Impacts of Electric Vehicles - Deliverable 2

Assessment of electric vehicle and battery technology

Report
Delft, April 2011

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Further information on this study can be obtained from the contact person Huib van Essen.

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Contents

Summary

Electric Vehicles (EVs) are a promising technology for reducing the GHG emissions and other environmental impacts of road transport. It is important for EU policy makers to get an overview of the possible impacts of the introduction of Electric Vehicles. Therefore DG CLIMA commissioned CE Delft, ICF and Ecologic to carry out a study on the potential impacts of large scale market penetration of Full EVs (FEVs) and Plug-in Hybrid EVs (PHEVs) in the EU, with a focus on passenger cars and light commercial vehicles. This study includes an assessment of both the transport part (e.g., composition of vehicle fleet) and electricity production and the impacts on well-to-wheel GHG emissions, pollutant emissions, other environmental impacts, costs, etc.

This report is the second deliverable of this project and provides an overview of the ongoing and expected developments in vehicle technology of EVs and their key components, including all types of energy storage. Since these systems are very new, a detailed forecast of the future development of these technologies is based on the opinions of experts at battery manufacturers, car manufacturers and research institutes.

Battery technology and cost to 2030

The range of FEVs and the All Electric Range (AER) of PHEVs continue to be a major determinant of costs as it drives the size of the battery and the cost of energy storage continues to be relatively high. It still is the single greatest challenge to the commercialisation of both PHEV and EV models.
By 2011/12, we anticipate that commercial volume production of batteries will start and we estimate battery cost in 2012 (unsubsidised) to be € 620 per kWh. Subsidised cost may be € 50 to € 100 per kWh lower.

Battery manufacturers also indicated that each battery generation is likely to be in production for four to five years at least to recoup capital investments and R&D costs, so that 2011/2012 introduction of the first generation of automotive lithium-ion batteries implies that the second-generation batteries could be commercialised in 2016/17 and third-generation batteries in the early 2020 time frame.

Based on our survey of battery technology development, we anticipate the following developments relative to a 2010 battery:

- Improvements of 20 to 25% in specific energy with a similar reduction in cost by 2016 primarily due to improved battery design and packaging.
- Improvements of 70 to 75% in specific energy and 50% reduction in cost per kWh by 2020 to 2022 with the introduction of advanced materials for the anodes and cathodes, such as silicon anodes.
- Potential for a tripling of specific energy and 70% cost reduction per kWh by 2030 with the introduction of lithium-sulfur batteries.

Based on available analysis and current battery data, it appears that current (2010) battery life should exceed seven years and may be around ten years for 'average' use. However, there is still much uncertainty regarding battery calendar life at more severe ambient temperatures while more moderate temperatures may allow real world battery life to be around ten years on average, and we anticipate continued improvement to 2020 by which time, expectations are that average life may be in the thirteen to fifteen year range.

It is generally understood that, unlike cadmium and lead based batteries, current known formulations of the Li-Ion battery materials do not present significant environmental concerns beyond fire safety and landfill utilisation. We believe that there are no major concerns that would distinguish recycling Li-Ion batteries relative to current lead acid and nickel metal hydride batteries. Battery recycling economics appear to be difficult and hard to predict ten years into the future but will likely require government mandates or subsidies to be economical.

The use of lithium batteries for EV and PHEV fleets in large numbers has raised concerns about lithium supply and future availability of lithium in large quantities. In comparison even to known global reserves, the demand from EVs is very small. If, as an extreme example, by 2040, all of the world's 2 billion cars are FEVs, the total lithium used would be ~3 x 2 billion kg, or 6 million tons, which is equivalent to less than 25% of the world's known reserves. Hence, there does not appear to be any case for long term supply shortages.

The current costs of lithium batteries are based on battery manufacturer quotations to car manufacturers at rates of about 20 thousand per year for supply starting in 2011/2012. Future costs to 2020 and 2030 are based on using current cost numbers and accounting for effects of volume, scale and in the case of the battery, new technology, as shown in Table 1.

Table 1 **Unsubsidised battery costs over time**

Battery type	Specific Energy density in Wh/kg	Cost to OEM*
2012 lithium Mn Spinel	105 ± 5	€ 200 per battery + € 620 per kWh
2020 Li Mn Spinel (Battery 1)	125 ± 5	€ 180 per battery + € 310 per kWh
2020 Silicon lithium (Battery 2)	160 ± 5	€ 200 per battery + € 350 per kWh
2025 Silicon lithium (Battery 1)	190 ± 10	€ 180 per battery + € 185 per kWh
2030 Silicon Li-S (Battery 2)	300 ± 20	€ 200 per battery + € 200 per kWh

Cost of 20 kWh battery in 2012 will be € 200 + € 620 per kWh * 20 kWh or € 12,600.
These are manufacturer costs, no retail prices.

Other major components
There are a number of other components on an EV or PHEV that are unique to such a vehicle and different from those in a conventional ICE-powered vehicle. The motor, inverter and controller are the most expensive components after the battery and special attention is paid to these components. The other components of interest include the DC/DC converter for 14 V supply for the lights and ignition (in a PHEV) high voltage wiring harness, the special HVAC unit and the regenerative brakes. Detailed cost estimates to 2030 for each of these components were developed and are presented in this report.

Vehicle energy use
Based on the energy density estimates, a set of vehicles has been defined, including a consistent set of specifications of vehicle performance and mass. This will be the basis for the analysis of impacts of EV in the next phase of this project. Based on available studies we conclude that the vehicle energy use is still the dominant part of total life cycle energy use, although the EV does require more energy to produce and recycle relative to an ICEV.

1 Introduction

1.1 Introduction to the project

Electric Vehicles (EVs) are a promising technology for drastically reducing the environmental burden of road transport. More than a decade ago and also more recently, they were advocated by various actors as an important element in reducing CO_2 emissions of particularly passenger cars and light commercial vehicles as well as emissions of pollutants and noise.

At the same time, EVs are still far from proven technology. There exist many uncertainties with respect to crucial issues like:
- The battery technology (energy capacity in relation to vehicle range, charging speed, durability, availability and environmental impacts of materials).
- Well–to-wheel impacts on emissions.
- Interaction with the electricity generation.
- Cost and business case of large scale introduction.

For EU policy makers, it is important to get a reliable and independent assessment of the state of the art of these issues in order to develop targeted and appropriate GHG reduction policy for transport. Therefore DG CLIMA commissioned CE Delft, ICF and Ecologic to carry out a study on the potential impacts of large scale market penetration of EVs in the EU, with a focus on passenger cars and light commercial vehicles. This study includes an assessment of both the transport part (e.g. composition of vehicle fleet) and electricity production and the impacts on well-to-wheel GHG emissions, pollutant emissions, other environmental impacts, costs, etc.

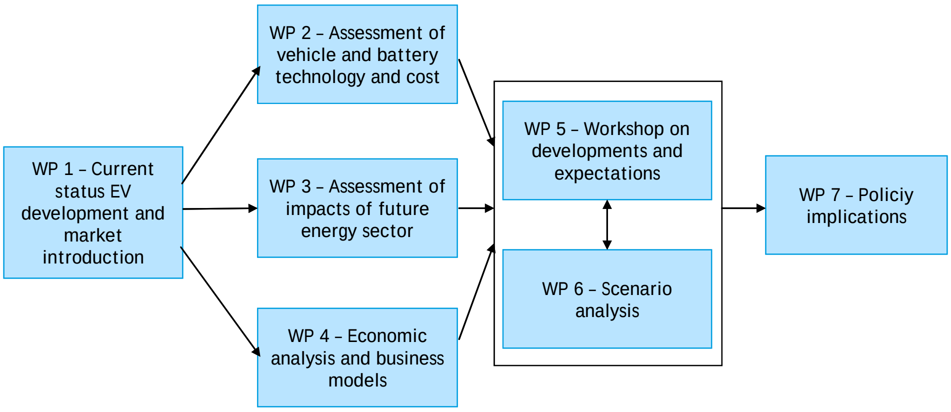
In this study three types of EVs are distinguished:
- Full Electric Vehicles (FEVs) that have an electric engine and no internal combustion engine (ICE).
- Plug-in Hybrid Electric Vehicles (PHEVs) that have both an ICE and an electric engine, with a battery that can be charged on the grid.
- Electric Vehicles with a Range Extender (EREVs) that have an electric engine and an ICE that can be used to charge the battery and so extend the vehicle's range. The battery of an EREV can be charged on the grid.

The results of the study should help the Commission with developing GHG policy for transport, in particular in the field of EVs and in relation to the wider EU transport policy and EU policy for the electricity sector.

The project is organised around seven work packages (WPs):
WP 1 Current status of EV development and market introduction.
WP 2 Assessment of vehicle and battery technology and cost.
WP 3 Assessment of impacts on future energy sector.
WP 4 Economic analysis and business models.
WP 5 Workshop on developments and expectations.
WP 6 Scenario analysis.
WP 7 Policy implications.

The following graph Figure 1 gives an overview of the main interactions between the various WPs. The approach for each WP is explained in the following paragraphs.

Figure 1 Project overview



The results of this project are presented in five deliverables: Deliverables 1 to 4 presenting the results of WP 1 to 4 and a final Deliverable 5 with the results of WP 5, 6 and 7. In addition there is a summary report, briefly summarizing the main results of the entire project.

This report is the second deliverable of the project and includes the results of WP 2.

1.2 Structure of this report

This report covers the following areas:
– Battery technology for Electric Vehicles (Chapter 2).
– Other components of electric power trains (Chapter 3).
– Energy use of Electric Vehicles, including energy use of vehicle production (Chapter 4).
– Noise, safety and maintenance issues (Chapter 5).
– Projections for market shares of Electric Vehicles (Chapter 6).
– Conclusions (Chapter 7).

Since these systems are very new, a detailed forecast of the future development of these technologies is based on the opinions of experts at battery manufacturers, car manufacturers and research institutes.

This report does not provide an assessment of the economics of EV models.

2 Battery technology

2.1 Introduction

As noted in Deliverable 1[1], the world light vehicle market as well as the EU market, is dominated by a dozen car manufacturers. While Electric Vehicles are now being manufactured by small niche market companies like Tesla and Think!, high penetrations of PHEV and FEV models can occur only if the major car manufacturers enter the market with a variety of reasonably priced models. The compilation of model developments under WP 1 provides a good snapshot of the system designs likely to be commercialised in the near future. In all cases, the most expensive component of the EV and PHEV is the battery and future costs and performance of batteries is the key issue governing future EV and PHEV penetration in the market.

The range of FEV and the All Electric Range (AER) of PHEV (or Electric with Range Extender Vehicles, EREV) continue to be a major determinant of costs as it drives the size of the battery, and the cost of energy storage continues to be single greatest challenge to the commercialisation of both PHEV and EV models. In this context, the cost of recharging infrastructure is not as large a problem as widely believed in the next five to ten years since most early adopters are those who will have access to home recharging facilities at night. The durability and life of the battery are also major concerns since under the deep cycling of state-of-charge (SOC) of the battery, battery life is impacted.

The preferred solution universally currently appears to be the lithium-ion battery. However, the term 'Lithium Ion' encompasses a number of different chemistries, each one of which has its trade-off in energy density, safety under abuse and overcharge situations and durability in automotive use. Table 2 shows many of the different chemistries under development, but the relative advantages of each chemistry is not yet well understood under automotive use. Here, the reference is to the formulation of the cathode and almost all batteries under commercial development now feature graphite anodes. As a result, car manufacturers are keeping their options open by having joint ventures with several battery suppliers as discussed in the WP 1 report.

The different battery developers all claim their chemistry offers the best combination of properties for automotive use, but some general facts are well known. The iron phosphate based systems are believed to be the safest and to have the lowest cost, but also have lower performance than other chemistries. However, firms like A123 claim to have substantially enhanced the performance of iron phosphate systems using nanotechnology so that performance is much closer to other systems. The nickel- and cobalt-based systems usually have the highest performance in terms of specific energy and power, but are also thought to be less safe and less durable than other systems. Manganese-based systems have properties between those of iron-phosphate and the Nickel systems in terms of energy density and specific power. The life and durability of these systems under in-use conditions is less well understood but additional discussion of battery life is provided under Section 1.3.3 of this report. Automotive batteries require a cycle life of at least 5,000 charge – discharge cycles and a calendar life of over ten years.

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[1] CE, 2011.

Table 2 Examples of current Li-Ion battery chemistry

Developer	Chemistry	Vehicle	MY
EnerDel	Lithium manganese titanate	Think	2009
A123	Doped lithium nanophosphate	Volt-EV Vue-PHEV Think	2010 2009 2009
Compact (LG) NEC	Manganese spinel	Volt-EV Nissan-EV	2010 2010
Panasonic JCI-Saft	Lithium nickel cobalt aluminium oxide	Toyota-PHEV S400-HEV Vue-PHEV	2010 2009 2009
Hitachi	Lithium cobalt oxide	GM-HEV	2010
Available Cells	Lithium manganese oxide	Tesla-EV	2008
Altair Nanotechnologies	Lithium titanate spinel	Phoenix Electric	2008

2.2 Battery technology to 2020

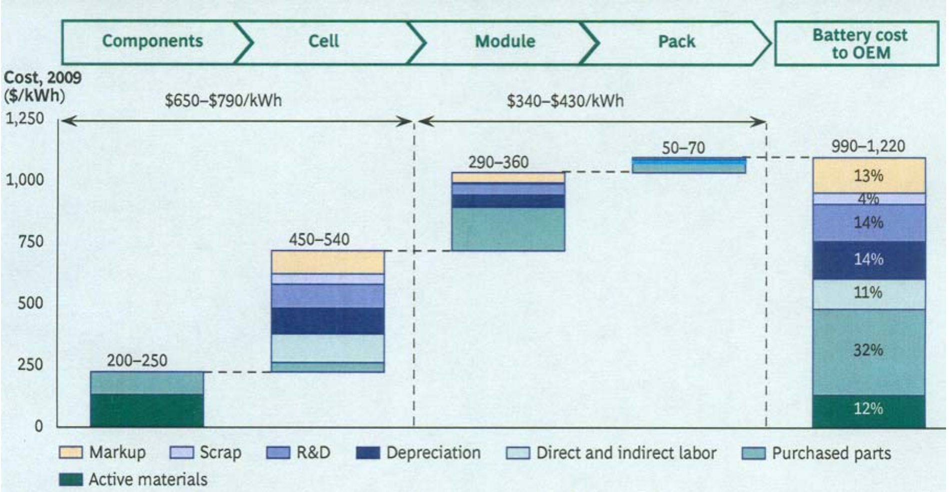
The performance of near-term batteries and their costs must distinguish between three levels at which costs and performance are (sometimes confusingly) quoted:

– The cell, which is the most basic level of a battery. At the cell-level, most batteries have an energy density of 130 to 160 Wh/kg, depending on chemistry and packaging.
– The module which is typically an assembly of four to ten cells, and features cell electrical interconnections and electrical management.
– The battery, which is a collection of modules and includes a crash proof box, cell monitoring system, battery thermal management system, safety protection and high voltage external connectors. These features add size and weight to the battery so that most batteries being commercialised in 2010 have energy density at the battery level of 80 to 110 Wh/kg, which is about 35 to 40% lower than at the cell-level.

The average energy density of EV batteries entering production in 2010 is expected to be around 95 Wh/kg, increasing to about 100 Wh/kg by 2012. These numbers are consistent with the battery weights and capacity for the Nissan Leaf, one of the first FEVs entering volume production by 2012.

Costs also vary significantly from the cell to the battery level.
A comprehensive recent analysis by the Boston Consulting Group (BCG), estimated battery costs starting from material costs and it provides a detailed breakdown of the total battery cost components. Here, the term cost refers to the cost to a car manufacturer and not the retail price to the consumer. Figure 2 shows the detailed breakdown starting from cell components to the battery pack estimated by BCG.

Figure 2 Li-Ion battery costs for 2009



Source: BCG.

