracted. However, these were not based on historical cost data. Instead, cost projections were used [Kalhammer et al., 2007; Kamath, 2009]. Therefore, it is uncertain to what extent these progress ratios do reflect reality.

9. Conclusions

9.1 Answers to research questions

How do battery chemistries that are currently considered in R&D activities compare on development stage and expectations on battery specifications and which battery technologies can be selected as a promising option in the near, medium and long term?

A large number of battery technologies was found. Research on the development of batteries for BEVs does focus on high specific energy batteries. Existing BEV batteries (Li-ion, ZEBRA) do have a high (theoretical) specific energy compared to other (not suitable) existing technologies like NiMH. Nevertheless, research and development activities do also focus on developing batteries (Li-S, metal-air) with a significantly higher (theoretical) specific energy compared to Li-ion batteries. Besides, various other innovative technologies were found that are currently only considered by a small amount of researchers.

Li-ion batteries were selected as the most important option in the short term. Also, in the medium term and possibly long term they will play an important role in BEVs. Li-ion batteries have good performance levels with regard to cycle life, recharge time and efficiency, but need enhancement of the specific energy, safety and costs. ZEBRA batteries were selected as an option in the near and medium term as they do show advantages over Li-ion with regard to costs, safety and lifetime. On the other hand, both the specific energy and specific power need to be enhanced. For the medium term, lithium-sulfur and zinc-air batteries were selected because of their high specific energy and good cost projections. But, the cycle life of Li-S and the specific power of Zn-air batteries are low. Finally, lithium-air batteries were selected as a very high energy technology. However, these batteries are still in very early stages of development and may only be an option in the long term. Also, the potential performance of these batteries is very uncertain yet. As for Zn-air batteries, the specific power is considered to be a potential barrier.

What pathways can be defined with regard to battery and cost developments of the selected battery technologies?

Li-ion batteries
The specific energy is mainly projected to increase at a rate of about 6% per year; from 110 Wh/kg present to 200 Wh/kg in 2020 and to the practical limit of 250 Wh/kg in 2025. However, these levels will only be possible if safety is guaranteed. The specific power and cycle life are projected to remain at present levels or improve slightly. Fast charging times can reduce to 15 minutes in the near or medium term. Faster recharge may only be economically feasible after 2020 of later. Prospects on lifetime, efficiency and operating temperature are highly uncertain. However, especially lifetime is an important parameter. Projections on cost reductions do vary widely, but on average the costs are expected to decline to a minimum of 250 or 300 $/kWh in 2025/2030.

ZEBRA batteries
Both the specific energy and specific power of ZEBRA batteries should be improved. However, substantial redesign of the cells is needed. At a high improvement rate, the specific energy could reach 200 Wh/kg in 2025. But, it is more likely that the focus will be on improvement of the specific power. Nevertheless, projections on the specific power are highly uncertain. This also counts for fast

recharge times. The operating temperature could be reduced to room temperature after 2020. The safety, lifetime, cycle life and efficiency of ZEBRA batteries do already meet USABC goals. No information was found that present levels will be improved.
At projected production levels, costs can reach 375 $/kWh in the near term. In the medium term, a level of 200 to 275 $/kWh can be attained, depending on the expansion of the production capacity. Producer FZ SoNicK SA states that costs of about 100 $/kWh are achievable; this might be true in the long term, but only if raw material prices are low.

Lithium-sulfur batteries
The improvement of the cycle life of Li-S batteries is a key issue. According to the aims of producer Sion Power, commercialization of batteries with a cycle life of 1000 cycles could start from 2020. The specific energy is estimated to be between 330 and 520 Wh/kg at this time. The specific power level will be relatively low, most probably equal to or below USABC goals. Safety can be an issue, but technological solutions are under consideration. Contrary to high temperature performance, low temperature performance is stated to be good. With regard to fast recharge times, efficiency and lifetime, no projections were found.
Cost projections are uncertain; depending on the use and price of metallic lithium, costs could ultimately be equal or lower compared to Li-ion batteries. An estimation for the long term of 250$/kWh was found.

Metal-air batteries
Commercialization of zinc-air batteries could start from 2020. Lithium-air batteries are in earlier stages of development and commercialization for BEVS is expected to start later, depending on technological advancements. Depending on the battery design, Zn-air batteries are expected to attain a specific energy of 150 to eventually 400 Wh/kg. Lithium-air batteries are projected to reach 500 to even 1000 Wh/kg. However, the specific power is expected to be below USABC goals, but it is uncertain what levels can be achieved. In contrast to lithium-air batteries, the safety of zinc-air batteries is believed to be very good. Projections on the lifetime, recharge time and operating temperature of metal-air batteries could not be made.
The ultimate costs of zinc-air batteries are projected to be below Li-ion batteries. One projection of 100 $/kWh was found. Lithium-air batteries, however, will cost much more. No predictions were found, but material prices (of metallic lithium) do indicate that costs will probably be higher than of Li-ion batteries.

Sustainability
With regard to raw material availability, it was assessed for which materials scarcity could be a limiting factor when a cumulative number of 1.6 billion battery electric cars will be produced until 2050. Cobalt, nickel and metallic lithium could limit the production of Li-ion, ZEBRA and metallic lithium (Li-S and Li-air) batteries respectively. Also, for all battery technologies the demand for raw materials will increase substantially compared to present levels.
With regard to the environmental impact of batteries during their cycle life, only information was found for Li-ion batteries. This information shows that the production of the electrodes and current collectors has the highest environmental impact and demands most energy. The extraction of raw materials has only minor impact. As drying of the electrodes for non-lithium based batteries may not be needed, the energy demand can potentially significantly be reduced for zinc-air batteries. Also ZEBRA batteries do not contain lithium, but need to be heated to 300 ºC.
Finally, recycling of batteries is believed to be essential to increase the availability of raw materials (and thus limit resource depletion) as well as to reduce energy consumption for battery production.

How do expectations on battery performance affect the energetic, environmental and economic performance of battery electric cars over time and how do these results compare to expectations for other vehicle technologies?

Based on the projections defined for the performance and cost of the five battery technologies, a NEDC driving cycle simulation was performed for six driving ranges, from 100 to 600 km. For reference also the use of present Li-ion and ZEBRA batteries was simulated.
The results show that the battery weight and energy consumption of the drive train (battery to wheel) are lower for all future batteries compared to present Li-ion and ZEBRA batteries. Li-S and Li-air batteries show the best results; about 200 kg and 105 Wh/km at a range of 600 km. Up to 200 km, the results of future Li-ion, ZEBRA and Zn-air batteries are comparable to metal-air batteries, but diverge fast with driving range because of a lower specific energy.
Nevertheless, the low efficiency of zinc-air and lithium-air batteries results in a very high WTW energy consumption. The levels (425 to 494 Wh/km) are comparable to those of present high performance ICEVs. Future Li-ion batteries show the lowest WTW energy consumption (314 to 372 Wh/kg) at all ranges, followed by future ZEBRA batteries at ranges up to 400 km, and by Li-S batteries at 500 and 600 km. For the WTW CO_2 emissions analogous results are found. But, at an average emission factor of 593 gCO_2eq/kWh_e, the WTW emissions are lower to present ICEVs for all batteries (76-120 vs. 150-170 gCO_2eq/km).

The high costs of Li-air batteries result in high total battery costs, which are only below the total costs of present Li-ion and ZEBRA batteries at driving ranges of approximately 250 and 400 km respectively. For ranges of 200 and higher, the total costs are lowest of future ZEBRA batteries (7,128-25,887 $), followed by future Li-ion and zinc-air batteries that cost at least 1000 $ more. Costs of lithium-sulfur and lithium-air batteries are much higher, but Li-S batteries approach zinc-air batteries at high ranges.
The total driving costs depend on both electricity consumption and battery costs. Therefore, the total driving costs related to lithium-air batteries are highest of all future batteries (1.00 to 1.21 $/km); present Li-ion batteries result in higher costs at ranges of 300 km or more. The economic performance of battery electric cars with other future batteries is significantly better: 0.43 to 0.81 $/km). Also, future ZEBRA batteries result in the lowest costs at all ranges, followed by Li-ion and zinc-air batteries.
At a yearly driving distance of 14,000 km the total driving costs for future ZEBRA batteries are significantly lower compared to present batteries. But, compared to present ICEVs, the costs are still 689-1223 $/year higher at a range of 100 km and 3,397-3,931 $/year higher at 600 km.

However, the low power levels of Li-S and metal-air batteries have considerable impact on the performance of the battery electric car. At sufficient power levels, the energetic, environmental and economic performance related to Li-S, Li-air and Zn-air batteries are all improved. But, there is no change in the ranking of the batteries. The WTW energy consumption of metal-air batteries remains relatively high. Also, the total driving costs related to lithium-air batteries are still significantly higher compared to the other future batteries. Only Li-S batteries become more attractive at lower ranges, as the economic performance of the BEV approaches zinc-air batteries.

How and in which time frame are battery chemistries, that are currently being developed, expected to fulfill battery requirements and to influence the performance and competitiveness of battery electric cars?

Projections on battery performance and cost were made for the short, medium and long term. Short term projections showed what was considered to be achievable for Li-ion and ZEBRA batteries in 2015. Medium term projections did the same for all battery technologies in 2025. Long term projections were not appointed to a specific year. Forecasting technological developments after 2025 is very speculative and highly uncertain. Therefore, the long term projection did show what performance and cost levels were believed to be ultimately attainable.
The projections do show that not one battery is with certainty expected to fulfill all battery requirements in the medium term. Li-ion batteries can achieve most requirements, but safety and lifetime are key issues that can slow down the enhancement of the specific energy and battery costs. Li-S and metal-air batteries can be commercially available in 2025, but Li-ion batteries show that time is needed to attain high performance and minimum costs. Therefore, these new battery technologies may only fulfill all battery requirements in the long term.
While only ZEBRA batteries are not expected to achieve a specific energy level of 200 Wh/kg in the medium term, only Li-ion batteries do reach a specific power level of 400 W/kg or higher. For all other batteries it is uncertain if and when this power level can be achieved. Also the lifetime is a highly uncertain parameter for all batteries except ZEBRA.
To maximize the performance and competiveness of battery electric cars, specific power, efficiency and battery cost are the most important parameters. Although the attainable specific power level is uncertain for most batteries, for ZEBRA and zinc-air batteries this has only impact on the performance of BEVs at driving ranges below 160 and 232 km respectively. However, for Li-S and Li-air batteries, the power/energy ratio is lower than 1 and the specific power impacts the BEV performance up to ranges of 465 km. Therefore, the battery weight, WTW energy consumption and WTW emissions remain constant up to this distance. Nevertheless, Li-S and lithium-air batteries have a relatively low battery weight at ranges of 300 km or more; their weight reaches approximately 200 kg at 600 km, while future Li-ion, zinc-air and ZEBRA batteries are two to three times heavier. However, the efficiency of the batteries has to be high to show advantages with regard to WTW energy consumption and emissions. Li-ion and ZEBRA batteries have an efficiency of 92 and 90% and their use results in WTW energy consumption levels of 314-374 and 330-405 Wh/km. The emission levels are 76-90 and 80-98 gCO_2eq/kWh_e. Metal-air batteries were projected to have an efficiency of 70% and WTW energy consumption and emission levels are 425 Wh/km and 103 $gCO2_{eq}$/km or higher. With a projected efficiency of 80%, Li-S batteries have high energy consumption and emission levels at low ranges, but pass ZEBRA batteries at approximately 400 km. Their maximum WTW energy consumption and emission levels are 378 Wh/km and 92 $gCO2_{eq}$/km.
Despite low efficiency levels, all batteries show similar or lower WTW energy consumption and lower WTW emissions compared to ICEVs, using an emissions factor of 593 gCO_2eq/kWh_e.
However, in the long term, only low cost (100 $/kWh) ZEBRA batteries could be cost competitive to present diesel ICEVs at driving ranges below 200 km; 0.40 $/km or 5,600 $/year compared to 5,344 $/year. At the projected medium term cost levels, the use of ZEBRA batteries results in the lowest total driving costs, followed by Li-ion and zinc-air batteries (0.43-0.62 $/km, compared to 0.43-0.71 and 0.52-0.80 $/km). Lithium-sulfur batteries approach zinc-air batteries at higher ranges and have comparable costs at 500 and 600 km. Costs lithium-air batteries are 0.30 $/km higher compared to Li-S at all ranges.

9.2 General conclusions

With regard to batteries for battery electric cars, the specific energy is widely considered to be an important parameter to reduce battery weight and improve the energetic and environmental performance of the car. The overview created in the first part of this research showed that the largest part of present R&D activities focuses on lithium-based battery technologies with high specific energies. Nevertheless, other technologies that show advantages on safety, costs and environmental impact do get attention as well.
Lithium-sulfur and Lithium-air batteries can achieve considerably higher specific energy levels compared to other present batteries. In the medium term, zinc-air batteries are projected to attain a specific energy similar or somewhat higher compared to Li-ion batteries. However, medium term projections for these innovative (not yet available) battery technologies on other performance parameters do not exceed the levels of Li-ion and ZEBRA batteries. Also, it is uncertain if they can meet the USABC requirements ultimately.
For all batteries considered in the second part, it remains a challenge to simultaneously achieve all requirements. For all technologies, except ZEBRA, the lifetime is an issue; a limited lifetime can negatively affect total driving costs, but it is uncertain when and to what extent required levels can be achieved. Also, safety is an important topic for lithium based batteries. The specific power is projected to be low for all batteries except Li-ion and should at least attain 400 W/kg to achieve acceptable BEV performance at ranges below 400/500 km. For Li-S and metal-air batteries, also cycle life and efficiency are important issues.
With regard to costs, batteries that do not contain lithium have best prospects to attain cost requirements. Zinc-air batteries are expected to reach lower levels compared to Li-ion batteries, and similar or lower cost levels compared to ZEBRA batteries. The costs of lithium-sulfur and lithium-air are not expected to reach levels below ultimate costs of Li-ion batteries. Besides, the price of metallic lithium is very uncertain, but will probably negatively affect the costs of Li-S and Li-air batteries. Also, for ZEBRA and zinc-air batteries, high levels are needed for all performance aspects to attain low energy consumption and driving costs and make BEVs cost competitive to ICEVs.

From the driving cycle simulation, the use of future Li-ion batteries results in the lowest WTW energy consumption and WTW emissions. ZEBRA batteries attain lowest total driving costs. If lithium-sulfur batteries can achieve the USABC requirements, especially with regard to costs and efficiency, the performance of the car can become better than or as good as for Li-ion and ZEBRA batteries. Low cost zinc-air batteries can become preferable with regard to total driving costs, but it will be more difficult to attain competitive WTW energy consumption and emission levels. High efficiency lithium-air batteries could attain low energy consumption and emission levels, but their high costs make the battery economically undesirable.
Furthermore, the WTW energy consumption and emissions related to ZEBRA batteries increase considerably when operation takes place at temperatures above ambient temperature. If the battery has to be heated continuously when not in operation, it will become very undesirable compared to all other batteries simulated. Thus, if the BEV is not frequently used (e.g. for commercial purposes) the battery will only be an option when it is possible to reduce the operating temperature in the medium term; possibly even to ambient temperature. However, this needs radical technological improvements. It is not clear what the effects are of non-continuously heating (by non-frequent users), e.g. on the battery's lifetime.

The sustainability assessment indicates that the environmental impact for BEVs can be lower compared to ICEVs, regardless of the battery technology used. Nevertheless, the environmental impact and energy consumption related to battery production and life cycle should be monitored and improved continuously.

Also, depending on choices for material use, material availability may not be a problem. But, reserves of many materials should be expanded. This could result in increasing material prices. Therefore, recycling of batteries is needed to limit environmental impact as well as to restrict resource depletion and keep material prices low.

9.3 Recommendations

It was showed that battery electric vehicles can be competitive to conventional fuel powered cars, especially with regard to environmental and energetic aspects. To make this true on large scale, the following recommendations can be made.

Firstly, in the projections many uncertainties exist. This is especially the case with regard to the specific power, lifetime, costs and characteristics that were not used in the simulation (recharge time, operational temperature). Besides, many projections were not based on figures from scientific literature, but other information sources. Therefore, the projections should be further verified, supported and complemented by for example consulting experts. Also, it would be a good option to update the data regularly. It this way, it is possible to monitor what developments take place and to what extent progress is made to attain the battery requirements for battery electric cars.

Secondly, from early stages of development a number of R&D activities should focus on BEV application specifically. Batteries for battery electric cars have to fulfill requirements totally different than for other applications. Therefore, an early focus on BEV purposes will center the research on issues that are most important for these batteries.
Furthermore, it is important to keep an eye on all aspects that play a role for battery electric cars. Batteries may achieve a very high specific energy, but when for example the specific power is too low, the battery will not be an attractive option. However, not only battery performance should be considered but also costs and sustainability.

Thirdly, it is likely that the choice of the battery does depend on the specific application. Therefore, the energetic, environmental and economic performance should also be assessed for vehicles other than compact passenger cars. Examples are multiple purpose vehicles (MPVs), vans and trucks. For these purposes, it should also be evaluated if battery requirements are different than for compact passenger cars.

Finally, more work is needed on experience curves for batteries. Verification of the progress ratios with historical data is required to get more and better insight in learning effects. Also, a multiple factor experience curve could show other mechanisms that affect costs.

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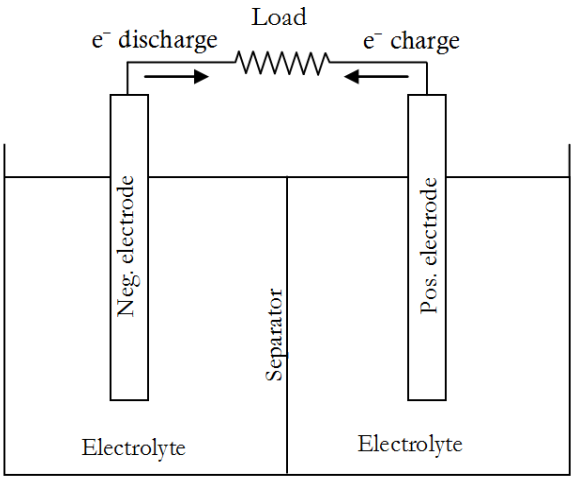
Appendix I: Technical background

I.I Battery technology explained

Batteries used for electric vehicles are called traction batteries [Rand et al., 1998], because they have to provide motive power over a longer period. In this they differ from starting, lighting, and ignition (SLI) batteries. SLI batteries are designed to provide high electric current for a short period of time ["Traction battery", n.d.; "Car battery", n.d.]. Furthermore, one can make a division in primary and secondary batteries. Primary batteries can only be discharged ones, while a secondary battery can be charged again [Rand et al., 1998]. Obviously, the latter is used in electric vehicles.

Batteries consist of cells that can store chemical energy, which can be converted to electric energy. Each cell has the following components (figure A1.1) [Rand et al., 1998; Husain, 2003; Chan & Chau, 2001]:

- Negative electrode: the negative electrode is a metal or alloy that undergoes an oxidation reaction during discharge. By this reaction, also called an anodic process, electrons are generated (equation A1.1).
- Positive electrode: this electrode is mostly an oxide or sulfide. For the duration of discharge, a reduction reaction or cathodic process takes place during which electrons from the external circuit are consumed (equation A1.2).
- Electrolyte: the electrolyte is a medium that provides an internal circuit between the positive and negative electrode. The electrolyte has a high and selective conductivity for ions that take part in the electrode reactions, but is a nonconductor for electrons. Sometimes, the electrolyte takes place in the reactions at the electrodes. The electrolyte can be made of liquid, gel or solid material.
- Separator: The separator physically separates the two electrodes. It is electrically insulating, but permeable to ions.



