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Performance of batteries for electric vehicles on short and longer term

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ABSTRACT

In this work, the prospects of available and new battery technologies for battery electric vehicles (BEVs) are examined. Five selected battery technologies are assessed on battery performance and cost in the short, medium and long term. Driving cycle simulations are carried out to assess the influence of the batteries on the energetic, environmental and economic performance of BEVs in the medium term.

Well-to-wheel energy consumption and emissions of BEVs are lowest for lithium-ion batteries; 314–374 Wh km^{-1} and 76–90 gCO$_2$eq km^{-1} (assuming 593 gCO$_2$ kWh^{-1} for European electricity mix), compared to 450–760 Wh km^{-1} and 150–170 gCO$_2$eq km^{-1} for petrol and diesel cars. The total driving costs are lowest for ZEBRA batteries (0.43–0.62 \$ km^{-1}). But, only if ZEBRA batteries attain a very low cost of 100 \$ kWh^{-1} and driving ranges are below 200 km, BEVs become cost competitive to diesel cars.

For all batteries, it remains a challenge to simultaneously meet requirements on specific energy, specific power, efficiency, cycle life, lifetime, safety and costs in the medium or even long term. Only lithium-ion batteries could possibly attain all conditions in the medium term. Batteries that do not contain lithium have best perspectives to attain low costs.

1. Introduction

Currently, the transportation sector is a large consumer of fossil fuels and contributes extensively to global greenhouse gas (GHG) emissions. In 2005, the transport sector was responsible for approximately 15% of global GHG emissions, to which road transport contributes 73% [1]. An important development that can improve fuel efficiency and decrease emissions is the introduction of Hybrid Electric Vehicles (HEVs) [2]. Further reduction of emissions could be achieved by substitution of fossil fuels. An alternative is electricity: full electric cars (energy provided by a battery) have a zero emission potential when electricity is produced with the use of for example renewable energy sources. Besides, the high energy efficiency of the battery system positively affects the tank-to-wheel (TTW) energy consumption of battery electric vehicles (BEVs) [3–5].

However, batteries that are currently applied in BEVs, mainly lithium-ion (Li-ion), also have various limitations. Campanari et al. [3] show that the battery weight and energy consumption of the car increase significantly with the driving range. Van Vliet et al. [4] state that at a cost level[1] of 1280 \$ kWh^{-1} for Li-ion batteries, the total cost of ownership of BEVs in 2010 was at least 3600 \$ year^{-1} higher compared to regular cars or parallel hybrid cars. At a cost level of 530 \$ kWh^{-1}, the difference would still be more than 1000 \$ yr^{-1}. To make battery electric cars competitive with internal combustion vehicles (ICEVs), the U.S. Advanced Battery Consortium (USABC) and others have defined performance and cost goals for the batteries. For example, the specific energy should increase from 100–125 to 150 or even 200 Wh kg^{-1} and the costs decrease from 700–1200 to 250 \$ kWh^{-1} or lower [[6–11],W. Robers, personal communication, October 1, 2010].

Lithium-ion 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 [2,11–14]. However, the challenges that have to be overcome to simultaneously achieve all goals are numerous [2,15]. It is not clear when or to what extent USABC goals can be achieved. Especially with regard to cost reduction, expectations diverge and the effect of learning is uncertain [4,14,16,17].

Abbreviations: ARB, California Air Resources Board; ARPA-E, Advanced Research Projects Agency - Energy; BCG, Boston Consultancy Group; BEV, battery electric vehicle; BMS, battery management system; CCS, carbon capture and sequestration; DoD, depth of discharge; FCEV, fuel cell electric vehicle; GHG, greenhouse gas; HEV, hybrid electric vehicle; ICEV, internal combustion engine vehicle; Li-ion, lithium-ion; Li–S, lithium-sulfur; LMP, Lithium Metal Polymer; LR, learning rate; NaS, sodium-sulfur; NEDC, New European Driving Cycle; NiMH, Nickel-metal-hydride; PR, progress ratio; R&D, research and development; TTW, tank-to-wheel; USABC, U.S. Advanced Battery Consortium; VAT, Value Added Tax; VRLA, valve-regulated-lead-acid; WTW, well-to-wheel; ZEBRA, Sodium-Nickel-Chloride (NaNiCl) battery; Zn-air, zinc-air.

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[1] Unless stated otherwise, all costs and prices in this article are given in US\$2010, using GDP inflators and annual currency exchange rates (www.bls.gov, www.oanda.com; assumption for 2010: 1€ equals 1.32US\$).

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Yet, other innovative battery technologies may overcome these issues. For example, metal-air batteries can attain a high specific energy, zinc-air batteries have a low cost potential and sodium-ion batteries are interesting with regard to safety [9,18–20]. Nevertheless, no comprehensive and quantitative assessment of the prospects of such battery technologies can be found in literature [8,11,12].

It is the aim of this paper 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. The remainder of this paper is organized as follows. Section 2 explains the methodology used. In Section 3, an inventory is made of existing and innovative battery technologies for battery electric cars. Section 4 analyses how the performance and costs of five selected technologies are expected to develop in time. Next, driving cycle simulations are carried out in Section 5 to assess how these technologies and their development will influence the energetic, environmental and economic performance of battery electric cars. The paper concludes with a discussion and conclusions in Sections 6 and 7.

2. Methodology

2.1. Inventory and comparison of battery technologies

An overview was made of battery technologies that are now available for BEV application or are currently subject to research, development and demonstration activities focusing on battery electric cars that are fully capable of high speed urban and extra-urban driving.[2] For each battery technology, the most important positive and negative features with regard to battery performance, costs and safety were identified. Five battery types that are considered to be promising candidates for the short (<5 years), medium (5–20 years) and long term (>20 years) were selected for further assessment.

2.2. Projections on battery development and costs

Based on white and gray literature and expert consultations, projections were made on how battery performance may improve in time. The assessed battery performance characteristics were:

Specific energy	Total energy storage per unit mass (Wh kg^{-1})
Specific power	Maximum available power per unit mass (W kg^{-1})
(Calendar) Lifetime	Period of time before a battery fails to meet specific performance criteria,[a] whether by active or inactive use (years)
Cycle life	Number of discharge/charge cycles a battery can experience before it fails to meet specific performance criteria.[a b]
Efficiency	Discharge/charge energy ratio (%)
Operating temperature	How the ambient and/or internal temperature affects the performance of the battery
Safety	Abuse tolerance (physical integrity, chemical and thermal stability), and compatibility with environment and human health

[a] Due to battery degradation, caused by mechanisms that are dependent of operational and/or ambient conditions, the performance of the battery (e.g. storage capacity) declines. Performance criteria define the lower performance limit of the battery.
[b] The cycle life is highly dependent on the level of discharge during each cycle; therefore, it is usually quoted together with the percentage of Depth of Discharge (DoD). At 100% DoD, the cut-off voltage is reached at which the battery is considered to be fully discharged [21].

[2] Battery requirements differ between BEV and HEV purposes. Therefore, only the battery development for the former application was considered.

Literature review was also used to make normalized cost projections. Besides, experience curves were composed (see below). Finally, cost breakdowns were made to assess the impact of various components on the total battery costs. This included the use of raw material prices to estimate the potential (minimum) cost of the batteries.

2.2.1. Experience curves

An experience 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 [22]. Equations (1) and (2) describe this curve and its logarithmic form.

$$C_{\mathrm{Cum}} = C_0 \mathrm{Cum}^m \tag{1}$$

$$\log C_{\mathrm{Cum}} = \log C_0 + m \log \mathrm{Cum} \tag{2}$$

(C_{Cum} = cost per unit, C_0 = cost of the first unit produced, Cum = cumulative (unit) production, m = experience index [22])

The progress ratio and learning rate are used to express the rate at which costs decline with a doubling of cumulative production. The progress ratio (Equation (3)) is equal to the slope of the experience curve; a progress ratio of 80% is equivalent to a learning rate of 20% (Equation (4)) and means that costs reduce by 20% when cumulative production doubles [22].

$$\mathrm{PR} = 2^m \tag{3}$$

$$\mathrm{LR} = 1 - 2^m \tag{4}$$

(PR = progress ratio, LR = Learning rate, m = experience index [22])

2.3. Electric vehicle performance

Driving cycle simulations were used to analyze the energy consumption, emissions and driving costs of battery electric cars equipped with different battery types and their respective performance characteristics. For these simulations, the New European Driving Cycle (NEDC) was modeled in Excel. This driving cycle consists of four repeated urban (ECE) driving cycles and one extra-urban (EUDC) cycle. In these cycles, driving under a slope was not included.

For all simulations, a compact 5-seater was used as a reference car. This class includes amongst others the VW Golf and Toyota Corolla [4,23]. Coefficients and other parameter values related to the reference car were derived from literature. Also, recent values for the efficiencies, emission factor and prices of electricity production and distribution were obtained from literature. The battery specific values (e.g. battery efficiencies) were based on the medium term battery performance and cost projections made in this study.

2.3.1. Calculations

For each time step of 1 s the motive force and power required at the wheels were calculated by Equations (5) and (6) [3,21,24]. To this end, the average speed between the beginning and the end of each time step was used; also see Campanari et al. [3]. The power to be supplied by the battery was calculated with the use of drive train efficiencies (Fig. 1) and taking into account extra power for auxiliary equipment (Equation (7)). During deceleration, power from regenerative braking is recovered to recharge the battery (Equation (8)) [3]. The average TTW energy consumption (average energy supplied by battery) was calculated by Equation (9).

$$F_m = F_L + F_a = F_r + F_d + F_c + F_a = \mathrm{mg}C_R + 0.5\rho C_D A_F v^2 + \mathrm{mg}\sin\alpha + m\delta a \ (\alpha = 0) \quad (5)$$

$$P_{\mathrm{wheels}} = F_m \cdot v \quad (6)$$

$$P_{\mathrm{el.supply}} = P_{\mathrm{aux}} + \frac{P_{\mathrm{wheels}}}{(\eta_{\mathrm{trans}} \cdot \eta_{\mathrm{motor}} \cdot \eta_{\mathrm{controller}})} \quad (P_{\mathrm{wheels}} > 0) \quad (7)$$

$$P_{\mathrm{el.recover}} = P_{\mathrm{wheels}} \cdot (\eta_{\mathrm{trans}} \cdot \eta_{\mathrm{motor}} \cdot \eta_{\mathrm{controller}}) - P_{\mathrm{aux}} (P_{\mathrm{wheels}} < 0) \quad (8)$$

$$E_{\mathrm{avg}} = \frac{\int P dt}{s_{\mathrm{total}}} \quad (9)$$

F_M = motive force	g = gravitational acceleration (m s^{-2})	P_{wheels} = power required at the wheels (W)
F_L = road load	C_R = coefficient of rolling resistance	$P_{\mathrm{el.supply}}$ = power supplied by the battery (W)
F_a = force required for acceleration	ρ = density of air (kg m^{-3})	$P_{\mathrm{el.recover}}$ = power recovered by the battery (W)
F_r = rolling resistance force	C_D = aerodynamic drag coefficient	P_{aux} = electric auxiliary equipment power (W)
F_d = aerodynamic drag force	A_F = frontal area (m^2)	η = energy efficiency
F_c = climbing force	α = angle of the road (degrees)	E_{avg} = average energy supply by battery (Wh km^{-1})
m = vehicle mass (kg)	δ = mass correction factor	s_{total} = total driving distance (km)
a = vehicle acceleration (m s^{-2})	v = vehicle velocity (m s^{-1})	