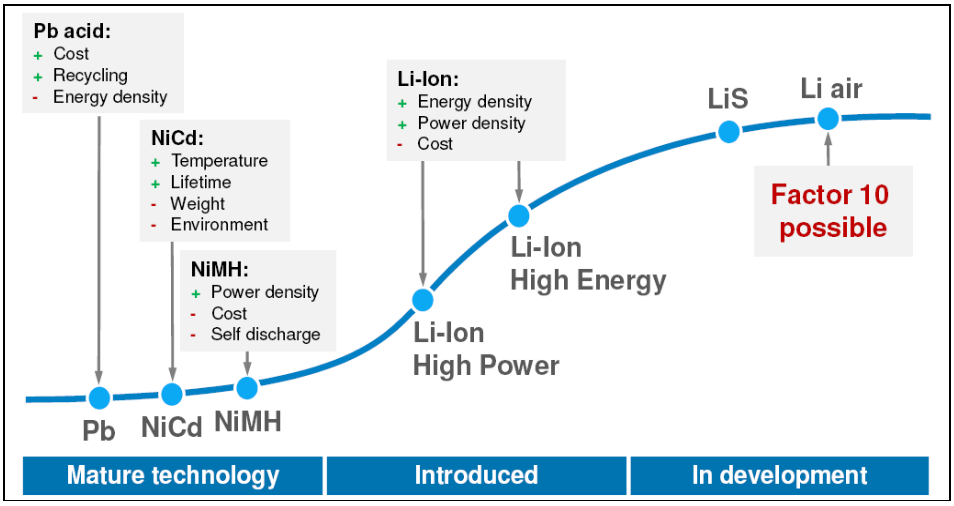
As can be seen, their estimate for the battery cost is $ 1,100 ± 110, which is more than 1.5 times the cell cost of $ 720 ± 70. Our contacts with battery manufacturers suggest that the lower end of the battery cost range is more reasonable, but they were in good agreement with cell costs suggesting that BCG may have overestimated cell to battery integration cost. More importantly, these are 2009 *unsubsidised* cost at low volume production (500 complete batteries per year). By 2011/12, we anticipate that commercial production of batteries will start and several battery manufacturers have indicated to us that preliminary production in 2012 will be about 2,000 batteries per month (Nissan-Renault may be higher) or about 25,000 per year. At this volume, battery manufacturers estimated cell costs to be about $ 500 per kWh which is 25 to 30% lower than the low volume cost estimated by BCG. Nissan has publicly claimed battery costs at $ 500/kWh but they are receiving significant subsidies towards capital equipment and building the manufacturing plant so that this is reasonable as a subsidised cost, as capital costs are about 10 to 12% of total costs. Integration to module and battery level have costs that are somewhat less volume sensitive, and we estimate total battery cost at $ 750 to 800 per kWh in 2012. At current exchange rates of $ 1.25 per €, we estimate battery cost in 2012 (unsubsidised) to be € 620 per kWh, but there are some small fixed costs for the battery like safety fuses and current leak detection that do not scale with battery size, so that an add on cost of € 200 per battery is utilised that is independent of kWh storage capacity. As noted, subsidised cost may be € 50 to € 100 per kWh lower.

Battery manufacturers also indicated that each battery generation is likely to be in production for four to five years at least to recoup capital investments and R&D costs, so that 2011/2012 introduction of the first generation of automotive lithium-ion batteries implies that the second-generation batteries could be commercialised in 2016/17 and third-generation batteries in the early 2020 time frame. Developments to 2020 and 2030 are considered below and a complete summary of cost projections can be found in Section 2.7.

2.3 Post-2020 technology of lithium batteries

The current generation of lithium-ion batteries typically uses a carbon-based anode and a metal oxide cathode. Research on next generation lithium batteries will continue the development of electrode and electrolyte materials and chemistries in order to increase the life and energy density of the battery while reducing size and weight. The most promising chemistries appear to involve silicon, sulfur and air (oxygen) and another important development is research into nanotechnologies. These trends have been widely recognised and a recent presentation by Limotive researchers showed the following battery technology roadmap in Figure 3. Per the request of the client, we have examined research from a wide variety of universities and new start-up firms to compile a profile of ongoing research that can shape future battery performance and cost.

Figure 3 **Battery technology roadmap**

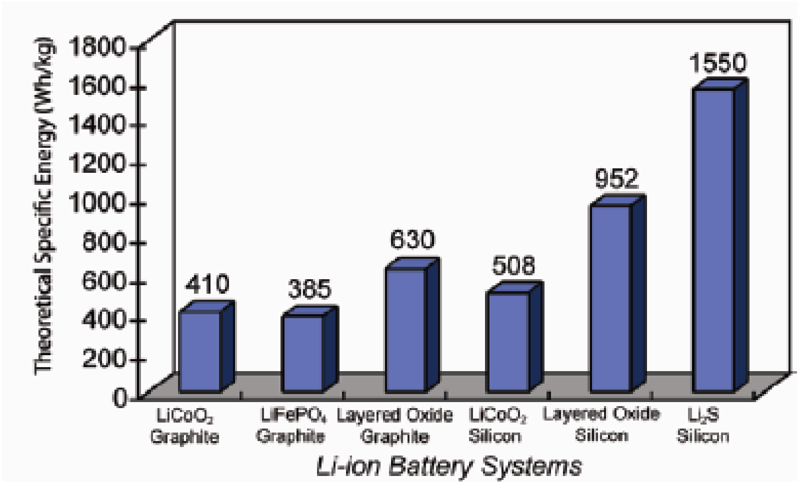


2.3.1 Lithium-silicon

Silicon is an attractive anode material for lithium-ion batteries because it has the highest known theoretical charge capacity of ~4,200 mAh/g – about ten times the amount of energy that a conventional graphite-based anode can contain. It also has a specific energy of 1,550 Wh/kg – about four times the energy of a conventional graphite-based anode. Furthermore, silicon is the second most abundant element on the planet and has a well-developed industrial infrastructure, making it a cheap material to commercialise with a cost comparable to graphite per unit of weight. Figure 4 provides some data on the theoretical potential of different lithium chemistries.

The problem with silicon is that it is very brittle and when lithium-ions are transferred during charge and discharge cycles, the volume expands and contracts by 400% which can pulverise the silicon anodes after just the first cycle. Another limitation is the cathode chemistry. Current cathodes made from oxides only have a capacity around 100-300 mAh/g. As a result, a silicon anode alone would not benefit from its high charge capacity.

Figure 4 **Theoretical specific energy for different types of Li-Ion batteries**

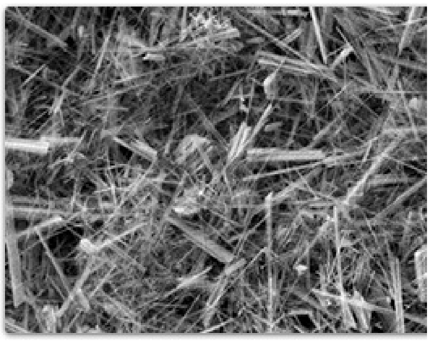


Recent research

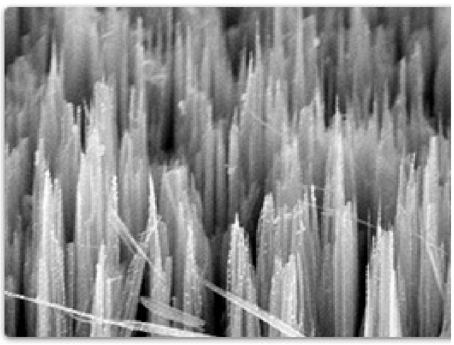
Panasonic has been developing an 18650-type (18 mm in diameter, 650 mm in length) battery using a nickel-based cathode and silicon alloy anode. The battery's capacity is increased by 13% from 65 mAh/g for the carbon-based anode to 74 mAh/g for the silicon-based anode. Panasonic has also overcome some of the issues related to the degradation of the silicon/graphite anodes and can maintain at least 80% capacity after 500 charge/discharge cycles, which is still only one-tenth the automotive requirement. These batteries will initially be used for laptops and the technology may see introduction for electric vehicle applications by 2020.

Nexeon Limited is developing a silicon anode nanostructure which reduces the expansion problem of silicon. Its first-generation anode has a capacity of 1,000 mAh/g and a second-generation anode may reach 3,600 mAh/g. Using a conventional cathode, capacity could be increased by 30-40% compared to current carbon-anode-based batteries. Nexeon has tested the battery over 300 cycles and claims consistent performance[2].

Figure 5 **Silicon anode nanostructures**



Nexeon's first-generation anode

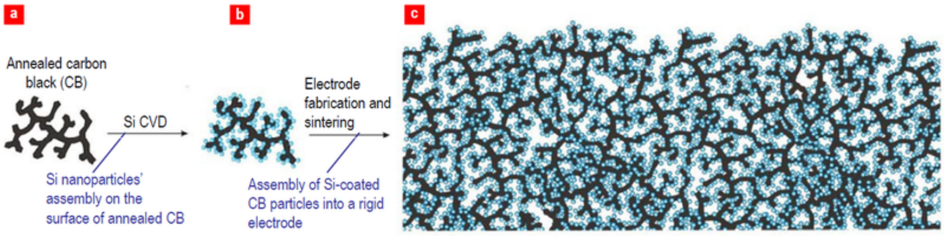


Nexeon's second-generation anode

2 http://www.nexeon.co.uk/technology/.

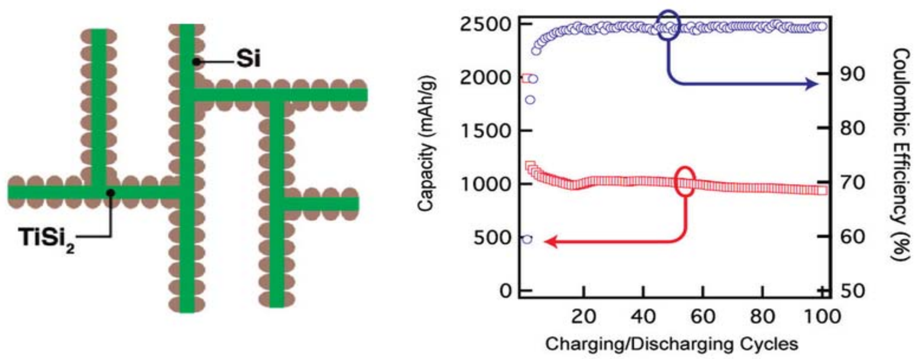
Georgia Tech has developed an anode-based on silicon-carbon nanocomposite materials. By annealing carbon black nanoparticles into a structure similar to the branches of trees, researchers can form silicon nanospheres inside the carbon structures similar to apples hanging from the branches. The space between the silicon-carbon nanospheres allows liquid electrolyte to carry lithium-ions at a fast rate, resulting in faster battery charging. Also, this space allows for the silicon to expand without pulverising the silicon. The researchers demonstrated a capacity of 1,950 mAh/g and claim the cell is simple to manufacture, low-cost, safe and broadly applicable. They have charged and discharged the anode over 100 times and believe that the material would remain stable for thousands of cycles because no degradation has become apparent[3].

Figure 6 Georgia Tech's annealed carbon nanoparticles with silicon nanospheres



Researchers at Boston College have created a nanostructure of nets made of $TiSi_2$ as the inactive component of the anode while a particulate Si coating stores and releases the Li-Ions. They have demonstrated a capacity greater than 1,000 mAh/g over 100 cycles with over 99% capacity retention per cycle[4].

Figure 7 Titanium-silicon nanonets with silicon coating (red: 1,000 mAh/g; blue: 99% capacity retention)



Hanyang University in South Korea has developed silicon particles that can withstand large strains without pulverisation after 100 cycles and can maintain a charge capacity of greater than 2,800 mAh/g. The changes in volume that occur upon charging and discharging cause only a small degree of expansion and contraction of the pore walls. The researchers annealed silicon dioxide nanoparticles with silicon particles. The outermost silicon atoms have short hydrocarbon chains attached to them. Then, the silicon dioxide particles were

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3 http://www.nature.com/nmat/journal/v9/n4/abs/nmat2725.html.

4 http://pubs.acs.org/doi/abs/10.1021/nl903345f.

removed by etching and the remaining structure was a continuous, three-dimensional, highly porous network of carbon-coated silicon crystals[5].

2.3.2 Lithium-sulfur

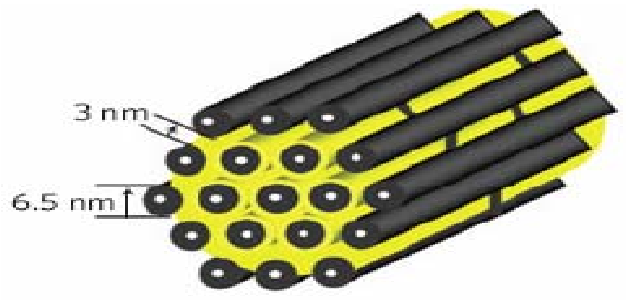
Lithium-sulfur batteries use a multi-step reduction-oxidation reaction which results in a number of intermediate sulfide ions: $Li_2S \rightarrow Li_2S_x \rightarrow Li_2S_8$. The reason for sulfur research is that lithium-sulfur systems have a theoretical specific energy of 2,600 Wh/kg which exceeds a current generation lithium-ion battery's theoretical specific energy by about a factor of 5. Current cathode materials, such as those based on transition metal oxides and phosphates, are limited to an inherent theoretical capacity of 300 mAh/g while the theoretical capacity of sulfur is 1,600 mAh/g. Other benefits of sulfur are that it is abundant and low cost.

Sulfur-based cathodes present a variety of problems, including low-electron conductivity, significant structural and volumetric changes during reaction, and dissolution of lithium poly-sulfides in the electrolyte. Also, the system has a voltage of about 2 volts versus Li/Li^+ of 3.6V.

Recent research

Sion Power is collaborating with BASF to increase density and battery life. Sion's Li-S cells can reach a specific energy of 350 wH/kg which is more than double the energy density of Li-Ion cells currently available. The company says that 500 wH/kg over 500 cycles are current targets for their cells while 600 wH/kg over 1,000 cycles may be achievable by 2016. They have also increased the sulfur utilisation from 46 to 87%. Sion states that manufacturing complexity of Li-S batteries is comparable to current generation Li-Ion batteries[6].

Figure 8 University of Waterloo's design of sulfur (yellow) impregnated into the interconnected structure of carbon nanotubes



The University of Waterloo in Canada has developed electrode materials for Li-S batteries using a conductive mesoporous carbon framework.
The researchers have impregnated molten sulfur into a structure of carbon nanotubes that are attached to carbon fibres. The space between the carbon nanotubes allows for expansion and contraction during discharging and charging. Polymer modification of the carbon surface further reduces the loss of sulfur from the cathode, improving the number of charging cycles.
They have demonstrated a reversible capacity of 1,320 mAh/g and claim that the assembly process is simple and broadly applicable[7].

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5 http://www3.interscience.wiley.com/journal/121520011/abstract?CRETRY=1&SRETRY=0.

6 http://www.sionpower.com/technology.html.

7 http://www.nature.com/nmat/journal/v8/n6/abs/nmat2460.html.

OXIS has been working on lithium-sulfur battery technology for over five years. The company started in 2004 to exploit some of the research results of the Ufa Research Institute in the Urals, a region at the geographical edge of Europe which is known as a centre of excellence in sulfur chemistry and electro chemistry. In addition, OXIS has been collaborating with the Materials Departments of Oxford and Cambridge Universities. The area of most technical difficulty is cycle life (the number of complete charge - discharge cycles a battery can perform before its nominal capacity falls below 80% of its initial rated capacity). The current level of 200-350 cycles is well below the usual life-time of an automotive battery (5,000+ cycles). Oxis expects to improve this to 500 cycles over the next eighteen months. OXIS has initiated a funding programme for new production equipment and believes it can achieve 2,000 cycles within three years. Oxis Energy will receive £ 235,000 from the UK Technology Strategy Board to improve the durability and quality of lithium-metal sulphide (Li-S) cells with a specific energy of 220-250 Wh/kg over 350-500 cycles and claims that 1,000 cycles is achievable. Oxis Energy aims to reduce costs to $ 800/kWh in volume production[8].

Idemitsu Kosan of Japan is developing a phosphorous sulfide (Li_2S-P_2S_5) solid-state electrolyte for lithium-ion battery. Liquid electrolytes pose dangers of leakage and flammability and also suffer from degradation and vaporisation. A solid electrolyte can reduce these problems but the main drawback of a solid electrolyte is its low conductivity. However, researchers claim that they can match the liquid electrolyte's conductivity of 4×10^{-3}S/cm at room temperature. Idemitsu Kosan has exhibited a Li-S battery which generated significant press attention and interest when it was showcased at the 1st International Rechargeable Battery Expo, which took place from March 3rd to March 5th, 2010, in Tokyo. The company aims to commercialise its all-solid Li-Ion battery in 2012 for commercial electronics. OXIS however says there is the possibility of a patent infringement since OXIS owns the key patent for lithium-sulphide electrochemistry.

Stanford University researchers led by Dr. Y. Cui combined silicon nanowire silicon anodes with a cathode comprising a nanocomposite in which Li_2S fills the pores of mesoporous carbon particles. The researchers believe that problems associated with the slow kinetics of Li_2S-based cathodes can be mitigated. They reported an initial discharge specific energy of 630 Wh/kg[9].