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

Equation A1.1: Oxidation reaction

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

Equation A1.2: Reduction reaction

Figure A1.1: Components of an electrolytic cell.

At discharge, an electrolytic cell can also be called a galvanic cell. Then, the negative electrode can be called the anode and the positive electrode the cathode. However, during charge an external voltage is applied and the cell is called an electrolysis cell. The reactions given in equations A1.1 and A1.2

then take place in the opposite direction. In this case, the negative electrode is the cathode and the positive electrode the anode [Rand et al., 1998].

I.II Cell voltage and energy available

The electrode potential (Volts) is defined as the propensity (natural tendency) of the electrode material to gain or lose electrons ["Cell Chemistries, how cells work", n.d.]. The standard electrode potential of a material is given by using zero Volts as reference for the standard hydrogen electrode (SHE) ["Standard electrode potential", n.d.]. The more negative the standard electrode potential of an agent is, the more easily this agent will lose electrons (undergo oxidation) in order to reduce another agent. Agents with a highly positive standard electrode potential will easily reduce by oxidizing another agent ["Cell Chemistries, how cells work", n.d.; "Standard electrode potential", n.d.]. In general, each material can be reduced by an electrode having a lower standard electrode potential and oxidized by any electrode having a higher potential ["Standard electrode potential", n.d.].

The cell voltage or electromotive force (EMF) is the difference between the standard electrode potentials of the two electrodes used in the cell [Rand et al., 1998]. The amount of energy stored in the cell is given by the Gibbs free energy (ΔG), equation A1.3:

$$\Delta G = -nFV \qquad \textit{Equation A1.3}$$

Where n is number of moles of electrons per mole of product, F is faraday (96,485 coulombs per mole) and V is the cell voltage [Rand et al., 1998; "Standard electrode potential", n.d.]. However, this amount of energy is a theoretical maximum under standard conditions. The real available amount of energy depends on temperature and can be calculated by the so called Nernst relationship [Rand et al., 1998].

The cells can be connected to each other in two ways to form a battery. The first is a monopolar configuration in which electric charged plates act as positive or negative electrodes in two adjacent cells and are parallel-connected, figure A1.2a. A number of these joined cell groups are connected in

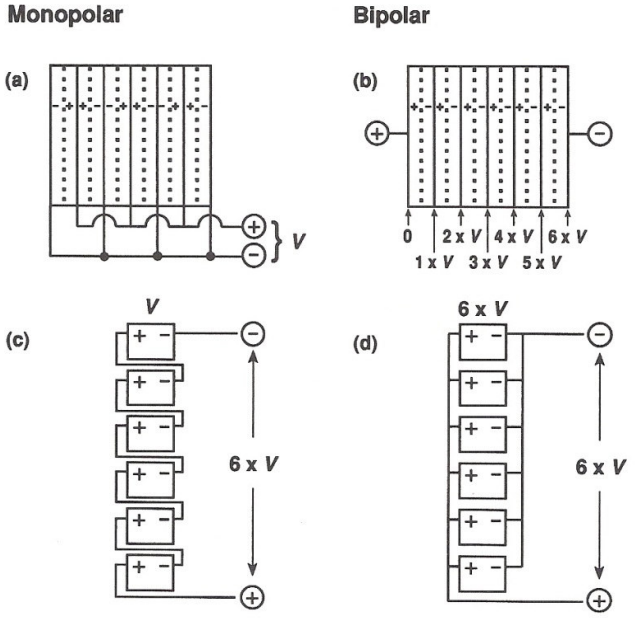


Figure A1.2: Monopolar and bipolar configuration, (a) & (b) geometry of joined cell group (dotted lines = separators), (c) & (d) connection of joined cell groups [Rand et al., 1998]

series to form one battery module, figure A1.2c. In the bipolar configuration the series connected plates act each as a negative electrode in one cell and as a positive electrode in the neighboring cell. Here, the joined cell groups are connected to each other in parallel (figure A1.2b and A1.2d). The resulting battery modules can be connected in a series and parallel combination to deliver the desired voltage and energy capacity [Rand et al., 1998; Husain, 2003].

I.III Battery types

In table A1.1, an overview is given of the classification of rechargeable batteries that are considered to be applicable as traction batteries. This overview is not complete, but shows those that are most discussed in literature [Rand et al., 1998; Husain, 2003; Chan & Chau, 2001]. As the zinc-air battery uses a gaseous positive electrode of oxygen (from ambient air), this battery is in practical only mechanical rechargeable by replacing the discharged product with fresh zinc electrodes. In most batteries a liquid electrolyte is used. In flow batteries, this electrolyte even flows through the cell. Conversely, the lithium-polymer battery has a solid electrolyte made of polymers. Also the sodium- β batteries have no liquid electrolyte, but a beta-alumina ceramic electrolyte [Husain, 2003].

Table A1.1: Classification of traction batteries and applied electrode materials

Classification	Sub-classification	Negative electrode (anode)	Positive electrode (cathode)
Lead acid	Flooded	Metallic lead (Pb)	Lead dioxide (PbO_2)
	Valve regulated (VRLA)	Metallic lead (Pb)	Lead dioxide (PbO_2)
Alkaline, Nickel based	Nickel-Cadmium NiCd	Metallic cadmium (Cd)	Nickel oxyhydroxide (NiOOH)
	Nickel-Zink NiZn	Zinc (Zn)	Nickel oxyhydroxide (NiOOH)
	Nickel-Metal-Hydride NiMH	Metal hydride (MH_x)	Nickel oxyhydroxide (NiOOH)
Alkaline, metal-air (electrical or mechanical rechargeable)	Zinc-Air Zn/air	Zinc (Zn)	Ambient air (O_2)
	Aluminum-Air Al/Air	Aluminum metal (Al)	Ambient air (O_2)
Sodium-β	Sodium-Sulfur NaS	Molten sodium (Na)	Molten sulfur/sodium polysulphides
	Sodium-Nickel-chloride $NaNiCl_2$ (ZEBRA)	Molten sodium (Na)	Solid nickel chloride ($NiCl_2$)
Flow batteries	Zinc-bromine (zinc halogen) ZnBr	Zinc (Zn)	Bromine (Br)
Ambient temperature lithium	Li-polymer	Metallic lithium (Li_x)	Transition metal intercalation oxide (M_yO_z)
	Li-ion	Lithium intercalated carbons (Li_xC)	Lithium metallic oxides ($Li_{1-x}M_yO_z$)

I.IV Important battery parameters

In table A1.2 the most important parameters of traction batteries are given. In order to be commercially interesting for use in battery electric cars, batteries have to perform at a certain level associated with these parameters [Rand et al., 1998; Husain, 2003; Chan & Chau, 2001].
The capacity is the amount of free charge generated at the negative electrode and consumed by the positive electrode [Husain, 2003]. However, the practical capacity of a battery depends on the discharge current and the cut-off time; the time at which the voltage has reached a predefined lower limit. Generally, the capacity is given for a constant discharge rate; the current at which the battery is discharged. This is called the rated or nominal capacity. Another parameter is the depth of discharge (DoD), which is the percentage of the rated capacity to which a battery is discharged. The cycle life, the maximum number discharge/recharge cycles, is always given for a certain depth of discharge [Husain, 2003].

Table A1.2: Key parameters of traction batteries

Parameter	Unit	Formula
Rated/nominal capacity	Ah	$Q = I \cdot t_{cut}$
Specific energy (gravimetric energy density)	Wh/kg	$SE = \frac{\left(\int_0^{t_{cut}} vi\,dt \right)}{M_B}$
(maximum) Specific power	W/kg	$SP = \frac{P}{M_B}$
Cycle life	# cycles @ % DoD	
Charging time	h or min	
Energy efficiency	%	$\eta_{energy} = \frac{E_{out}}{E_{in}}$
Charge efficiency	%	$\eta_{charge} = \frac{Q_{discharged}}{Q_{charged}}$
Cost	US$/kWh	

Appendix II: Current research topics

II.I Li-ion

Specific energy

Improving the specific energy of Li-ion batteries is a main goal in research activities. This can be done by increasing the cell specific energy and/or reducing the share of inactive materials in the battery system. As the cell specific energy is the product of storage capacity and cell voltage, it can be enhanced by expanding the storage capacity of the electrode materials and by extending the voltage of the cell [Tarascon, 2010].

Electrode storage capacity

Expanding the electrode storage capacity means that the amount of electrons and lithium ions that can be reversibly inserted in a certain amount of electrode material is increased. At the anode, it is aimed to do so by substituting graphite (330-370 mAh/g) by an alternative material. Options are:

- Lithium metal alloys: LiSi (4000 mAh/g), LiSn (990 mAh/g) [Notten, 2010; Scrosati and Garche, 2010]
- Metal carbon (nano)composites: SnC and SiC [Scrosati and Garche, 2010]
- Metallic lithium (3863 mAh/g) [Chan and Chau, 2001]

Lithium metal alloys face the problem of large volume expansion and reduction during charge and discharge (insertion and extraction of Li-ions) respectively. This causes mechanical stresses and results in degeneration, reducing storage capacity and ultimately failure of the electrode [Scrosati and Garche, 2010; Magasinki et al., 2010; F. Ooms, personal communication, June 15, 2010]. Metal carbon composites are better capable of accommodating volume changes [Magasinki et al., 2010]. However, adding carbon and binder to silicon to form the composite structure also results in a reduced storage capacity of the electrode [F. Ooms, personal communication, June 15, 2010]. On the other hand, the storage capacity is still some times higher than graphite; Magasinki et al [2010] do for example report a reversible capacity of 1,950 mAh/g for a SiC nanocomposite in which carbon particles are coated with silicon nanoparticles.
Because of safety issues related with the use of metallic lithium, also other components of the battery have to be adapted. This will further be discussed in the sections about lithium metal polymer, lithium sulphur and lithium-air batteries.
At the cathode, the storage capacity is primarily enhanced by improving existing materials. The number of available materials is already extensive. The most utilized materials can be classified as following[1]:

- Lithium metal oxides:
  - Layered structures: $LiCoO_2$, $LiNiO_2$, $LiMnO_2$, $Li(NiCo)O_2$, $Li(NiMnCo)O_2$ (NMC), $Li(NiCoAl)O_2$ (NCA) [Fergus, 2010a]
  - Spinel structures: $LiMn_2O_4$ (LMO), $Li(NiMn)O_4$ [Fergus, 2010a]
- Lithium metal phosphates:
  - Olivine structures: $LiFePO_4$ (LFP), $LiMnPO_4$, $LiCoPO_4$, $LiNiPO_4$ [Fergus, 2010a]

[1] Components between brackets: various ratios between these components can be applied.

All cathode materials have their own pros and cons. With regard to storage capacity, layered lithium metal oxides are most favorable [Howard and Spotnitz, 2007]. The maximum capacity of these materials is 250-300 mAh/g. However, their practical capacity in current available batteries is 160-170 mAh/g. This is due to operational limitations; when all lithium ions would be removed out of the material, the structure would collapse. Recent research at Argonne National Laboratory (US) showed that the structure can be stabilized by applying layers with different compositions between cobalt, nickel and manganese [F. Ooms, personal communication, June 15, 2010].

Cell voltage
The cell voltage is defined by the potential of both electrode materials. To let the cell voltage increase, the potential of the cathode should be as high as possible, while the potential of the anode should be as low as possible [Rand et al., 1998]. Therefore, researchers are looking for high voltage cathodes. The potential of these new electrodes is higher than of present cathodes [ARPA-E, 2009; W. Robers, personal communication, June 14, 2010].

Role of anode and cathode
As the negative and positive electrodes have a low and high potential respectively, increasing the specific energy of the cell is done most effectively by adapting the positive electrode. Tarascon [2010] states that doubling the storage capacity of the cathode can result in a 57% increase in cell specific energy, while improving the capacity of the anode by a factor 10 is needed to get a 47% increase in cell specific energy. Howard and Spotnitz [2007] show that cathode materials containing cobalt and/or nickel have a substantial advantage over manganese and iron based materials.
Besides, an example of innovative cathodes with a high storage capacity are conversion cathodes (section 3.1.8).

Inactive materials
Batteries do not only consist of active materials, i.e. materials that participate in the electrochemical charge and discharge reaction. For example, current collectors and packaging have a substantial share in cell and battery weight distribution. This affects the specific energy of the battery. Compared to the cell level, the specific energy can be up to 40% lower on pack level [Kalhammer et al., 2007; BCG, 2010]. Therefore, reduction of inactive materials by improving the technology of building batteries would be a good opportunity [E. Kelder, personal communication, July 7, 2010].
A main solution is the packaging of battery cells in polymer pouches instead of steel or aluminum cans [ARB, 2009]. A transition to pouches can reason 5-10% lower costs and 30% energy density improvement. But, pouches are also considered to offer less protection in case of battery failure. Therefore, safe chemistries are required [ARPA-E, 2009].

Projections specific energy

Several projections were found on the improvement of specific energy of Li-ion batteries. These are based on average improvement per year and/or on technological improvements. In the summary report of the ARPA-E workshop the intrinsic specific energy is given for three Li-ion classes. However, these values have to be adapted for losses due to the weight impact of non-active materials. On cell level this is a reduction of 40-60%, followed by a further reduction of up to 40% at pack level [ARPA-E, 2009; Gauch et al., 2009; Roland Berger, 2009; Kalhammer, 2007; BCG, 2010]. Table A2.1 shows what specific energies can approximately be achieved by the three Li-ion designs.
These results are consistent with values from Kelder [personal communication, July 7, 2010]. He states that a specific energy of 150 Wh/kg will be achievable with silicon and present cathode materials. To achieve 200 Wh/kg new cathode materials have to be applied. Furthermore, a specific energy of more than 250 Wh/kg will be very difficult to reach [E. Kelder, personal communication,

July 7, 2010]. A comparable specific energy of 240 Wh/kg is stated to be the technological limit for advanced lithium ion batteries by Rozenkranz [in: Cars21, 2010].
Perhaps, a higher utilization factor at pack level (packaging in pouches) could lead to even higher values. In the ARPA-E report it is stated that the use of a metallic lithium anode combined with present intercalation cathodes can result in 250-350 Wh/kg at cell level [ARPA-E, 2009]. With a utilization factor of 0.8 or higher the specific energy could then approach 300 Wh/kg.

Table A2.1: ARPA-E projections on specific energy for present and advanced Li-ion technology and adapted for weight losses at cell and pack level

Electrode couple	Intrinsic specific energy (Wh/kg)	specific energy, cell level (cell level utilization factor 0.4) (Wh/kg)	Specific energy, pack level (pack level utilization factor 0.7) (Wh/kg)
LiCoO2-graphite	380	152	**106**
best performing intercalation cathodes-silicon	670	268	**188**
conversion cathodes-high capacity metal anodes	**900**	**360**	**250**

Projections from several sources are presented in figure A2.1. Values of ARB [2009] and Winter [in: Miller, 2009] are adapted from cell to battery pack level, using a utilization factor of 0.7. In its report of 2009, the ARB states that “super” Li-ion batteries could be available for automotive application from 2015. These batteries will be based on next generation Li-ion technology and have a specific energy of 200 Wh/kg at cell level [ARB, 2009]. Also, Kelder [personal communication, July 7, 2010] stated that the aim of his research group was to develop a battery system of 200 Wh/kg in the next four years. As the whole process of development takes 6 to 10 years, it is assumed that another 4 years are needed before commercialization of this battery can start [W. Robers, personal communication, June 17, 2010; Matheys and Van Autenboer, nd].

The projections present different scenarios. First, in the ARPA-E summary report a historic improvement rate of 6% per year is mentioned. Although this rate does probably count for consumer electronics Li-ion batteries, expectations from Kelder and ARB (optimistic scenario) are in line with this rate. Rozenkranz, from battery concern Johnson Controls-Saft, expects that the technological limit of 240 Wh/kg will be approached by 2020 [Cars21, 2010]. However, it is not clear at what level of development such batteries will be at that time. Commercialization in 2020 would imply an improvement rate of more than 6% in the next years. This does not seem very likely when comparing to the other projections. Therefore, it is assumed that these 240 Wh/kg batteries will have attained cell production and the start of prototype testing in 2020. From then, it will take another 3 or 4 years before commercialization can start [Winter in: Miller, 2009; W. Robers, personal communication, June 17, 2010; Matheys and Van Autenboer, nd]. According to this scenario, the technological limit of 250 Wh/kg will be reached around 2025.

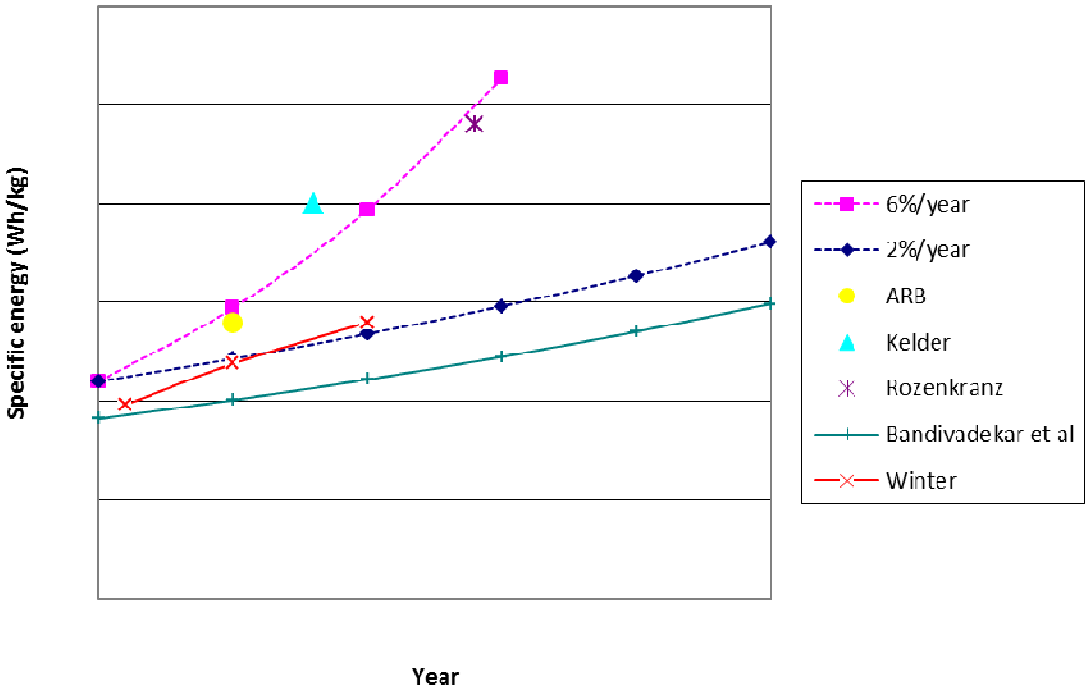


Figure A2.1: Projections on the specific energy of Li-ion batteries for BEVS on pack level and at commercialization level [Bandivadekar et al., 2008; Winter, in: Miller, 2009; ARPA-E, 2009; ARB, 2009; E. Kelder, personal communication, July 7, 2010; Rozenkranz, in: Cars21, 2010].

Secondly, Bandivadekar et al [2008] assume that the specific energy will increase with a rate of 2% per year. In their projection, a value of 150 Wh/kg would be reached in 2035. When applying this 2% scenario for a present specific energy of 110 Wh/kg, the 150 Wh/kg milestone would be reached around 2025. Finally, projections from Winter [in: Miller, 2009] show an average increase of 4% per year.

The different scenarios show that improvements in specific energy are highly dependent on how fast technological breakthroughts can be realized. Also, it is very difficult to forecast these technological developments for ten or more years from now [B. Scrosati, personal communaication, September 8, 2010]. Besides, Anderman [2010] states that "significant improvements in performance (…) will only be beneficial if they do not reduce the battery's ability to meet the four important key requirements" (of safety, reliability, durability, and cost respectively).