As the battery weight affects the TTW energy consumption, an iterative calculation procedure [3] was applied to find the required battery weight and the related energy consumption. Depending on the maximum power and total energy needed for one cycle, the battery weight is defined by the specific energy or specific power of the battery. 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 (10)). Then, the battery weight is a function of the storage capacity and specific energy (Equation (11)). When the specific power is decisive, the battery weight depends on the maximum power required (Equation (11)). In this case the battery capacity is defined by the battery weight and specific energy (Equation (13)).

$$C_{\mathrm{battery}} = \frac{E_{\mathrm{avg}} \cdot d}{DoD \cdot \eta_{\mathrm{battery}}} \quad \text{(specific energy is decisive for battery weight)} \quad (10)$$

$$\text{And}: \ M_{\mathrm{battery}} = \frac{C_{\mathrm{battery}}}{E_{\mathrm{spec}}} \quad (11)$$

$$M_{\mathrm{battery}} = \frac{P_{\mathrm{peak\ max}}}{P_{\mathrm{spec}} \cdot \eta_{\mathrm{battery}}} \quad \text{(specific power is decisive for battery weight)} \quad (12)$$

$$\text{and}: \ C_{\mathrm{battery}} = M_{\mathrm{battery}} \cdot E_{\mathrm{spec}} \quad (13)$$

C_{battery} = battery storage capacity (Wh)	M_{battery} = battery weight (kg)
d = driving range (km)	E_{spec} = specific energy of battery (Wh kg^{-1})
DoD = Depth of discharge (%)	$P_{\mathrm{peak\ max}}$ = maximum peak power (W)
η_{battery} = charge/discharge efficiency of battery (%)	P_{spec} = specific power (W kg^{-1})

Since we want to show how different battery technologies influence the performance of BEVs, the TTW energy consumption was calculated over an array of driving ranges (100, 200, …, 600 km). Subsequently, the WTW energy consumption, WTW emissions and total driving cost were calculated. These are respectively determined by the energy efficiency (Equations (14)–(16)), the electricity emission factor (Equation (17)), and costs of electricity and the car, including capital costs and maintenance (Equations (18) and (19)).

$$E_{\mathrm{cons.battery}} = \frac{E_{\mathrm{avg}}}{\eta_{\mathrm{battery}}} \quad (14)$$

$$E_{\mathrm{elec.prod}} = \frac{E_{\mathrm{cons.battery}}}{\eta_{\mathrm{elec.distr}} \cdot \eta_{\mathrm{bat.charger}}} \quad (15)$$

$$E_{\mathrm{WTW}} = \frac{E_{\mathrm{elec.prod}}}{\left(\eta_{\mathrm{elec.prod}} \cdot \eta_{\mathrm{extr/distr.raw\ mat}}\right)} \quad (16)$$

$$\mathrm{EM}_{\mathrm{WTW}} = E_{\mathrm{elec.prod}} \cdot \mathrm{EF}_{\mathrm{elec}} \quad (17)$$

$$C_{\mathrm{drive}} = C_{\mathrm{fuel}} + C_{\mathrm{car}} = \frac{E_{\mathrm{cons.battery}}}{C_{\mathrm{elec}}} + \frac{\alpha_{\mathrm{car}} \cdot I_{\mathrm{car}} + \alpha_{\mathrm{battery}} \cdot I_{\mathrm{battery}}}{s_a} + C_{\mathrm{MRT}} \quad (18)$$

The capital recovery factor is calculated by:

$$\alpha = \frac{r}{1 - (1 + r)^{-1}} \quad (19)$$

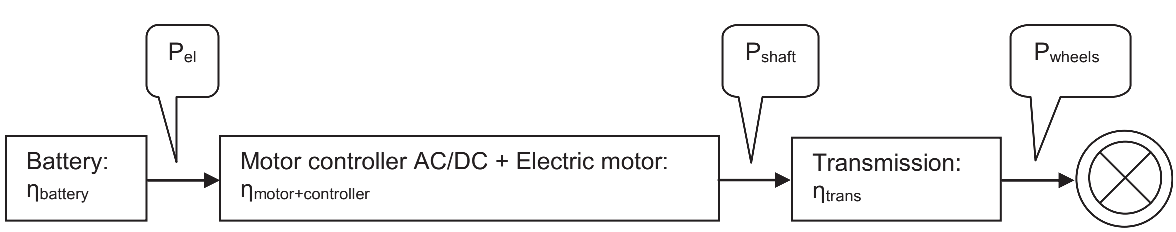

Fig. 1. Main elements and power flow inside a battery electric vehicle, adapted from Campanari et al. [3].

$E_{cons.battery}$ = energy supply to battery (Wh km^{-1})	C_{fuel} = cost of electricity use (\$ km^{-1})
$E_{elec.prod}$ = electricity production demand (Wh km^{-1})	C_{car} = cost of car (\$ km^{-1})
E_{WTW} = WTW primary energy consumption (Wh km^{-1})	C_{elec} = electricity price (\$ Wh^{-1})
$\eta_{bat.charger}$ = energy efficiency battery charger (%)	α = capital recovery factor (yr^{-1})
$\eta_{elec.prod}$ = energy efficiency electricity production (%)	I_{car} = investment cost of car (\$)
$\eta_{elec.distr}$ = energy efficiency electricity distribution (%)	$I_{battery}$ = investment cost of battery (\$)
$\eta_{extr/distr.raw\ mat}$ = energy efficiency of raw material extraction and distribution (%)	s_a = annual driving distance (km yr^{-1}) C_{MRT} = maintenance, repair and tire costs (\$ km^{-1})
EM_{WTW} = WTW emission (from electricity production) (gCO$_2$eq km^{-1})	r = discount rate
EF_{elec} = electricity emission factor (gCO$_2$eq Wh^{-1})	L = lifetime of the car or battery (yr)
C_{drive} = total driving cost (\$ km^{-1})	

2.3.2. Sensitivity analysis

Making battery performance and cost projections involves sometimes substantial uncertainties in data. To assess the impact on the performance of the electric car, a sensitivity analysis was carried using the ranges found in underlying data. In addition, the simulation results were compared to data from recent literature.

3. Battery selection

3.1. Technologies

Table 1 gives an overview of the battery types that are regarded as (possible) viable options for use in BEVs. Below, the current status of each technology is discussed.

Of all battery technologies, *lead-acid batteries* have the longest development history. The batteries use metallic lead as the negative electrode (anode) and lead dioxide as the positive electrode (cathode). On discharge, both electrodes are converted into lead sulfate. The electrolyte, a sulfuric acid solution, participates in the electrochemical reactions [21]. For EV applications, so-called advanced valve-regulated-lead-acid (VRLA) batteries have proven to provide save and maintenance free operation [21,25]. At cost levels of 100–150 \$ kWh^{-1}, they are a very affordable option compared to other existing batteries [25,119]. Yet, current applications in BEVs are limited to industrial vehicles like fork-lift trucks and to other low speed vehicles [25,114–117]. The most important reason is the low specific energy of 35–40 Wh kg^{-1} [114,118]. Also, the lifetime is limited to 3–5 years [119,120]. As a result, in the last decade, research and development (R&D) activities have mainly focused on applications in (micro) HEVs [121–125].

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 [25]. In the past NiMH batteries were considered to be a good interim solution for BEVs, as lithium-ion batteries showed important safety problems [23,26]. However, with a specific energy of 50–70 Wh kg^{-1} they cannot deliver the specific energy of 150–200 Wh kg^{-1} demanded for BEVs [27]. Also, the high share of nickel in NiMH batteries (7–8 kg kWh^{-1}) might limit future cost reductions due to high nickel prices [23,28,29]. Therefore, NiMH batteries are not seen as a serious candidate for large scale application in battery electric cars [29–31].

Lithium-ion batteries represent the largest share of commercial batteries for BEV purposes. At present, these batteries provide commercial battery electric cars with a range of around 150 km [32–34]. Li-ion batteries have electrodes that intercalate lithium, i.e. the electrode materials are a host structure for lithium ions [35,36]. A range of cathode materials is being used, with varying strengths and weaknesses [2]. In all cases, however, further development of the technology is needed to improve performance levels as well as to decrease costs (700–1200 \$ kWh^{-1}), while safety is guaranteed [[9,10,37,38] E. Kelder, personal communication, July 7, 2010]. Important aspects are the specific energy, which has now reached levels up to 125 Wh kg^{-1}, battery degradation and power capacity decline at low ambient temperatures [[9], E. Kelder, personal communication, July 7, 2010].

High temperature or sodium-beta batteries are based on sodium-ion transport between the cathode and anode. There are two variants: the sodium-sulfur (NaS) and ZEBRA battery. Both batteries have an anode that consists of molten sodium [25]. The NaS battery has a molten sulfur cathode, the ZEBRA battery has a transition metal halide cathode. The metal is either nickel or iron. The use of nickel chloride (Sodium-Nickel-Chloride battery) is the most common option [20]. To attain good ionic conductivity of the ceramic electrolyte, the internal operating temperature of these batteries lays between 300 and 350 °C [20]. Because of this temperature, application of ZEBRA batteries is currently only considered to be an option when they are used frequently, like in for example commercial and public transport vehicles [39]. The specific energy (115 Wh kg^{-1}) approaches that of Li-ion batteries, but the specific power has to be drastically improved from 180 to 400 W kg^{-1} [8,9]. Current costs are relatively low at a level of 600 \$ kWh^{-1}, but still substantially higher than the demanded 100–250 \$ kWh^{-1} [8,40]. NaS batteries are commercially available for stationary applications, but do not appear to be suitable for BEVs because of fundamental safety issues; damage to the ceramic electrolyte can lead to fire and explosion [20].

Lithium Metal Polymer (LMP) batteries are closely related to Li-ion batteries. Metallic lithium is applied instead of a lithium intercalation anode material; on charge, lithium ions migrate to the negative electrode and undergo a reduction reaction by which metallic lithium is formed [21]. The use of metallic lithium should have a positive effect on the specific energy. However, at a level of 100 Wh kg^{-1}, batteries that are to be used in electric cars show no performance advantage (yet) compared to Li-ion batteries. Their specific power (150–200 W kg^{-1}) lags behind, and LMP batteries do not seem to meet a cycle life of 1000 cycles currently[3] [28,41,42].

Also other lithium based battery technologies undergo research and development activities. *Lithium-sulfur (Li–S) batteries* have a sulfur cathode in which sulfur is typically paired with carbon [43]. For the anode, metallic lithium as well as other materials can be used [44]. In *lithium-air (Li-air) batteries*, lithium is applied as anode material and oxygen from ambient air acts as cathode material. Demonstrated specific energy levels at cell level[4] are 350 and 260 Wh kg^{-1} for lithium-sulfur and lithium-air batteries respectively, compared to about 150 Wh kg^{-1} for Li-ion [9,45–48]. However, other aspects like specific power, efficiency, and lifetime need more attention [9,44,49–54].