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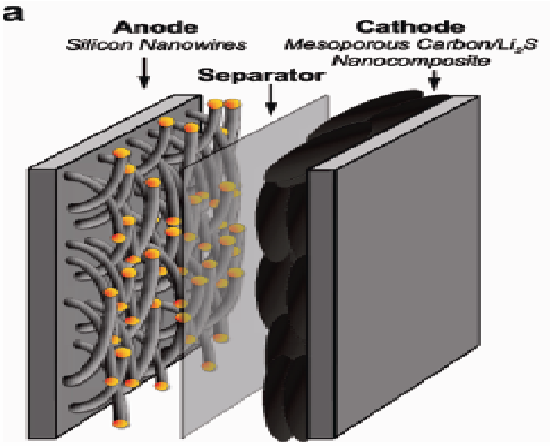
8 http://www.innovateuk.org/_assets/pdf/press-releases/press%20release%20lcv-idp2%207jan10%20final.pdf.

9 http://pubs.acs.org/doi/abs/10.1021/nl100504q.

Figure 9 Diagram of silicon nanowire anode and carbon/lithium-sulphide cathode



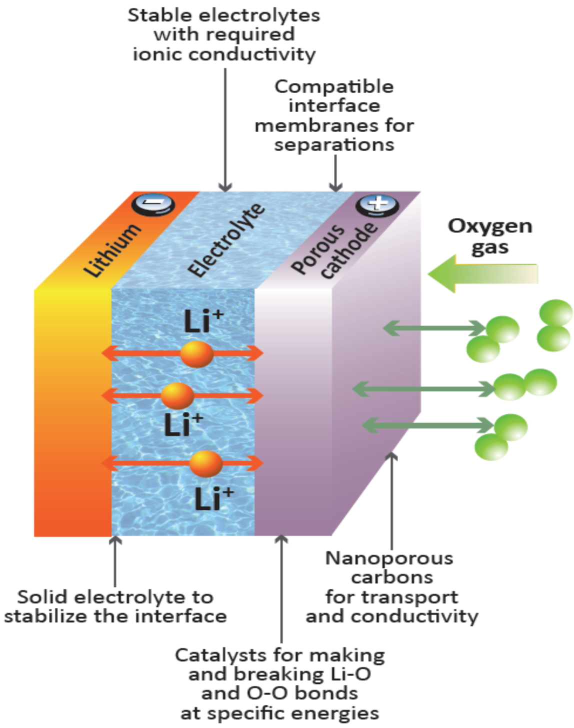
Università degli Studi di Roma La Sapienza fabricated a lithium-sulfide-carbon (Li_2S-C) cathode in the discharged state instead of the charged S-C form and a low cost and safer tin-carbon nanocomposite anode can be used. The researchers also replaced the liquid electrolyte with a plastic-like gel membrane which could reduce vaporisation and safety issues of a liquid electrolyte. They report a charge capacity of 500-600 mAh/g and claim that the battery could withstand several thousand cycles without dramatic capacity failure. They believe that a specific energy of 1,100 Wh/kg can be achieved[10].

2.3.3 Lithium-air

This technology uses oxygen as a catalytic air cathode to oxidise a metal anode such as lithium or aluminium, shown schematically below. Theoretically, with oxygen as essentially an unlimited cathode reactant source, the capacity of the battery is limited only by the lithium anode. Estimates of energy density vary from two to ten times the energy capacity of current lithium-ion batteries.

10 http://www3.interscience.wiley.com/journal/123304780/abstract?CRETRY=1&SRETRY=0.

Figure 10 Diagram of a lithium-air cell



Also, it could greatly reduce costs as lithium batteries currently use a cathode which is the most expensive component of lithium batteries. Lithium-air with a theoretical specific energy of 13,000 Wh/kg is one of the few, promising technologies that can potentially approach the energy density of a hydrocarbon fuel.

There are many challenges that need to be overcome in order to increase power output and life of the battery. Oxygen diffuses at a very low rate in the porous air cathode. The reaction creates a solid which accumulates on the cathode and hinders contact between electrolyte and air. Also, a stable electrolyte must be found since even the slightest amount of water contact with the metal anode would create hydrogen gas and create a fire hazard.

Recent research

University of St. Andrews is developing a lithium-air battery with £ 1.6 million in funding from UK's Engineering and Physical Sciences Research Council (EPSRC). Instead of using $LiCoO_2$ as a cathode, the researchers use porous carbon to draw oxygen in from the air. They are targeting a 5-10 times increase in storage capacity from current Li-Ion batteries and claim to have attained 4,000 mAh/g[11].

The University of Dayton Research Institute (UDRI) is developing a solid-state, rechargeable lithium-air battery. The cell comprises a Li-metal anode, a highly conductive solid electrolyte membrane laminate fabricated from glass–ceramic (GC) and polymer–ceramic materials, and a solid-state composite air cathode prepared from high surface area carbon and ionically conducting GC powder.

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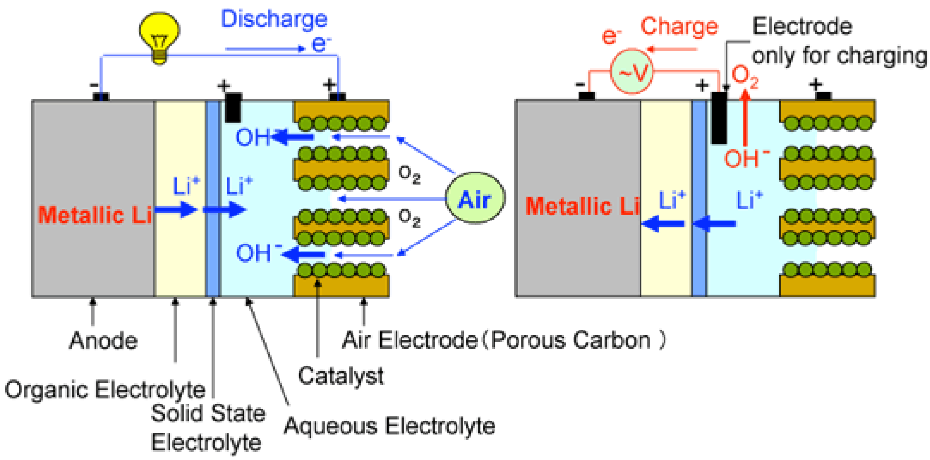
11 http://ukerc.rl.ac.uk/cgi-bin/ercri5.pl?GChoose=gregsum&GRN=EP/E03649X/1&GrantRegion=10&GrantOrg=19&HTC=4547CEB&SHTC=6992AB; http://www.epsrc.ac.uk/newsevents/news/2009/Pages/airfuelledbattery.aspx.

They have successfully tested the system through 40 charge/discharge cycles and are targeting 1,000 Wh/kg for 4,000 cycles for commercial use[12].

The National Institute of Advanced Industrial Science and Technology (AIST) of Japan is developing a lithium-air system that uses a three stage electrolyte. Since an aqueous electrolyte would react to the metallic lithium and a non-aqueous electrolyte creates blockages at the air electrode, AIST is experimenting with an organic, solid and aqueous electrolyte. The organic electrolyte on the anode (metallic lithium) side and the aqueous electrolyte on the cathode (air) side are separated by a solid-state electrolyte (lithium super-ion conductor glass film, LISICON) so that the two electrolytic solutions do not intermix and only lithium-ions pass through the solid electrolyte. AIST claims to have attained a capacity of 50,000 mAh/g[13].

Figure 11 Diagram of a lithium-air system that uses a three stage electrolyte



2.3.4 Outlook summary

Based on our survey of battery technology development, we anticipate the following developments relative to a 2010 battery:

1. Improvements of 20 to 25% in specific energy with a similar reduction in cost by 2016 primarily due to improved battery design and packaging.
2. Improvements of 70 to 75% in specific energy and 50% reduction in cost per kWh by 2020 to 2022 with the introduction of advanced materials for the anodes and cathodes.
3. Potential for a tripling of specific energy and 70% cost reduction per kWh by 2030 with the introduction of lithium-sulfur batteries.

Within the next five years, cells for small devices using a silicon graphite alloy anode are expected to come to market because even though it does not realise silicon's 4,200 mAh/g theoretical capacity, silicon will still improve the energy density of the battery. There is much promising research in the ability of nanostructures to take advantage of silicon's high capacity potential but this technology may still be ten years away from commercialisation in automotive batteries since high volume manufacturing techniques have not yet been developed. We expect the first such automotive batteries to be introduced around 2020, and we anticipate that energy density will increase by 75% relative to *current* Li-Ion cells and may improve further with improved cathode

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12 http://scitation.aip.org/getabs/servlet/GetabsServlet?prog=normal&id=JESOAN000157000001000A50000001&idtype=cvips&gifs=yes&ref=no.

13 http://www.aist.go.jp/aist_e/latest_research/2009/20090727/20090727.html.

chemistry. Researchers interviewed for this analysis stated that silicon's cost per gram will be highly competitive with graphite's cost, and they anticipate that battery costs per unit weight will be similar at similar levels of manufacturing maturity. This implies that costs per kWh will decline by the same percentage as the inverse of energy density (i.e., 1/1.75) when production reaches the same level of maturity.

With respect to cathode research, lithium-sulfur could make a promising cathode material for silicon anode batteries. Like silicon battery research, nanotechnology may be able to assemble structures to increase sulfur's utilisation rate. However, much research is still required to increase the performance and durability of these batteries. As a result, sulfur-based batteries may not be commercialised until the 2025 to 2030 time frame. Performance and cost estimates for such a product are highly speculative. We anticipate that initial versions of the Li-S cells will have at least three times the energy density at similar cost per unit weight and there is the potential to be at five times the energy density of current cells.

With a theoretical specific energy capable of achieving the energy density of hydrocarbon fuels, research in lithium-air batteries will likely increase over the next few years. However, lithium-air is still at a very experimental stage and many obstacles hinder the practicality of this chemistry, so it could take at least 15 to 20 years to make a commercially viable product for portable electronics and perhaps 25 to 30 years before a vehicle battery is developed. At this point, we have not included this technology in any cost calculations but recognise that such a battery could change the entire vehicle transport system.

2.4 Effect of battery ageing

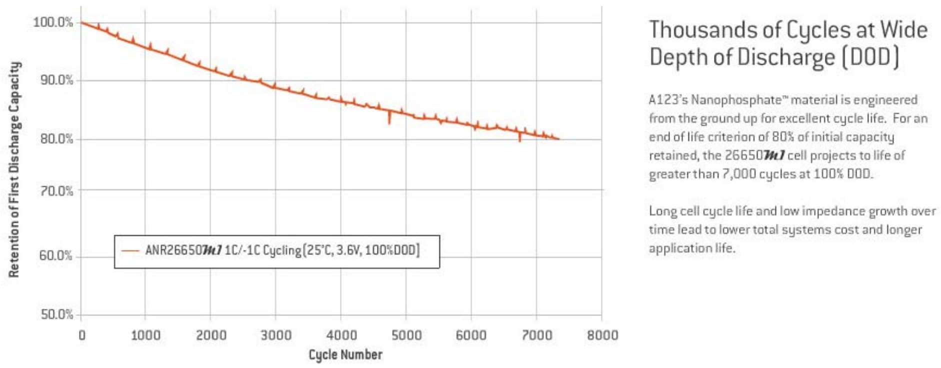
With use and over time, battery performance can substantially degrade, with reductions in peak power capability, energy density and safety. There are four key measures of battery durability, which are:

- Calendar life which is a measure of degradation with time.
- Deep cycle life which is the number of cycles of charging and discharging to low state-of-charge (SOC) levels.
- Shallow cycle life which measures the number of cycles that a battery can withstand of small SOC variation cycles of a few percent.
- Survival temperature range which is the range of temperature that a battery can be subjected to when **not** in operation.

Car manufacturers have set goals or targets for all of these measures, but it is not clear if current batteries can meet them. For calendar life, the goals are typically for fifteen years at a temperature of 35˚C, where exposure to hotter temperatures degrades life, but current targets are for ten years at which point a battery retains at least 80% of its power and energy density. For deep cycle life, where the charge cycles go from 90 to 10% of SOC, the goal is typically 5,000 cycles, while the shallow cycle life expectation is 200,000 to 300,000 cycles. The goal for the temperature range is - 40˚C to + 66˚C, but this has not been directly addressed by battery manufacturers.

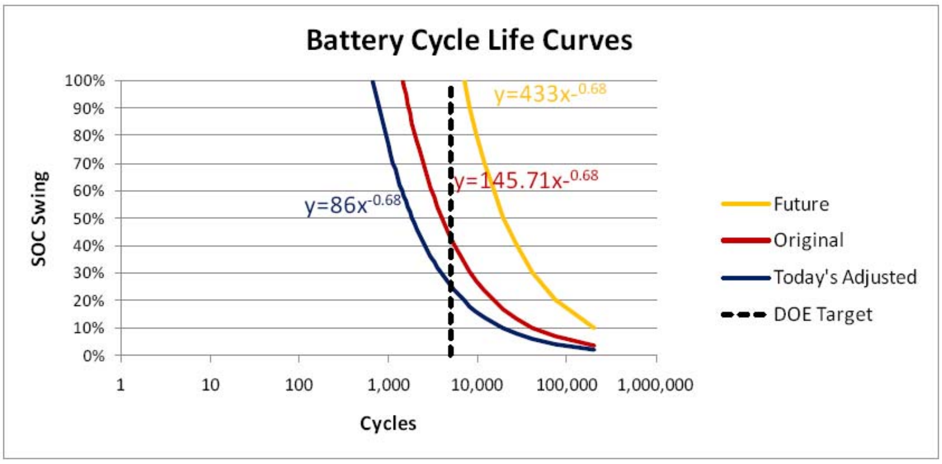
It is difficult to state if current batteries meet or exceed targets in any area because of the highly interactive effects of many variables. For example most batteries available today have met the 5,000 cycle deep discharge goals and the 200,000 cycle shallow discharge goals. One such example is shown below from A123, where the battery degradation to 80% of its original energy density occurs at over 7,000 cycles.

Figure 12 Example of a battery degradation curve



However, it should be noted that this test result is valid only for some specific charging and discharging rate and some specific range of ambient temperature exposure. It is still not clear if the test rates are more or less severe than the actual cycles a battery will be subjected to in an EV and the interaction of ambient temperature with deep SOC cycling is also an unknown factor.
The driving distribution has important implications on battery life and sizing. For PHEV and EV batteries, the trip length is used to estimate the level of discharge to the battery based on the vehicle's charge depleting efficiency. Analysis done by the US National Renewable Energy Laboratory in 2006 attempted to examine these questions using data available from battery manufacturers. Each discharge causes a specific level of battery wear based on data from Johnson Controls, as seen in Figure 13. Using the trip driving distribution data, battery discharge efficiency and battery cycle life data, the average charge depleting wear per mile was calculated. The acceleration and regenerative breaking cycle wear per mile based on the drive cycle simulations, which can account for as much as 5% of the wear for low range PHEVs, was then added to calculate the total wear per mile.

Figure 13 Original and modified battery cycle life curves



The original battery life curve in Figure 13 represents the published data. Since this data does not consider calendar, temperature, or power level effects for the current technology case, the trend was adjusted to match published Nissan Leaf and Chevy Volt battery life expectations. The future case was adjusted to match the 7,000 cycle life published by A123 shown above, which is similar to the US Department of Energy's (DOE) target. It is used for the future improved case because again the published data does not include the calendar, temperature, or power level effects that would occur for a vehicle application.

Based on the NREL analysis and current battery data, it appears that current (2010) battery life should exceed seven years and may be around ten years for 'average' use. However, there is still much uncertainty regarding battery calendar life at more severe ambient temperatures such as those encountered in North Africa, South Spain or Arizona. In most of the EU, the more moderate temperatures may allow real world battery life to be around ten years on average and we anticipate continued improvement to 2020 by which time, expectations are that average life may be in the thirteen to fifteen year range.

2.5 Recycling options and cost

There are many Li-Ion battery chemistries developed for markets such as consumer electronics and power tools, as well as Hybrid and Electric Vehicles currently sold in low volume. Many more Li-Ion formulations are under development but chemical composition of the new technology is usually held as proprietary. Table 3 identifies some prevalent materials used in battery electrode components. Lithium in cathodes is combined with oxygen and other compounds such as cobalt, phosphorus and iron. The anode materials are usually based on carbon or titanate. Electrolytes in Li-Ion batteries consist of lithium salts such as $LiPF_6$, $LiBF_4$ or $LiClO_4$ in an organic solvent such as ethylene carbonate. The battery packaging is done using variety of materials such as aluminium or steel (housing), copper (electrical leads) and plastics (insulators and housing).