Specific power

The specific power depends on the rapidity at which the lithium ions diffuse into and out of the electrode material. First of all, this is partly defined by the electrode structure. For example, spinel structures offer fast three dimensional Li ion transport, layered structures provide two dimensional diffusion, and in olivine structures only slow one dimensional Li ion transfer is possible [Howard, 2007]. The anode material lithium titanium oxide, $Li_4Ti_5O_{12}$ (LTO), has a spinel structure and provides a very high specific power. However, its electrode potential is high and its storage capacity is low (about 170 mAh/g). Therefore, it negatively affects the specific energy of the battery [Scrosati and Garche, 2010; F. Ooms, personal communication, June 15, 2010]. Although LTO is already exploited for PHEV batteries [EnerDel, n.d.; Altairnano, n.d.], the use of this material for BEV purposes seems to be much less attractive.

Secondly, to optimize the diffusion process, the diffusion length has to be as short as possible. For most electrode materials in present batteries the diffusion rate is high enough to deliver the required power to battery electric cars. Lithium metal phosphate cathode materials, of which $LiFePO_4$ is most common, are an exception. Their electronic conductivity is low and consequently reduces the ionic conductivity as well [Howard and Spotnitz, 2007; E. Kelder, personal communication, July 7, 2010]. To enhance the ionic conductivity, nanostructured cathode material is used. Besides, the $LiFePO_4$ nanoparticles are coated with a fast ion conducting material [Scrosati and Garche, 2010; E. Kelder, personal communication, July 7, 2010].
The use of nanostructures, however, can also create operational problems. As the surface of reactive material increases, the reactivity between the electrode and electrolyte intensifies as well [E. Kelder, personal communication, July 7, 2010]. Besides, the large surface area reduces the volumetric energy density (Wh/liter) [Scrosati and Garche, 2010]. Therefore, for most electrode materials it is not desirable to use nanostructures. A more convenient approach is to make use of conventional electrode structures with particle sizes that enable the required power rate, but limit reactivity with the electrolyte [Scrosati and Garche, 2010; E. Kelder, personal communication, July 7, 2010].

Finally, the power capacity declines substantially at low temperatures. This is caused by present electrolytes that constrain the performance of Li-ion batteries at such temperatures; in the ARPE-A report, it is stated that the power ability declines to 20% at -30°C. To enhance low temperature performance, it is needed to improve present battery chemistries [ARPA-E, 2009].

Projections specific power

As research activities are primarily focused on increasing the specific energy, it is not expected that the specific power of Li-ion batteries will increase substantially. The USABC requirement is a power-energy ratio of 2:1. As the specific power of present batteries is 400 W/kg or more it has not to be improved before 2020. If the specific energy will exceed 200 Wh/kg, a specific power of 500 W/kg would be sufficient. When higher power-energy ratios would be used the power should be 600 W/kg or more.

Safety and reliability

The safety of a Li-ion battery depends largely on the electrolyte. Problems related to present used electrolytes (solution of lithium salts in an organic solvent) are:

- Narrow stability window: the range of battery operating voltages within which the electrolyte is stable, i.e. decomposition of the electrolyte on the electrode surfaces is negligible. The narrow stability window restricts the use of electrodes; cathode materials with a high potential do not operate within this window [Scrosati and Garche, 2010; Xu et al., 2001].
- High vapor pressure: due to decomposition processes, gas evolution takes place
- Flammability/thermal instability: due to an increase in temperature an exothermic reaction can start that reinforces itself and finally can result in an explosion. This is called thermal runaway [Scrosati and Garche, 2010; “thermal runaway”, n.d.].
- Incompatibility with environment and human health

A graphite anode operates outside the stability window of these organic electrolytes. However, the initial decomposition of the electrolyte results in the formation of a so called Solid-Electrolyte-Interface (SEI). This interface extends the stability window and makes continued operation possible [Scrosati and Garche, 2010]. When overcharge occurs, however, decomposition of the electrolyte

takes place at the cathode side. It this case, no protective film is formed that protects from further disintegration [Scrosati and Garche, 2010].

The safety is increased by measures that enhance the formation of a stable SEI, improve the thermal stability of the electrolyte, prevent thermal runaway and protect from overcharge [Scrosati and Garche, 2010]. Also, alternative lithium salts are considered that are less toxic [Scrosati and Garche, 2010].

Another approach is the search for new types of electrolytes. These are ceramic and polymeric solid electrolytes, polymer gels and ionic liquids.
Ceramics and polymers are a very attractive alternative with regard to safety, but their application has been limited until now. The reason for this is the ionic conductivity. For polymers, the ionic conductivity is only high enough at operating temperatures above 70 °C [Scrosati and Garche, 2010; Fergus, 2010b]. R&D activities are focused on finding solutions to increase the ionic conductivity at ambient temperature. The addition of small (nano-sized) ceramic particles in the polymer matrix improves the ionic conductivity of the electrolyte [Croce et al., 2003; Scrosati and Garche, 2010]. This positively affects the charge and discharge kinetics. On the other hand, however, the conductivity remains too low for adequate operation below 70 °C [Croce et al., 2003]. Yet, while some believe that good power performance at ambient temperature is essential, others do not consider the elevated operational temperature to be a problem in automotive applications [ARPA-E, 2009; Scrosati and Garche, 2010].
Ceramic electrolytes that have been investigated for lithium-ion batteries are sulfide, oxide and phosphate compounds. The most commonly used polymer is poly(ethylene oxide) (PEO), to which lithium salts are added to make ionic conductivity possible [Fergus, 2010b].
Polymer gel electrolytes (PGEs) consist of an organic liquid electrolyte locked in a polymer matrix. The high ionic conductivity of PGEs, which is near to that of liquid electrolytes, is a great advance compared to polymer electrolytes. Also, the safety and reliability are improved when weighted against liquid electrolytes. However, problems relating to these topics cannot be totally solved [Scrosati and Garche, 2010; Fergus, 2010b]. The most frequently used polymer gel electrolyte is poly(vinylidene fluoride) (PVdF) [Fergus, 2010b].
A last alternative to liquid electrolytes are ionic liquids (ILs). These are low temperature molten salts that have very positive properties for safe battery operation. However, researchers have not been able yet to prove the stability of ILs in battery operation tests [Scrosati and Garche, 2010; E. Kelder, personal communication, July 7, 2010]. Also, the present high costs of ionic liquids do limit their practical use [Scrosati and Garche, 2010]. More likely options seem to use ionic liquid components to adjust lithium salts and to add ionic liquids to organic liquid, polymeric or ceramic electrolytes [E. Kelder, personal communication, July 7, 2010; Scrosati and Garche, 2010; Fergus, 2010b].

Finally, with regard to safety the so called battery management system (BMS) plays an important role. The BMS monitors the condition of the battery, e.g. temperature and voltage, and intervenes when needed [Notten et al., n.d.; F. Ooms, personal communication, June 15, 2010]. Thus, the BMS reduces the need to build in physical measures in the battery to guarantee safety [F. Ooms, personal communication, June 15, 2010].

Prospects safety

At present a number of Li-ion chemistries exist, which all have their pros and cons, figure A2.2 [BCG, 2010; Lache et al., 2009]. Therefore, it is needed to find compromises with regard to performance, costs and safety. Yet, safety is an absolute condition for commercialization. This means that safety

enhancements may even demand sacrifices in battery performance and cost [E. Kelder, personal communication, July 7, 2010; ARPA-E, 2009; Anderman, 2010].

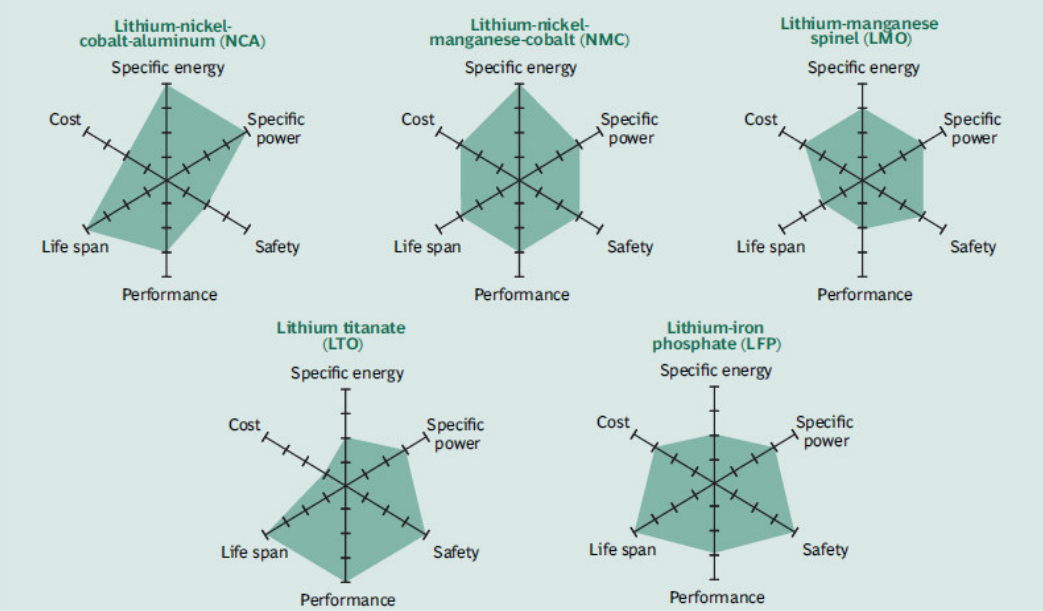


Figure A2.2: Present status of five Li-ion chemistries. The farther the colored shape extends along the axis, the better the performance along that dimension [BCG, 2010]

Cycle life and lifetime

The cycle life and lifetime of Li-ion batteries are limited due to degradation of these batteries. This degradation is caused by various mechanisms of which some are dependent and others are independent of charge/discharge conditions.
Decomposition of the electrolyte and electrodes is accelerated by high temperatures, high currents and high voltages [W. Robers, personal communication, June 14, 2010]. The resulting, non reversible, losses of active material cause reduction of the nominal battery capacity. This loss is denoted by the coulombic efficiency [E. Kelder, personal communication, July 7, 2010]. The coulombic efficiency of Li-ion batteries is already high compared to other battery types; 0.1% of the nominal capacity is lost after each charge-discharge cycle. However, to enhance the battery's cycle life this efficiency should even be above 99.9% [E. Kelder, personal communication, July 7, 2010]. Besides, the number of required cycles for electric cars is much higher than for present Li-ion applications like mobile phones. Therefore, there is very little knowledge about the battery's degradation process and coulombic efficiency after 1,000 cycles or more [E. Kelder, personal communication, July 7, 2010]. Also with regard to the lifetime counts that there is little data yet about what is practically achievable. Projections are based on tests of a few years, but should be validated by more real-life data [E. Kelder, personal communication, July 7, 2010; Cars21, 2010]. It is difficult to control and extend the lifetime, as degradation is related to state-of-charge, temperature and time [Anderman, 2010]. The battery management system plays an important role here [Anderman, 2010; Notten et al., n.d.; F. Ooms, personal communication, June 15, 2010]. Also, the lifetime can be enhanced by only using half of the nominal capacity. However, overdimensioning makes the batteries bigger and more expensive [F. Ooms, personal communication, June 15, 2010; W. Robers, personal communication, June 14, 2010].

Prospects lifetime and cycle life

The number of required cycles for electric cars is much higher than for present Li-ion applications like mobile phones. Therefore, there is very little knowledge about the battery's degradation process and coulombic efficiency after 1,000 cycles or more [E. Kelder, personal communication, July 7, 2010]. However, more than 1000 or even 2000 cycles are demonstrated at 70-80% DoD by battery developers [Kalhammer et al., 2007; Anderman, 2010]. Thus, it seems very likely that the USABC requirements will be met.

With regard to the lifetime, there is little data yet about what is practically achievable. Projections are based on tests of a few years, but should be validated by more real-life data [E. Kelder, personal communication, July 7, 2010; Cars21, 2010].

Charging

As stated before, high currents and voltages can accelerate degradation of the battery. Therefore, for each battery a maximum charge voltage can be determined. Thus, it is preferred that the charging process should be adapted to the limitations of the battery. Also, drive and charge behavior of the consumer and requirements with regard to battery lifetime are of influence on the so called charge algorithm [W. Robers, personal communication, June 14, 2010].
Nevertheless, there exist different standard algorithms. One is the constant-current-constant-voltage (CCCV) algorithm, which consists of an initial constant current mode (i.e. the charging current is kept constant) which is followed by a constant voltage mode at the maximum charge voltage [Notten et al., n.d.].
Another strategy is called boostcharging. The so called boostcharge period is a constant voltage mode applied at the initial stages of charging at a low SoC. As a result of very high currents in the boostcharge phase, a battery can be recharged to a considerable share of its rated capacity in a small period of time. Experiments by Notten et al. [2005] showed that a fully discharged battery can be recharged to one third of its rated capacity in 5 minutes. The boostcharging mode can be followed by standard CCCV charging to fully charge the battery. The experiments also showed that boostcharging has no significant impact on the cycle life of a Li-ion battery [Notten et al., 2005].
When the charging algorithm is adjusted to the battery's status, the battery management system plays an important role. The BMS sends information about the battery to an on board controller or to the charging station which subsequently decides about the charging algorithm [W. Robers, personal communication, June 14, 2010].

At present, batteries in the latest battery electric cars can be recharged to 80% of their capacity in 30 minutes. Robers [personal communication, June 14, 2010] believes that partial recharge can be reduced to 5 minutes in the future. However, he does not expect that full recharge times will become less than 15 to 30 minutes. Charging stations that can deliver high power are available and batteries with a high power rate are technological feasible. Thus, charging times shorter than 15 minutes are possible in theory. However, prices for such batteries (with LTO anode) will be quite high. The use of such batteries will only be feasible for commercial purposes like busses and taxis [W. Robers, personal communication, June 14, 2010].

Prospects charging

At present, batteries in the latest battery electric cars can be recharged to 80% of their capacity in 30 minutes. Robers [personal communication, June 14, 2010] believes that partial recharge can be reduced to 5 minutes in the future. However, he does not expect that full recharge times will become

less than 15 to 30 minutes. Charging stations that can deliver high power are available and batteries with a high power rate are technological feasible. Thus, charging times shorter than 15 minutes are possible in theory. However, prices for such batteries will be higher compared to batteries with lower power rates. The use of such batteries will only be feasible for commercial purposes like busses and taxis [W. Robers, personal communication, June 14, 2010]. Also the BCG [2010] does not expect large scale availability by 2020 of battery technologies that can recharge in a few minutes.

II.II ZEBRA

Specific power

The specific power is an important topic for ZEBRA battery development. It has to be substantially improved to achieve BEV requirements [ARPA-E, 2009]. There are several directions to enhance the specific power. First, the ionic conductivity of the ceramic electrolyte is an important issue. The conductivity is already relatively high and comparable to that of aqueous electrolytes (as used in alkaline batteries) [Lu et al., 2010]. However, it is dependent on the temperature of the battery and increases with this temperature [Dustmann, 2004]. It is therefore that the current operational temperature is 350 °C. Better specific power (at lower temperature) could be achieved by improvement of the ceramic electrolyte or by applying another electrolyte. The conductivity of the ceramic can be enhanced by increasing its surface area, decreasing its thickness and optimizing its composition and structure. The latter could for example be done by adding materials to the electrolyte [ARPA-E, 2009]. For instance, the presence of excessive sodium ions in the electrolyte enhances the ionic conductivity [Lu et al., 2010].
Second, also the chemistry of the cathode plays an important role. In the past, doping of the cathode with iron already improved the battery's peak power significantly [Böhm and Beijermann, 1999; Brett et al., 2006]. But, further improvements are necessary. A high conductivity of the liquid electrolyte is again needed to enhance electronic and ionic transport through the cathode [ARPA-E, 2009; Lu et al., 2010]. Besides, increasing the surface of the active material in the cathode raises the reaction surface area between nickel chloride and sodium ions. Applying a 3-D micro-structured or a nano-structured cathode would be approaches to achieve this [ARPA-E, 2009].
Also, the power rate significantly declines with the battery's depth of discharge. This is due to an increasing diffusion length in the cathode as the reaction front moves from the ceramic electrolyte [Böhm and Beijermann, 1999]. In the past, the surface of the electrolyte and thickness of the cathode have already been changed [Böhm and Beijermann, 1999]. However, further change of the cell's geometry or chemistry is believed to be required to further reduce the dependence on charge level [ARPA-E, 2009].

Specific energy

ZEBRA batteries have a relatively low operational voltage. Alternative electrode materials that form an electrochemical couple with a higher voltage may be considered to improve the specific energy [ARPA-E, 2009]. Furthermore, degradation of the cathode through cycling is an issue [ARPA-E, 2009]. During discharge, sodium ions react with nickel chloride to form sodium chloride and nickel metal. During charge, however, this reaction is not fully reversed: a thin nickel chloride layer forms on the nickel surface. The conductivity of this layer is low and prevents all nickel to be utilized. This restricts the battery capacity [Lu et al., 2010].
Capacity loss during cycling is also taking place due to the growth of nickel grains in the cathode [Lu et al., 2010]. Composition modification of the $NaAlCl_4$ electrolyte and cathode by the use of additives limits this and can enhance ion transport and capacity utilization [Lu et al., 2010].

Projections specific energy and specific power

In the workshop report on electrical energy storage of the DOE [2007] it was projected that a substantial redesign of NaNiCl cells can result in specific energy and peak power values of more than 200 Wh/kg and 400 W/kg on cell level. At a utilization rate of 80%, as derived from DOE [2007, p.28] for ZEBRA batteries, the specific energy would be 160 Wh/kg at pack level. The calculation of the specific power at pack level is less straightforward. When fully charged, the specific peak power could be around 280 W/kg [DOE, 2007]. Although this is a substantial improvement, the USABC requirements are not met. Not only are the specific energy and power below what is needed for BEVs, also the energy/power ratio is too low; 1.75.
Nevertheless, estimations made at the ARPA-E workshop state that the upper limits for energy and power are 300 Wh/kg and 1500 W/kg respectively [ARPA-E, 2009]. This suggests that requirements could be achieved in the long run. But, this demands serious technological improvements, especially with regard to power.

There was no information found about how the specific energy and power of ZEBRA batteries could improve over time. However, the scale at which ZEBRA batteries are developed and marketed currently is much smaller than for Li-ion batteries. Therefore, a yearly improvement of 6% in specific energy seems unlikely. Table A2.2 shows how the specific energy would increase at an improvement rate of 2% and 4%.

Table A2.2: Specific energy increase of ZEBRA batteries at 2% and 4% annual improvement rate

Year	Specific energy (Wh/kg) 2%/year improvement	Specific energy (Wh/kg) 4%/year improvement
2010	115	115
2015	127	140
2020	140	170
2025	155	207

At an improvement rate of 4% the required specific energy of 200 Wh/kg could be achieved in 2025. To attain an energy/power ratio of 1:2, the specific power should improve at a higher rate. This rate should be 4.5% or 6.6% respectively to reach the required ratio in 2020. The rate is higher or lower when the ratio should be achieved earlier or later respectively.

Lifetime and cycle life

As was already discussed, degradation of the cathode through cycling takes place. As this causes a decline of the battery capacity, it also limits the cycle life of the battery. Changes in cathode chemistry and structure should therefore be prevented [Lu et al., 2010].
Furthermore, also degradation the ceramic electrolyte takes place by the formation of cracks. Degradation can be limited by increasing the fracture strength of the electrolyte. This strength depends on the electrolyte's micro structure (porosity and grain size) and increases with higher density of the electrolyte material and smaller grain size. Large grains, cracks, pores and impurities in the material affect the mechanical strength of the ceramic. The fracture strength can be enhanced by addition of ZrO_2 into the crystal structures. This improves the battery life and recharge time; higher charge currents can be applied without the occurrence of electrolyte degradation [Lu et al., 2010].