Next to lithium, other materials like zinc, aluminum and iron can be used as anode material in metal-air batteries. Of these concepts, *zinc-air (Zn-air) batteries* get most attention. Their stage of development is significantly ahead of other types, and it is believed that they could reach the cost levels required for BEVs [9,36,55]. For BEV purposes, a zinc-air flow battery is being

[3] Based on a driving range of 250 km and a lifetime of 200,000 km.

[4] The specific energy of a battery pack is lower compared to separate cells, because of the extra weight of packaging materials.

Table 1
Development stage, theoretical specific energy and qualitative judgment of the specific energy, specific power, energetic efficiency, cycle life, lifetime, operating temperature, costs and safety of battery technologies potentially suited for use in battery electric cars (see main text for explanation).

	Development stage	Theoretical specific energy (Wh kg^{-1})[e]	Specific energy	Specific power	Eff.	Cycle life	Life-time	Temperature	Costs	Safety
Lead-acid	Com.[a]	110–170[f]	−	+/−		+/−	−		++	+
NiMH	Com. (HEV)	>200[g]	−	++	−	+			−	+
Lithium										
Li-ion	Com. (BEV)	300–600[h]	+	+	+	+	+/−	−	−	−
LMP	Com. (BEV) expected[b]	500–890[i]	+	−		−	+	−[o]	−	−[q]
Li–S	Dem. (not BEV)[c]	2500[j]	++	+/−		−			+	−[q]
High temperature										
ZEBRA	Com. (BEV)	790[k]	+	−	+	+/−	+	−[o]	+/−	+
NaS	Com. (stationary)	750[k]	+	−		+/−	+	−[o]		−
Metal-air										
Zn-air	Com. (not BEV) expected[d]	1200[j]	++	−					++	
Li-air	R&D	11,000[l]	++	−						−[q]
Al-air	R&D	8000[l]	++	−	−	−[n]				
Fe-air	R&D	1880[l]	++	−	−	−				
Silicon-air	R&D	8470[m]								
Other innovative battery technologies										
Conversion	R&D		+							
Organic lithium	R&D		−	−				−[p]		
Ambient temperature Na-ion	R&D		−					+[o]	+	+
Mg-ion	R&D		+						+	+
Ni–Li	R&D		+	+						
Li–Cu	R&D									
All electron (potentially)	R&D		+	+			+			

Com: commercial; Dem: demonstration; R&D: Research & Development. NiMH: Nickel-metal-hydride; Li-ion: lithium-ion; LMP: Lithium Metal Polymer; Li–S: lithium–sulfur; ZEBRA: Sodium-Nickel-Chloride (NaNiCl) battery; NaS: sodium-sulfur; Zn-/Li-/Al-/Fe-air: zinc/lithium/aluminum/iron-air; Mg-ion: magnesium-ion; Ni-Li: nickel-lithium; Li–Cu; lithium–copper.

[a] commercial application in low speed BEVs and micro HEVs [114,125].
[b] commercial launch of BEV with LMP batteries announced to take place in 2011 [97].
[c] demonstration/pack field trial in unmanned aerial vehicles [45,98].
[d] zinc flow battery for BEVs in development stage (ReVolt), commercial production of a rechargeable zinc-air battery for small electronic applications is expected in the short term [55].
[e] theoretical specific energy (not taking into account electrochemical inactive materials in the battery): for comparison, the specific energy of gasoline is 13,000 Wh kg^{-1}. When taking into account efficiency losses in ICEVs, the TTW specific energy is 1700 to 2500 Wh kg^{-1} [54,99].
[f] [25,126].
[g] Depends on composition of metal-hydride alloy [27].
[h] Depending on chemistry: choice and composition of active materials [27,35].
[i] depending on chemistry: cathode capacity and voltage; higher value based on vanadium oxide cathode [27,35,50].
[j] [35].
[k] [27,35].
[l] [100].
[m] [66].
[n] Not electrically rechargeable.
[o] internal temperature.
[p] thermal instability.
[q] reactivity of metallic lithium.

developed by ReVolt; the anode is a liquid zinc slurry which flows through tubes that function as air cathode [55]. *Aluminum-air and iron-air technologies* were widely considered in the past, but interest declined as interest in and expectations of other battery types grew [36].

Conversion, organic, nickel-lithium and lithium-copper batteries are all based on the migration of lithium ions. In conversion batteries, conversion instead of intercalation takes place; a new lithium-oxide matrix is formed in which metallic particles are embedded [37,56]. The organic lithium battery is made from organic materials [56]. The nickel-lithium battery consists of a metallic lithium anode and a nickel hydroxide cathode [57]. In the lithium-copper battery, a metallic copper cathode is applied [58].

Because of the high operating temperature of current sodium-ion batteries, research also focuses on developing *ambient temperature sodium-ion batteries*, i.e. batteries that can operate at room temperature [18,20]. *Magnesium-ion batteries* are based on transport of magnesium ions between the electrodes [59]. *The all-electron battery* is a concept in which electrons are used instead of ions to store energy [60,61].

Conversion, magnesium-ion and all-electron batteries are believed to have the potential to attain higher specific energy levels compared to state-of-the-art Li-ion batteries [18,61,62]. In the personal view of Tarascon [18], organic lithium and ambient temperature sodium-ion batteries can reach specific energy levels comparable to present Li-ion batteries. The reduced use of non-renewable resources in the first battery type, and the safety of the latter, together with the abundance of low cost sodium, are considered to be great virtues [18,20,63].

3.2. Selection

Based on the discussion above, Li-ion and ZEBRA batteries are considered to play the most important role in the short term. Other commercial available battery technologies (lead-acid, NiMH and NaS) are considered to be less attractive for BEVs. Although Li-ion batteries are by many authors expected to dominate the market in the medium term, other technologies are presumed to be commercialized as well [[9,12,18,40,65], James Miners in: [64]]. Of battery technologies that are in an advanced stage of development, lithium-sulfur and zinc-air batteries are selected as the most promising options. For the long term, lithium-air batteries are included for further assessment. The development of other innovative battery technologies is in a very early stage and research activities are often carried out by only a small group of researchers [57,58,66]. Therefore, making statements about their prospects would bring too large uncertainties for meaningful quantitative analysis.

4. Battery performance and cost projections

4.1. Performance projections

Based on data found in literature, battery performance projections for 2015, 2025 and beyond 2025 are given in Table 2. Due to ranges found, also more progressive or conservative projections could be made. The most important considerations underlying the projections are discussed below.

4.1.1. Lithium-ion

Many efforts in Li-ion battery development target substantial increases of the specific energy. By using innovative electrode materials, a level of 250 Wh kg^{-1} could be achieved eventually [[9],Rozenkranz in: [64],E. Kelder, personal communication, July 7, 2010]. When this can be achieved is highly dependent on how fast technological breakthroughts can be realized [B. Scrosati, personal communication, September 8, 2010]. While Bandivadekar et al. [12] and Winter [in [67]] assumed an yearly improvement rate of 2 and 4% respectively, a rate of 6% corresponded to the expectations of the majority of sources consulted [[9,11], Rozenkranz in: [64], E. Kelder, personal communication, July 7, 2010]. On the other hand, safety is an absolute condition for battery commercialization and safety enhancements may require sacrifices in battery performance and increase of costs [[9,38], E. Kelder, personal communication, July 7, 2010]. Finally, more knowledge and experience is needed to understand how battery degradation can be controlled and lifetime extended. Next to improvement of the battery chemistry, the battery management system (BMS) will play an important role in controlling operational parameters like temperature and enhancing both safety and lifetime [[38,68],E. Kelder, personal communication, July 7, 2010, F. Ooms, personal communication, June 15, 2010].

4.1.2. ZEBRA

In the previous section, main issues identified for ZEBRA batteries were the low specific energy and specific power, and the high operational temperature. No projections were found on how these aspects can improve in time. However, the U.S. Department of Energy [36] and Lu et al. [20] state that substantial redesign of the cells or even radical changes in chemistry are needed. In that case, specific energy and peak power values of more than 200 Wh kg^{-1} and 400 W kg^{-1} at cell level could be achieved [36]. Yet, improving the power/energy ratio is regarded to be a key requirement [9]. Therefore, it may be expected that research will mainly focus on the enhancement of the power rate and not of the specific energy.

4.1.3. Lithium-sulfur

For lithium-sulfur batteries, R&D activities focus on increasing the cycle life [49,51,69]. Based on development goals of Sion Power, it is expected that batteries with a satisfying cycle life (1000 cycles or more) could be commercialized from approximately 2020 [9,65]. With goals of 550–650 Wh kg^{-1} at cell level, their specific energy will be considerably higher compared to Li-ion batteries [9,51,65]. In Kalhammer et al. [8] and the summary report of the Advanced Research Projects Agency - Energy (ARPA-E) [9] it is stated that the required power level of 400 W kg^{-1} is attainable. But, Mikhaylik et al. [46] show that power declines with higher specific energy and trade-offs have to be made. Safety is an important issue when metallic lithium is used as negative electrode material[5] [44,50]. Therefore, it is proposed to replace metallic lithium, for example with silicon [44].

4.1.4. Zinc- and Lithium-air

With regard to zinc-air and lithium-air batteries there is relatively little knowledge about their future performance. Lithium-air batteries are in initial stages of development and their techno-economic feasibility has to be proven yet [11,48]. Projections on the possible specific energy are very good. Tarascon [18] expects a level of 500 Wh kg^{-1} at commercialization, 1000 Wh kg^{-1} may be attained eventually [[19,70], Girishkumar in: [54]]. On the other hand, the specific power, cycle life and safety[5] are considered to be important issues [9,18,19,50,54,70].

Girishkumar [in [54]] expects that zinc-air batteries can attain specific energy levels up to 600 Wh kg^{-1} at cell level. The specific energy of a standard zinc-air battery will be higher compared to a zinc-air flow battery [9,54]. But, expectations on the cycle life of a zinc-air flow battery are very high: 2000–10,000 cycles [55]. As no volatile materials are applied, safety risks for zinc-air batteries are believed to be low [55,71]. For the specific power no projections were found, but it is considered to be an important issue in the ARPA-E summary report [9]. Also the charge/discharge efficiency is low; it is aimed to reach 80% in the future [9].

4.2. Cost projections

4.2.1. Projections in literature

For Li-ion batteries, cost projections were found in 13 different sources. Fig. 2 shows a progressive and conservative scenario based on optimistic and pessimistic projections. Costs are expected to reduce significantly in the short term, and can achieve levels of 350–500 \$ kWh^{-1} in 2020 and to 200–300 \$ kWh^{-1} in 2030.

For ZEBRA batteries, cost projections were found in Kalhammer et al. [8]. These are related to the annual production volume (Table 3). It is not stated when these volumes could be reached. Information from the Solartaxi website indicates that battery costs are believed to decline to approximately 200 \$ kWh^{-1} [72]. Galloway and Dustmann [73] even state that costs can potentially reduce to about 86 \$ kWh^{-1} at high volume production.