Table 3 Common cathode and anode materials in Li-Ion batteries

Cathode material	Anode material
Lithium Cobalt Oxide $LiCoO_2$	Graphite (LiC_6)
Manganese Spinel $LiMn_2O_4$	Hard Carbon (LiC_6})
Lithium Nickel Oxide $LiNiO_2$	Titanate ($Li_4Ti_5O_{12}$})
Lithium Iron Phosphate $LiFePO_4$	
Lithium Iron Fluorine Phosphate Li_2FePO_4F	

Table 4 provides one typical example of the Li-Ion battery weight distribution by component. The compact prismatic battery cell LP053048AH was manufactured by BYD for mass volume consumer electronics applications and is based on the lithium cobalt oxide chemistry with a carbon anode. While the large format vehicle batteries will require more sophisticated control, cooling and packaging, the cell-level material basic distribution is expected to follow similar pattern with the cathode being the heaviest component of the cell with the housing weight depending on material used (in this case steel for durability).

Table 4 **An example of the lithium cobalt oxide cell material distribution**

Battery component	Component weight distribution (%)
Lithium Cobalt Oxide cathode	26
Carbon anode	12
Electrolyte $LiPF_6$	12
Copper	10
Aluminium	4
Plastics	3
Steel (housing)	30
Other	3

Source: BYD 3.7V Prismatic Cell LP053048AH.

There is substantial discussion in the literature concerning ways to recycle the future large format vehicle batteries with minimal environmental impact. Furthermore, it is considered feasible to develop business models that would use the secondary battery application value to offset some of the primary battery cost thereby making the technology more affordable. Both these paths are explored below.

2.5.1 Secondary applications for the EOL vehicle batteries

The secondary use of batteries after the end of their automotive life is under study but many barriers and uncertainties exist before a viable business model can be developed. EV batteries are generally considered at the end-of-life (EOL) when the battery capacity is decreased by 20% and/or peak power has decreased by 25%. Recognising that the EOL batteries can be still suitable for stationary applications, there is substantial interest in the secondary market possibilities. Particularly the EV batteries are candidates for reuse because of their large cell format. Sandia National Laboratory in the US has published a report identifying several potential stationary applications for the second-use batteries. The applications listed in Table 5 can be classified by market into either electric utility or light commercial/residential.

Table 5 **Potential secondary use applications for the EOL EV batteries**

Utility applications	Commercial/residential applications
Transmission support	Light commercial load following
Area regulation and spinning reserve	Distributed node telecom backup power
Load levelling/energy arbitrage/transmission deferral	Residential load following
Renewable supply firming	
Power reliability and peak shaving	

Source: The US DOE Sandia National Laboratory.

A more recent study at the University of California–Davis (Burke, 2009) also recognised that there are several possible secondary applications for the EOL batteries. However, since the energy storage and power requirements for the end-user applications are comparable to those of the original vehicle applications and would require only minor reconfiguring of the packs, the light commercial and residential applications are better suited for the second-use. The applications closely related to utility operations require large power and energy storage capacity, which are orders of magnitude larger than that of the vehicle applications. As a result the utility facilities might be less interested in this battery source.

In addition to the obvious cost and remaining life uncertainties, there are many technical and market barriers to the potential secondary applications related to highly variable cell technology and specifications, lack of testing procedures or concerns for thermal runaway control and liability. Furthermore, the EV batteries will be designed for the full useful life (100,000 to 150,000 miles) and any significant supply of the EOL batteries is ten years away. As a result, the economically viable business models are not yet developed and the winning secondary applications are speculative at this point.

2.5.2 Battery recycling

It is generally understood that, unlike cadmium and lead based batteries, current known formulations of the Li-Ion battery materials do not present significant environmental concerns beyond fire safety and landfill utilisation. There is some concern with nickel metal hydride batteries commonly used in current generation of Hybrids but these batteries are highly recyclable.

Toyota, Honda and other manufacturers currently have infrastructure in place to collect the batteries at their dealerships. Toyota puts a phone number on each hybrid battery, and in most areas, they pay a 'bounty' of several hundred Euro for each battery to help ensure that it will be properly recycled. The process is designed to transfer the batteries to a preferred recycler to disassemble the battery pack, recover metals and neutralise the alkaline material before sending it to a landfill. The new Li-Ion battery technology will have similar disposal procedures.

Because lithium-based batteries are considered more environmentally benign compared to the nickel metal hydride batteries, there are indications that battery manufacturers themselves will be in a position to recycle the EOL vehicle batteries together with their internal battery scrap. For example Renault and Nissan just announced intent to establish a joint venture with the French Energy Commission (CEA) and the French Strategic Investment Fund (FSI) to produce Li-Ion batteries in France. The venture is envisioned to develop, manufacture and recycle the FEV batteries in one facility.

Similar battery recycling capabilities exist in other parts of Europe. Umicor has decided to build an industrial scale recycling facility for the EOL rechargeable batteries in Hoboken, Belgium. The investment will enable Umicor to deal with the expected growth in the availability of the EOL lithium-ion, lithium-polymer and nickel metal hydride rechargeable batteries from vehicles and other sources. The company believes that regulations in Europe will become increasingly more stringent for efficient and eco-friendly recycling of all materials including batteries. The company already operates facilities to recycle Li-Ion batteries coming primarily from portable electronics equipment. However, the material value in end-of-life batteries in very high and battery recycling may be *commercially profitable, depending on the consumer value of used batteries from other applications discussed above.*

In North America, Inmetco and Toxco are among the best-known recycling companies for advanced batteries. Toxco has just announced that it has been awarded $ 9.5 million from the US Department of Energy to expand their current battery recycling operations and build an advanced lithium battery recycling facility. A new plant will be built to support the battery recycling infrastructure from the growth of Hybrid and Electric Vehicles. The company claims to have adequate capability to recycle both primary and secondary lithium batteries.

As a result, we believe that there are no major concerns that would distinguish recycling Li-Ion batteries relative to current lead acid and nickel metal hydride batteries.

2.5.3 Battery recycling economics

Currently rechargeable batteries are recyclable and the process generally starts by removing the remaining charge (large format batteries) and electrolyte. The combustible materials, such as plastics and insulation, are burned of with a thermal oxidiser. The clean cells are chopped into small pieces (or pulp) and heated until the metals liquefy. Sometimes cryogenic cooling is required before pulping for highly reactive batteries, including the Li-Ion battery[14]. Some metals such as cadmium are vaporised, collected and condensed using coolers. Other metals such as iron, chromium and nickel settle according to their weights and are separated to be shipped for later processing. Lithium is reacted with other chemicals to form the lithium carbonate (LC - Li_2CO_3). The remaining battery 'fluff' is disposed of in a landfill.

Current battery recycling methods are energy intensive. Emissions after-treatment and transportation/handling costs are also high, so the industry claims that rough cost for battery recycling is about $ 1,000 to $ 2,000 per ton. There are projections that the costs will decline after new battery streams will become available and new plants are build with optimised large scale processes. Currently, however, the metal recovery alone can not pay for recycling costs. Government and private subsidies are required according to a battery type. In some regions, the subsidy is in the form of tax added to each manufactured cell. Some chemistries such as lead and nickel-based are nearly profitable from metal recovery, so subsidies are minimal. The Li-Ion battery receives among the highest subsidies since the cells generally contain little retrievable metal.

In order to understand the economics of recycling, its helps to understand the virgin material production processes. Current lithium supply is relying on the metal extraction from salt brines. The pure metal is highly reactive so the virgin lithium is traded in the stable LC form.

Quantities of lithium and, therefore, the LC yield from recycling will obviously depend on a battery chemistry. The US Argonne National Laboratory (ANL) is currently studying various battery chemistries and Table 6 summarises their work for several most promising Li-Ion chemistries: NCA/graphite, LFP/graphite, MS/graphite and MS/titanate[15]. Elgowainy et al. (2010) found that, assuming the battery size required to provide 100-mile range at 300 W-hrs/mile energy consumption, various chemistries will consume from 3.4 kg to 12.7 kg of lithium per battery pack (including electrodes and electrolyte).

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[14] Toxco Li-Ion battery recycling process description, http://www.toxco.com/processes.html.

[15] Linda Gaines, Argonne National Laboratory, Presentation 'Lithium-Ion Recycling Issues', May 21, 2009.

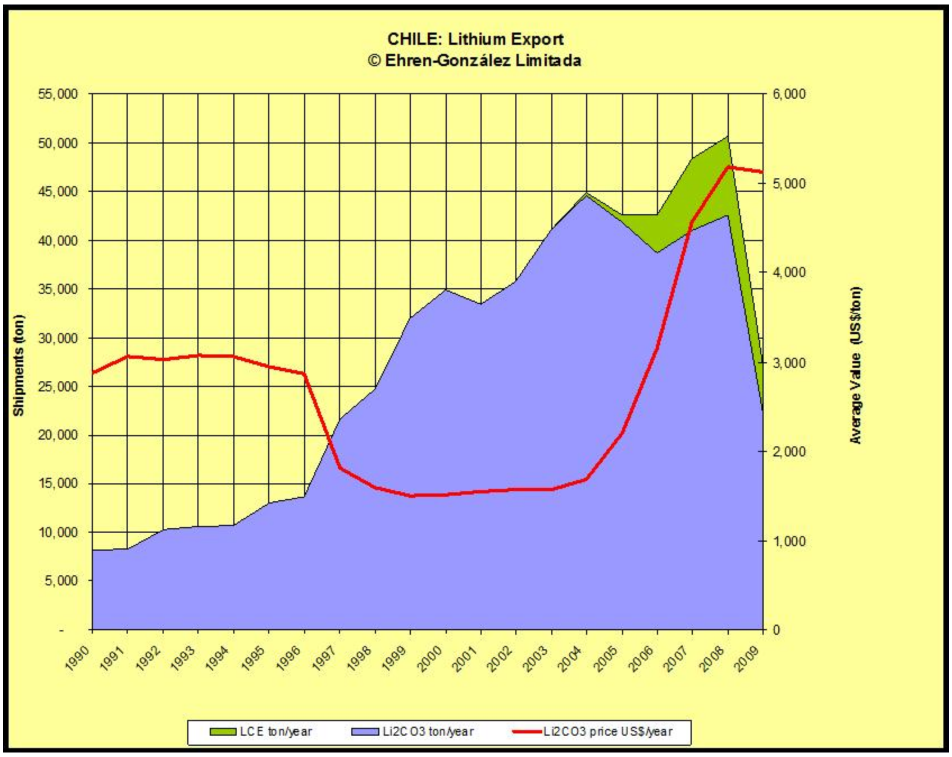
Table 6 **Lithium content in various battery packs (assumes battery size required for 100-mile range at 300 W-hr/mile energy consumption)**

Battery type (cathode/ anode	NCA/graphite	LFP/graphite	MS/graphite	MS/titanate
Li in cathode (kg)	6.9	4.0	3.0	5.8
Li in anode (kg)	0	0	0	6.1
Li in electrolyte (kg)	0.55	0.66	0.43	0.85
Total Li in pack (kg)	7.4	4.7	3.4	12.7
Total battery mass (kg)	350	376	289	523

The ANL study suggests that the MS/graphite (manganese spinel) would be the least economical to process in order to recover the lithium value. Based on the atomic weight of Li_2CO_3, the lithium ratio is 0.188 and 1 kg of lithium will yield about 5.3 kg of LC. According to information supplied by Chemetall, the lithium extraction efficiency through battery pulping is expected to be about 75%. Therefore the 3.4 kg of lithium in the MS/graphite battery would yield 0.75 x 3.4 x 5.3 = 13.5 kg of LC.

LC pricing has been volatile as for any other industrial material. Figure 7 provides one example of the LC price volatility based on exports from Chile. Over the past twenty years the LC price was as low as about $ 1.50/kg and as high as $ 5/kg. Assuming that high prices continue from demand increases due to battery production, the analysis above suggests that 13.5 kg of LC would have a market value of about $ 68 (yield from 289 kg battery). One ton of unprocessed MC/Graphite batteries would, therefore, yield 1,000/289*68 = $ 235 of LC, which is well below the cost of recycling.

Figure 14 **An example of the LC price volatility, exports from Chile**



Source: SQM.

According to the Rechargeable Battery Recycling Corporation, if a steady stream of batteries, sorted by chemistry, were available at no charge, recycling would be profitable[16]. Our analysis show that the Li-Ion batteries with high value content, such as MS/titanate, would approach the process cost break-even at high historical LC prices. For the low lithium content chemistries, such as MS/graphite, recycling economics would be poor.
The economics would drastically improve for cell chemistries that contain other high value metals, especially nickel and cobalt. Lower value metals such as iron and manganese would improve recycling revenue but not enough to alter the overall economics. Knowing that the metal prices will remain volatile, the battery recycling economics appear to be difficult and hard to predict ten years into the future but will likely require government mandates or subsidies to be economical.

2.6 Material use

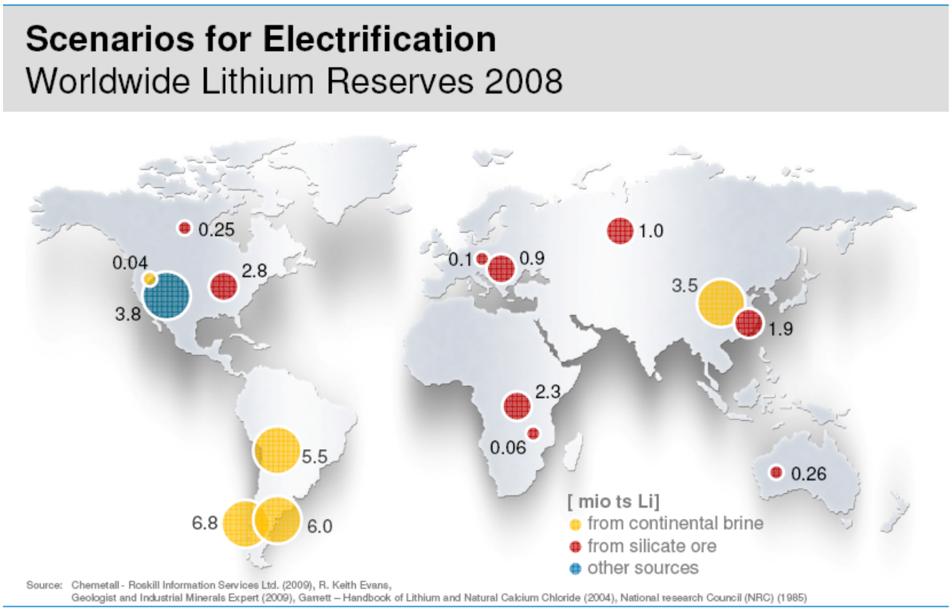
The use of lithium batteries for EV and PHEV fleets in large numbers has raised concerns about lithium supply and future availability of lithium in large quantities. Some observers have suggested that the developed world would be trading dependence on the OPEC oil cartel to a new lithium cartel of Bolivia and Chile, where most of the current lithium mining activity is centred. Such concerns have been proved to be false by detailed studies of lithium production and reserves.

About half of current production of 27,000 tons of lithium is from brine, from which lithium carbonate is produced. Lithium is 16% of the weight of lithium carbonate so that production from brine is sometimes reported as 80,000 tons of lithium carbonate. The other half is mined form minerals such as spodumene (lithium aluminium silicate) which typically contains 4 to 5% by weight of lithium, or about 300,000 tons of minerals. Even at this production level, there is a global oversupply and some producers like Australia's Talison have been shutting down mines due to falling prices.

Global lithium reserves from brine and minerals have been studied in detail over the last five years and Figure 15 shows the largest global reserves and their locations. Total known global reserves are estimated at 28 million tons of which about 18 million tons are in South America. However, geologists point out that many parts of the world have not been explored for lithium and other deposits could exist. More recently, it has been reported that Afghanistan and Serbia may have significant resources of lithium ores, for example. Hence, the 28 million ton estimate may be quite conservative and global reserves could be much higher.

[16] Rechargeable Battery Recycling Corporation (RBRC). Website: http://www.call2recycle.org/case-studies.php?c=1&d=82&e=358&w=1&r=Y.