Prospects lifetime and cycle life

The present lifetime and cycle life of ZEBRA batteries do fulfill the USABC goals. Also, it is claimed that ZEBRA batteries have a coulombic efficiency of 100% [Sudworth, 2001]. As the improvement of specific energy and specific power is of more importance, it is expected that the lifetime and cycle life will remain constant. Nevertheless, Lu et al. [2010] state that a cycle life of more than 2000 cycles was demonstrated at cell level. Therefore, it is assumed that the present cycle life 1000 cycle could eventually improve to 1500 cycles.

Operating temperature

The operational temperature is kept high in order to attain good ionic conductivity of the ceramic electrolyte. However, the elevated temperature also has some disadvantages. For example, thermal insulation is needed to prevent thermal energy losses [Sudworth, 2001]. Reduction of the temperature could positively affect thermal management and lifetime of materials or allow the use of other materials. As was discussed earlier, this could be achieved by improved conductivity of the ceramic at lower temperature or by using alternative electrolytes [Lu et al., 2010]. An option could be NASICON, a ceramic material [Lu et al., 2010]. Also, the cathode chemistry should be adapted to make operation at lower temperatures possible.
However, reduction of the temperature is limited by the melting point of sodium. To make ambient temperature operation possible would require radical changes in battery design and chemistry [Lu et al., 2010].

Prospects temperature

Besides specific energy and power, reducing the operating temperature is an important issue. ZEBRA batteries can certainly profit from the development of materials for room temperature sodium ion batteries. But is unclear how the operating temperature could reduce in time.
The personal view of Tarascon [2010] is that room temperature sodium ion batteries could be commercialized after 2020. Thus, ZEBRA batteries at intermediate operating temperature (lower than present, but above room temperature) might be available on a shorter term. Nevertheless, it takes 6 to 10 years to develop and apply a new material [W. Robers, personal communication, June 14, 2010].
Galloway and Dustmann [2003] state that the heat conductivity of an insulated ZEBRA battery pack is 0.006 W/mK. When in use, enough heat is produced by efficiency losses to keep the battery temperature constant [Meridian International Research, 2005]. However, when the battery (or electric car) is not used, energy is needed to heat the battery. Table A2.3 shows how much energy is needed at different operating temperatures of the battery.

Table A2.3: Power requirement to maintain the operating temperature of the ZEBRA battery, assuming an ambient temperature of 20 °C.

Operating temperature (°C)	Delta Temp (K)	Heat loss /power required (kW)
300	280	1.68
200	180	1.08
100	80	0.48
50	30	0.18

Safety and reliability

When the ceramic electrolyte has small cracks or breaks, the $NaAlCl_4$ electrolyte reacts with the molten sodium and salt and aluminum are formed. Small cracks are closed by the reaction products, otherwise the cell is short-circuited. In the latter case, other cells in the battery pack can continue to operate. Only the voltage will be reduced by the voltage of the broken cell [Dustmann, 2004]. 5 to 10 % of the cells can fail before further operation of the battery pack is not possible anymore [Dustmann, 2004]. Thus, breakdown of the ceramic electrolyte does not cause safety problems. Also, overcharge and overdischarge do not pose serious problems to battery operation. Still, cell voltage may drop and undesirable loss of electrolyte and current collector material can take place [Lu et al., 2010].

II.III Lithium Sulfur

Cycle life

In completely charged lithium sulfur batteries, lithium ions (Li^+) and sulfur (S_8) exist as active materials. During discharge, the sulfur is lithiated and lithium-polysulfides are formed (Li_2S_x). High order Li-polysulfides (x=3 to 8) are soluble in the liquid electrolyte, migrate to the anode and dissolute into lower order Li-polysulfides. The migration of the polysulfides is called the polysulfide shuttle mechanism, see figure A2.3 [Nazar, 2009; Sion Power, n.d.]. Finally, solid Li_2S_2 is formed and transforms to Li_2S. This last reaction product is stored in the cathode and is the result of complete discharge [Sion Power, n.d.].

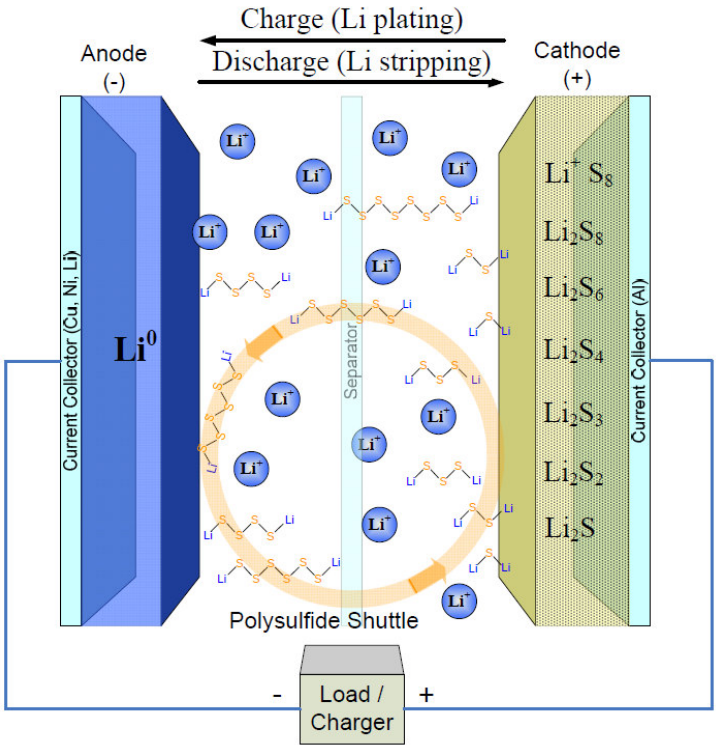


Figure A2.3: Li-S battery, polysulfide shuttle [Sion Power, n.d.]

At recharge, Li_2S is again transformed to lithium-polysulfides that have to oxidize to Li^+ and S_8. However, the shuttle mechanism prevents complete recharge; because this mechanism also works during the charging process, it counteracts the complete oxidation of the polysulfides [Aurbach, 2009]. As a result, recharge is only possible to 50-75% of original cathode capacity, i.e. the utilization of sulfur is low, and the cycle life is limited substantially [Aurbach, 2009].
Several strategies to maximize the utilization of sulfur are under consideration. First, additives in the liquid electrolyte can control the polysulfide shuttle [McKenna, 2010]. Another solution is the use of non-liquid electrolytes. Amongst others, polymer electrolytes have been widely considered [Zhang et al., 2009]. For example, composite polymers are regarded as a good option [Zhu et al., 2005]. Also, ionic liquids are examined [Cairns, 2009].
Finally, modification of the sulfur cathode is an approach to enhance sulfur utilization and cycle life [Cairns, 2009]. Sulfur composite cathodes can overcome problems related to the use of elemental sulfur. Also, nanostructured cathodes and/or cathode additives inhibit polysulfides to diffuse away from the cathode and positively affect the cycle performance [Nazar, 2009; Zhang et al., 2009]. Besides, improved cathode structures increase the electrode capacity (hence discharge capacity) and rate capability [Sion Power, n.d.; Zhang et al., 2009].

Prospects cycle life

The present cycle life of Li-S batteries is low, about 100 cycles [Kalhammer et al., 2007]. However, Cairns [2009] states that cycle lives of more than 500 cycles are demonstrated and sulfur utilization of more than 90% can be achieved with the use of ionic liquids. Sion Power [n.d.] even states that their technology achieves 100% sulfur utilization by the usage of additives.
Also, Sion Power has the aim to achieve cycle lives of 500 and 1,000 cycles for their cells to be produced in 2012 and 2016 respectively [ARPA-E, 2009; Green Car Congress, 2010b]. Furthermore, Sion Power [n.d.] states that the highest cycle life can be attained at 100% depth of discharge.

Operating temperature

In contrast with Li-ion batteries, lithium-sulfur batteries perform well at low temperatures. Although their specific energy does decline, values of 100 Wh/kg or more are demonstrated at -60 °C [ARPA-E, 2009; Sion Power, n.d.]. Also, Sion Power [n.d.] stated that their battery can be recharged at -60 °C. However, thermal runaway of the battery is an important issue at high temperatures. This can be prevented by a protective layer on the anode [Sion Power, n.d.].

Safety

Theoretically, liquid (non aqueous) as well as solid state electrolytes can be used for batteries that contain metallic lithium. However, the reactivity of metallic lithium in liquid electrolytes is a problem: the lithium metal anode corrodes in the electrolyte and a non reactive layer forms on the electrode surface. The effect of this (non-uniform) layer is that lithium deposits irregularly on the anode during charge-discharge cycling and so called dendrites (branched shapes) can form. These dendrites can ultimately cause short circuit in the cell [Scrosati et al., 2001; Yang et al., 2010]. This problem can be solved in two ways.
The first method is replacing the liquid electrolyte by a liquid free membrane [Scrosati et al., 2001]. Often, a solid polymer electrolyte is chosen as the liquid free membrane [Scrosati et al., 2001]. Present polymer electrolytes are mainly PEO-LiX polymers; poly(ethylene oxide) hosting a lithium salt. As a result of ceramic additives, dendrite formation is largely prevented [Scrosati and Garche, 2010]. Another advantage of polymer electrolytes is the lack of liquids and flammable components.

This prevents thermal runaway, which is considered to be an important problem in Li-ion batteries [Berkeley Lab, 2008]. On the other hand, the stability window of the composite electrolytes is limited. This might restrict the use of high voltage cathodes to prevent serious decline of the cathode capacity [Croce et al., 2003; Jiang et al., 2005].
Second, an alternative anode material could be used instead of replacing the electrolyte. An example is the use of silicon as substitute for metallic lithium [Yang et al., 2010].

Specific power and specific energy

Sulfur has a low electronic and ionic conductivity. This restricts the power rate of the battery. Therefore, it has to be combined with a good conducting agent to form the positive electrode, for example in a carbon/sulfur (nano)composite or by the use of metal additives [Nazar, 2009; Yang et al., 2010].
As discussed for the cycle life of the Li-S battery, low sulfur utilization reduces the cathode capacity considerably [Cairns, 2009]. Therefore, it also restricts the specific energy of the battery. Hence, strategies to maximize sulfur utilization do also help to increase the specific energy.
On the other hand, safety measurements might negatively affect the specific energy. The theoretical specific energy will be lowered when a non-metallic lithium anode and adapted sulfur cathode are used (for example a Si-Li_2S anode-cathode couple as proposed by Yang et al. [2010]).

Prospects specific power and specific energy

Rechargeable Li-S batteries from Sion Power, as demonstrated in unmanned aerial vehicles, consisted of cells with a specific energy of 350 Wh/kg and a specific power of 100-200 W/kg [Sion Power, 2010; Mikhaylik et al., 2008]. However, higher power levels are already achieved. Kalhammer et al. [2007] indicate that Sion Power has developed Li-S cells with a specific power of more than 600 W/kg. Also, in the APRA-E summary report, current power levels are stated to be above 400 W/kg [ARPA-E, 2009].
Moreover, through improvements cells have demonstrated specific power up to 3500 W/kg [Mikhaylik et al., 2008]. However, the specific energy declines substantially with increasing specific power (figure A2.4); at continuous discharge a specific power up to 2000 W/kg can be achieved at 200 Wh/kg. Higher specific power values can only be achieved by short period (10 s) high current pulses [Mikhaylik et al., 2008].

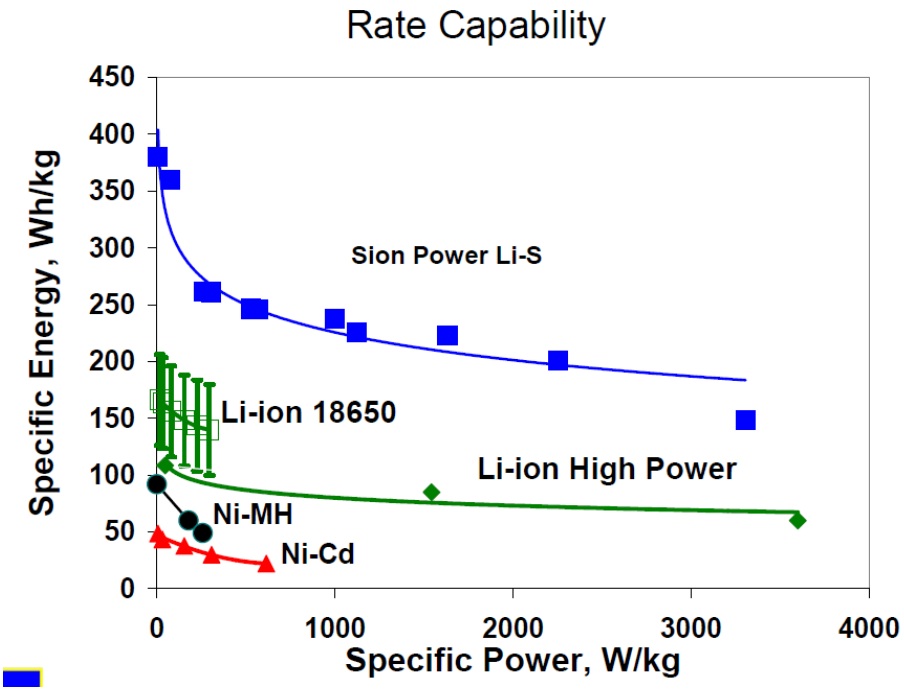


Figure A2.4: Relationship between the specific energy and specific power of lithium-sulfur and other batteries [Sion Power, n.d.]

Furthermore, Sion Power has the aim to produce Li-S cells for BEV purposes with a specific energy of 550 Wh/kg in 2012 and of 600 Wh/kg in 2016 [ARPA-E, 2009; Green Car Congress, 2010b]. This corresponds to the aim stated by Nazar [2009] to develop cells of 550-650 Wh/kg. The specific energy will be lower at battery pack level. However, it is not clear what the utilization rate will be. Table A2.4 shows the impact of various rates for the specific energy at pack level, assuming a low, middle and high specific energy at cell level.

Table A2.4: Potential specific energy of a Li-S battery pack, considering various values for the utilization rate and cell specific energy

	Cell specific energy (Wh/kg)	Pack specific energy (Wh/kg) - utilization 0.6	Pack specific energy (Wh/kg) - utilization 0.7	Pack specific energy (Wh/kg) - utilization 0.8
Middle	550	330	385	440
Low	450	270	315	360
High	625	375	438	500

Commercialization

As stated before, Sion Power has the aim to produce Li-S cells for BEV purposes with a specific energy of 550 Wh/kg in 2012 and of 600 Wh/kg in 2016 [ARPA-E, 2009; Green Car Congress, 2010b]. After cell production, prototype testing and battery pack production will take about another 4 years before the Li-S battery can be brought to the market [W. Robers, personal communication, June 17, 2010; Matheys and Van Autenboer, nd]. Thus, commercialization could start from approximately 2020. This is in line with the expectations of Tarascon [2010].

II.IV Metal-air

Specific energy and energy density

The theoretical specific energy of metal-air batteries is very high. However, there should be given some short comments on this. The theoretical specific energy of lithium-air batteries, for example, is 11,000 Wh/kg. But, this value only accounts when oxygen from the air is not taken into account. During discharge, reaction products that contain oxygen form in the cell. Therefore, the mass of oxygen in the cell increases with discharge and causes the mass of the battery to increase as well [ARPA-E, 2009]. As a result, the adjusted theoretical specific energy of a lithium-air battery is 3,500-5,000 Wh/kg [Thackery, 2009].
In addition, lithium is very light. Therefore, the impact of non-active materials on the weight, and thus specific energy, of a complete battery pack will be higher compared to other battery technologies [Green Car Congress, 2010].

Besides, energy density (Wh/liter) is of importance to limit the volume of the battery. When comparing metal-air with Li-ion cells on energy density, the difference is much smaller than for the specific energy. This has two reasons. First, the cathode needs to be porous to maximize oxygen flow from the air into the cell. Therefore, its volume is high [ARPA-E, 2009]. Second, excess lithium is needed for efficient cycling. This excess might be three times the theoretical amount needed and drastically decreases the energy density. Therefore, cycling of lithium should be more effective to limit the need for lithium excess [Green Car Congress, 2010a; Dahn, 2009].

Zinc flow battery

The development of Zn-air batteries by ReVolt focuses on applications for consumer electronics. However, they are also looking at EV purposes. For electric vehicles, however, they are developing a new type of Zn-air battery. The anode is liquid zinc slurry that flows from a storage compartment through the air cathode (tubes). After the oxidation reaction with air, zinc oxide flows to a second storage compartment. Here, the slurry is stored until recharge; during charge it flows in the opposite direction [Bullis, 2009b].
The theoretical specific energy of this battery system is lower than for current Zn-air designs (depending on the size of the storage tanks). However, because of the amount of zinc that can be stored in the tank, the energy density (Wh/l) would increase compared to standard zinc-air batteries [Bullis, 2009b].

Prospects specific energy

Zinc-air cells showed a specific energy of 400 Wh/kg in tests [ARPA-E, 2009]. However, Girishkumar [in: Green Car Congress, 2010a] states that "existing metal-air batteries, such as Zn-air, typically have a practical energy density of about 40-50% of their theoretical density"[2]. It is assumed that primary (non-rechargeable) batteries are denoted here. If such percentages can be attained with batteries for BEV purposes, the specific energy can increase to 480-600 Wh/kg at cell level.
The theoretical specific energy of a zinc-air flow cell is stated to be 800 Wh/kg, which is significantly below conventional zinc-air cells [ARPA-E, 2009]. The present specific energy tested at cell level is 300 Wh/kg [ARPA-E, 2009]. However, it is not clear what the utilization rate will be at pack level. Table A2.5 shows the impact of various rates for the specific energy at pack level, assuming a low and high specific energy at cell level.

[2] Note that the term energy density refers here to the specific energy in Wh/kg

Girishkumar [in: Green Car Congress, 2010a] states that the utilization factor of Li-air cells will be below that of Zn-air cells; because of the very low weight of lithium, the impact of other materials will be much higher. Also, "the energy density of the complete battery system may be only half of the density realized at the cell level"[2] [Girishkumar in: Green Car Congress, 2010a]. Girishkumar states that 1700 Wh/kg at cell level will be achievable. Then, this would result in a specific energy of about 850 Wh/kg at pack level (approximately 15% of theoretical value).
Kumar et al. [2010] expect that the specific energy of lithium-air cells could exceed 1,000 Wh/kg in practical configurations. This corresponds to the belief of Tarascon [2010] that the specific energy of Li-air batteries will be 500 Wh/kg at commercialization.
Researchers from the Argonne National Laboratory (ANL) estimate that Li-air batteries could have a specific energy that is five to ten times greater than of Li-ion batteries. This would mean that a specific energy of 1,000 Wh/kg or more could be achieved at pack level [ANL, 2009]. Kumar et al. [2010] estimate that Li-air batteries could ultimately even attain specific energies of 3,000 Wh/kg. However, it can be questioned if this will also be the case for batteries for BEV purposes. At present, the highest specific energy attained is reported to be 362 Wh/kg for a Li-air cell laboratory test model [Zhang, 2010; Kraytsberg and Ein-Eli, 2010].

Table A2.5: Potential specific energy of a Zn-air battery pack, considering various values for the utilization rate and cell specific energy

	Cell specific energy (Wh/kg)	Pack specific energy (Wh/kg) - utilization 0.5	Pack specific energy (Wh/kg) - utilization 0.6	Pack specific energy (Wh/kg) - utilization 0.7
Low	300	150	180	210
High	600	300	360	420

Cycle life

In metal-air batteries, aqueous as well as non-aqueous electrolytes can be used. For a lithium-air battery, the chemistry of depends on the chosen electrolyte type. The reactions for aqueous and non-aqueous electrolytes are given in table A2.6.