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^{-1} [9]. Also, in the same report it is stated that the chance for lithium-sulfur batteries to achieve 250 \$ kWh^{-1} is high. For lithium-air batteries, no cost estimates were found.

4.2.2. Learning

Table 4 gives an overview of progress ratios found in literature and derived from (projected) cost data. The PRs are about 83% for

[5] Reactivity of metallic lithium in liquid electrolytes and with water. In the former case, the lithium metal anode corrodes in the electrolyte and a non reactive layer forms on the electrode surface. As a result, lithium deposits irregularly on the anode during charge-discharge cycling and so-called dendrites (branched shapes) are formed. These dendrites can ultimately cause short circuit in the cell [44,50]. The latter reaction causes explosion and fire, because of its exothermic nature and the production of hydrogen gas.

Table 2
Battery performance projections for the short, medium and long term (2015–2025-beyond 2025).

	Li-ion[a]	ZEBRA[b]	Li–S[c]	Zn-air[d]	Li-air[e]
Specific energy (Wh kg^{-1})	150–200–250	130–160–200	n/a–400–500	n/a–250–350	n/a–500–1000
Specific power (W kg^{-1})	400–500–500	230–280–320	n/a–300–*400*	Unknown	Unknown
Efficiency (%)	90–92–*95*	90–90–*95*	Unknown	n/a–70–80	n/a–70–85
Cycle life (# cycles)	1000–3000	1000–1500–1500	n/a–1000–1000	n/a–2000–2000	Unknown
@ DoD	80%	80%	100%	Unknown	–
Lifetime (years)	7–*10–12*	15	Unknown	Unknown	Unknown
Operating temperature	Improving, but uncertain	From 300 to 350 °C to ambient	Low temperature good, high temperature improving	Unknown	Unknown
Safety	Good	Good	Uncertain	Good	Uncertain; key issue

n/a: not applicable; *Italic*: weakly supported projection, or based on opposing views. Projections based on.
[a] [[8,9,11,12,38], E. Kelder, personal communication, 2010; Rozenkranz in: [64], Winter in: [67], W. Robers, personal communication, 2010].
[b] [8,9,18,20,36].
[c] [8,9,45,46,51,69,101].
[d] [[9,43,71], Girishkumar in: [54]].
[e] [[18,19,47,48,53,70], Girishkumar in: [54]].

Li-ion batteries, and about 90% for NiMH batteries. For comparison, most PRs found for photovoltaic solar energy and onshore wind energy vary between 78–83% and 85–92% respectively. Long term average progress ratios are around 80% and 89% respectively [22].

To project cost reductions of Li-ion batteries by means of a learning curve, a scenario is defined assuming large scale BEV sales take off from 2012 and increase to globally 1.5 million BEVs per year in 2020 (compared to 50,000 BEVs per year in 2010). This scenario is in accordance with the steady pace scenario from the Boston Consultancy Group [74] and the projections from Bosch [in [75]] and Lache et al. [13].

The resulting cumulative battery production in 2020 is 7.1 million or almost 180,000 MWh, assuming an average battery capacity of 25 kWh [14]. Using progress ratios of 90% and 83% and present battery cost of 1200 and 800 \$ kWh^{-1}, Fig. 3 shows that costs can decrease to 200–600 \$ kWh^{-1} in 2020. An expansion of annual battery production volumes to more than 1.5 million batteries in 2020 would result in steeper cost reduction. It should be noted, however, that cost reductions below 200 \$ kWh^{-1} may be possible but depend on technological advances. It is therefore not considered realistic to simply extrapolate the learning curve

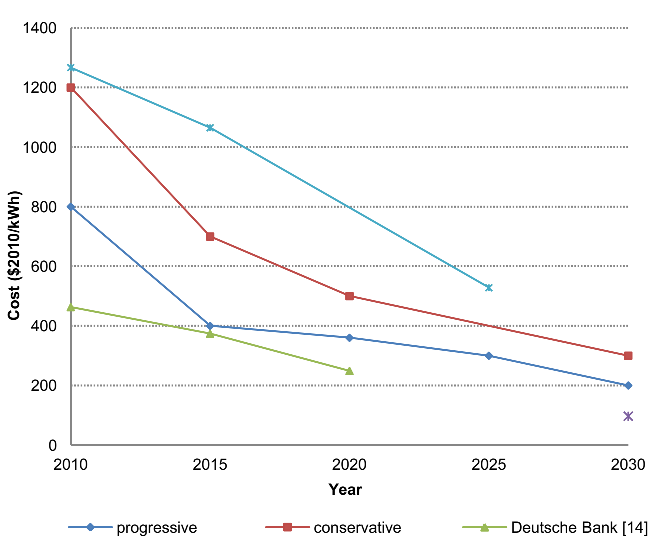

Fig. 2. Cost reduction scenarios based on projections from literature [2,4,10–15,38,40,93–95].

further, given that fundamentally new technologies may require a (partly) new development pathway.

FZ SoNick SA is the only present producer of ZEBRA batteries for electric car purposes. As its production capacity goals are far below the projected global BEV sales, battery cost scenarios (Fig. 4) are made for both the scenario used for Li-ion batteries and for the capacity goals of FZ SoNick SA [8,76].

Applying the progress ratio of 84.6% to the aimed expansion of production capacity, costs of ZEBRA batteries could reduce from 562 \$ kWh^{-1} in 2007 to 436 and 374 \$ kWh^{-1} in 2010 and 2015 respectively. The present production facility of FZ SoNick has a maximum production capacity of 30,000 batteries per year (approximately 630 MWh yr^{-1}). At this capacity, the costs can decline to about 275 \$ kWh^{-1} [77].

4.2.3. Battery cost breakdown

For Li-ion batteries, the Boston Consultancy Group (BCG) [10] and the Deutsche Bank [14] give a breakdown of current low and high volume and future high volume production costs (Table 5). 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. The numbers show that costs can be reduced at all levels when scaling up to high volume production. Especially costs other than for cell materials are to a large extent dependent of production volumes [10].

In the last column of Table 5, the projections are used to assess what battery costs could eventually be attained. Based on BCG figures, it is assumed that non-material based cell costs and costs at battery pack level will drop to respectively 125 and 100 \$2009 kWh^{-1} [10]. According to the Deutsche bank, cell material costs can be reduced to 135 \$2009 kWh^{-1}. However, the cost breakdowns are based on cathode materials containing cobalt and nickel. Cathode material prices are stated to be 55–66 \$2009 kWh^{-1} and represent 34% of cell material costs [14,78]. Materials for lithium-manganese-oxide and lithium-iron-phosphate based cathodes are about 30 \$2009 kWh^{-1} and have

Table 3
Cost projections for ZEBRA battery as function of production volume [8].

Battery systems/yr	Cost (\$2007 kWh^{-1})	Cost (\$2010 kWh^{-1})
1000	600	631
10,000	335	352
20,000	275	289
100,000	200	210

Table 4
Progress ratios for batteries.

Battery type	PR	Time	R^2	Notes
Li-ion cells for consumer electronics	83%	1993–2003	n/a	Found by Nagelhout and Ros [16]
NiMH for HEVs	89.8%	1997–2008	0.9845	Based on HEV sales numbers from Toyota [103] and cost projections from Kalhammer et al. [8]
NiMH for HEVs	91.0%	1998–2004	0.9312	Based on global HEV sales numbers from IIT [102] and cost projections from Kalhammer et al. [8]
Li-ion	83.7%		0.989	Derived from cost curve from Kamath [17] (based on costs estimates from 5 studies; 15% cost reduction with doubling of production volume)
Li-ion	83.4%		0.991	Derived from cost curve from Kamath [17] (based on costs estimates from 1 study; 10% cost reduction with doubling of production volume)
ZEBRA	84.6%		0.9955	Based on cost projections of Kalhammer et al. [8], assuming an average battery capacity of 21 kWh (based on production capacity per year, not cumulative capacity)

a share of 20% in cell material costs [78,79]. Based on these numbers, costs for cathode and anode materials can reduce to 50 \$2009 kWh^{-1} [14]. The Deutsche Bank also states that through new cell designs, separators may be removed from the cell [14]. This results in halving the costs of other cell materials to about 25 \$2009 kWh^{-1}.

Based on these cost reductions, total battery costs could eventually drop to roughly 300 \$2009 kWh^{-1} (305 \$2010 kWh^{-1}). The Boston Consultancy Group [10] confirms that attaining lower costs levels for current Li-ion technology is not likely; it states that a cost target of 250 \$ kWh^{-1} could only be achieved by a major breakthrough in chemistry, which is needed to attain fundamentally higher specific energy without significant increase in cost of materials or production process [10].

A cost breakdown of Galloway and Dustmann [73] for the 86 \$ kWh^{-1} ZEBRA battery shows that nickel accounts for 63% of the cell material costs. Here, the nickel price is assumed to be 13.74 \$ kg^{-1}. However, its price varied between 9 and 55 \$ kg^{-1} in the last five years [80]. Using a nickel price of 55 \$ kg^{-1} instead of 13.74 \$ kg^{-1} results in substantially higher battery cell and pack costs: 84.18 \$ kWh^{-1} and 149 \$ kWh^{-1} respectively (250% and 173% of costs as projected by Galloway and Dustmann).

In order to give an indication of the potential costs of other battery types, raw materials prices are compared to Li-ion batteries (Table 6). Assuming that for each technology the same amount of anode and cathode material is needed, the electrode costs are calculated for Li–S, Zn-air and Li-air batteries.

In Li-ion batteries, cathode materials represent a high share of total costs. As metal-air and Li–S batteries use air and sulfur as cathode materials, they benefit from using low cost raw materials. Furthermore, zinc-air systems use relatively inexpensive zinc as the anode material. Table 7 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. For Li–S batteries, this is especially true when silicon is used as anode material. 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.

4.2.4. Synthesis

By comparing the findings from Sections 4.2.1 and 4.2.2 we conclude the following about future battery cost levels. At a progress ratio of 83%, Li-ion battery costs can theoretically drop below 300 \$ kWh^{-1} by 2020. However, comparison with projections from literature suggests that a progress ratio of 91% is more likely. Also, the cost breakdowns indicate that a level of 300 \$ kWh^{-1} is the lower limit for present Li-ion technology.