Figure 15 **Location and size of world lithium reserves**



The amount of lithium needed for batteries is relatively small, at about 0.1 to 0.13 kg/kWh. Hence, a typical EV battery with 25 kWh of electrical storage capacity will have about 2.5 to 3.3 kg of lithium. Limotive has calculated the amounts of lithium demanded under the various scenarios shown in Figure 24 of this report and the results are shown in Table 7. In the base case and fuel economy scenarios, lithium demand is 3,000 to 5,000 tons which represents 10 to 20% of current production and there should be no major issues concerning supply expansion by this amount especially given the current excess supply. Only in Limotive's high EV scenario does lithium demand become sizeable compared to current production, but we do not consider this scenario to be realistic. In addition, even these concerns are related to current production but in comparison even to known global reserves, the demand from EVs is very small. If, as an extreme example, by 2040, all of the world's 2 billion cars are EVs, the total lithium used would be ~3 x 2 billion kg, or 6 million tons, which is equivalent to less than 25% of the world's known reserves. Hence, there does not appear to be any case for supply shortages in the near term.

Table 7 **Limotive estimates of battery materials demand under different scenarios**

Resources	Base case	Fuel economy	EV scenario	Worldwide production	Reserve
Aluminium, Al	35.000 t	64.000 t	246.000 t	92 Mio. t	12.150 Mio.t
Copper, Cu	27.000 t	48.000 t	187.000 t	16 Mio. t	550 Mio. t
Lithium, Li	3.000 t	5.000 t	18.700 t	27.000 t	28 Mio. t
Nickel, Ni	5.000 t	9.000 t	35.000 t	1.6 Mio. t	70 Mio. t
Cobalt, Co	5.000 t	9.000 t	35.000 t	71.000 t	7.1 Mio. t
Mangan, Mn	17.000 t	31.000 t	132.000 t	14 Mio. t	500 Mio. t

2.7 Battery cost and weight summary

The current costs of lithium batteries are based on battery manufacturer quotations to car manufacturers at rates of about 20 thousand per year for supply starting in 2011/2012. A number of vehicle manufacturers are starting volume production of EV and PHEV models in this time frame and we have obtained battery costs on a confidential basis from several battery manufacturers. These costs are the ones paid by car manufacturers to battery manufacturers, and are not the retail price to consumers. Many of the contracts for the near term appear to be around \$ 500 to 550 per kWh for the battery cells. Nissan executives have publicly claimed a cost of 'less than \$ 500 per kWh' but we believe that this cost includes some of the subsidies received by Nissan from the US and Japanese governments to set up battery manufacturing facilities. We have used an *unsubsidised* cost of \$ 525 per kWh, equivalent to € 420 per kWh for cells supplied at volumes to build 25,000 batteries per year in 2011/2012. Based on the mark-up shown for the relationship of cell cost to battery cost, this works out to € 620 per kWh for a battery. In addition, there are some costs independent of battery kWh associated with battery safety and cooling that is estimated at about € 200 per battery.

Future costs to 2020 and 2030 are based on using current cost numbers and accounting for effects of volume, scale and in the case of the battery, new technology.

The effect of increased production volume (V) has been extensively studied for the auto-industry, and we used an elasticity of - 0.15 for the battery to convert low volume costs (C) to high volume cost, with all high volume cost referring to component production at 200,000 units annually. The - 0.15 value is an estimate from confidential data on cost reduction provided by battery manufacturers. Note that this does not refer to sales of a particular vehicle model but to a particular battery as components can be shared by several vehicle models. The - 0.15 elasticity is converted to costs using the formula

$$\text{Log}(C/Co) = -0.15 * \text{Log}(V/Vo)$$

Where Co and Vo are the current costs and production volumes respectively and C is the future cost while V is 200,000 units per year, except for batteries in 2012 which are at 25,000 per year. Hence, the factor of 8 increase in production volume should result in a 27% decrease in cost.

The effect of learning has been studied but the elasticity estimates of the cost to cumulative production (Q) in the literature vary from - 0.1 to - 0.2.
Our approach was to fit the estimates of costs in 2020 obtained from the manufacturers to the data. The model is identical to the one above but in cumulative production terms.

$$\text{Log}(C/Co) = -0.12 * \text{Log}(Q/Qo)$$

We assumed that total cumulative production in 2012 would be about 50,000 batteries and that production would ramp up linearly from 2013 to 2020 to 200,000 units per year, which yields a net cumulative production of 950,000 units in 2020, a factor of 19 increase over 2012. The learning rate elasticity of - 0.12 which is derived (and in the common range) results in a 30% decrease in cost so that the net cost decrease is 49% = 1-(1-0.27)*(1-0.3). This estimate closely paralleled manufacturers' expectations of a 50% reduction in cost by 2020 with increase in volume and learning. One problem is that these cost estimates assume that volumes will grow to the standard 200,000 per year level, but this will depend on the sales forecast.

No new technology breakthroughs are forecast for motor, power electronics and inverter technology, or for wiring harness and heat pump technology since these are mature products. Battery technology changes will be significant and are outlined below.

Battery cost and weight account for the cells, cell interconnections, battery cooling ducts, fuses, battery monitoring system and battery box. We expect that next generation lithium batteries with silicon anodes will emerge in 2018 to 2020 time frame and third-generation batteries with lithium-sulfur cathodes will enter initial production around 2030 but this is highly speculative. Cost data for second- and third-generation lithium batteries are based on predictions from researchers at the cell-level and scaled up to battery levels. In each case, we have assumed that materials cost and processing costs are similar and the cost reductions per kWh parallel the increases in energy density. There will be a period of time when battery generations overlap with the newer battery generations costing more initially than the more mature previous generation battery but offering substantially better performance. All costs exclude any government subsidy for capital costs and battery sales. 2012 costs in the market will be lower because of large government subsidies. *Note that new batteries in 2020 and 2030 are not low volume production cost but high volume cost*, i.e., they have realised economies of scale but not of learning.

Table 8 Unsubsidised battery costs over time

Battery type	Specific energy density in Wh/kg	Cost to OEM*
2012 lithium Mn spinel	105 ± 5	€ 200 per battery + € 620 per kWh
2020 Li Mn spinel (Battery 1)	125 ± 5	€ 180 per battery + € 310 per kWh
2020 silicon lithium (Battery 2)	160 ± 5	€ 200 per battery + € 350 per kWh
2025 silicon lithium (Battery 1)	190 ± 10	€ 180 per battery + € 185 per kWh
2030 silicon Li-S (Battery 2)	300 ± 20	€ 200 per battery + € 200 per kWh

* Cost of 20 kWh battery in 2012 will be € 200 + € 620 per kWh * 20 kWh or € 12,600. These are not retail prices.

3 Other vehicle components

3.1 Introduction

There are a number of other components on an EV or PHEV that are unique to such a vehicle and different from those in a conventional ICE-powered vehicle. In this chapter we present a comprehensive review of incremental components for EV and PHEV relative to a conventional vehicle. The aim of this exercise is to:

- Identify current motor/controller costs as a function of power output.
- Examine ongoing developments in motor/controller technology based on manufacturer inputs to forecast future cost and performance.
- Identify all other incremental technologies for EV/PHEV including AC, heating, power steering and 12 V systems.
- Develop current and future cost estimates for all ancillary equipment.
- Possible changes to the glider and possible impacts in vehicle weight and performance.
- Assess the weight of these components.

Of course, the motor, inverter and controller are the most expensive components after the battery and special attention is paid to these components. The other components of interest include the DC/DC converter for 14 V supply for the lights and ignition (in a PHEV) high voltage wiring harness, the special HVAC unit and the regenerative brakes.

3.2 Motor, inverter and controller

Virtually all Hybrid and Electric Vehicles have migrated to the permanent magnet (PM) brushless DC motor and other choices such a the induction motor and switched reluctance motor have not made much inroads, although the BMW Mini EV uses an induction motor. However, most manufacturers we have contacted appear to prefer the PM motor because of its higher power density and higher efficiency and we have considered cost for this motor. Although the basic technology of PM motors has been around for 100 years, high volume production designs for automotive applications have not been a focus of research historically.

In addition, developments in power electronics for automotive applications have not been researched until recently. Significant progress has been made in the last decade to provide motors for hybrid applications and many suppliers believe that Toyota has the most experience and the most advanced designs of motors, controllers and power electronics in the market today. The second-generation Camry Hybrid which has 100+ kW peak power motor and a 50 kW motor/generator, features a number of advanced technologies that we expect will be replicated by other manufacturers by 2012 and the Toyota designs are a baseline for this forecast. A key innovation by Toyota was the use of voltage booster that permitted tailoring input voltage to motor RPM and this had made motors more efficient at high RPM. Historically, field weakening has been used to reduce the reverse voltage at high RPM which resulted in efficiency loss.

3.3 Power control unit

The Toyota inverter/converter (or Power Control Unit-PCU) represents one of the newest generation inverters, which is more compact, lighter and more efficient that other designs. The PCU was designed to fit in space freed-up by the 14 V battery transferred to the trunk compartment. As a result, the PCU is sized and shaped similar to a 14 V battery. The PCU's main function is to boost the battery DC voltage and convert it to 3-Phase AC to drive the motor/generators.

Figure 16 Camry HEV power control unit schematic and exploded view

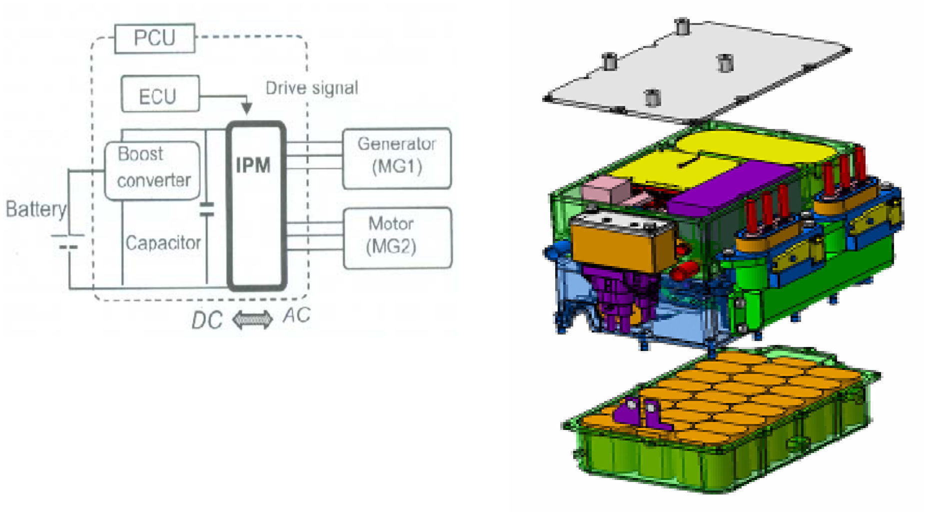
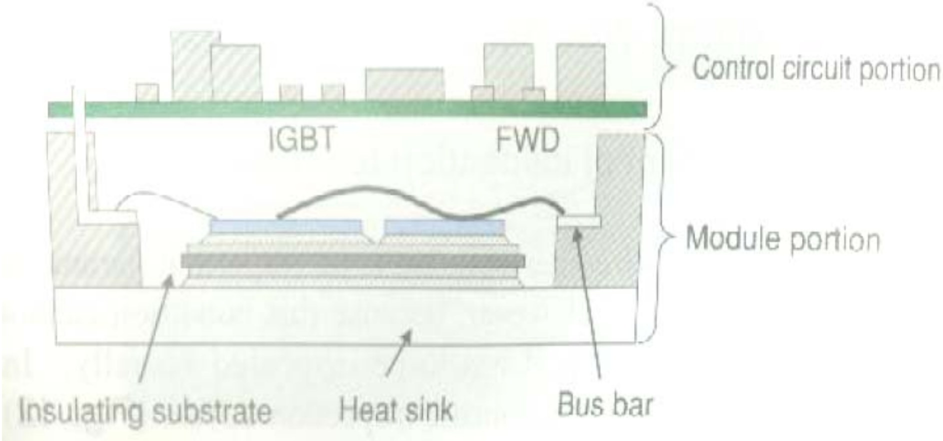


Figure 16 illustrates the PCU's basic design. It incorporates a voltage boost converter, ECU, smoothing capacitor and Intelligent Power Module – IPM. The boost converter is capable of increasing the battery voltage to maximum 650 V DC. The mid-section of the PCU houses the IPM with two sets of inverters controlling each of the two motor/generators (MG). The IGBTs (Insulated Gate Bipolar Transistor), which are Toyota's in-house product, are used to perform DC-AC conversion.

Toyota continuously refines its IGBTs with each generation of IPM and new Hybrids to achieve higher power density, size reduction and loss reduction. The company claims that back in 2005, Toyota was the only company in the world to manufacture IGBTs from 8-inch silicon wafers, which resulted in lower costs since the technology yields more chips per wafer than conventional 5-inch wafer technology.

The IPM includes the module portion, which handles the high voltage and current. This module contains the heat sink, insulating substrate, IGBTs and Free Wheeling Diodes (FWD). The IGBTs and FWD are paired in parallel to form a reverse-conducting switch. The circuit portion is packaged in the same area and controls the IPM functions.

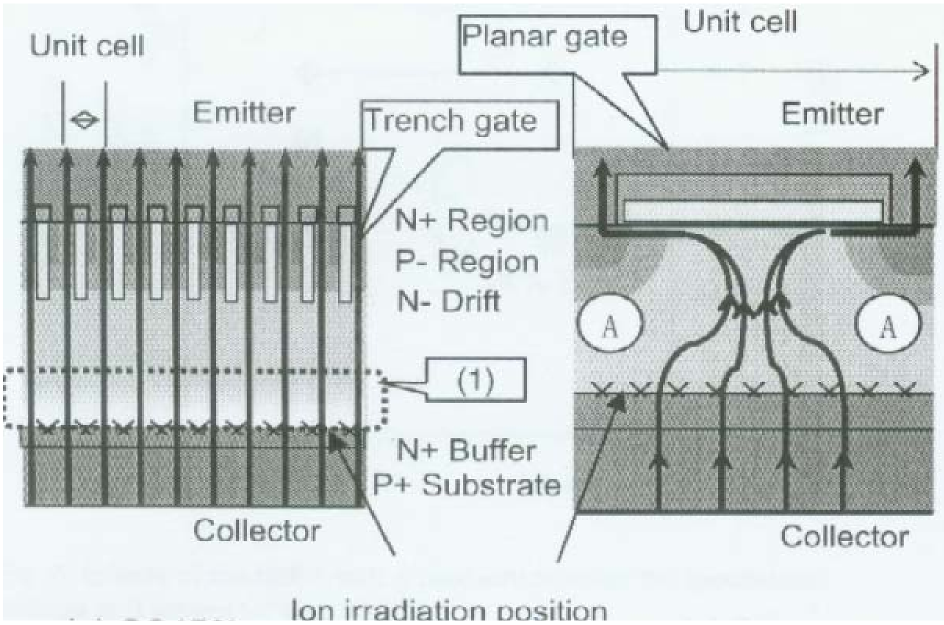
Figure 17 Toyota Camry HEV IMP layout



IGBTs used in the Camry were first installed on the Lexus RX400h, followed by the GS450h. All IPMs in this group belong to a common 120 kW class. In order to reduce the size and increase power and voltage capacity (650 V nominal rating) Toyota changed the IGBT design from the 'planar gate' design (used in 50 kW class IPM in Prius, which operates at up to 500 V voltage to the 'trench' structure (see Figure 18). This structure contains deep vertical trenches in which gate electrodes are embedded. Compared to the Prius planar IGBT, the trench design can be packaged in a smaller surface area.

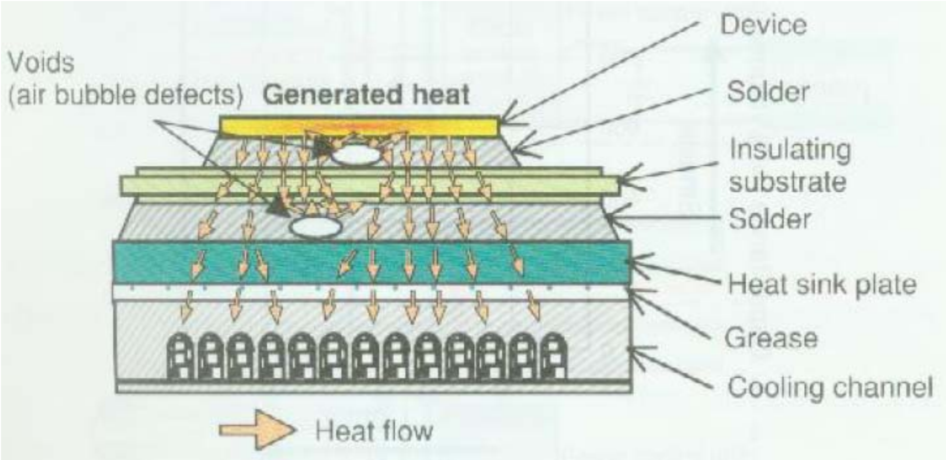
Because of the higher peak voltage, Toyota had to refine the IGBT structure to minimise the electrical losses by adding the 'concentration optimised' (shown as (1)) layer. The redesigned wafer structure enables the devices to operate with a higher reverse breakdown voltage. The IGBTs are designed to operate at currents up to 200A.Toyota had to further modify the Trench IGBT to deal with the increase in short-circuit current which degrades the resistance to surge current. The emitters of the IGBT were arranged in a stripe-like structure and the gate width was decreased.