Table A2.6: Chemical reactions for a Li-air battery with an aqueous or non-aqueous electrolyte [Green Car Congress, 2010a; ARPA-E, 2009].

	Li-air
Non-aqueous electrolyte	$2Li + O_2 \leftrightarrow Li_2O_2$ (dominant reaction) $4Li + O_2 \leftrightarrow 2\ Li_2O$
Aqueous, basic electrolyte	$4Li + O_2 + 2H_2O \leftrightarrow 4LiOH$
Aqueous, acidic electrolyte	$4Li + O_2 + 4H^+ \leftrightarrow 2H_2O + 4Li$

For Li-air batteries, non-aqueous (organic) electrolytes are widely considered because of the aggressive reactivity of lithium with water. However, their use has also disadvantages. The most important issue is the solubility of lithium peroxide and lithium oxide (Li_2O2 and Li_2O) in the electrolyte. As this solubility is low, the reaction products cause clogging of the porous cathode. This restricts further discharge and limits the discharge capacity [ARPA-E, 2009; Zhou, 2009]. Besides, it negatively affects the cycle life of the battery as the discharge capacity declines further after each cycle [ARPA-E, 2009; Ogasawara et al., 2006]. Catalysts are needed to enhance the solubility of the discharge reaction products and to limit clogging [Scrosati et al., 2010; Bullis, 2010].

Zinc-air batteries generally contain an aqueous electrolyte. However, through interaction with the battery's environment, water from the electrolyte can evaporate and cause dry out of the battery [Hamilton, 2009; ReVolt, 2007]. Besides, the electrochemical window of the electrolyte is relatively low, which means that its decomposition will already start at low voltages. The company Fluidic Energy aims to solve these two problems by replacing the water based electrolyte with ionic liquids. They state that ionic liquids have a larger electrochemical window and dry out of the battery does not take place anymore [Hamilton, 2009]. ReVolt does not change the electrolyte, but modifies it by using gelling and binding agents. These agents prevent dry out and also dendrite formation [Bullis, 2009]. Through such adaptations, dendrite formation has been overcome and is not considered anymore as an urgent issue for further development of zinc-air batteries [ARPA-E, 2009; ReVolt, 2007].

Next to the electrolyte, there are also other sources that limit the cycle life of zinc-air batteries. First, at high currents degradation of the air cathode takes place [ReVolt, 2007]. ReVolt, a company that develops zinc-air batteries, states that degradation can be limited by good cell design. Proper choices with regard to materials and electrode structure are important [ReVolt, 2007].
Second, at open circuit, i.e. when the battery is not (dis)charged, dissolution of the zinc electrode occurs and capacity is lost. This is called self-discharge [ReVolt, 2007]. ReVolt prevents its batteries from self-discharge by alloying the zinc electrode [ReVolt, 2007].

Prospects cycle life

At present, 500 cycles for Zn-air batteries are achieved in laboratory tests [ARPA-E, 2009]. Yet, ReVolt expects their EV (flow) batteries can last 2,000 to 10,000 cycles [Bullis, 2009b]. For lithium-air batteries, no information was found on their potential cycle life.

Power

The specific power of metal-air batteries is low. This is due to slow (dis)charge kinetics at the cathode and catalysts are needed to enhance charge and discharge reactions [ARPA-E, 2009]. Furthermore, the electric current density (mA/cm^2) of Li-air cells is very low. Thus, in order to deliver the required power the total internal surface of the cell has to be very large. Mesoporous cathode material provides a high surface area and short lithium ion diffusion distances [Bruce, 2007]. As the volume of the battery should be limited, the current density of Li-air cells has to be increased substantially [Green Car Congress, 2010a].

Prospects specific power

No information could be found on what levels of specific power can be attained with metal-air batteries. Presently, the specific power of Li-air cells achieved in laboratory tests is approximately 0.46 mW/g; about a tenth compared to commercial (consumer electronic) Li-ion cells [Kraytsberg and Ein-Eli, 2010]. Also, Scrosati [personal communication, September 8, 2010] states that the power capability will be low, as these batteries are developed for high energy content.

Efficiency

The charging voltage of metal-air batteries is considerably higher than the discharge voltage. This is called overvoltage or overpotential. As a result, the energy delivered by the battery at discharge will always be less than the energy delivered to the battery at charge. Therefore, the charge-discharge

efficiency is only 60-70% for Li-air batteries and 65-70% for Zn-air batteries [Green Car Congress, 2010a; ARPA-E, 2009]. For Zn-air batteries, the target is to achieve an efficiency of 80% in the future. A catalyst can reduce the overvoltage and promote the charge and discharge reactions [Bullis, 2010; ARPA-E, 2009]. MIT researchers state that they were able to achieve 77% cycle efficiency for Li-air by using platinum and gold as catalysts for the charge and discharge process respectively. Also, an efficiency of 85-90% could be achievable in the future [Bullis, 2010].

Prospects efficiency

The present charge-discharge efficiency is only 60-70% for Li-air batteries and 65-70% for Zn-air batteries [Green Car Congress, 2010a; ARPA-E, 2009]. MIT researchers state that they were able to achieve 77% cycle efficiency for Li-air by using platinum and gold as catalysts for the charge and discharge process respectively. Also, an efficiency of 85-90% could be achievable in the future [Bullis, 2010]. For Zn-air batteries, the target is to achieve an efficiency of 80% in the future [ARPA-E, 2009].

Safety and reliability

It is widely believed that metal-air batteries have a safety advantage compared to Li-ion batteries. This is due to the fact that oxygen is not stored in the cell. Therefore, the energy for reactions that can cause thermal runaway is not available in the battery [Green Car Congress, 2010a; ARPA-E, 2009].

However, lithium-air batteries do, like other metallic lithium battery types, face safety problems due to dendrite formation. Therefore, solutions as discussed before for Li-S batteries do also apply to Li-air technology; alternative anode materials like (lithium-)silicon and/or alternative electrolytes could be used to restrict dendrite formation [Scrosati et al., 2001; Yang et al., 2010].
Furthermore, metallic lithium reacts very aggressively with water. Besides, also other contaminants can reduce the battery performance. Carbon dioxide, for example, causes carbonation of the electrolyte [Green Car Congress, 2009d]. Therefore, a membrane is needed that only permeates O_2. Thus oxygen has to be separated from ambient air, such that the inlet of H_2O, CO_2 and other components is avoided [Green Car Congress, 2010a]. Also, a protective layer over the lithium electrode can prevent lithium metal and water to come into contact [Frost & Sullivan, 2009]. PolyPlus has shown that operation of a battery with a coated lithium anode is even possible in water [Polyplus, 2009; Frost & Sullivan, 2009].

The safety of zinc-air batteries seems to be quite good; short circuit as well as over(dis)charge have no safety or damage implications. At short circuit, the battery's chemistry shuts the battery down and no further operation and discharge can take place. Besides, air supply can be shut off to stop battery operation [Tahil, 2007]. Also, it is stated that zinc air batteries do not contain volatile materials that can cause aggressive reactions like in some Li-ion batteries [Bullis, 2009b].
However, at a workshop on electrical energy storage for vehicles of ARPA-E (Advanced Research Projects Agency – Energy, part of the U.S. Department of Energy), it was stated that the abuse tolerance of Zn-air batteries has not been tested yet [ARPA-E, 2009].

Commercialization

The commercialization of metal-air batteries is believed to take place from 2020 [James Miners in: Cars21, 2010; Tarascon, 2010]. As the development of Zn-air batteries is in a more proceeded stage, these batteries are projected to be earlier available for battery electric cars. The development of Li-air batteries requires essential technological improvements. Thus, their commercialization is highly

dependent of how fast progress will take place. Besides, even if the feasibility of Li-air batteries is proven for consumer electronics, it will take more time before their viability for automotive applications will be demonstrated [ARB, 2009].
Nonetheless, the US company Excellatron Solid State claims that it recently has demonstrated the feasibility of rechargeable Li-air batteries and has already delivered demonstration samples to costumers [Excellatron, 2010]. The company Frost & Sullivan [2009] states that commercialization of Li-air batteries by this company will take place on a very short term. They also expect that Li-air batteries from other developing parties can be commercialized within five years [Frost & Sullivan, 2009]. If this is the case, Li-air batteries for BEVs will profit from technological developments made for these consumer electronic batteries. According to researchers from the Argonne National Laboratory (ANL), commercialization can start in one or two decades [ANL, 2009].

Appendix III: Battery cost projections

Literature

Li-ion

Table A3.1 gives an overview of cost projections for lithium-ion batteries as found in various sources. These do differ substantially from each other, which can partially be explained by differences in production volume and battery capacity. However, often these conditions are not provided and it remains unclear what assumptions the projections are based on.

Table A3.1: Cost projections for Li-ion batteries for BEV purposes

Source	year	Production conditions	Cost ($/kWh)	Cost ($2010/kWh)
IEA, 2008	2010		800	810
	'long term future'		300	304
IEA, 2009	Near term	High volume	500	508
ARB, 2009	After 2015	High volume	<400	<406
	Longer term future	High volume	<300	<305
	Near term [1]	Moderate volume	500-600	508-610
	Next generation battery design [1]	Moderate volume	400-500	406-508
Matheys and van Autenboer, n.d.	2012-2015		500	577 [2]
Kalhammer, 2007		20,000 bat/yr	306 (40 kWh) 475 (25 kWh)	322 499
		100,000 bat/yr	210 (40 kWh) 326 (25 kWh)	221 343
Van Vliet, 2010	2015		800 euro/kWh	1056
	Longer term		400 euro/kWh	528
Bandivadekar et al., 2008 Based on: Kromer and Heywood, 2007 Based on: Anderman et al., 2000 Gaines and Cuenca, 2000	2035 2030	 100,000 bat/yr	250 (48 kWh) 250 (48 kWh) 270 224	253 263 342 284
Anderman, 2010	2015 2018-2020	500 MWh (20,000 bat/yr) 2500 MWh (100,000 bat/yr)	500-700 375-500 (25 kWh)	500-700 375-500
Offer et al., 2010 Based on: BERR & DfT, 2008 [2]	2030 2010 2020 2030		200-300 £18,000 £8750 £1800 (35 kWh)	200-300 966 470 97
BCG, 2010 (2009 costs)	2010 2020	500 bat/yr 1.1 million bat/yr	990-1220 360-440 (15 kWh)	1006-1240 366-447
Lache et al., 2008	2015		500 (22 kWh)	506
Lache et al., 2009	2010 2015 2020	100,000 bat/yr >100,000 bat/yr ,, ,,	456 370 245 (25 kWh)	463 376 249

[1] As reported by some automakers inquired by ARB; [2] Cost projection assumed to be made in 2004; report was not dated, but related paper on SUBAT project states that the project officially ran from 1 January 2004 to 31 March 2005 [Van den Bossche et al., 2006].

It is tried to make a graphical representation of these figures by assuming the following definitions: Near term: 5 years from now, 2015; long(er) term: 15 yrs from now, 2025; moderate volume production: >10,000 batteries/yr; high volume production: >100,000 batteries/yr.
Figure A3.1 shows a progressive and conservative scenario based on optimistic and pessimistic projections from table A3.1 respectively. Thus, the lines give a bandwidth within which cost reduction could take place.
The projections of Kalhammer et al. [2007] and Anderman et al. [2000] are not represented in figure 6 as these are only based on yearly production volumes. No statements are made about when these volumes could be achieved. Also the projection of and Gaines and Cuenca [2000] is not represented as no statements were made about production volume and year. The 2030 projection of BERR & DfT [2008] and the projections of Van Vliet [2010] are given individually, as they are very opportunistic and pessimistic respectively compared to the other estimates. Also, projections from the Deutsche Bank [Lache et al., 2009] are shown separately. These figures do assume current costs to be already 455 $/kWh at high volume production. Furthermore, the projections for 2015 and 2020 are even more optimistic than the progressive scenario.

The scenarios from figure A3.1 show that costs are expected to reduce significantly in the next five years; after 2015, costs will keep declining at a lower rate. The former can be explained by the considerable expansion of battery production volumes. According to Dan Galves [personal communication, August 30, 2010], associate analyst at the Deutsche Bank, current cost estimates of 800-1000 $/kWh are based on the exact cost of batteries today. However, these costs are based on very low production levels for prototype and vehicle testing. For expected production volumes of 15-30 thousand batteries per year in the near term (2012 and beyond) costs could reduce to 500$/kWh and less [D. Galves, personal communication, August 30, 2010].

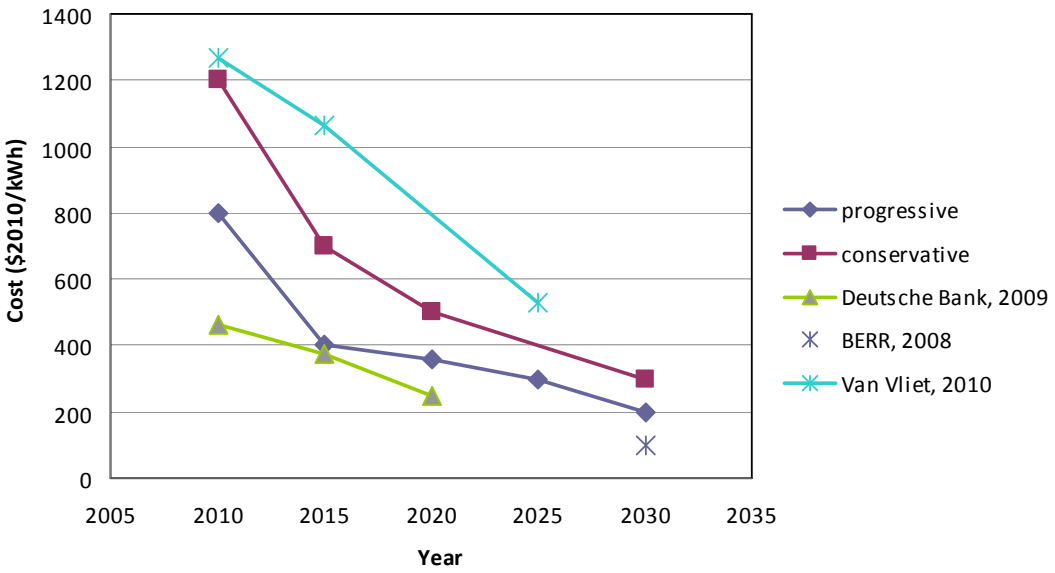


Figure A3.1: Cost reduction scenarios based on projections from table 5, assuming conservative and progressive cost reduction (at moderate and high volume battery production respectively).

Furthermore, Galves states that production volumes of 100,000 batteries per year can be reached by manufacturers in 2015 as they produce batteries for more than one EV program. According to the report of the Deutsche Bank, about half of the key battery producers will have reached capacities of 2,500 MWh (BEV-volume equivalent of 100,000 batteries) per year or more in 2015 [Lache et al., 2009]. A volume inflection point is expected in 2012 [Lache et al., 2010].
However, the cost projections in table A3.1 do not show a coherent view on when high volume production can be reached and on what rate costs will decline with production expansion. This will be further looked at later in this section.

ZEBRA
For ZEBRA batteries, cost projections were found in Kalhammer et al. [2007]. These are related to the annual production volume (table A3.2). It is not stated when these volumes could be reached. Furthermore, on the Solartaxi website it is stated that the cost of a 14.1 kWh ZEBRA battery is believed to reduce to €2000, which is approximately 200 $2010/kWh [Solartaxi, n.d.]. Finally, Galloway and Dustmann [2003] even state that battery costs can potentially reduce to about 86 $2010/kWh at high volume production.

Table A3.2: Cost projections for ZEBRA battery as function of production volume [Kalhammer et al., 2007]

Battery systems/yr	Cost ($2007/kWh)	Cost ($2010/kWh)
1,000	600	631
10,000	335	352
20,000	275	289
100,000	200	210

Other battery technologies
For battery technologies other than Li-ion and ZEBRA, less information is available about costs. However, a few statements about potential costs were found. According to the ARPA-E summary report, it is thought that zinc-air could reach costs below 100 $/kWh [ARPA-E, 2009]. Also, in the same report it is stated that the chance for lithium-sulfur batteries to achieve 250 $/kWh is high. For lithium-air batteries, no cost estimates were found.

Learning

Table A3.3 gives an overview of progress ratios found in literature and derived from cost data found in different sources (see appendix III). The progress ratios vary from 83% to 91%. The ratios are lowest for Li-ion batteries and highest for NiMH batteries. However, only the progress ratio from Nagelhout and Ros [2009] is based on historic battery cost data. The other progress ratios are derived by using cost projections for defined production volumes or capacities. Thus, these are not based on historic cost reductions.
However, the values can be used as an indication of how battery costs could develop in the future. For Li-ion batteries, projections on global BEV sales are used (table A3.4). The related annual battery production volumes are shown in figure A3.2. Based on these projections, a scenario is defined assuming sales take-off from 2012 and increase to 1.5 million BEVs per year in 2020. This scenario is in accordance with the steady pace scenario from the Boston Consultancy Group [2009] and the projections from Bosch [in: Green Car Congress, 2010d] and Lache et al. [2008].

Table A3.3: Progress ratios for batteries, from literature [Nagelhout and Ros, 2009] and derived from data found [Kalhammer et al., 2007; Toyota, 2009; IIT, 2005; Kamath, 2009]

Source	PR	Battery type	Time	R^2	Notes
Nagelhout and Ros, 2009	83%	Li-ion cells for consumer electronics	1993-2003	n/a	
	89.8%	NiMH for HEVs	1997-1998	0.9845	Based on HEV sales numbers from Toyota [2009] and cost projections from Kalhammer et al. [2007]
	91.0%	NiMH for HEVs	1998-2004	0.9312	Based on global HEV sales numbers from IIT [2005] and cost projections from Kalhammer et al. [2007]
	83.7%	Li-ion		0.989	Derived from cost curve from Kamath [2009] (based on costs estimates from 5 studies; 15% cost reduction with doubling of production volume)
	83.4%	Li-ion		0.991	Derived from cost curve from Kamath [2009] (based on costs estimates from 1 study; 10% cost reduction with doubling of production volume)
	84.6%	ZEBRA		0.9955	Based on cost projections of Kalhammer et al. [2007], assuming an average battery capacity of 21 kWh (based on production capacity per year, not cumulative capacity)

The resulting cumulative battery production is 7.1 million 2020. Assuming an average battery capacity of 25 kWh [Lache et al., 2009], the cumulative battery capacity will increase to almost 180,000 MWh in 2020. Using progress ratios of 90% and 83% and present battery cost of 1200 and 800 $/kWh, it is shown in figure A3.3 how costs can reduce according to this production scenario. From figure A3.3, it can be derived that battery costs can be between 210 and 611 $/kWh in 2020. An expansion of annual battery production volumes to more than 1.5 million batteries in 2020 would result in steeper cost reduction and costs could even drop below $200/kWh. However, no lower limit for costs is taken into account here. But, there will be a certain point at which costs cannot be reduced any further because of volume independent cost components (for example raw material prices). In the next section it will be assessed what this limit is.

Table A3.4: Projections of global BEV sales, annual volumes.