If significant production capacity expansion can be realized in the medium term, ZEBRA batteries can attain cost levels of

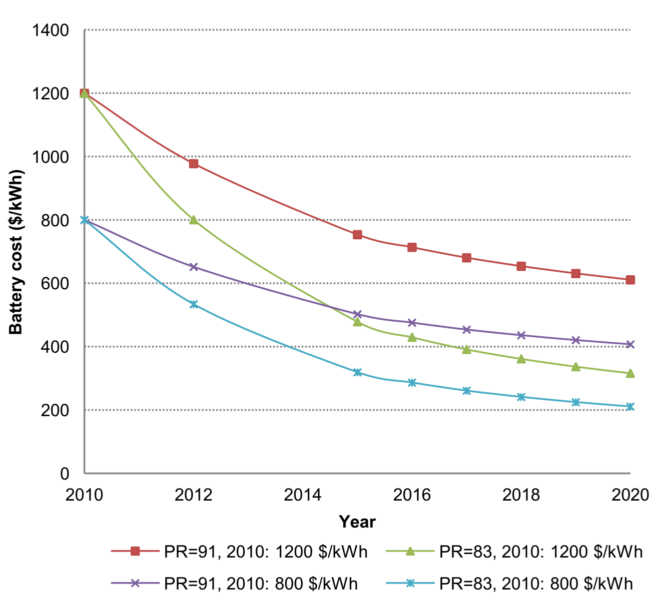

Fig. 3. Li-ion cost scenarios based on market projections and assessment of progress ratios.

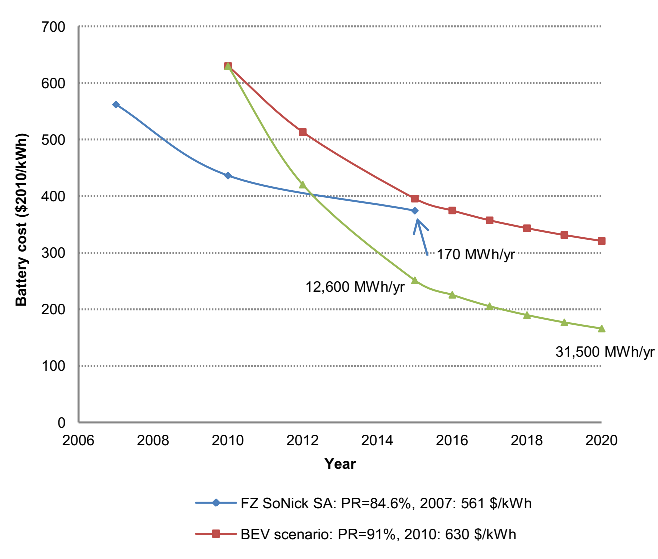

Fig. 4. ZEBRA battery cost scenarios, based on cost data from Kalhammer et al. [8]. Blue line: based on production capacity goals of FZ SoNick [76]; red and green line: based on cumulative production volume of 7.1 million batteries in 2020. Annual production capacities in 2015 and 2020 are given for FZ SoNick and BEV scenarios. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 5
Cost breakdown for low and high volume battery production.

	NCA 2009 500/yr 15 kWh [10]	NMC 2009 100,000/yr 25 kWh [14]	NCA 2020 1.1 million/yr 15 kWh [10]	Potential: Low material cost, high volume
	$2009 kWh^{-1}	$2009 kWh^{-1}	$2009 kWh^{-1}	$2009 kWh^{-1}
Cell materials (cathode, anode, electrolyte, separator, current collectors)	200–250	135	146–178	75
Other cell costs (casing, labor, depreciation, overhead, R&D)	450–540	161	124–152	125
Other costs (module and pack materials, assembly, depreciation, overhead, R&D)	340–430	160	90–110	100
Total	990–1220	456	360–440	300

Considered cathode material: NCA = Nickel–Cobalt–Aluminum, NMC = Nickel–Manganese–Cobalt. Production volume is given in amount of batteries produced per year. Average capacity batteries produced is given in kWh.

200–300 $ kWh^{-1}. Statements from the producer were found that costs below 100 $ kWh^{-1} are achievable if nickel prices are low. High price variations in the past, however, indicate that this is scenario is unlikely.

According to both literature and cost breakdowns, zinc-air batteries have the lowest cost potential. In the long term, costs can with high certainty drop below Li-ion costs. In the ARPA-E report it was stated that Li–S batteries can attain 250 $ kWh^{-1}. The assessment of raw material prices shows that these batteries may indeed equal or pass Li-ion costs. But, this is only considered to be likely if no expensive metallic lithium is used. The price of metallic lithium has also considerable impact on Li-air batteries. It is very uncertain what cost levels can be achieved eventually, but these will not be below Li-ion batteries.

Based on the findings, final cost projections for the short, medium and long term are shown in Table 7. 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.

5. Driving cycle simulation

5.1. Input parameters

5.1.1. Battery performance and cost parameters

The performance of BEVs with present-day Li-ion and ZEBRA batteries (Table 8) are defined as reference case. For the simulation of future BEVs, it is chosen to use projections made on the battery performance in the medium term (2025), Table 9.

Assuming that commercialization will start around 2020 for Li–S and Zn-air, cost values are chosen to reflect what is expected to be achievable at intermediate production volumes. Commercialization of Li-air batteries is expected to take off beyond 2020. Though, in order to make a fair comparison, cost levels for similar production volumes (but with a high uncertainty range) are used in the simulation.

Table 6
Raw material prices of electrode materials and total materials costs for Li-ion, Li–S, Zn-air and Li-air batteries.

	Cathode		Anode		Total		Sources
Li-ion	$Li(NiMnCo)O_2$	$LiFePO_4$	Graphite				
$ kg^{-1}	34	18	20				[14,79]
$ kWh^{-1}	68	37	19		87	$Li(NiMnCo)O_2$	[14,79]
					56	$LiFePO_4$	
Li–S	Sulfur	Li_2S	Metallic lithium	Silicon			
$ kg^{-1}	0.60	15[a]	61–128	4.00			[80,85, 104–106]
$ kWh^{-1}	1.20	30	58–122	3.80	59–123	Li–S	
					34	Si–Li_2S	
Zn-air	Air	Catalyst	Zinc				
$ kg^{-1}	0	15[b]	4.50				[80]
$ kWh^{-1}	0	30	4.30		35		
Li-air	Air	Catalyst	Metallic lithium				
$ kg^{-1}	0	15[b]	61–128				[85,105]
$ kWh^{-1}	0	30	58–122		88–152		

For lithium-ion materials, sulfur, zinc and silicon, the highest price found is used. For metallic lithium, prices did vary significantly and a higher and lower value are used.
[a] Assumed: mean of sulfur and lithium carbonate costs.
[b] Assumed: half of Li-ion (NMC) cathode material cost.

Table 7
Battery cost projections based on figures from literature review, assessment of progress ratios and battery cost breakdowns.

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

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

Table 8
Base case battery performance of Li-ion and ZEBRA batteries (2010).

	Specific energy (Wh kg^{-1})	Specific power (W kg^{-1})	Charge/discharge efficiency (%)	Cycle life (# cycles)	DoD (%)	Lifetime (yr)	Cost ($2010 kWh^{-1})
Li-ion	110[a]	400[c]	90[d]	1000[f]	80[f]	8[h]	1000[j]
ZEBRA	115[b]	180[b]	90[e]	1000[g]	80[g]	15[i]	630[g]

Based on: [a] [8,10,28,94,109]; [b] [8,9,28]; [c] [8,94]; [d] [3,28,94]; [e] [8,28]; [f] [8,94,109]; [g] [8,40]; [h] [8,110,111]; [i] [8,9]; [j][[4,10,11,40,93,107,108],W. Robers, personal communication, October 1, 2010].

Table 9
Projected performance (2025) of five battery technologies, at pack level (based on Tables 2and 8).

	Specific energy (Wh kg^{-1})	Specific power (W kg^{-1})	Charge/discharge efficiency (%)	Cycle life(# cycles)	DoD(%)	Lifetime (yr)	Cost ($2010 kWh^{-1})
Li-ion	200 (150–250)	500 (400–600)	92 (90–95)	2000 (1000–3000)	80 (70–90)	10 (7–15)	300 (250–350)
ZEBRA	160 (130–200)	280 (250–320)	90 (90–95)	1000 (1000–1500)	80 (70–90)	15	250 (100–350)
Li–S	400 (300–500)	300 (200–400)	*80 (70–90)*	1000 (500–1000)	100 (90)	*7 (5–10)*	375 (250–500)
Zn-air	250 (150–350)	*300*	70 (65–80)	2000 (1000–3000)	*80 (70–90)*	*7 (5–10)*	225 (100–350)
Li-air (2030)	500 (500–1000)	*300*	70 (60–85)	*1000 (500–1000)*	*80 (70–90)*	*7 (5–10)*	500 (300–700)

Italic: no information was found on these performance characteristics and values were assumed, based on qualitative statements in literature (see Section 4.1) and values found for other batteries. *Between brackets*: bandwidth for sensitivity analysis.

5.1.2. Other parameters

Tables 10 and 11 include all non-battery related parameters, associated with the reference car and with electricity supply respectively.

5.2. Results simulation

5.2.1. Battery

Fig. 5 shows the required battery weight and Fig. 6 the resulting battery costs in relation to the driving range. With regard to battery weight, the weight of present Li-ion and ZEBRA batteries is significantly higher for a range of 200 km or more compared to all future batteries. Also, from 300 km onwards, the difference between the weight of future Li-ion, ZEBRA and zinc-air batteries on the one hand and of lithium-sulfur and lithium-air batteries on the other hand increases.

For the latter two batteries, the weight remains constant until a range of 400 km. This is caused by the fact the weight required to deliver the total energy needed was lower than the weight required to deliver the maximum power demanded for acceleration. As the maximum power required does not depend on the range of the car, the battery is over-dimensioned to be able to deliver this power. Thus, the range of the car is larger than suggested by the results. At low ranges, this phenomenon does to a lesser extend also affect the results of the other batteries (except present Li-ion).

The Li–S battery weight is lower compared to the Li-air battery, because the Li–S battery was projected to have a higher charge/discharge efficiency. Besides, Equations (10) and (11) (methodology) showed that when the battery weight is defined by the specific energy, it is also dependent on the battery's depth of discharge. As the Li–S battery has a high depth of discharge, this maximizes the energy output of the battery and positively affects its weight.

Despite its low weight at higher ranges, the high cost per kilowatt-hour makes the Li-air 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 onwards 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. For a 100 km range, future Li-ion battery costs are about 1100 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.

In comparison to these results, the weight of a present lead-acid battery of 40 kWh kg^{-1} and 150 W kg^{-1} is 450 kg at a range of 100 km, and over 1100 kg at 200 km. At a cost of 100 $ kWh^{-1}, the total battery costs are about 1800 and 4600 $ at 100 and 200 km, respectively.

Table 10
Parameters for reference car used in the driving cycle simulation.

	Unit	Value	Source
Coefficient of rolling resistance, C_R	–	0.01	[23]
Aerodynamic drag coefficient, C_D	–	0.32	[23]
Frontal area, A_F	m^2	2.10	[23]
Inertia, δ	–	1	[3]
Weight (excl. battery)	kg	1120	[4]
Overweight[a]	(% of battery weight)	15	[3]
Efficiency motor	%	92	[3]
Efficiency controller	%	97	[3]
Efficiency transmission	%	98	[3]
Power auxiliary	W	400	Ross and Wu, 1995 in: [112]
Annual driving distance	km	14,000	[4]
Discount rate	%	10	[4]
Vehicle depreciation period	year	10	[4]
Cost vehicle platform[b]	$	20,717	[4]
Cost drive train (excl. battery)[c]	$	5895	[23]
Cost maintenance, repair and tires	$ km^{-1}	0.057	[4]

[a] The basic vehicle weight is based on a battery weight below 200 kg. If the battery is heavier, overweight is added to the basic vehicle weight.
[b] Everything but the drive train (chassis, suspension, doors, seats, windows, assembly).
[c] Electric drive train: motor controller, electric motor and transmission.