Figure 18 IGBT design for GS450h (left) versus Prius II (right)



The IGBT has a maximum junction temperature limit of 150°C. The heat sink and cooling circuit design was a special challenge given the PCU's packaging requirements. Figure 19 details the IPM cooling design. The silicon chips are soldered to a Direct Bonded Aluminium (DBA) ceramic substrate, which is brazed on a Cu-Mo alloy base plate. The base plate is bolted on a water-cooled heat sink with thermal grease to conduct heat. The top surfaces of the silicon chips are connected to electric terminals by aluminium bonding wires.

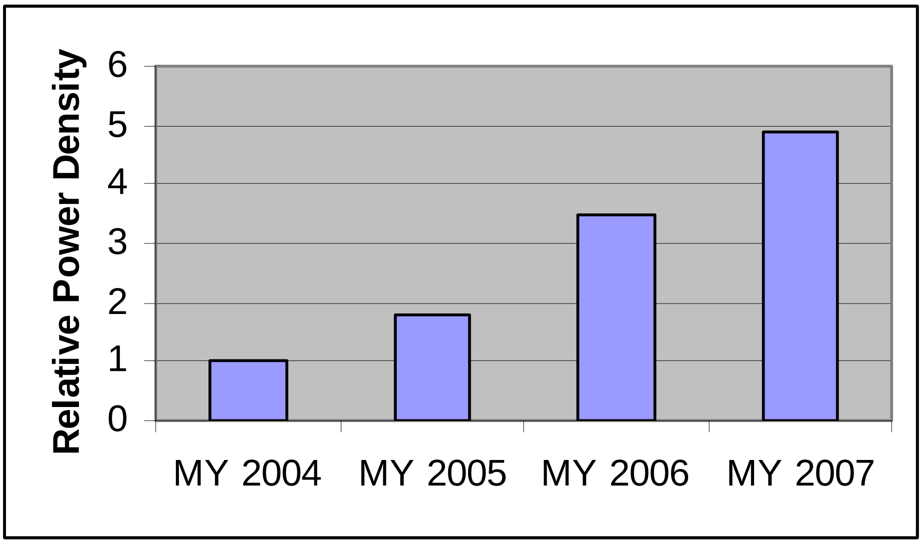
Figure 19 Heat dissipation structure for IPM chips



Toyota indicated that they use special soldering techniques to avoid trapped ambient gas 'bubbles' (shown in Figure 19), which can greatly reduce the thermal conductivity of the device. The technique involves a special soldering foil that exhibits discrete softening and melting temperature characteristics. Heat is applied gradually to flatten the solder while trapped gases are purged from the joint. After flattening and some delay the solder is then melted quickly to complete the joint. This technique does increase cycle times, however. The company claims that the new IGBTs enabled 41% higher breakdown voltage. At the same time the IGBT losses were reduced by 14%. The resulting new inverter is lighter and smaller, requiring 10% less surface area.

Toyota has released information about the newest Control Unit design used in the LS600h, which shows that further power density increases can be expected from their new generation PCU designs. Because of even higher power requirements and more constrained packaging (once again, the space freed up by the 14 V battery), the LS600h PCU achieved yet another leap in performance. Figure 20 (provided by Toyota) illustrates the relative power density of the LS600h PCU (MY2007) compared to older generations.
The performance for MY2006 corresponds to that of the Camry/GS450h.
The MY2005 is the design utilised in the RX400h, while the MY2004 data represents the 2004 Prius. Toyota was able to increase the power density of the newest PCU design by more than four times compared to the 2004 Prius.

Figure 20 **Toyota PCU power density progression with each new Hybrid**



To achieve this, Toyota has developed a new cooling design, called the Double-Sided Power Modules (DSPM) stack. The power chips have oxide-free copper heat spreaders, soldered on both sides. Silicon nitride ceramic insulators, with heat conducting spacers in the chip area, are stacked on top of the copper spreaders, also on both sides. The resulting DSPMs are inserted into the gaps between cooling plates with thermal grease. The aluminium cooling plates are stacked into a cooler assembly following an assembly approach similar to an A/C evaporator.

Toyota's new DSPM design doubles the heat sink area per chip. Because of thermal resistance reduction (less than half of a single-sided cooling design) Toyota was able to increase the maximum chip current from 200A to more than 300A. The result is that LS600 PCU requirements were achieved with only 24 IGBT/FWD modules. 40 modules at 200A rating would be required to achieve the same performance using a conventional one-sided cooling design. However, the assembly process is quite complicated and difficult for high volume production and they do not expect mass market vehicles like the Prius or Camry to incorporate this type of cooling in the near future. The Camry's inverter and boost converter specifications provide good indicators of the components' performance for EV and PHEV application. The specifications are as follows:

- Inverter peak specific power: 9.2 kW/kg.
- Inverter peak power density: 11.5 kW/L.
- Voltage boost converter specific power: 4.5 kW/kg.
- Voltage boost converter power density: 8.5 kW/L.

Toyota's electric motors have also achieved high performance, especially with the voltage boost converter. The Pruis and Camry Motor deliver about 1.4 and 1.5 peak kW/kg specific power respectively, although Toyota does not specify the peak power rating duration. Their competitors speculate that the rating is for short duration power surges of 20 to 30 seconds, as the cooling performance of the motors is not high.

The technology for motors is relatively mature now and we do not anticipate large cost reductions or performance increases in permanent magnet motors. We have assumed that the motors will be of the high RPM type (about 13,000 RPM max.) and will require a boost converter for increasing the voltage as RPM increases to enable the very high RPM operation. However, the Power control unit will likely employ silicon carbide/gallium nitride technology and will reduce weight by a factor of 2 from current levels where silicon and silicon carbide are used. The inverter will likely use trench gate IGBT technology and we expect specific power and cost for both the inverter and boost converter to improve by 20% per decade based on the historic record of the last five years. Cost data were obtained for a recent US National Academy of Sciences study by ICF interviewing the technical staff of Toyota, Honda and Hitachi (in 2009) and have been used as the baseline 2012 values for this study. The cost and performance estimates are shown below.

Table 9 **Costs of motor/controller systems**

Motor	kW/kg, 30 second peak	kW/kg, continuous	Cost
2012	1.6	1.25	€ 50 per motor + € 8.0 per peak kW
2020	1.8	1.40	€ 40 per motor + € 6.40 per peak kW
2030	2.0	1.60	€ 32 per motor + € 5.1 per peak kW

Inverter	Peak kW/kg	Peak kW/l	Cost
2012	9.5	12.0	€ 50 per inverter + € 10 per kW
2020	11	14.5	€ 40 per inverter + € 8.0 per kW
2030	13	17	€ 32 per inverter + € 6.40 per kW

Boost converter	Peak kW/kg	Peak kW/L	Cost
2012	4.5	8.6	€ 10 per converter + € 3.0 per kW
2020	5.5	10	€ 8 per converter + € 2.4 per kW
2030	6.5	12	€ 6.4 per converter + € 1.9 per kW

The control unit size and weight are only weakly dependent on motor power output and we suggest using a fixed weight of 8 kg and a cost € 150 in 2012, declining to 5 kg and € 120 in 2020 and staying constant thereafter.
In addition, EVs will require a high voltage to 14 V uni-directional DC-DC converter for lights and convenience items, and we estimate the cost of these converters at € 65 per kW, with the typical requirement being a 1.2 to 1.5 kW unit. Depending on design, PHEV models will need either a unidirectional or bidirectional unit, and the latter type is expected to cost € 100 per kW in high volume production. The converters are already in volume production and are mature technology, so no change in cost expected over the forecast period.

Table 10 **Costs and weight of control units**

Control unit	2012	2020	2030
Weight	8 kg	5 kg	5 kg
Cost	€ 150	€ 120	€ 120

3.4 High voltage harness and battery safety

The high voltage wiring harness weighs about 12 kg in a Hybrid Camry that has two electric motors with a combined peak rating of about 100 kW. This can be used as a default value for the weight of a harness for a small car since the actual weight will depend on battery placement and exact motor location in the body. A wiring harness for midsize EV is estimated at 14 kg and for a large EV at 16 kg. Battery leak current detection and wiring harness disconnects in case of accidents will add another 3 kg. Total cost of the harness and safety equipment is estimated at € 120, € 150 and € 180 for small, midsize and large cars, respectively. These are mature products and no cost reduction is expected at the same volume.

3.5 HVAC units

We expect that both the FEV and PHEV will need to use heat pump during operation on pure electric mode since resistance heating is too inefficient. The electric heat pump will add a 10% weight increase over a current air-conditioning system, and is a mature product. Cost by vehicle size assuming volume production is shown below and we estimate a 10% decrease in cost per decade for this product.

Table 11 Cost of HVAC system for Electric Car (in €)

Heat Pump	2010	2020	2030
Small Car	900	810	730
Midsize car	1,000	900	810
Large Car	1,100	990	900

3.6 Regenerative brakes

The regenerative braking system apportions the braking force to the electrical motors and mechanical brakes so that as electric braking energy decreases, the mechanical energy absorption increases for a desired total braking level. Such brakes are used in all current hybrid products, and their costs for midsize car (Cor D class in Europe) has been estimated at $ 300 or € 240 increment to the current mechanical brakes, assuming high volume production.
We anticipate a 10% cost reduction per decade so that the cost will decline to € 215 in 2010 and € 193 by 2030. However, braking requirements for all cars will have to be enhanced in 2012 to meet new European safety requirements, and this may reduce the marginal cost of regenerative brakes to much lower levels relative to a post-2012 ICEV.

4 Energy use projections for EV

4.1 Introduction

Energy use of the entire vehicle for either Full Electric or Plug-in Hybrid Vehicles is a complex issue, as the duty cycles and operating profiles for these vehicles are not well defined or known at this point. In electric mode, the energy consumption depends not only on vehicle speed and driving profile but also on accessory use. For example, operating an Electric Vehicle in winter with the vehicle heater, de-fogger and headlights can double the energy consumption relative to energy use on a sunny spring day. Hence, real world energy use is a significant concern.

The sections below detail what is currently known about real world energy use and also the assumptions employed by the project team in terms of vehicle design parameters for modelling the cost and performance of future Electric Vehicles.

4.2 Energy use per kilometre of travel

This section focuses on 'plug-to-wheel' energy use. For a comprehensive picture of energy consumption, data from three types of testing are examined:

1. Testing on the dynamometer, under alternative specifications, that include a more aggressive driving style and/or the use of accessories.
2. Testing on controlled on-road tests using expert drivers and specified routes and speeds, with the use of air-conditioning or heating.
3. From fleet use in the hands of actual consumers, where there is no control of route type, speed or accessory use but overall averages represent actual consumer use.

This section integrates the data from all three test types to develop a composite picture of energy use and emissions for different duty cycles (highway/urban/other roads). Our focus will be on the tank/plug–to–wheel energy use and emissions (the well–to–tank/plug are covered in WP 6). At the time of writing this report, we have been unable to get actual data from the few ongoing fleet trials in Europe but we have contacted the manufacturers for access to this data. The analysis described here is based mostly on work done in the USA by the Department of Energy's (USDOE) national Laboratories that have procured and tested small fleets of electric and PHEV models in the US.

As noted, there are two types of Plug-in Hybrid Vehicles – one that is similar to a HEV with a larger battery and the second that is similar to a battery Electric Vehicle with an on-board charger. We have used the PHEV nomenclature to refer to the first kind of Plug-in Vehicle while the second kind is referred to as an Extended Range Electric Vehicle (EREV).

For PHEVs, we found that the USDOE has tested some PHEV models (PHEV America program) and detailed reports are available on the their website. The PHEV America tests were performed using dynamometer tests over series of UDDS (Urban Dynamometer Driving Schedule) and HWFET (Highway Federal Emissions Test) cycles.

The key challenge for PHEV analysis is the fact that the overall fuel economy is dependent on the driving distance. It should be noted that in this context, there is no pure electric mode independent of driving cycle since the engine is turned on if power demand exceeds available battery power, independent of the state-of-charge of the battery. Confusingly, the ARB has not distinguished this type of PHEV and has derived EER numbers only for the EREV type of Plug-in Hybrid. For this analysis of PHEV EER, we evaluated fuel economy at a 32.7 mile driving distance. This distance is the average daily driving distance per vehicle as reported in the last DOT Household Travel Survey, 2001.

As an additional data source for PHEVs, we found that Google has a well documented vehicle testing program designed to demonstrate real-world technology capabilities. The program is called Recharge IT[17] and it was launched in summer 2007. Google's program involves driving PHEV models through 257 trips, covering a total distance of 2,228 miles. Professional drivers were hired to test different types of vehicles in order to reduce test-to-test variation. Accessories were used during testing, including 'moderate' use of air-conditioning.

For real world test data on Electric Vehicles, the US DOE has partnered with Southern California Edison (SCE) in a testing program, while their website also maintains detailed reports[18] of their own in-house testing. The test data on EVs are for older technology vehicles marketed by major OEMs in California during the late 1990s. The SCE test program was conducted on public use roads in Los Angeles and attempted to replicate actual city and highway driving conditions with and without the use of air-conditioning.

In order to properly compare various fuel economy estimates, it is also necessary to account for vehicle attribute differences. For example, most HEVs are equipped with continuously variable transmissions, whereas their conventional counterparts use regular automatic transmissions - a significant attribute difference affecting fuel economy. Also, EPS (Electric Power Steering), aerodynamic drag improvement devices and low rolling resistance tires are often adopted by more advanced technology vehicles.

The adjustment for differences in attributes is based on a multiplicative fuel consumption reduction approach used by the National Academy of Sciences in its 2002 report on CAFE. Essentially, if two technologies each reduce fuel consumption by 10%, the model assumes that the combined effects are 1-(0.9*0.9) or 19%, not 20%. Each successive technology has a smaller absolute impact since the base vehicle fuel consumption is lower. The technology differences considered do not have any significant synergy or dis-synergy and the reductions are independent of each other. In each case, the adjustment was made to the comparable gasoline vehicle's fuel economy since the sensitivity of fuel economy to technology improvements are known for gasoline vehicles.

The adjustments were made, where applicable, for the following technologies:

– Rolling resistance reduction by 15%, equivalent to a 2.2% fuel consumption improvement. Most advanced technology vehicles specify lower rolling resistance tires, and/or higher inflation pressures. Our contacts with manufacturers revealed that (except in the case of high performance vehicles) typical rolling resistance coefficient for HEV/FEV are in the 0.006

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17 Program description, vehicles tested and testing methodology is described on the RechargeIT website at http://www.google.org/recharge/.

18 Southern California Edison (SCE) Fleet and Pomona Loop Testing program, data available at http://avt.inl.gov/fsev.shtml.

to 0.0065 range while typical values for a 2007/2008 model year conventional vehicle range from 0.0070 to 0.0075.

- Electric Power Steering – 2% fuel consumption improvement. This feature is typically standard on Hybrid and Electric Vehicles but is also now found on some conventional vehicles.
- Aerodynamic drag reduction by 10% (1.8% fuel consumption improvement). This improvement was used since many HEV/FEV models feature underbody covers and add-on aerodynamic aids. Typically, addition of an underbody cover reduces the drag coefficient by 0.02 while add-on devices reduce drag by 0.01. Given the average co-efficient for compact and mid-size cars is in 0.30 to 0.32 range, the 10% drag reduction appears appropriate where the vehicles share the same body or have similar levels of body aerodynamic drag coefficient.
- Transmission differences (for HEVs and PHEVs only). The adjustments were made according to a basic assumption that 4-speed vs. CVT results in fuel consumption difference of 5.7% (5-speed vs. CVT – 3.4%). No adjustments were made for transmissions with 6 speeds or higher since the difference relative to a CVT is very small.
- Rated power differences. A linear power/fuel economy relationship was assumed (for every 10% reduction of rated power, a 2.2% fuel consumption improvement is realised).

Since OEM-level PHEV technology is not yet commercially available in the US, there is no certification test data for these vehicles. However, EEA found that government labs such as DOE's Idaho National Laboratory (INL) have tested PHEV models that are conversions of HEV models (in the PHEV America program) and detailed reports are available on the INL website.