Year	BCG, 2009 Steady pace scenario [(1)]	BCG, 2009 acceleration scenario [(1)]	Bosch, 2010 (BEV+PHEV) [in: Green Car Congress, 2010d]	AAB, 2010 [in: Green Car Congress, 2010c]	Lache et al., 2008	Lache et al., 2009
2010						56,000 (0.1%)
2012			300,000 (total 70 million)			
2015				0.13%	470,000	742,000 (0.9%)
2016					621,000	
2017					824,000	
2018					983,000	
2019					1.15 million	
2020	1.5 million (2.7% of total)	5.5 million (10% of total)	3 million (2.9% of total)	400,000 (0.50% of total)	1.26 million	4,092,000 (4.6% of total)

[(1)] Total of four markets: Western Europe, China, Japan and North America [BCG, 2009]

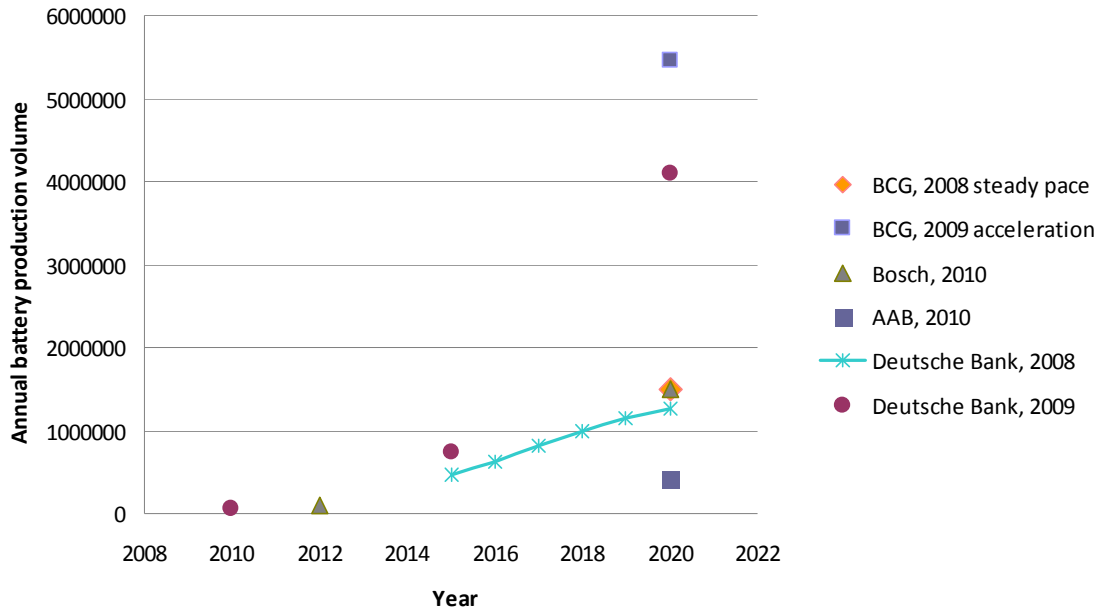


Figure A3.2: Projected annual battery production volumes, based on projected BEV sales.

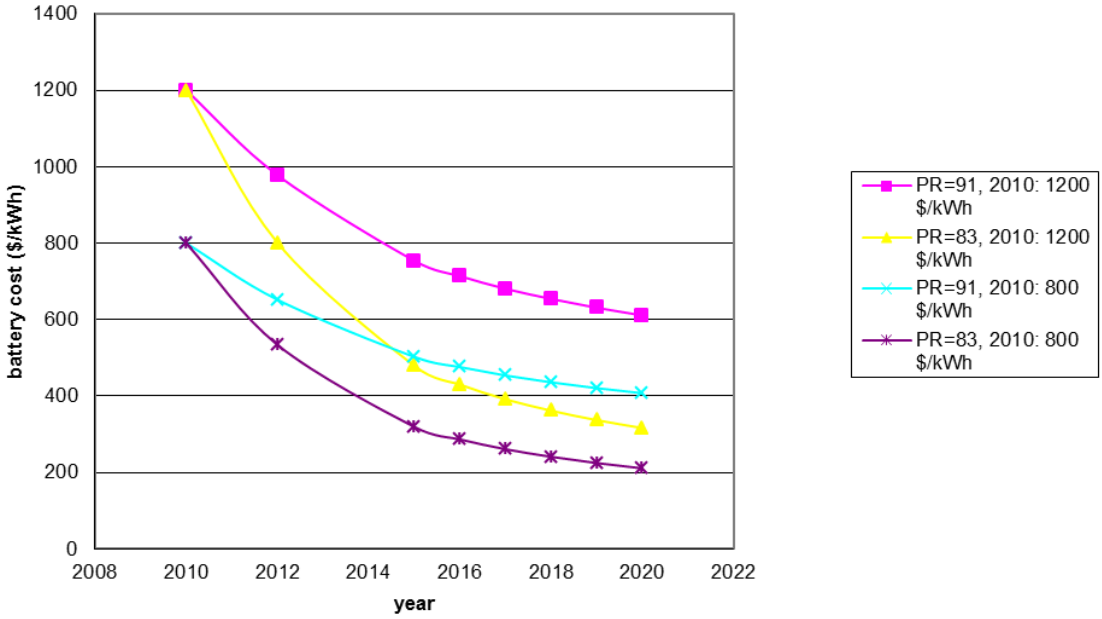


Figure A3.3: Battery cost reduction scenarios based on expansion of annual production volumes to 1.5 million batteries in 2020, present battery costs of 800 and 1200 $/kWh and progress ratios of 83% and 90%.

The same production volume scenario can be applied for ZEBRA batteries (figure A3.4). However, FZ SoNick SA is the only present producer for electric car purposes. Therefore, the scenario is very unlikely for ZEBRA batteries. Therefore, the production capacity numbers of FZ SoNick SA are used to assess potential cost reduction. In 2007, the production capacity was stated to increase from 1,000 to 1,500 batteries per year [Kalhammer et al., 2007]. Cebi, the parent company of FZ SoNick SA, states on its website that FZ Sonick SA has the aim to increase the battery production capacity from 90 MWh in 2010 to 170 MWh in 2015 [Cebi, 2010].

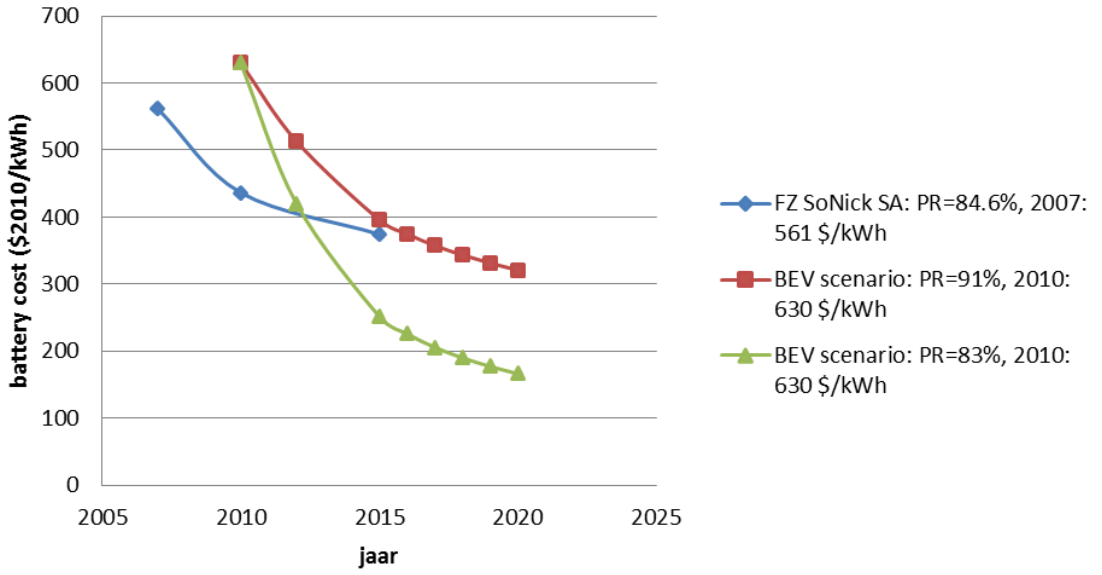


Figure A3.4: Projected ZEBRA battery costs, based on cost data from Kalhammer et al. [2007] and production capacity goals from Cebi [2010].

Applying the progress ratio of 84.6% (15.4% cost reduction trough doubling of annual capacity) to the aimed expansion of production capacity, costs of ZEBRA batteries could reduce from 562 $2010/kWh in 2007 to 436 and 374 $2010/kWh in 2010 and 2015 respectively (figure A3.4).
The present production facility of FZ SoNick has a maximum production capacity of 30,000 batteries per year (approximately 630 MWh/yr). At this capacity, the costs can decline to about 275 $2010/kWh [Dustmann, 2004].

Battery cost breakdown

Li-ion and ZEBRA

The assessment of potential battery cost reduction in the previous sections was based on the expansion of battery production volume and capacity and the battery market. However, it is also useful to consider the breakdown of costs at battery pack and cell level. This will give insight in where cost reductions are possible. Also, it will give a view on what the lower cost boundary might be (i.e. when further cost reduction is restricted because of volume independent cost factors).

The Boston Consultancy Group [2010] and the Deutsche Bank [Lache et al., 2009] give a breakdown of current Li-ion battery production costs for low and high volume production respectively. Also, BCG gives a projection of future battery costs at high volume production. A comparison of the costs is given in tables A3.5 and A3.6.

Table A3.5: Cost breakdown for 2009 low and high volume battery production [BCG, 2010; Lache et al., 2009]

	BCG, 2010 NCA, low volume production (500/yr), 15 kWh		**Deutsche Bank [Lache et al., 2009] NMC, high volume (100,000/yr), 25 kWh**	
	Cell/pack distribution	Cost component distribution	Cell/pack distribution	Cost component distribution
	$2009/kWh	$2009/kWh	$2009/kWh	$2009/kWh
-Active materials (cathode + anode)	118.8-146.4	118.8-146.4	85.6	85.6
-Electrolyte, separator, current collectors	81.2-103.6	81.2-103.6	49.5	49.5
-Other cell materials			57	
-Equipment depreciation, factory overhead, R&D, labor	450-540		103.5	
Cell costs	**650-790**		**295.6**	
-Other materials, purchased parts (casings, electronic and mechanical parts, BMS)		235.6-286.8	149.3	206.2
-Labor		108.9-134.2	10.7	114.2
-Equipment depreciation, factory overhead, R&D		445.5-549		
Pack manufacturing	**340-430**		**160**	
Total costs	**990-1220**	**990-1220**	**455.5**	**455.6**

Table A3.6: Cost breakdown for present low volume and present and future high volume battery production [BCG, 2010; Lache et al., 2009]

	BCG, 2010 NCA, low volume (500/yr), 15 kWh	BCG, 2010 NCA, 2020 high volume (1.1 million/yr), 15 kWh	Deutsche Bank [Lache et al., 2009] NMC, high volume (100,000/yr), 25 kWh
	$2009/kWh	$2009/kWh	$2009/kWh
Cell materials (cathode, anode, electrolyte, separator, current collectors)	200-250	145.8-178.2	135.1
Other cell costs (casing, labor, depreciation, overhead, R&D)	450-540	124.2-151.8	160.5
Other costs (module and pack materials, assembly, depreciation, overhead, R&D)	340-430	90-110	160
Total	**990-1220**	**360-440**	**455.6**

Furthermore, Galloway and Dustmann [2003] state that ZEBRA battery costs can potentially reduce to about 86 $2010/kWh at large volume production. The corresponding cost breakdown is showed in table A3.7. Unfortunately, no breakdown of present ZEBRA costs was found.

The numbers from tables A3.5 and A3.6 show that costs of Li-ion batteries can be reduced at all levels when scaling up to high volume production. At low volume, non-material costs for labor, equipment depreciation, factory overhead and R&D account for more than 50% of total costs. At high volume cost estimates of the Deutsche Bank their share has reduced to 25%. Important drivers for this are experience and economies of scale [BCG, 2010; Lache et al., 2009]. This is not surprising for two reasons. First, low volume production concerns a high share of manual assembly [BCG, 2010]. An increase of the production volume relates to more automation and a reduction of labor [BCG, 2010]. Also, depreciation costs decline as the total equipment costs can be spread over a larger number of products [BCG, 2010].

Table A3.7: Projection of potential cost breakdown for ZEBRA battery [Galloway and Dustmann, 2003]

	$2010/kWh	$2010 (21 kWh)
Cell materials (cathode, anode, electrolyte, current collectors)	33.51	
Cell assembly	16.37	
Module and pack materials	11.10	
Pack assembly	11.10	
Sub Total	**72.09**	**1,513.80**
Controller		296,21
Total	**86.19**	**1,810.01**

Cell costs do account for the largest share of battery costs; about 65% for present BCG and Deutsche Bank estimates, and 75% for future BCG projections. Again, non-material costs can significantly be reduced by scaling-up production volumes. Volume dependent costs could be reduced by approximately 75%. However, also costs of cell materials can be lowered; materials and components can become less expensive when suppliers do also profit from economies of scale [Lache et al., 2009]. Also, through improved battery design, the amount of non-active materials can be reduced. This reduces total material costs as well as specific costs because of a higher specific energy [Lache et al., 2009]. According to the projections of BCG, cell material costs can be reduced with 25%. Furthermore, changes in chemistry can positively affect battery costs. The cost breakdowns from the BCG and the Deutsche Bank are based on cathode materials containing cobalt and nickel. Other cathode materials are less expensive and result in lower materials costs. Table A3.8 gives an overview of prices for different cathode materials.

Table A3.8: Cathode material prices

Cathode material	Price ($2009/kg)	Price ($2009/kWh)	
$LiCoO_2$	35-45		Lache et al., 2009;
	41	84 [(1)]	Howard and Spotnitz, 2007
$Li(NiMnCo)O_2$	20-26		Roland Berger, 2009;
	33	66	Lache et al., 2009
$LiMnO_4$	15-28		Roland Berger, 2009;
			Lache et al., 2009;
	10	28 [(1)]	Howard and Spotnitz, 2007
$LiFePO_4$	15		Lache et al., 2009;
	15-18	~30-36 [(2)]	Roland Berger, 2009;
	16	32 [(1)]	Howard and Spotnitz, 2007
$Li(NiCoAl)O_2$	36	55 [(1)]	Howard and Spotnitz, 2007

[(1)] Standard battery (single cell) for consumer electronic purposes: based on material price per cell ($) and cell capacity (Wh), [(2)] Based on present need for $LiFePO_4$: approximately 2 kg/kWh [Roland Berger, 2009]

A breakdown of raw material costs at cell level shows what influence cathode materials have on these costs. For a nickel-manganese-cobalt based cathode (figure A3.5), the cost share of the cathode active material is one third of total costs. For a lithium-iron-phosphate based cathode (figure A3.6), the share is reduced to one fifth. The share of the separator is now increased. But, the Deutsche Bank [Lache et al., 2009] states that there is a significant opportunity for cost reduction; through new cell designs, separators may even be removed from the cell [Lache et al., 2009]).

In addition to differences in costs between various materials, material prices itself do also have influence on material costs. In table A3.9 it is showed how prices have varied over the last year and over the last five year. Especially for nickel and cobalt, the variation in price has been considerable. Therefore, also ZEBRA battery costs are affected significantly by material prices. For the cost projection of Galloway and Dustmann, a cost breakdown of raw materials (figure A3.7) shows that nickel accounts for 63% of material costs at cell level. Here, the nickel price is assumed to be 13.74 $2010/kg. However, its price varied from 9 to 55 $/kg in the last five years [MetalPrices, 2010]. Using a nickel price of 55 $/kg instead of 13.74 $/kg results in substantially higher battery cell and pack costs: 84.18 $/kWh and 149 $/kWh respectively (250% and 173% of costs as projected by Galloway and Dustmann).

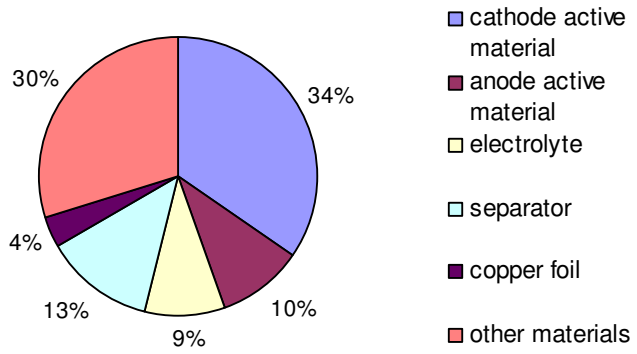


Figure A3.5: Breakdown of raw material costs ($/kWh) for a battery cell with a nickel-manganese-cobalt based cathode [Lache et al., 2009].

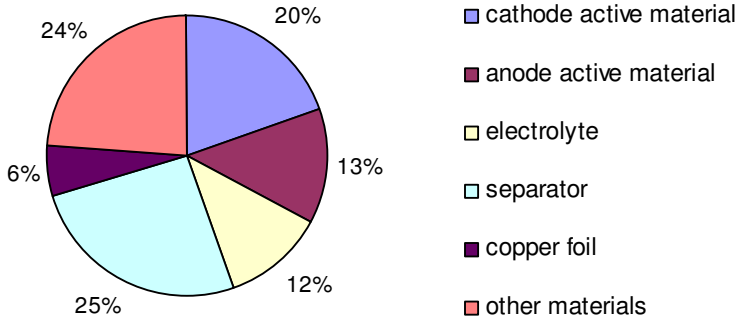


Figure A3.6: Breakdown of raw material costs ($/kWh) for a battery cell with a lithium-iron-phosphate based cathode [Roland Berger, 2009].

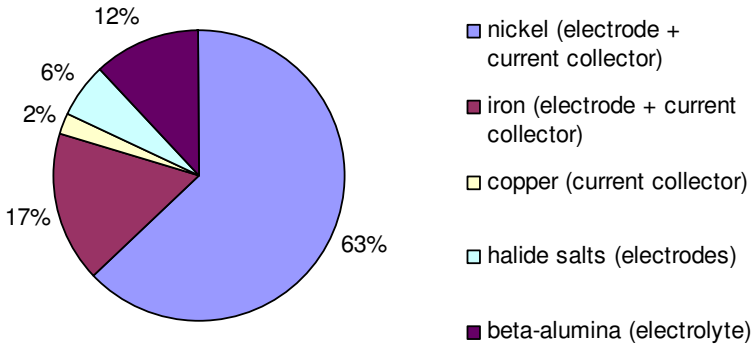


Figure A3.7: Projected breakdown of raw material costs ($/kWh) for an 86 $2010/kWh ZEBRA battery cell [Galloway and Dustmann, 2003]

Table A3.9: Raw material prices of electrode materials for Li-ion, ZEBRA, Li-S, Zn-air and Li-air batteries

No spot prices (US$2010/kg)				
Lithium carbonate	6-8 (2008/09) [1] 13 (2008) [2] 30 (2010 projection) [2]			
Lithium metal	61 (2008) [3] 128 (1998) [4]			
Sodium chloride	0.34 (2003) [5]			
Sulfur	0.18 (2010) [6] 0.60 (2008) [7]			
Spot prices ($2010/kg) [8]				
	last year		**last 5 years**	
material	**Low**	**high**	**low**	**high**
nickel	16.00	27.50	9.00	55.00
cobalt	38.50	52.00	30.00	115.00
manganese	2.00	3.70	1.40	5.50
zinc	1.60	2.60	1.00	4.50
tin	14.00	22.00	5.00	25.00
silicon	2.50	3.30	1.50	4.00
copper	6.00	8.00	3.00	9.00
aluminium	1.70	2.50	1.20	3.20

[1] [Roland Berger, 2009; Canada Lithium, 2010; Roskill, n.d.;]; [2] [Getsinger, 2009]; [3] [Angerer, 2009]; [4] [USGS, n.d.]; [5] [Galloway and Dustmann, 2003]; [6] ["Himfr Reports Sulfur Prices Will Rise", 2010]; [7] record high [USGS, 2010a]; [8] [MetalPrices, 2010]

Based on the information about the cost breakdown of Li-ion batteries and battery cells, it can be estimated what further battery cost reductions at high production volumes could take place (table A3.10). Compared to present costs from the Deutsche Bank in table A3.5, the use of low price cathode materials (approximately 30 $/kWh) can reduce cathode and anode materials to 50 $/kWh. Also, removing the separator results in halving the costs of other cell materials to about 25 $/kWh. Also, the BCG estimates show that non-material based cell costs can drop to 125 $/kWh. Similarly, costs at battery pack level are for a large share volume dependent and could drop to 100 $/kWh or even lower [BCG, 2010]. Based on these cost reductions, battery costs could drop to roughly 300 $2009/kWh (305 $2010/kWh).