Table 11
Parameters for electricity supply used in the driving cycle simulation.

	Unit	Value	Source
Energy eff. extraction and transport of raw materials	%	95	[3]
Energy eff. Production	%	43	[3]
Energy eff. Distribution (EU average)	%	92.8	[3]
Energy efficiency battery charger	%	90	[3]
WTT emission factor electricity (UCTE European Electricity mix)	gCO_2eq kWh^{-1}	593	[113]
Electricity price (The Netherlands)	$ kWh^{-1}	0.110[a]	[4]

[a] 83 € MWh^{-1} flat rate incl. VAT, excl. energy tax.

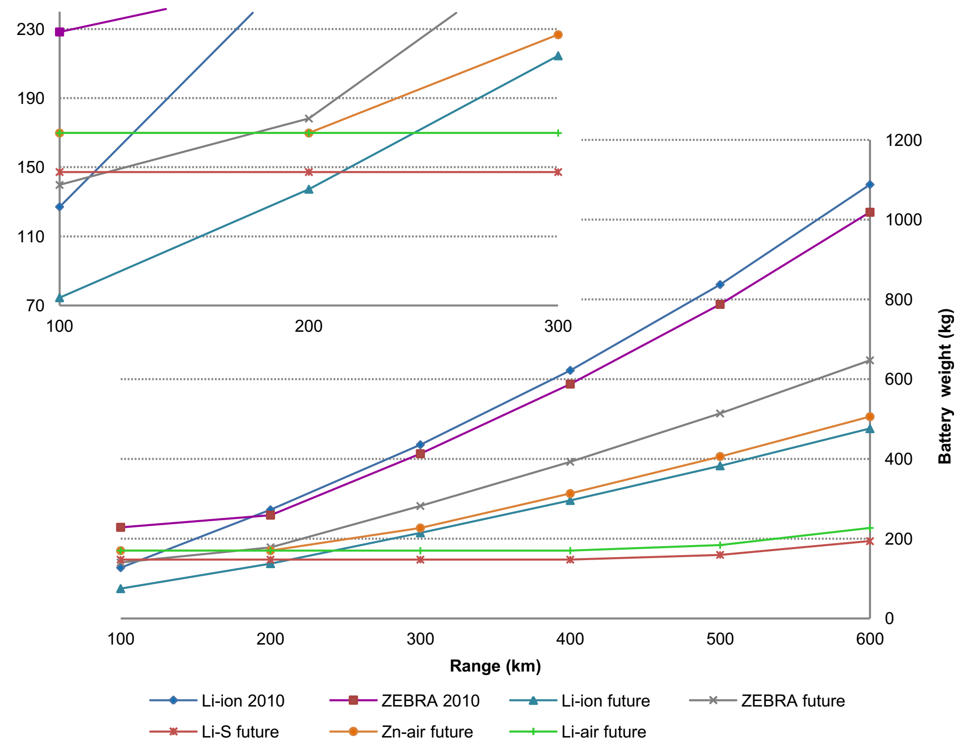

Fig. 5. Battery weight as a function of the driving range.

5.2.2. *Energetic and environmental performance*

Fig. 7 shows the average amount of energy supplied (Wh km^{-1}) by the battery to the drive train. As the energy consumption of the drive train is directly related the battery weight, Fig. 7 shows the same trends as Fig. 5.

The WTW energy consumption (Fig. 8) is 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. Thus, the low energy efficiency of metal-air (and to a lesser extend Li–S)

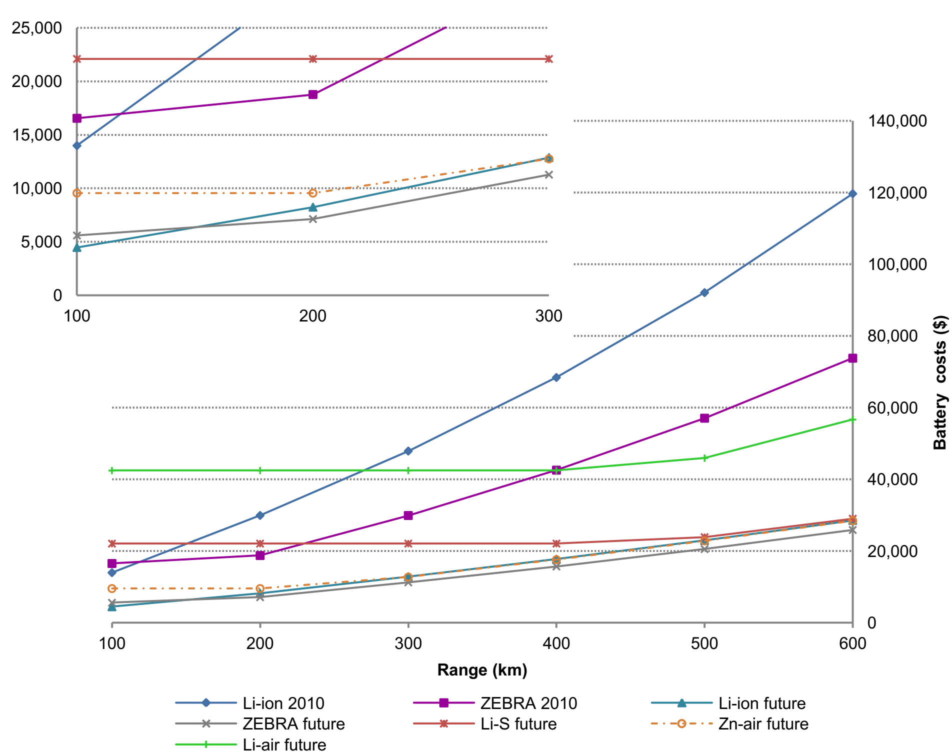

Fig. 6. Battery cost as a function of the driving range.

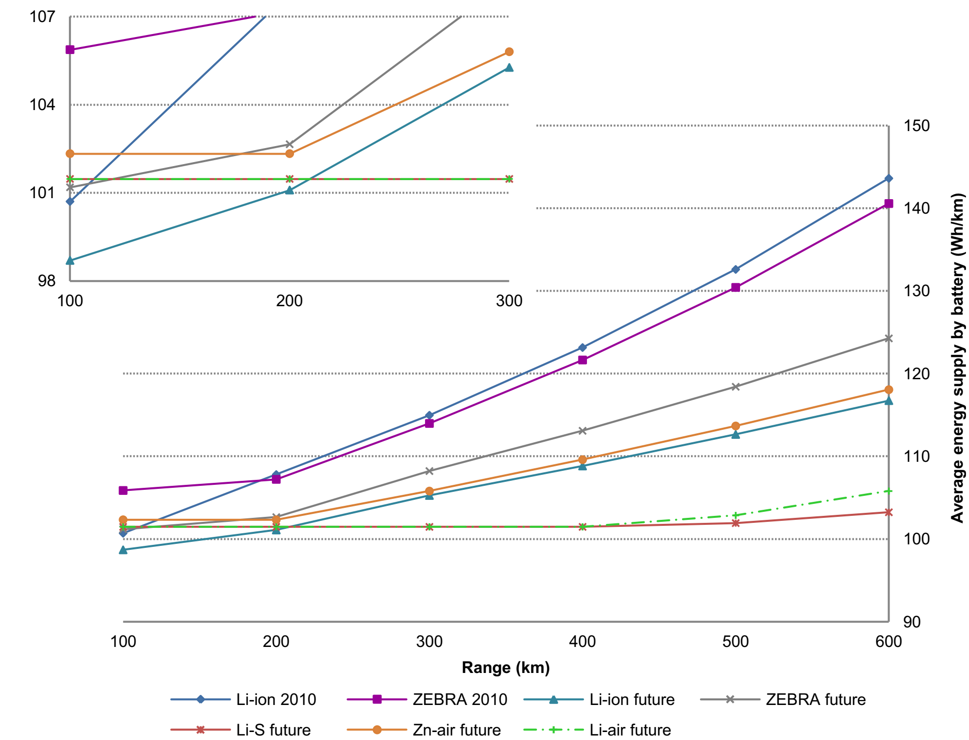

Fig. 7. Energy consumption of the drive train (energy delivered by the battery) as a function of the driving range.

batteries negatively affects the WTW energy consumption. 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.

The WTW emissions (Fig. 9) are directly related to the electricity consumption of the car. Therefore, the results do correspond to the outcomes of the WTW energy consumption. Because of their high efficiency, future Li-ion and ZEBRA batteries are favorable at most ranges. Only after more than 400 km, the Li–S battery is favored over the future ZEBRA battery.

However, note that the results only include energy consumption for driving. The ZEBRA battery needs to be heated when the car is not in use. At an annual driving distance of 14,000 km, the battery is not in operation for about 8343 h per year. At the present internal temperature of 300 °C and a heat conductivity of 0.006 W mK^{-1} [73], the WTW energy consumption would then increase with 2640 Wh km^{-1}. At 100 °C the additional energy use would reduce to 760 Wh km^{-1}. This is considerably higher than the energy consumption levels in Fig. 8 and will also result in significant higher emission levels.

Comparison of these results to the lead-acid battery, shows that the high weight of the lead-acid battery significantly affects the

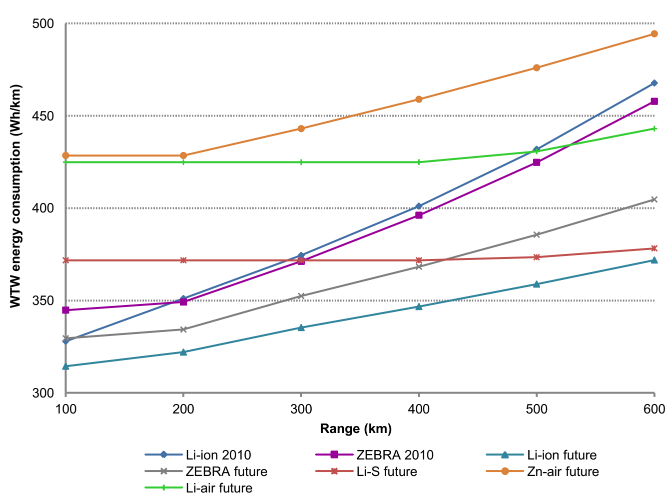

Fig. 8. WTW energy consumption of battery electric car as a function of the driving range. Energy consumption for heating of the ZEBRA batteries (when not in operation) is not included.