ICF examined the baseline performance reports for Hymotion PHEV and Energy CS PHEV conversions, both of which are derived from the Toyota Prius, mainly by a battery replacement with higher capacity Li-Ion batteries. Table 12 summarises the two PHEV conversions and their attributes, including the battery pack specifications. The original Toyota Prius HEV data is provided for reference purposes, while the Toyota Corolla is used as the conventional gasoline counterpart for the baseline.

The PHEV America tests were performed using dynamometer driving over series of UDDS (Urban Dynamometer Driving Schedule) and HWFET (Highway Fuel Economy Test) cycles. The key challenge for estimating energy efficiency is the fact that overall fuel economy is dependent on the driving distance, as illustrated in Figure 1. While PHEVs are typically designed to effectively operate as an electrical vehicle for short distances and light loads, the battery pack is depleted over some distance (typically 30 to 70 km) and the vehicle reverts back to a conventional HEV operation. In conventional HEV operation, these vehicles suffer a small penalty relative to the HEV model due to the extra weight of the battery pack. The dyno test data shows a fuel economy of 60 mpg on the UDDS for the PHEV as compared to 66.6 mpg for the normal Prius as certified by EPA, which indicates a 10% EER penalty. For this analysis we used a 52.7 km driving distance to estimate PHEV fuel economy. (52.7 km is the average daily vehicle miles of travel in the USA[19]). An assumption is made that PHEVs are charged overnight and no charging is done between trips during the day.

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19 The US Department of Energy, 2008.

Table 12 The PHEV America vehicle test results compared to conventional models

Year	Model	Engine & Trans.	Total System Power (hp)	Battery Details	Combined FE as Tested (mpg)*	EPA 5-cycle Adjusted (mpg)
2007	Toyota Prius Hymotion PHEV Conversion	1.5L ECVT	110	184.8V 4.7 kW-hr Lil-on battery, 2.69 kW-hr usable energy	109.13	71.10
2006	Toyota Prius Energy CS PHEV Conversion	1.5L ECVT	110	230.4V 10 kW-hr Li-Ion battery, 4.88 kW-hr usable energy	117.67	76.05
2006	Toyota Prius (EPA tested)	1.5L ECVT	110	230 V 1.3 kW-hr NIMH battery, 0.3 kW-hr usable energy	65.78	46.49
2007	Toyota Corolla (EPA tested)	1.8L 4 AT	126	None	39.11	29.31

* Tested fuel economy for PHEVs was derived from reported data by DOE PHEV American program. The city and highway results were interpolated for 32.7-mile driving distance.

Because PHEV America test procedures involve dynamometer tests, for comparison purposes, we used EPA Fuel Economy guide unadjusted values for conventional Prius and Toyota Corolla. The PHEV's fuel consumption rate is critically dependent on driving distance, since the batteries are rapidly depleted. When the batteries are fully depleted, the fuel consumption rate is almost identical to a similar Hybrid Vehicle. At the 52.7 km trip length used for comparison, we found the test fuel consumption rate to be 2.155 L/100 km counting the electric and fuel energy and converting them to a fuel energy basis (not including electricity generation related losses). For very long trip lengths, the PHEV fuel consumption rate went up to 3.72 L/100 km, virtually identical to that of the standard Prius HEV at 3.57 L/100 km with the small penalty due to the increased weight of the batteries.

On road tests of older generation Electric Vehicles revealed that energy economy for models such as the Toyota RAV-4, the Ford Ranger truck and the Honda EV Plus were quite similar (the models all weighed about 1,800 ± 100 kg) and actual on-road fuel economy averaged about 33 kWh/ 100 km (i.e., 3 km per kWh) but the dynamometer testing showed fuel consumption rates of only about 25 kWh per 100 km, suggesting actual fuel consumption on the road is 32% higher.

More recent statements by BMW and Nissan confirm that the on-road discount is around 32%. For example, the Mini EV has a range of 240 km based on dyno test energy consumption but real world range is only 160 km indicating 33% higher consumption. The Nissan Leaf has a test range of 160 km but real world range is 110 km according to recent news reports. Nissan's chief engineer also confirmed that in very cold conditions, the deterioration of battery capacity as well as the heating and defrost energy requirement could double energy consumption from the test value.

4.3 Overview of energy use estimates of entire FEV and PHEV

Under this project, we collaborated with another ongoing project for DG CLIMA that assesses technology and cost for meeting the 2020 CO_2 regulation for passenger cars (lead by TNO). We supplied that project with data on electric component cost and weight in the future. They feeded this into a platform model, which results are summarised in this section.

Performance criteria were agreed with TNO on:
- Electric driving range.
- Acceleration times from 0-50 km/h and 0-100 km/h (at kerb weight).
- Top cruise speed on a 4% gradient.
- Gradeability at 15 km/h (at GVW).

Table 13 below summarises these vehicle performance specifications as jointly elaborated by the two projects.

Table 13 Vehicle specifications utilised for projections

	Fuel	Vehicle segment	EV range (km)	Power train configuration
1	Petrol	Small-B	50	PHEV
2	Petrol	Medium-C	50	PHEV
3	Petrol	Large-D	50	PHEV
4	Diesel	Small-B	50	PHEV
5	Diesel	Medium-C	50	PHEV
6	Diesel	Large-D	50	PHEV
7	Petrol	Small-B	50	EREV
8	Petrol	Medium-C	50	EREV
9	Petrol	Large-D	50	EREV
10	Diesel	Small-B	50	EREV
11	Diesel	Medium-C	50	EREV
12	Diesel	Large-D	50	EREV
13	-	Small-B	150	EV in 2020
14	-	Medium-C	175	EV in 2020
15	-	Large-D	200	EV in 2020
16	-	Small-B	250	EV in 2030
17	-	Medium-C	300	EV in 2030
18	-	Large-D	350	EV in 2030

Performance Requirement	Small A segment	Medium C segment	Large D segment
Acceleration 0-50 km/h	< 4.5s	< 4.0s	< 3.5s
Acceleration 0-100 km/h (PHEV)	< 14.0s	< 13.0s	< 11.5s
Acceleration 0-100 km/h (EREV & EV)	< 14.0s	< 13.0s	< 13.0s
Gradeability at 15 km/h	> 30%	> 30%	> 30%
Top cruise speed (PHEV)	160 km/h	180 km/h	200 km/h
Top cruise speed (EREV & EV)	125 km/h	125 km/h	125 km/h

These vehicle specifications and the considerations made in this section are the basis for the energy use estimates used in the impact assessment. They can be found in Deliverable 5 of this project.

The analysis and vehicle specifications assume that improving range takes precedence over cost reduction, so that as battery technologies improve, the weight of the battery is reduced only slightly (and costs decline only slightly) but range continues to improve significantly; for a small C-class car like the

Nissan Leaf, range goes up from 150 km on the NEDC in 2012 to 175 km by 2020 and 250 km by 2030. Hence, overall cycle energy consumption stays near constant, as Ricardo did not assume significant changes in the rest of the body in terms of mass reduction, rolling resistance reduction or drag reduction.

4.4 Energy use of vehicle production[20]

Most studies indicate that EVs produce less greenhouse gases (GHGs) than conventional internal combustion engine vehicles (ICEVs) on a well-to-wheel basis (Huo et al, 2009). However, a complete life cycle analysis (LCA) would need to assess all life cycle emissions, including the impact of the battery from cradle-to-grave. That is, the LCA must incorporate both the production of the vehicle and the treatment of the vehicle at the end of its useable life into the analysis.

In general, we can distinguish the life cycle impacts from:
- Energy carrier production (fuels and electricity).
- Vehicle production and end-of-life processes.

The impacts related to electricity production and its interaction with EV are discussed in Deliverable 3 of this project and will be further assessed in the scenario work in WP 6. In this section, we discuss the life cycle impacts related to vehicle production and the vehicle production emissions as share of the entire life cycle. The emissions from end of life processes are not studied that often, but it seems the contribution of those emissions is very small.

The manufacturing and scrappage of an EV and an ICEV are similar with the exception of the production of the battery system and its subsequent recycling. As a result, this review focuses on the additional GHGs associated with the battery manufacturing process and whether these increased emissions would outweigh the benefits from reduced GHG emissions during the lifetime of the vehicle, which includes the operation and disposal of the vehicles.

The GHG associated with battery production is a complex issue as much depends on the exact composition of the battery materials and the recycling of the battery discussed in Section 2.5. The credits associated with secondary use of the battery (if any) are also an issue that must be considered in this computation.

The outcomes of different studies for emissions from battery production are presented in Section 4.4.1. In Section 4.4.2 the GHG associated with battery production are taken into account in the entire life cycle.

4.4.1 Battery production

Most current HEVs (Hybrid Electric Vehicles) utilize NiMH batteries. However, the most likely alternative battery chemistry for the use in PHEVs, EREVs and FEVs is Lithium-ion (Li-ion). Li-ion batteries have the advantage of higher energy densities (per unit volume and per unit mass).

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20 This section builds on work carried out by CE Delft in a parallel project on vehicle emissions: see the interim report for Service Request #1 of the project *Support for the revision of Regulation (EC) No 443/2009 on CO2 emissions from cars*, Framework Contract No ENV.C.3./FRA/2009/0043, TNO et al, March 2011.

According to Notter et al. the production of the battery is dominated by the production of the cathode, anode and the battery pack (steel box, printed wiring board and cables). Their contribution to the overall impact of the battery is some 80% (Notter, 2010).

GREET
The US Argonne National Laboratory has been developing the Greenhouse gases, Regulated Emissions, and Energy use in Transportation model - The Transportation Vehicle-Cycle Model (GREET 2.7). Unlike the *fuel-cycle* GREET model, this *vehicle-cycle* model evaluates the energy and emission effects associated with the production and disposal of the vehicle. With respect to the lithium-ion (Li-Ion) battery, GREET bases its assumptions on a Japanese report which estimates the energy required to assemble and to test a Li-Ion battery to be 25.1 kWh/kg (Ishihara, et al 1999). This produces 7.5 kg of CO_2 equivalent GHG emissions/kg of Li-Ion battery, using the average US electricity generation mix. However, Argonne is not confident of these numbers because that same study estimates the energy required for the assembly and testing of a nickel metal hydride (NiMH) battery to be less than 10 kWh/kg, and maybe these values can be replaced in the near future with more reliable numbers (Burnham and Wang, 2006).

Samaras
A seminal study in the LCA of Li-Ion batteries was conducted by Samaras and Meisterling (2008) They noted the deficiencies in GREET's assumptions and decided to base their assumptions on the results of Rydh and Sandén (2005). Using a Toyota Corolla/Prius-sized vehicle (about 1,200-1,300 kg), they assumed that the energy required for battery production, input material production, resource extraction and processing, transportation of materials, and recycling of a Li-Ion battery would total 47.2 kWh/kg. This results in 12.0 kg of CO_2 eq./kg of Li-Ion battery, and the analysis was done for a Plug-in Hybrid battery.

Notter et al.
A more recent and comprehensive LCA of Li-Ion battery production was completed by Notter et al. (2010) They account for Li-Ion production steps ranging from the extraction of lithium, input material production and the transportation of materials. They used four different impact assessment methods: abiotic depletion potential (ADP), non-renewable cumulated energy demand (CED), global warming potential (GWP) and Eco-indicator 99 H/A (EI99 H/A). All these methods produce similar results except for the EI99 H/A methodology, but that method is based on a point system, so those numbers are hard to compare with those from other methods. Using the average from the other three methodologies, energy requirements for Li-Ion battery production total 28.9 kWh/kg and produce 6.0 kg of CO_2 eq./kg using European electricity generation mix.

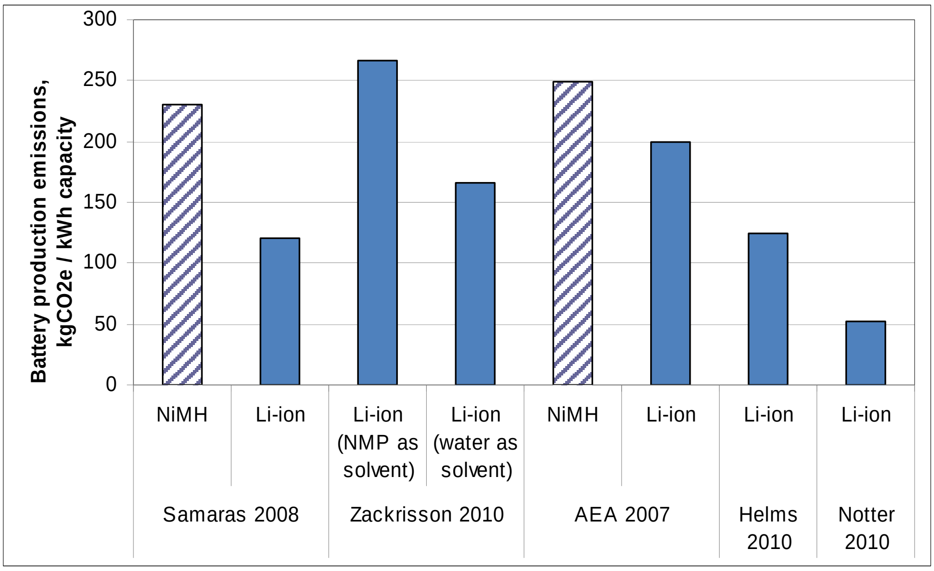
Table 14 Comparison of different life cycle analyses results for lithium-ion production

	GREET	Samaras	Notter
Energy Requirement, kWh/kg	25.1	47.2	28.9
Kg of CO_2 eq./kg of battery (avg. electric generation mix)	7.5 (US Generation mix)	12.0 (US Generation mix)	6.0 (EU Generation mix)

It appears that the Samaras study has the highest estimate of Li-Ion battery production energy but some of the difference may be attributable to the battery type (PHEV vs. FEV), It may also reflect a more complete accounting of metal extraction energy although the Notter work also looks to be very thorough. We conclude that the primary energy for battery production is potentially in the range of 25 to 30 kWh per kg of battery.

Where Table 14 shows the range in energy requirement and emissions for different Li-Ion-batteries, Figure 21 shows the battery production emissions for Li-Ion batteries as well as NiMH-batteries (in kg CO_2e/kWh capacity). The new Li-ion battery packs are most likely to be used in PHEVs and FEVs and in general those battery packs have lower lifecycle GHG emissions per unit capacity compared to the NiMH batteries which are nowadays used in conventional hybrid electric vehicles (HEV). GHG emissions for production of NiMH batteries were estimated to be up to double the emissions for Li-ion batteries.

Figure 21 **Battery production emissions (kg CO2 eq. per kWh capacity)**



Source: Samaras, 2008; Zackrisson, 2010; SEI, 2007; Helms, 2010; Notter, 2010.

4.4.2 Incorporating battery production into the life cycle analysis

GREET

The US GREET model provides only a vehicle energy use well-to-wheels comparison that does not include vehicle production energy. For a US midsize car, the model estimates 294 g/km for the ICEV and 209 g/km for the FEV with the US average electric generation mix.

Samaras

Samaras compares the LCAs of ICEVs, HEVs, and PHEVs and measures the GHG emissions during the operational phase of the vehicle from a well-to-wheel perspective. The PHEVs have an electric range of 30 to 90 km. When combined with the production and disposal of the vehicle and battery, the study concludes that a Corolla size ICEV produces 269 g of CO_2 eq./km and the PHEV produces between 181 to 183 g of CO_2 eq./km using the current US electricity mix. Samaras decided not to include the GHG emissions from the end-of-life recycling energy of the vehicle which are very small on a g/km basis.
The study assumes a battery life of 250,000 km.

Notter

Notter compares ICEVs to FEVs and the total GHG emissions include the manufacture of the battery and the vehicle, the operational life, and the disposal of the vehicle. The study projects that from cradle-to-grave, a VW Golf size ICEV emits 251 g of CO_2 eq./km and that FEVs emit 162 g of CO_2 eq./km using the average electricity production mix (UCTE) in Europe. They estimate that the disposal of an ICEV produces less than 8 g of CO_2 eq./km. The recycling of the FEV reduces GHGs by 2 g CO_2 eq./km with respect to the ICEV and that is probably because the battery has more recyclable components.

The comparison of results from the different studies is provided in Table 15.