Table A3.10: Cost breakdown for low and high volume battery production [BCG, 2010; Lache et al., 2009]

	BCG, 2010 **NCA, 2009 low volume (500/yr), 15 kWh**	BCG, 2010 **NCA, 2020 high volume (1.1 million/yr), 15 kWh**	Deutsche Bank **[Lache et al., 2009] NMC, high volume (100,000/yr), 25 kWh**	**Potential: low material cost, high volume**
	$2009/kWh	$2009/kWh	$2009/kWh	$2009/kWh
Cell materials (cathode, anode, electrolyte, separator, current collectors)	200-250	145.8-178.2	135.1	**75**
Other cell costs (casing, labor, depreciation, overhead, R&D)	450-540	124.2-151.8	160.5	**125**
Other costs (module and pack materials, assembly, depreciation, overhead, R&D)	340-430	90-110	160	**100**
Total	**990-1220**	**360-440**	**455.6**	**300**

Other battery technologies

In table A3.11, the cost breakdowns for low cost Li-ion and ZEBRA batteries are compared. The figures show that the shares of various cost components do differ significantly between the two batteries. Also, costs other than cell costs are estimated to be almost three times higher for Li-ion batteries than for ZEBRA batteries. Unfortunately, too little information is available to explain these differences. Therefore, it is not possible to derive some estimates from these numbers about (volume dependent) costs of other battery types.

Nevertheless, comparing prices of raw materials for these new batteries to material prices of Li-ion batteries can give some indication of their potential costs. In table A3.12, prices for cathode and anode materials are given for Li-ion, Li-S, Zn-air and Li-air batteries. Assuming that for each technology the same amount of anode and cathode material is needed, the cost is calculated in dollar per kWh.

Table A3.11: Comparison cost breakdown of low cost Li-ion (potential cost as derived in this section, table 11) and ZEBRA batteries [Galloway and Dustmann, 2003]

	Potential Li-ion	**Cost share (%)**	**Potential ZEBRA**	**Cost share (%)**
	$2010/kWh		$2010/kWh	
Cell materials (cathode, anode, electrolyte, separator, current collectors)	76	25	33.51	39
Other cell costs (casing, labor, depreciation, R&D)	127	42	16.37	19
Other costs (module and pack materials, assembly, depreciation, R&D)	101	33	36.31	42
Total	**305**		**86.19**	

Table A3.12: Raw material and total prices of electrode materials for Li-ion, Li-S, Zn-air and Li-air batteries

		Cathode		Anode		Total
Li-ion		**$Li(NiMnCo)O_2$**	**$LiFePO_4$**	**Graphite**		
	$2010/kg	33,53	18.29	20,32		
	$2010/kWh	67,58	36.58	19,41		86.99 ($Li(NiMnCo)O_2$) 55.99 ($LiFePO_4$)
Li-S		**Sulfur**	**Li_2S**	**Metallic lithium**	**Silicon**	
	$2010/kg	0.60	15 [(1)]	61-128	4.00	
	$2010/kWh	1.21	30.23	58-122	3.82	59-123 (Li-S) 34 (Si-Li_2S)
Zn-air		**Air**	**Catalyst**	**Zinc**		
	$2010/kg	0	15 [(2)]	4.50		
	$2010/kWh	0	30.23	4.30		35
Li-air		**Air**	**Catalyst**	**Metallic lithium**		
	$2010/kg	0	15 [(2)]	61-128		
	$2010/kWh	0	30.23	58-122		88-152

[(1)] Assumed: mean of sulfur and lithium carbonate costs; [(2)] assumed: half of Li-ion (NMC) cathode material cost

For lithium-ion materials, sulfur, zinc and silicon, the highest price from tables A3.8 and A3.9 are used. For metallic lithium, a higher and lower value is used to see how this influences the costs. Furthermore, for the metal-air technologies a price is assumed for the catalyst needed at the cathode side of the battery.

In Li-ion batteries, cathode materials have the highest share in costs. As metal-air and Li-S batteries use air and sulfur as cathode materials, they profit from cost advantages at this side. Furthermore, zinc-air systems use relatively inexpensive zinc as the anode material. On the other hand, lithium-air and lithium-sulfur batteries will be disadvantaged by the high price of metallic lithium.
In current Li-ion batteries, lithium only represents a small part of costs at cell level. According to the cost assessment by the Boston Consultancy Group [2010] this share is 2%. However, battery grade lithium carbonate (99.5% lithium) is used here. As metallic lithium can be applied as a substitute for graphite or another anode material in Li-air and Li-S batteries, the amount of lithium needed will increase compared to lithium carbonate use in Li-ion batteries. This will apply even more for Li-air batteries when excess lithium is needed for efficient cycling. The cost share of lithium in Li-S batteries was projected to be about 10% of total costs (coming after 20% for the electrolyte). In Li-air batteries lithium was even stated to be the most expensive material in the cell [ARPA-E, 2009].

Table A3.12 shows that for Li-S and Zn-air batteries anode and cathode material costs have the potential to be below the costs for Li-ion batteries. However, the costs for Li-S batteries do depend on the price of metallic lithium. On the other hand, Li-S batteries do not necessarily need metallic lithium, and silicon is a good cost effective option. The material costs for Li-air batteries are the same or higher compared to Li-ion, but are highly depending on the price of metallic lithium.

Synthesis cost projections

Li-ion

In figure A3.8, the scenarios based on projections from literature are compared to the projections based on experience curves and BEV market forecasts. From this comparison, it seems that a progress ratio of 83% is quite opportunistic. In this case, costs would reduce drastically in especially the next five years. Also, in both cases of a present cost of 800 and 1200 $/kWh respectively, costs would be below that of the progressive scenario in 2020.
On the other hand, a progress ratio of 91% shows slow cost decline compared to both scenarios. In reality, the progress ratio might be somewhere in between the values used.

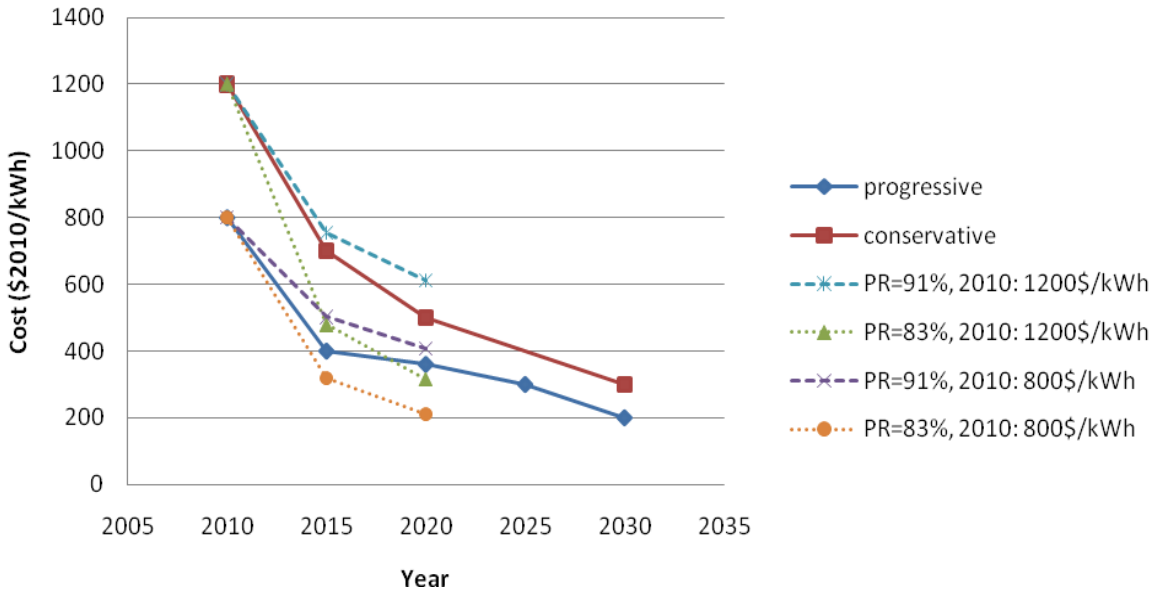


Figure A3.8: Comparison scenarios derived from literature and from market/experience curve approach

From assessing the cost breakdown of Li-ion batteries, it was estimated that costs can reduce to approximately 300 $/kWh. Considering the projections from literature, 250 $/kWh could also be achievable [Bandivadekar et al., 2008; Kromer and Heywood, 2007; Lache et al., 2009]. Only Kalhammer [2007] and the BERR & DfT [2008] do state that costs of approximately 200 and 100 $/kWh could be attainable respectively. Nevertheless, BCG [2010] states that a major breakthrough in chemistry is needed to attain fundamentally higher specific energy without significant increase in cost of materials or production process. Only in such a case a cost target of $250/kWh could be achieved [BCG, 2010].
Besides, cost breakdowns of Li-ion batteries showed that low priced raw materials have to be used to achieve costs of 300 $/kWh or lower. Also, wide variation over time in material prices (especially with regard to nickel and cobalt) can influence battery costs substantially.

ZEBRA:

According to literature, it seems to be likely that ZEBRA batteries can reach a cost of 200 $/kWh. Even when no new production facilities will be build, costs can decline to 300 $/kWh or lower as a result of production expansion and learning within the present battery plant. Galloway and Dustmann [2003] state that battery costs can potentially reduce to about 86 $2010/kWh at large

volume production. However, using the progress ratio of 84.6% from section 4.3.2 results in a required production capacity of more than 75 GWh per year (a production volume of approximately 3.6 million batteries per year). This is far from reality yet, but possible if these batteries will be used at large scale in the future. However, even when assuming the most positive projections for BEV sales from section 4.3.2 this volume can only be reached in 2020 if the majority of the batteries will be based on ZEBRA technology. Therefore, it is very plausible that costs can only drop below 100 $/kWh in a much longer term.
Again, such cost levels can only be reached when raw material prices are low. In section 4.3.3 it was showed that prices of nickel have varied from 9 to 55 $/kg in the last five years. Compared to 300 $/kWh Li-ion batteries, a high nickel price could even turn the potential advantage of material costs at cell level into a disadvantage.

Other battery technologies
In literature only a few statements were found about the costs of batteries other than Li-ion and ZEBRA. It is assumed that these projections account for high volume production. However, the cost assessments for Li-ion and ZEBRA batteries show that lower cost values can only be achieved after some time of production and market expansion; most projections predict 15-20 years from now. However, as the BEV market will have grown in 2020 and beyond, it is plausible that commercialization of new battery technologies will take off faster compared to current technologies. On the other hand, it may take some time before new technologies are considered to be a good substitute for existing (mature) technologies.
With regard to material prices, lithium sulfur and metal-air batteries can take advantage of low costs for sulfur, zinc (and air). However, the use of metallic lithium can largely undo this benefit. Zinc-air batteries will cost less than Li-ion batteries, Li-S batteries can cost less of the same. Li-air will cost the same or more, depending on metallic lithium.

Appendix IV: Progress ratios

In literature, very little information can be found about experience curves for batteries. One experience curve was found in a document of Nagelhout and Ros [2009], figure A4.1. This curve applies to Li-ion cells for consumer electronics. The progress ratio found is 83%. Nagelhout and Ros remark that the progress ratio of Li-ion batteries for EVs might be different because of adjusted requirements regarding (cell) size, life time and so on. However, the experience curve shows that expansion of battery volume could result in fast cost reduction [Nagelhout and Ros, 2009].

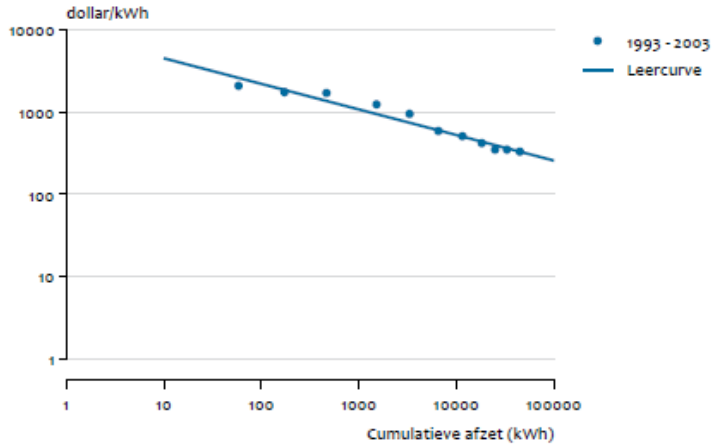


Figure A4.1: Learning curve for Li-ion cells (consumers electronics, e.g. Laptops). The progress ratio is 0.83 [Nagelhout and Ros, 2009]. On the horizontal axis: cumulative battery capacity (kWh), on the vertical axis: battery cost ($/kWh)

Kalhammer et al. [2007] give cost projections for various production volumes of NiMH batteries for HEV purposes (table A4.1). Using these numbers, an equation is defined for the battery costs as a function of the annual production volume (figure A4.2). Furthermore, data was found for cumulative (Toyota) and annual (global) HEV sales (table A4.2).

Table A4.1: NiMH battery costs as a function of annual production volume [Kalhammer et al., 2007]

Battery systems/yr	Cost 2007 ($/kWh)
20,000	2198
100,000	1545
250,000	1210
1,250,000	1055

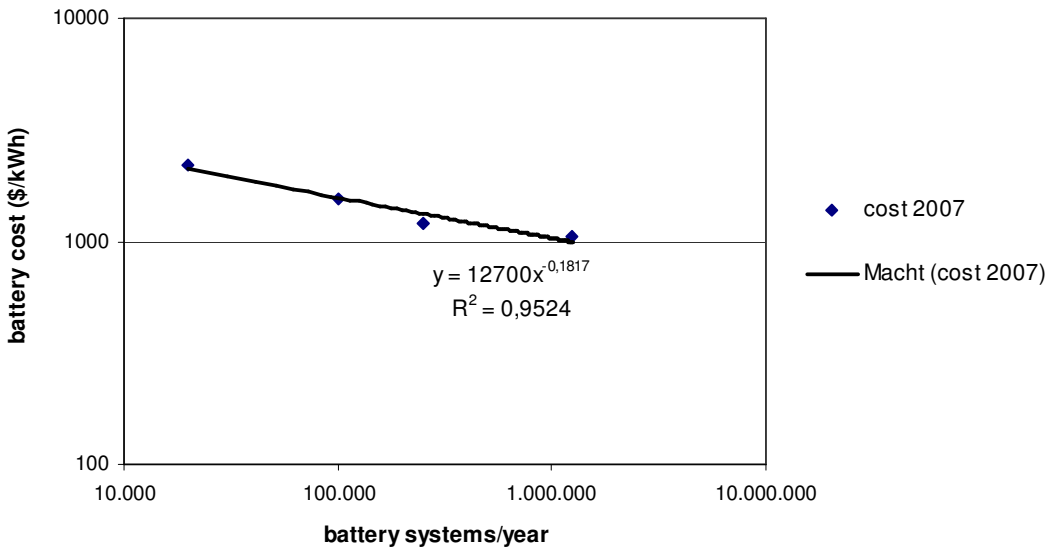


Figure A4.2: Battery cost as function of production volume [Kalhammer et al., 2007]

Table A4.2: HEV sales numbers (x1000)

Year:	97	98	99	00	01	02	03	04	05	06	07	08
Toyota HEV cum. [1]	0.3	18.0	33.2	52.3	89.2	130.5	183.8	318.5	553.5	866.0	1,295.4	1,725.1
IIT yearly [2]		18	15	25	45	60	83	168				
Toyota yearly	0.3	17.7	15.2	19.1	36.9	41.3	53.3	134.7	235.0	332.5	409.4	429.7
IIT cum.		18	33	58	103	163	246	414				

[1] [Toyota, 2009]; [2] [IIT, 2005]

For each data set, the yearly production volume (assumed to be equal to yearly sales volume) is used to calculate the battery cost for that year. Assuming an average capacity of 1.3 kWh [Lache et al., 2008; Kalhammer et al., 2007] for a NiMH battery, the costs are showed as a function of the cumulative battery capacity in figure A4.3.

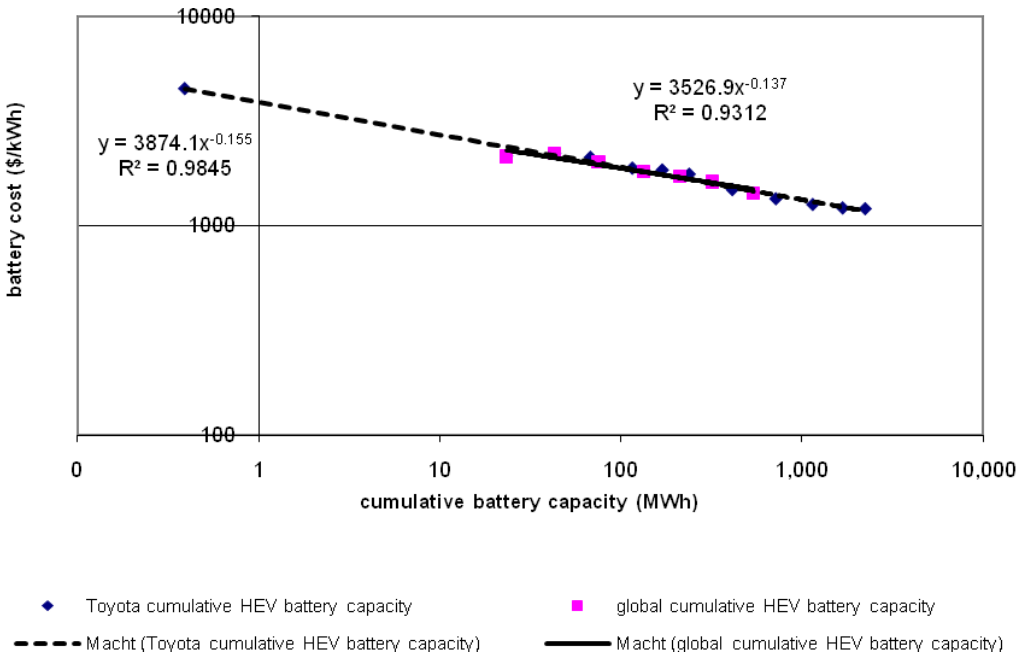


Figure A4.3: Experience curve for NiMH batteries, based on Toyota and global HEV sales and cost projections from Kalhammer et al. [2007]

The Toyota and global data show good resemblance. The experience indexes for the corresponding power trendlines (-0.1547 and -0.1368) result in progress ratios of 89.8% and 91.0% respectively. The progress ratios may be somewhat higher, as the assumption that production volumes are equal to sales volumes is no reality; not all batteries are produced by the same manufacturer.
On the other hand, the Toyota data result in 2008 costs of $1200/kWh. In literature, costs of $1000/kWh are mentioned [Lache et al., 2008].

Kamath [2009] gives two cost curves for Li-ion batteries. These curves are based on costs as a function of production volume and projected battery demand. The first is based on 15% cost reduction through doubling of production volume, the second on 10% reduction. These percentages are based on cost estimations found in different sources [Kamath, 2009]. By analyzing the cost values for cumulative battery capacity, the curves from Kamath are converted into experience curves (figure A4.4).