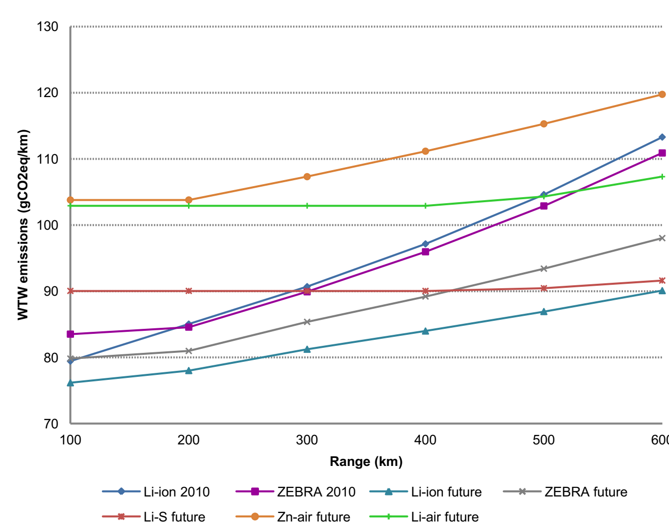

Fig. 9. WTW emissions (European electricity mix) of the battery electric car as a function of the driving range. Energy consumption for heating of the ZEBRA batteries (when not in operation) is not included.

energy consumption and emissions of the BEV. At a range of 100 km, the energy supply by the battery is 116 Wh km^{-1}, the WTW energy consumption is 424 Wh km^{-1}, and the WTW emissions are 103 gCO$_2$eq km^{-1}. At 200 km, these figures increase to 146 Wh km^{-1}, 535 Wh km^{-1} and 130 gCO$_2$eq km^{-1}, respectively. This means that up to a range of 400 km, the WTW performance of a BEV with a present Li-ion battery is better compared to a BEV with a lead-acid battery at a range of 100 km. At 200 km, the lead-acid battery is even outperformed by a present Li-ion battery at a range of 600 km.

5.2.3. Total driving cost

In Fig. 10 the total driving costs of the battery electric car are shown. As the costs for MRT and the vehicle's platform and drive train are equal for all simulated BEVs, the differences in driving costs are caused exclusively by the battery cost and lifetime and the electricity consumption of the car.

The total driving costs of 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 lifetime.

The high energy consumption of the BEVs with metal-air batteries does negatively affect the results. However, the low costs of zinc-air batteries counteract the higher energy costs. Overall, the total driving costs for Zn-air batteries are significantly lower compared to Li-air batteries. Lithium-sulfur batteries have relatively high driving costs at low ranges, but come closer to zinc-air batteries at high ranges.

The total battery costs of a lead-acid battery were found to be very low compared to a present Li-ion battery. The lifetime of 3–5 years, however, results in a high annual recovery factor and affects the total driving costs. At a lifetime of 3 years, the total driving costs are found to be 0.43 \$ km^{-1} at a range of 100 km and 0.52 \$ km^{-1} at 200 km. At a lifetime of 5 years, the costs decline to 0.42 and 0.47 \$ km^{-1} at 100 and 200 km respectively. At both ranges, this is well below the costs found for present Li-ion and ZEBRA batteries. Also, at 100 km, the values are comparable to the total driving costs of future Li-ion and ZEBRA batteries. At a range of 200 km, only lead-acid batteries with a lifetime of 5 years are still competitive to future Li-ion batteries.

5.3. Comparison literature

For the simulation, most parameter values for components other than the battery were taken from Van Vliet et al. [4,23]. Their TTW energy consumption figures for present Li-ion based BEVs [4] correspond well to the results found in this work (Table 12). Consumption values from Notter et al. [81] and Campanari et al. [3] are 40% to almost 90% higher respectively. Comparison with present gasoline and diesel ICEVs [23,81] shows that BEVs can reduce TTW energy consumption with about 300–400 Wh km^{-1}, depending on the battery type. The WTW energy consumption gain is ambiguous, as Van Vliet et al. [23] gives large ranges to account for uncertainty in marginal oil refining. For Li-ion batteries, the reduction is at least 75 Wh km^{-1}. Compared to a fuel cell electric vehicle (FCEV) [23], the simulated BEVs have a lower TTW energy consumption in most cases, but a comparable or higher WTW energy consumption.

Comparison of WTW emissions shows that BEVs attain levels 30–100 gCO$_2$ below ICEVs. The WTW emission reduction compared to FCEVs depends on hydrogen production; WTW emissions of an FCEV are zero when hydrogen is produced from renewable power sources (solar, wind), and 131 gCO$_2$ km^{-1} when produced from coal without carbon capture and sequestration (CCS) [23].

The driving costs other than for the battery were all taken from Van Vliet et al. [4,23] (without Value Added Tax (VAT)).

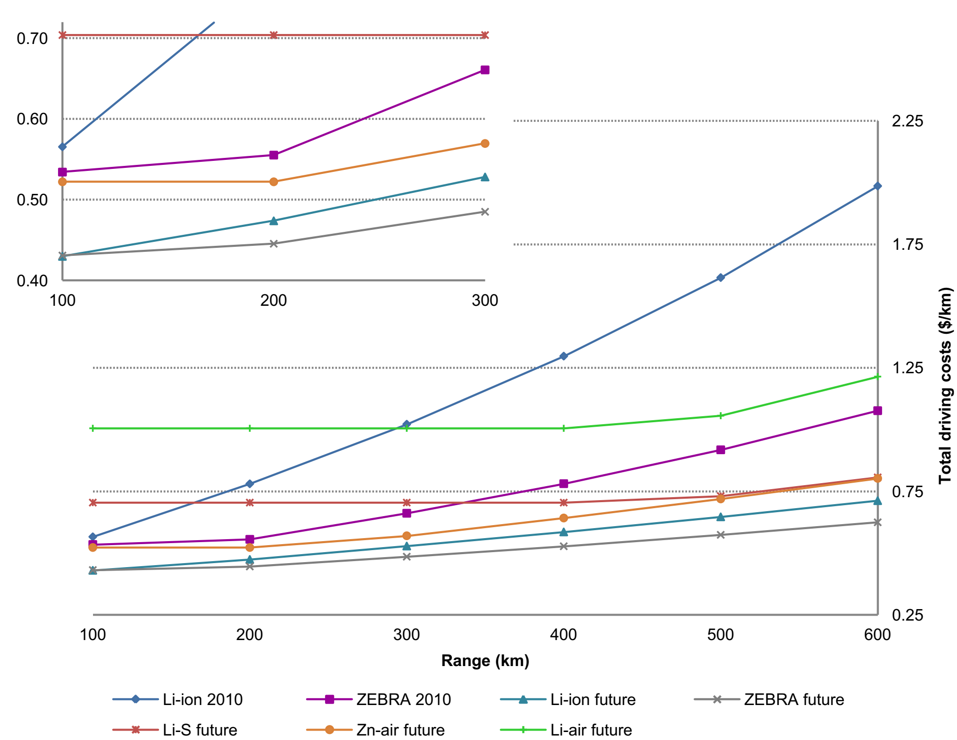

Fig. 10. Total driving costs of the battery electric car, considering a number of present and future battery technologies (at an electricity price of 0.110 \$ kWh^{-1}, including VAT [4,96]).

Table 12
TTW and WTW energy consumption and emissions: comparison of results from driving cycle simulation to data from other literature.

	Range (km)	TTW energy consumption (Wh km^{-1})[c]	WTW energy consumption (Wh km^{-1})[c]	TTW emissions (gCO_2eq km^{-1})[d]	WTW emissions (gCO_2eq km^{-1})[c,d]
BEV, simulation results					
Li-ion 2010	100–300	112–128	328–374	–	79–91
	600	160	468		113
Best (Li-ion future)	100–300	107–114	314–335	–	76–81
	600	127	372		90
Worst (Zn-air future)	100–300	146–151	429–443	–	104–107
	600	169	494		120
BEV, other literature					
Li-ion 2010 [4]	250 ± 34	127 ± 35		–	0–166
Li-ion 2015 [4]	250 ± 34	124 ± 32		–	0–163
Li-ion present [81]	200	170		–	
Li-ion present [3]	100–600	200–300	700–1000		150–210
ICEV					
Diesel [4,23]	550	492	558 ± 111	131	156 ± 5
Gasoline [4,23]		528	608 ± 153	140	163 ± 6
Gasoline [81]		462[b]		120[e]	n.a.
FCEV					
[a]		194 ± 39	289 ± 58	–	0–131 [(e)]

[a] on board hydrogen storage, no fuel reformer [23].
[b] assuming 32 MJ_{LHV} $liter^{-1}$ for gasoline.
[c] for BEV simulation results from this work and Campanari et al. [3], lower energy consumption and emission figures are true for the lower driving range given and vice versa.
[d] Emissions for European electricity mix.
[e] gCO_2 km^{-1}.

Nevertheless, the total driving costs (Table 14) from the simulation are higher compared to Van Vliet et al. [4] for a present Li-ion battery; at a range of 250 km the total costs are 12,557 \$ yr^{-1} and approximately 10,700 respectively. 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 et al. [4].

Because of the long lifetime and relatively low cost of the future ZEBRA battery, the total driving costs can be reduced most when using this battery. The costs are 1885 to 19,062 \$ $year^{-1}$ lower at 100–600 km compared to current BEV costs for Li-ion. On the other hand, Table 8 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 \$ $year^{-1}$ higher compared to costs for diesel and gasoline ICEVs respectively. At 600 km, the divergence increases to about 3400 and 4000 \$ $year^{-1}$. When ZEBRA costs would in the most positive scenario reduce to 100 \$ kWh^{-1} in the long term, total driving costs could drop to 5600 \$ $year^{-1}$ (at 100–200 km) and closely approach diesel ICEV costs. But, total BEV costs do increase with the driving range to 6700 \$ $year^{-1}$ at 600 km.

The results for FCEVs are not directly comparable to the simulation results, as another discount rate was used [23]. However, results from Van Vliet et al. [23] suggest that the future costs of FCEVs and best performing BEVs may come close on the longer term.

6. Discussion

6.1. Sensitivity analysis

The WTW energy consumption and emissions are affected most by variation in the batteries' efficiencies. As the efficiencies of Li–S and metal-air batteries show high uncertainty ranges, this can change the ranking. In the simulation, the Li-ion battery showed to be the best option at levels of 372 Wh km^{-1} and 90 gCO_2eq. However, at an efficiency of 85% instead of 70%, the Li-air battery can reach levels of 354 Wh km^{-1} and 86 gCO_2eq. On the other hand, a lower efficiency can mean that this battery becomes the worst option, instead of the zinc-air battery. For the zinc-air battery itself, the WTW energy consumption and emissions can reduce to 420 Wh km^{-1} and 102 gCO_2eq. At an efficiency of 90% instead of 80%, the Li–S battery will even be a better option than a high efficiency Li-air battery (333 Wh km^{-1} and 81 gCO_2eq).

Next to the efficiency, the WTW energy consumption and emissions are affected by the specific energy of the batteries and their depth of discharge. However, the ranking only changes when the Li-ion battery has a lower specific energy.

The total driving costs are most affected by the battery costs. Low cost (250 \$ kWh^{-1}) Li–S batteries could result in lower total costs compared to Li-ion batteries (0.66 and 0.71 \$ km^{-1} respectively). At a very low cost of 100 \$ kWh^{-1}, the total driving costs of the zinc-air and ZEBRA battery could even reduce to 0.57 \$ km^{-1} and 0.46 \$ km^{-1} respectively. Through cost reduction of the Li-air battery (from 500 to 300 \$ kWh^{-1}), the total costs (0.88 \$ km^{-1}) will approach but not pass zinc-air or Li–S batteries (0.80 \$ km^{-1} and 0.81 \$ km^{-1} respectively). The total driving costs for the Li-air battery are also considerably affected by its lifetime, efficiency and depth of discharge, but do not drop below 1.04 \$ km^{-1}. For other batteries, the impact of these parameters is less significant, but not negligible. Also, the impact of the specific energy is relatively small for all batteries.

6.2. 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. This has a considerable effect on the results. There are various reasons for these uncertainties.

First, the number and credibility of information sources did fluctuate. For all batteries, future performance and cost expectations 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 [8,10,11,14]. However, for zinc-air, ZEBRA and Li–S batteries references did lead to only one manufacturer of each technology. Concerning Li-air batteries, various commercial companies do conduct research on this technology but most sources only discussed their

Table 13
Total driving cost: comparison of results from driving cycle simulation to data from van Vliet et al. [4].

	Range (km)	Total driving cost ($ km^{-1}) [(c)]	Total driving cost, no VAT ($ $year^{-1}$)[c]
BEV, simulation results[a]			
Li-ion 2010	250	0.90	12,560
Best (ZEBRA future)	200–300	0.45–0.49	6240–6790
Worst (Li-air/Li-ion 2010)	200–300	1.00–1.02	14,070–14,300
BEV & ICEV, Van Vliet et al. [4] [b]			
Li-ion 2010	250 ± 34		±10,700
Li-ion 2015	250 ± 34		±9600
Diesel	550		±5300
Gasoline			±4800

[a] total driving costs based on production costs and electricity price.
[b] 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 [4].
[c] 14,000 km $year^{-1}$ [4].

specific energy [18,48,54,70]. Besides, data on the performance of the different batteries was not always focused on BEV purposes.

Secondly, very little data was found about learning or experience curves for batteries. The derived progress ratios were not based on historical cost data, but cost projections [8,17]. Therefore, it is uncertain to what extent these progress ratios do reflect reality.

Finally, subsequent reports of the Deutsche Bank [14,82] and the California Air Resources Board [8,11] show that developments (for Li-ion batteries) are going very fast. However, as these developments depend on many factors, expectations on how fast they will take place do vary considerably. More research is needed to verify and complement existing projections.

6.3. Sustainability aspects

In addition to the energetic, environmental and economic performance of BEVs, also the sustainability aspects of batteries should be considered. In other studies it was already shown that material availability might constrain battery production [83–86]. Especially the demand for cobalt, nickel and lithium could be a limiting factor for large scale deployment of Li-ion, ZEBRA and metallic lithium based batteries respectively. Table 13 shows that large scale substitution of ICEVs with BEVs will increase the demand for raw materials substantially for all battery technologies. For some materials, the demand could exceed present world reserves (manganese, nickel and zinc) or even the world reserve base (cobalt and metallic lithium). Clearly, Angerer [85], Andersson and Råde [83] and Gaines and Nelson [86] do all emphasize that recycling of metals is essential to ensure material availability.

With regard to their life cycles, Van den Bossche et al. [87] show that the production phase of Li-ion and ZEBRA batteries has the highest environmental impact. For Li-ion batteries, fossil fuel demand contributes 22% to the total impact of production [88]. The most energy consuming processes are the production of the anode and cathode (19 and 30% of a total 104 MJ_{eq} respectively) and of electronic components for the battery management system (13%). The extraction of raw materials demands low or moderate energy consumption [81,88].

For the electrodes, an important factor is the need to assemble Li-ion batteries 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, drying may not be needed. This means that, compared to Li-ion, the energy demand could be significantly lower for zinc-air batteries. ZEBRA batteries do also not contain lithium. But, when in operation, they need to be heated to 300 °C. This significantly increases the energy consumption in the use phase of the life cycle.

To reduce the environmental impact of batteries, recycling is very important [87,89]. At present recycling rates of 35–55% (for aluminum, cobalt, nickel and zinc), 30 to almost 40% energy is saved during material extraction [90–92]. Also, Dewulf et al. [89] show that the consumption of fossil resources during the production of Li-ion cathode materials reduces significantly when recovered cobalt and nickel are used.

The present level of recycling of lithium is low, but is expected to increase through the recycling of lithium batteries [90]. Other materials like sulfur, manganese and silicon are not recycled yet [90].

Table 14
Total demand for raw materials for a cumulative number of 1.6 billion EVs in 2050[a] (with 25 kWh batteries that all contain the same chemistry) and present other demand, world reserves and reserve base.

		Demand (kg kWh^{-1})	Demand EVs 2050 (k tonne)	Other demand 2009 (k tonne)[h]	World reserves (k tonne)[h]	World reserve base (k tonne)[i]
Li-ion	Lithium	0.150[b]	6000	14	9900	11,000
	Nickel ($LiNiO_2$)	1.2[c]	48,000	1430	71,000	150,000
	Cobalt ($LiCoO_2$)	1.2[c]	48,000	62	6600	13,000
	Manganese ($LiMnO_4$)	1.2[d]	48,000	10	540	5,200,000
	Phosphate ($LiFePO_4$)	0.8[d]	32,000	158	16,000	n/a
	Aluminum ($Li(NiCoAl)O_2$)	0.04[d]	1600	37	n/a	n/a
	Iron/steel ($LiFePO_4$)	0.4[d]	16,000	1200	77,000	n/a
ZEBRA	Nickel	2.4[c]	96,000	1430	71,000	150,000
Li–S	Lithium (metallic)	0.52[e]	20,800	14	9900	11,000
	Sulfur	1.2[f]	48,000	70	n/a	5,000,000[j]
Zn-air	Zinc	0.26[g]	10,400	11	200	1,900,000[j]
Li-air	Lithium (metallic)	0.52[e]	20,800	14	9900	11,000

[a] IEA scenario to meet IPCC CO2-reduction goals, characterizing an aggressive adoption of advanced technologies [86].
[b] [83,85].
[c] [83].
[d] Based on the proportion of cumulative demand of this material and of nickel, derived from Table 5 in Gaines and Nelson [86].
[e] Based on Li-metal/Vanadium battery [83].
[f] No data available, assumption based on high cathode metal demand values for Li-ion batteries.
[g] No data available, assumption based on lithium metal demand in Li-air battery and corrected for lithium excess.
[h] [90].
[i] [86].
[j] World resources [90].

7. Conclusions

From a list of eighteen battery types, five technologies were selected as the most promising options for BEVs for the short, medium and long term. Currently, Li-ion batteries significantly represent the largest market share of batteries for BEVs. Therefore, they were considered to be the most important option in the short term. Also, in the medium term and possibly long term they are expected to play an important role in BEVs. As ZEBRA batteries show cost, safety and lifetime advantages over Li-ion batteries, they were selected as an option in the near term. For the medium term, lithium-sulfur and zinc-air batteries were selected because of their specific energy and cost perspectives. Finally, lithium-air batteries can reach a very high specific energy. But, they are still in very early stages of development and may only be an option in the long term.

To maximize the performance and competiveness of battery electric cars, specific power, efficiency and battery costs are the most important parameters. In the medium term, it is expected that only Li-ion batteries will have a specific power level of 400 W kg^{-1} or higher. For all other batteries it is uncertain if and when this power level can be achieved. For Li–S and Li-air batteries, the power/energy ratio is expected to be lower than 1 and the specific power impacts the BEV performance up to driving ranges of 450 km. Nevertheless, Li–S and lithium-air batteries have a relatively low battery weight at ranges of 300 km or more. But, the efficiency of the batteries has to be higher than 80% to reach WTW energy consumption and emission levels found for future Li-ion batteries. Future Li-ion and ZEBRA batteries have a charge/discharge energy efficiency of 92 and 90% and show WTW energy consumption levels of 314–374 and 330-405 Wh km^{-1}. The WTW emission levels are 76–90 and 80-98 gCO_2eq km^{-1} for an electricity emission factor of 593 gCO_2eq kWh_e^{-1}. Metal-air batteries were projected to have an efficiency of 70% and WTW energy consumption and emission levels are 425 Wh km^{-1} and 103 gCO_2eq km^{-1} or higher. With a projected efficiency of 80%, Li–S batteries have high energy consumption and emission levels at low ranges, but catch up with ZEBRA batteries at approximately 400 km. Their maximum WTW energy consumption and emission levels are 378 Wh km^{-1} and 92 gCO_2eq km^{-1} at 600 km. Despite low efficiency levels, all batteries show similar or lower WTW energy consumption compared to ICEVs. Using the EU electricity mix, WTW emissions are reduced with 20–55%.

However, in the long term, only low cost (100 \$ kWh^{-1}) ZEBRA batteries could be cost competitive to present diesel ICEVs at driving ranges below 200 km; 0.40 \$ km^{-1} or 5600 \$ $year^{-1}$ compared to 5344 \$ $year^{-1}$. However, it is very unlikely that such a low cost level will be reached. 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^{-1}, compared to 0.43–0.71 and 0.52–0.80 \$ km^{-1}). Lithium-sulfur batteries approach zinc-air batteries at higher ranges and have comparable costs at 500 and 600 km. The total driving costs of lithium-air batteries are 0.30 \$ km^{-1} higher compared to Li–S at all ranges.

Compared to these results, it was found that the low specific energy of 40 kWh kg^{-1} for a present lead-acid battery results in a significantly higher battery weight at all driving ranges. This considerably affects the energy consumption and emission levels of the BEV. At a cost of 100 \$ kWh^{-1}, however, the BEV is cost competitive to future Li-ion and ZEBRA batteries at a range of 100 km.

The results reveal that all battery technologies show various advantages and disadvantages, and that not one battery will with certainty fulfill all battery requirements in the medium term. Future Li-ion batteries are projected to fulfill most requirements. Their use results in the lowest WTW energy consumption and WTW emissions. But, if extra measures have to be taken to guarantee safety, or the lifetime is shorter than projected in this work, this can have a negative effect on the performance and cost of the battery and the electric vehicle.

Li–S and metal-air batteries can be commercially available in 2025. They may, if possible at all, only fulfill all battery requirements in the long term. High efficiency lithium-sulfur and lithium-air batteries could show good energetic and environmental performance. But, batteries that do not contain lithium have best economic prospects.

On the other hand, low battery costs are not sufficient to make BEVs cost competitive to ICEVs. ZEBRA and zinc-air batteries also require improved efficiency to attain low driving costs. This is expected to be a challenge for zinc-air batteries. The results for ZEBRA batteries are seriously affected by the operating temperature. Reduction of this temperature, preferably even to ambient temperature, is needed to make this battery a viable option for large scale application.

Finally, many projections were not based on figures from scientific literature, but other information sources. Further verification of the given projections is desired, for example through engineering studies and real life experience. This especially concerns the specific power, lifetime, costs and parameters not covered in the simulation (recharge time, operational temperature). Also, more work is needed on experience curves for batteries. Supporting the progress ratios with historical data is required to get more and better insight in potential learning effects.

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