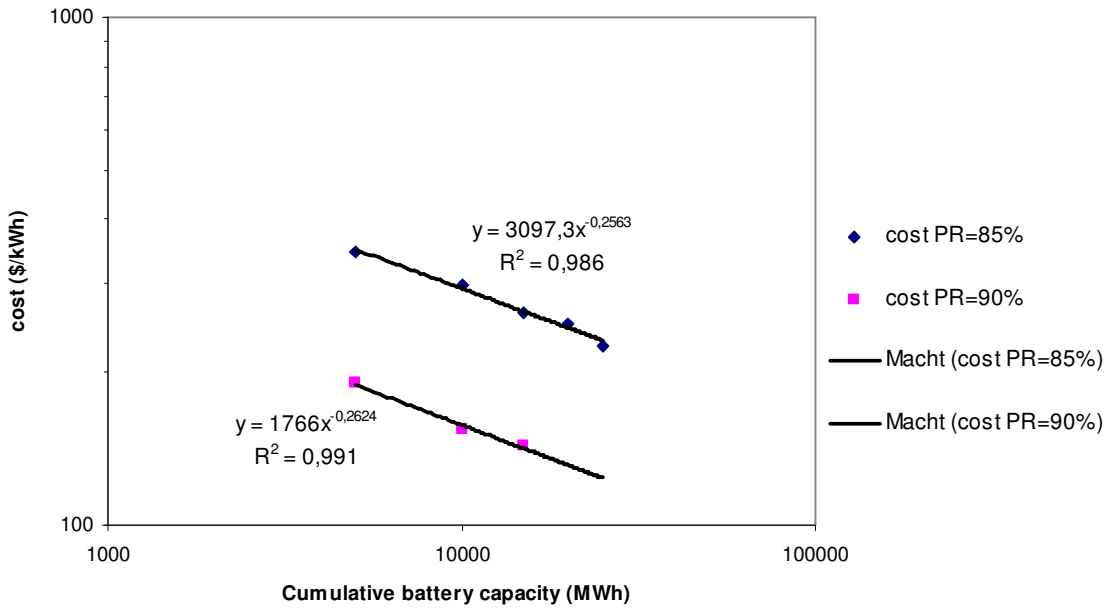


Figure A4.4: Experience curves for Li-ion batteries, derived from Kamath [2009] and based on 15 and 10 percent cost reduction through doubling of production volume.

The experience curves show progress ratios of 83.7% and 83.4% for volume based cost reduction percentages of 15 and 10 percent respectively. However, the two curves show very dissimilar costs at the same battery capacity. This is because of a difference among the two datasets in the projected costs at low volume production [Kamath, 2009].

Finally, Kalhammer et al. [2007] give cost projections for ZEBRA batteries at various production volumes (table A4.3). Also, the production capacity was stated to increase from 1,000 to 1,500 batteries per year in 2007 [Kalhammer et al., 2007]. Cebi, the parent company of FZ SoNick SA, states on its website that FZ Sonick SA has the aim to increase the battery production capacity from 90 MWh in 2010 to 170 MWh in 2015 [Cebi, 2010].
The cost projections are used to define an experience curve (figure A4.5), assuming an average battery capacity of 21 kWh [Galloway and Dustmann, 2003]. This experience curve results in a progress ratio of 84.6%. Note that costs are a function of annual production capacity, not of cumulative capacity. Thus, costs reduce with 15.4% when the annual production capacity is doubled.

Table A4.3: Cost projections for ZEBRA battery as function of production volume

Battery systems/yr	Cost ($2007/kWh)	Cost ($2010/kWh)
1,000	600	631
10,000	335	352
20,000	275	289
100,000	200	210

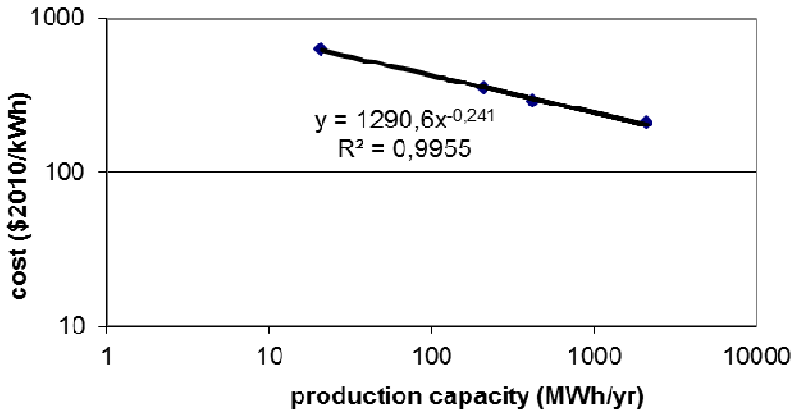


Figure A4.5: Experience curve for ZEBRA batteries, based on cost projections from Kalhammer et al. [2007] and an average battery capacity of 21 kWh.

Appendix V: Results sensitivity analysis

Table A5.1: Sensitivity of simulation model output parameters to changes in future Li-ion characteristics

	Percentage of original value	battery weight	energy supplied	WTW energy consumption	Direct emissions	battery cost	total driving costs
specific energy	75%	144%	108%	108%	108%	108%	104%
	125%	77%	96%	96%	96%	96%	98%
Depth of Discharge	88%	118%	103%	103%	103%	118%	109%
	113%	87%	98%	98%	98%	87%	94%
Efficiency	98%	103%	98%	100%	100%	103%	101%
	103%	96%	100%	97%	97%	96%	98%
battery costs ($/kg)	83%					83%	92%
	117%					117%	108%
lifetime	70%						112%
	150%						91%

Table A5.2: Sensitivity of simulation model output parameters to changes in future ZEBRA characteristics

	Percentage of original value	battery weight	energy supplied	WTW energy consumption	Direct emissions	battery cost	total driving costs
specific energy	81%	132%	107%	107%	107%	107%	103%
	125%	76%	94%	94%	94%	94%	98%
Depth of Discharge	88%	119%	104%	104%	104%	119%	108%
	113%	86%	97%	97%	97%	86%	94%
Efficiency	106%	93%	98%	93%	93%	93%	97%
battery costs ($/kg)	40%					40%	74%
	140%					140%	113%

Table A5.3: Sensitivity of simulation model output parameters to changes in Li-S characteristics

	Percentage of original value	battery weight	energy supplied	WTW energy consumption	Direct emissions	battery cost	total driving costs
specific energy	75%	139%	104%	104%	104%	104%	102%
	125%	79%	98%	98%	98%	98%	99%
Depth of Discharge	90%	114%	102%	102%	102%	114%	107%
Efficiency	88%	117%	102%	91%	91%	117%	109%
	113%	88%	99%	113%	113%	88%	94%
battery costs ($/kg)	67%					67%	82%
	133%					133%	118%
lifetime	71%						115%
	143%						89%

Table A5.4: Sensitivity of simulation model output parameters to changes in Zn-air characteristics

	Percentage of original value	battery weight	energy supplied	WTW energy consumption	Direct emissions	battery cost	total driving costs
specific energy	60%	197%	118%	118%	118%	118%	110%
	140%	67%	94%	94%	94%	94%	97%
Depth of Discharge	88%	118%	103%	103%	103%	118%	110%
	113%	87%	97%	97%	97%	87%	93%
Efficiency	93%	110%	102%	110%	110%	110%	105%
	114%	85%	97%	85%	85%	85%	92%
battery costs ($/kg)	44%					44%	71%
	156%					156%	129%
lifetime	71%						115%
	143%						89%

Table A5.5: Sensitivity of simulation model output parameters to changes in Li-air characteristics

	Percentage of original value	battery weight	energy supplied	WTW energy consumption	Direct emissions	battery cost	total driving costs
specific energy	200%	75%	97%	97%	97%	97%	98%
Depth of Discharge	88%	116%	102%	102%	102%	116%	111%
	113%	87%	98%	98%	98%	87%	91%
Efficiency	67%	137%	104%	122%	122%	137%	124%
	121%	80%	97%	80%	80%	80%	86%
battery costs ($/kg)	60%					60%	73%
	140%					140%	127%
lifetime	71%						119%
	143%						86%

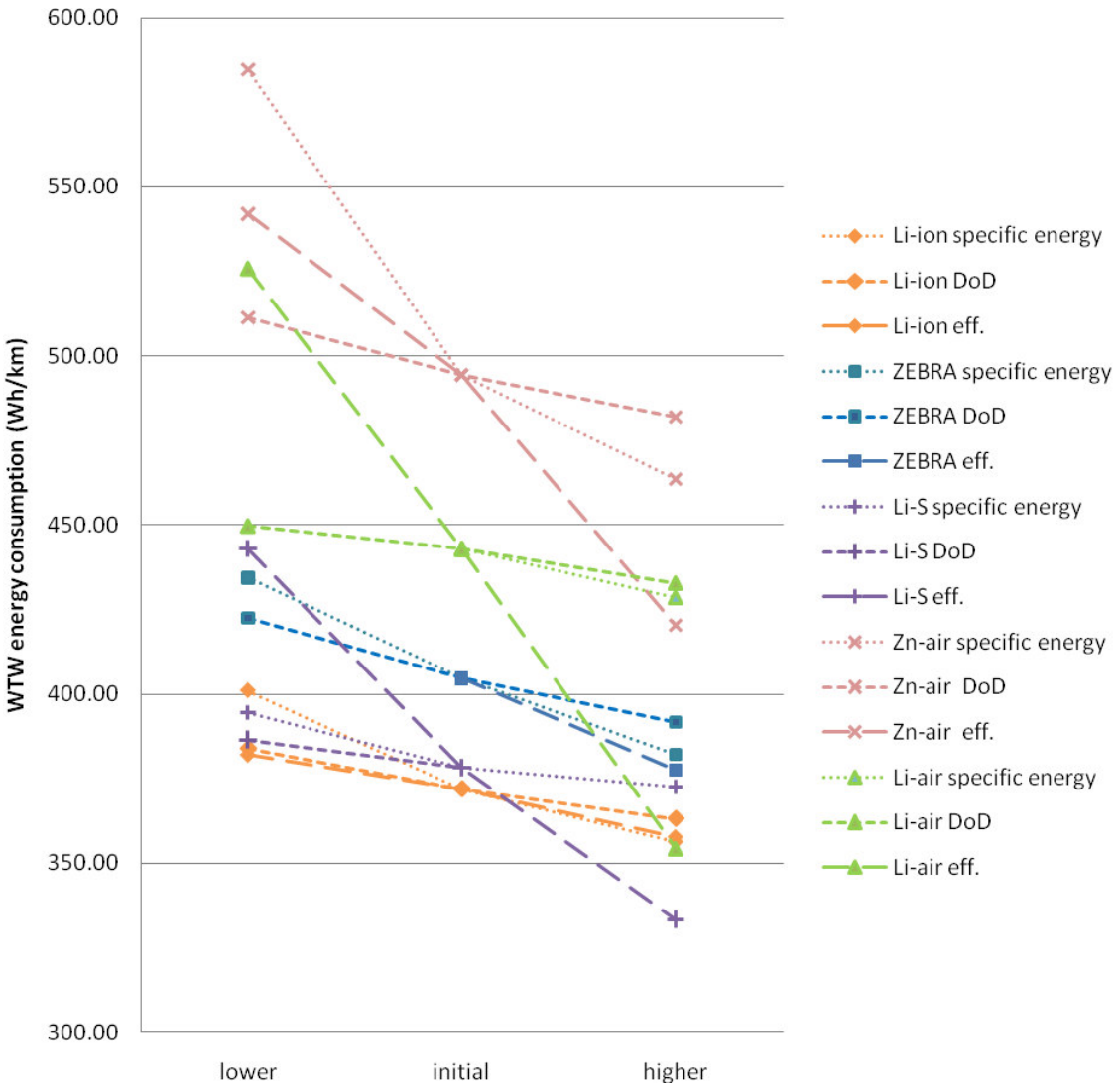


Figure A5.1: Change of WTW energy consumption due to adaption of the battery's specific energy, depth of discharge or efficiency (to the lower or higher value defined for the sensitivity analysis).

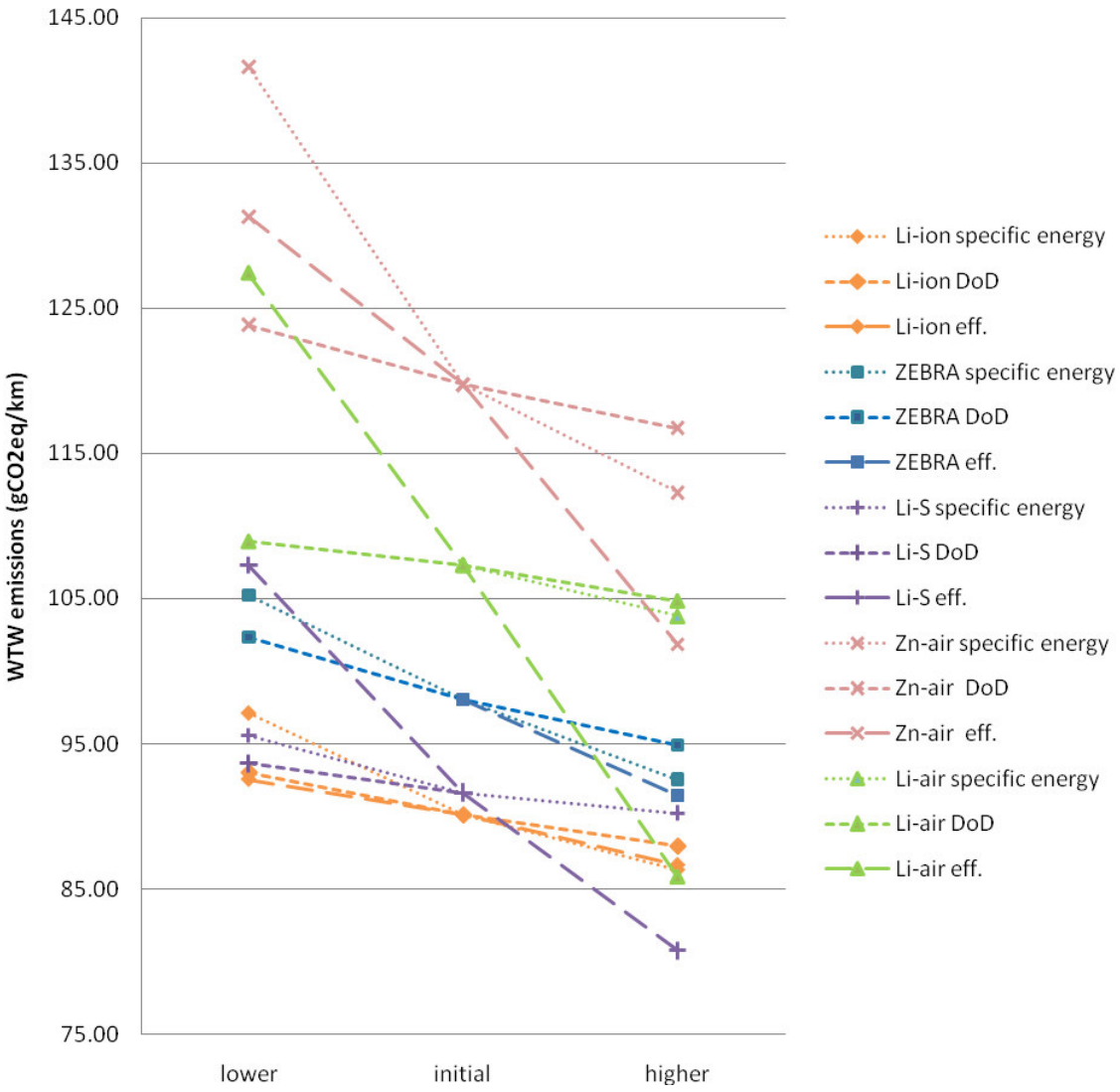


Figure A5.2: Change of WTW emissions due to adaption of the battery's specific energy, depth of discharge or efficiency (to the lower or higher value defined for the sensitivity analysis).

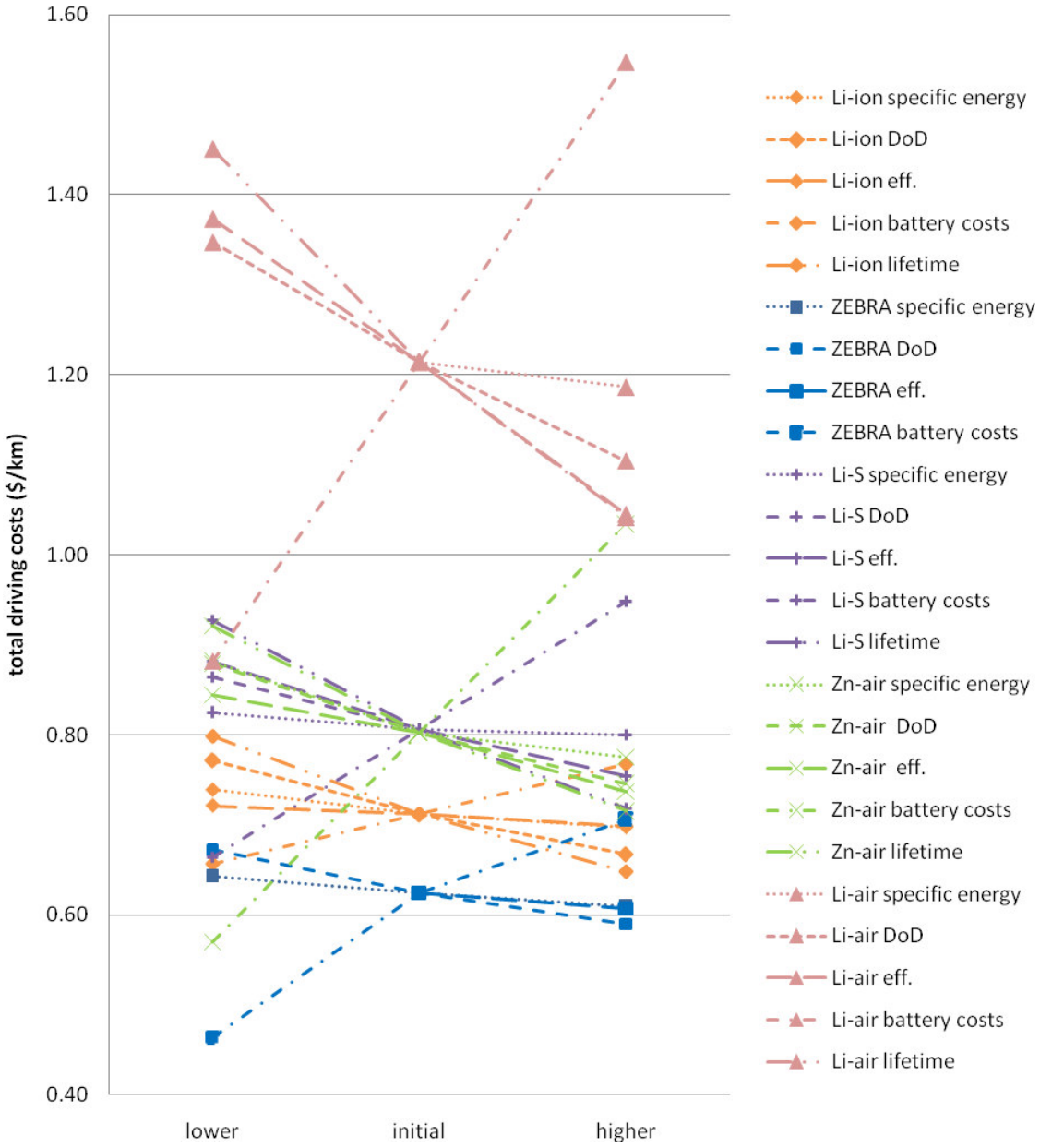


Figure A5.3: Change of total driving costs due to adaption of the battery's specific energy, depth of discharge, efficiency, specific costs ($/kWh) or lifetime (to the lower or higher value defined for the sensitivity analysis).