Table 15 Comparison of greenhouse gas emissions from cradle-to-grave

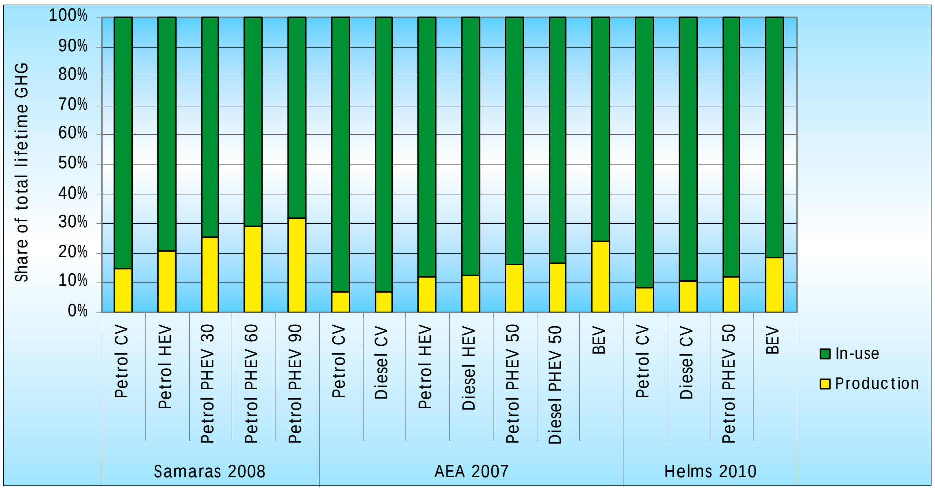
	ICEV	PHEV	FEV
Samaras	269 g of CO_2 eq./km	182 g of CO_2 eq./km	
Notter	251 g of CO_2 eq./km		162 g of CO_2 eq./km
GREET	294 g of CO_2 eq./km	262 g of CO_2 eq./km*	209 g of CO_2 eq./km*

* GREET's PHEV and FEV figures are only from well-to-wheel and do not include the GHG emissions from the production and recycling of the battery.

The numbers on the emissions for battery production in combination with the emissions from vehicle use illustrate that the life cycle GHG emissions are still dominated by emissions associated with vehicle use. For example, if the battery weighed 200 kg for a 20 kWh capacity unit, battery manufacturing energy would add about 6 g CO_2/km over a life of 250,000 km.

In Figure 22 the relative share of GHG emissions from total production in total emissions is shown. For conventional vehicles the share of production emissions is around 10%, where the shares for PHEVs and HEVs are higher. This can be explained by the additional emissions from battery production on the one hand and by the decreasing share of vehicle use emissions on the other hand.

Figure 22 **Estimated proportion of GHG emissions from production and usage phases for hybrid and electric vehicles based on different literature sources**



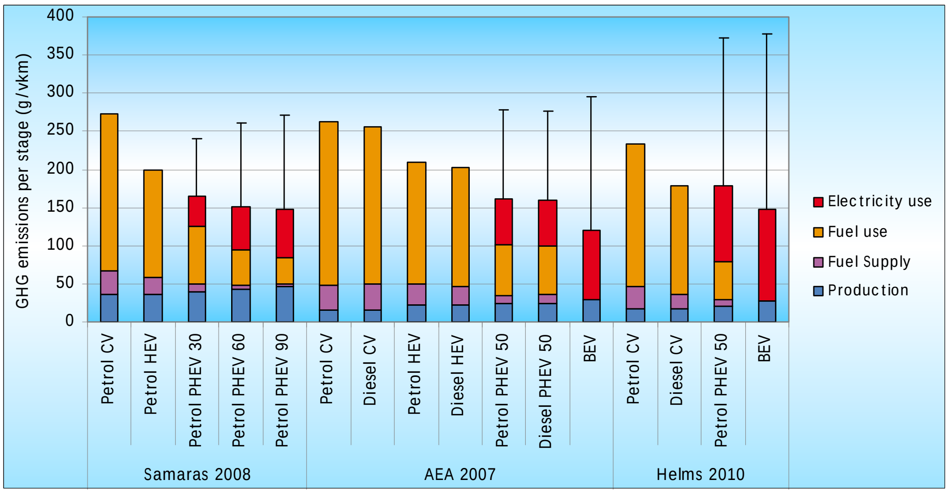
Source: Samaras, 2008; SEI, 2007; Helms, 2010.

Notes: Used data has been normalised from original sources to the GHG intensity of the EU electricity mix (based on JRC, 2008) and an assumed average EU vehicle lifetime of 238,000 km (based on data from TREMOVE).

* Based on battery production GHG emissions for Li-ion batteries for PHEVs and NiMH for HEVs.

Due to the emissions from battery production, the share of vehicle production in the overall lifetime emissions increases. However, the life cycle emissions are still dominated by the electricity generation mix and still provide sizeable reduction potential for Europe. The dependency on the electricity generation mix is presented in Figure 23: the tick bars represent emissions of the average EU electricity mix in 2010. Next to this, the error bars represent emissions if the electricity is produced with coal fired power plants.

Figure 23 **Absolute lifecycle GHG emissions allocated to use and production (g CO_2 eq./km)**



Source: Samaras, 2008; SEI, 2007; Helms, 2010

Notes: Used data has been normalised from original sources to the GHG intensity of the EU electricity mix in 2010 (based on JRC, 2008) and an assumed average EU vehicle lifetime of 238,000 (based on data from TREMOVE). * Based on battery production GHG emissions for Li-ion batteries for PHEVs and NiMH for HEVs. The error bar represents coal fired power (900 g/kWh).

5 Noise, safety and maintenance

5.1 Introduction

In this chapter we discuss various other issues that are important ingredients when assessing the impacts of Electric Vehicles. The issues discussed are the following:

– Noise and safety impacts (Section 5.2).
– Maintenance (Section 5.3).

5.2 Noise and safety impacts

Noise levels of Electric Vehicles are much lower than conventional vehicles in cases where engine sound is the main noise source of a vehicle. This is typically the case at low speeds, so mainly in urban areas. Therefore, Electric Vehicles could have benefits in the field noise abatement, particularly in urban areas.

At the other hand, there are concerns about potentially higher accident risks of very silent vehicles, again particularly in urban areas. Both aspects are discussed in the following subsections. In terms of direct noise impacts, a comprehensive study was performed by the US Department of Transportation using Prius Hybrids operating in pure electric modes Noise levels were compared with conventional ICE cars in a wide variety of conditions The overall sound levels of the Prius when stationary and at low speeds below 10 km/hr were significantly lower than the ICE vehicles. At speeds of about 20 km/hr the noise level of EV operation was only slightly lower (2dbA) and the noise levels converged at higher speeds, becoming almost equivalent at speeds over 30 km/hr. The study also noted that the Prius emitted a higher pitch sound when decelerating that was attributable to the regenerative braking related noise from the motor and power electronics.

The DOT study also examined the effects of blind subject's ability to detect a pure EV, which is also a function of ambient noise conditions. In most cases, EVs were detected later by subjects than ICE vehicles, with the only exception being the deceleration condition, where the high pitched whine of the Prius resulted in earlier detection the ICE vehicles. 2 of 48 subjects in the test never detected an EV approaching at 10 km/hr while 5 of the 48 subjects never detected an EV backing out at very low speed (~ 5 km/hr). Hence, it is clear that there are safety issues associated with low speed driving conditions and the low level of EV noise.

5.2.1 Safety aspects of silent vehicles

There are concerns expressed by various safety groups that 'silent' vehicles present a safety hazard for visually impaired, cyclists, runners, small children, and other pedestrians. As noted above, Electric Vehicles and Hybrid Vehicles may not be audibly detectable by the visually impaired when a vehicle's internal combustion engine is not operating and vehicle is moving at low speeds. The problem can be especially acute at urban intersections with loud background noise and where blind pedestrians make decisions about crossing streets based on what they can hear in their environment.

Societal concerns about the adverse effects of noise pollution have caused automakers to steadily reduce automobile-emitted sound. Advanced technology vehicles such as Hybrids have achieved very low noise levels. To date, we are not aware of regulations that set *minimum* sound level requirements applicable to motor vehicles in Europe or the United States. To the contrary, there are regulations at various government levels that specify maximum sound emission requirements.

5.2.2 Potential technical solutions

In response to the 'silent' vehicle issue there were several recent studies performed to better understand the issue and a number of technical solutions were proposed. The solutions can be broadly classified into the following technology types:

- Infrastructure-based. Examples include intersection rumble strips and audio warnings at intersections.
- Communications-based, which include personal proximity warning transmitters, electronic travel aids.
- Vehicle-based, which include artificial vehicle sounds when approaching intersections or moving at low speed.

The current trend appears to be moving toward the vehicle-based solutions as the most practical implementation measure. However, there appears to be little agreement over what the artificial vehicle sound should be, how loud, and whether manufacturers should be allowed to create their own distinctive audio tracks.

Japanese car manufacturers have an early electrified vehicle lead and have achieved mass production volumes of some popular Hybrid Vehicles. Honda has patented a simulated sound generator concept in the mid-1990s. Toyota, the leader in Hybrids, and Nissan/Renault which announced mass production of FEVs, are studying the issue and technical solutions will be announced as vehicles are launched in near term. The Nissan Leaf FEV will generate a sine-wave sound resembling a 'whistle' while the vehicle is travelling at less than 19 mph. The Leaf system will sweep the sound frequency from 2.5 kHz to 600 Hz through a loudspeaker device located in an engine compartment. GM/Opel is planning to equip the upcoming Chevrolet Volt-based EREVs with a driver-activated warning system. The cars will emit a short audible horn pulse when the driver pulls back on the turn-signal handle. A similar system was used on the first-generation GM electric vehicle, Chevy EV1 in the United States. Some OEMs are not convinced that adding artificial sounds is warranted. For example, Tesla has sold a number of the electric Roadster FEVs designed for minimal noise, and is concerned to will lose some competitive advantage because of a customer preference for a more silent vehicle.

Vehicle-based artificial sound systems do not appear to be a complicated or costly solution. Modern vehicles are build using the Digital Signal Processing (DSP) integrated CAN electronics with basic inputs such as vehicle speed and direction already used by other processors. Examples of artificial sound generators such as active noise cancellation (used with cylinder deactivation engines) are already available in marketplace.

The most widely publicised technical effort to provide synthetic engine noise for quiet vehicles in Europe is from Lotus Engineering, UK. Lotus claims to have been working on the active noise-cancellation (ANC) for more than 20 years and believes that the same technology can also generate synthetic engine noise to warn pedestrians. The company has demonstrated a number of sound simulations using an exterior loudspeaker.

5.2.3 Safety regulations for silent vehicles

Car manufacturers and their trade associations generally recognise that 'silent' vehicles can present a safety hazard to pedestrians, especially those who are visually impaired. The industry is advocating a regulatory solution to make sure that the issue is addressed in a consistent manner among various markets. Government regulators also believe that the electrified vehicles, such as Hybrids, have reached substantial market penetration and sufficient anecdotal evidence exists to warrant a regulatory action.

As far back as 2008, the United Nations World Forum for Harmonisation of Vehicle Regulations agreed to get involved in this issue. The European Commission is reviewing a proposed legislation and regulatory action is expected in near term. The Japanese government is working with the car manufacturers and is also conducting studies. The guidance document is anticipated this year.

The US auto industry supported by the National Federation of the Blind (NFB) and the American Council of the Blind (ACB) announced in May 2010 that they have agreed on proposed legislative language that will protect blind pedestrians and others from the danger posed by silent vehicle technology. The organisations are urging the US Congress to adopt and pass the language as part of the Motor Vehicle Safety Act of 2010 - which is currently pending. The proposed language would require the Department of Transportation to promulgate a motor vehicle safety standard requiring automobiles to emit a minimum level of sound to alert the blind and other pedestrians.

To support the regulatory effort, the Society of Automotive Engineers has established the Subcommittee on Vehicle Sound for Pedestrians (VSP) under the Safety and Human Factors Committee. The subcommittee will research the electrified vehicle sound levels and develop test procedures.

In conclusion, an adequate number of low cost solutions to address the problem of very quiet vehicles exist and regulatory bodies are expected to propose specific industry-wide solutions to this issue in all OECD countries in the near future.

5.3 Maintenance of EV/PHEV relative to conventional vehicles

This report provides cost analysis for several different future fuel price paths, but maintenance costs of EV and PHEV are a major unknown. At present, little information is available on EV and PHEV maintenance costs since only a few relatively new vehicles exist. However, the main components of the EV and PHEV that are different form a conventional vehicle are the battery, motor and power electronics, all of which are claimed to be maintenance free. However, the battery will probably need to be inspected annually, and occasional cell balancing may be required. We do not foresee the need for any normal maintenance on the motor or power electronics. Nissan has publicly stated that they believe that maintenance costs would be reduced by 10% over a normal ICE and that seems like a reasonable estimate. Others have claimed larger benefits due to reduced brake and tire wear but this is much less clear.

A more significant concern is the life of the battery itself, which is discussed in Section 3.3. As noted, in moderate climates such as those present in Southern Europe, we anticipate a battery life of about ten years on average, and a deep cycle life of 1,500 to 2,000 cycles in real world conditions. Assuming that each deep cycle provides 100 to 120 km of travel, the end-of-life condition would allow total travel of 150,000 to 240,000 km, which is significantly more than the average ten year accumulated kilometres for a conventional car. Hence, calendar life may be the limiting condition for first-generation batteries. By 2020, we anticipate that calendar life will increase to thirteen to fifteen years and deep cycle life to 2,500 to 3,000 cycles, based on battery manufacturer expectations. These values will be utilised for the life cycle cost analysis. In more extreme climates of Northern Europe, battery life may be impacted by continuous exposure to very cold ambient conditions, and we will attempt to characterise this effect for the life cycle cost calculations.

6 Projections of the EV market share

6.1 Overview of existing forecasts of market shares

The size of the market for pure battery Electric Vehicles and Plug-in Hybrid Electric Vehicles is a major driver of costs of these vehicles since economies of scale and scope are possible with large markets. Companion reports for WP 1 (Deliverable 1) and WP 6 (Deliverable 5) also contain estimates of EV and PHEV market share for the EU, but this section provides some global estimates derived from manufacturer and supplier data.

Unfortunately, there is little or no consensus on the size of the EU and global markets for EV and PHEV models. The Chairman of VW publicly said that there were as many forecasts of penetration as there were consultants, and the variation in expected sales in 2020 between forecasts covers an order of magnitude. However, we can bracket the forecasts and the reasoning behind some of the forecasts to provide a forecast with internally consistent assumptions about battery developments, reliability, cost and market size.

At the one end of the scale, we have 'pessimistic' forecasts that show PHEV and EV models each taking *less than 1%* of global light vehicle sales (under 4 tons gross weight) in 2020, which is estimated at about 80 million vehicles. Such forecasts have been made, for example, by Dr. Anderman at the Advanced Automotive Batteries Symposium in May 2010. This implies global sales of about 600 thousand EVs (about 200 thousand in the EU), and most of the sales are expected to be in the OECD countries. The theses behind such forecasts are:

1. Consumers purchase such vehicles only for pure economic benefits in terms of fuel cost savings.
2. Global subsidies are relatively low. And
3. Battery costs do not fall very fast under a slow growth scenario and battery life in real world conditions continues to be an issue.

At the other end of the spectrum, we have optimistic forecasts by the Chairman of Nissan-Renault, Mr. Ghosn, who has claimed that EV models could account for 10% of global sales in 2020, or about 8 million sales.
The theses behind such forecasts are:

1. Consumers are attracted to such vehicles due to their green credentials of low energy use and low emissions and are willing to pay extra for such features.
2. Governments will continue to strongly support these developments with significant global subsidies. And
3. Battery costs fall quickly due to both scale economies and innovation, and life will be longer than ten years.

Most other forecasts fall between these two; as an example, Figure 24 shows sales forecasts in three scenarios by SB Limotive, a joint venture between Bosch and Samsung, to the year 2015. The EV scenario shows sales of almost 4 million EVs by 2015 so that a 8 million forecast for 2020 would be in line with this number. However, our contacts with several car manufacturers and suppliers suggest that the Nissan-Renault forecast is an outlier, and most other manufacturers believe that EV and PHEV sales will be closer to the low end of projections, but all manufacturers admit to being uncertain about the future of EV sales.

The forecasts also have some elements in common. First, most analysts agree that the battery electric vehicle concept is better suited to small cars to minimise battery size and accessory loads, and the PHEV concept is better suited to large and luxury vehicles. This would imply that North America would have the largest share of the PHEV market, while EVs would be most popular in other parts of the world.

Second, milder climates are expected to be more hospitable to EVs, both in terms of battery life and accessory loads. Hence, Southern Europe and the coastal parts of the USA are likely to have larger EV penetrations than other areas with more severe climate.

Third, there is agreement that significant subsidies are required to make the EV affordable and that EVs will not become cost competitive with petrol and diesel vehicles until the post-2020 era. While the OECD countries are planning significant subsidies in the near term, the current global financial situation may not permit this to continue to 2020.

Many OECD countries have set EV penetration targets. In addition, China, which could have the largest automotive market in the world by 2020, is aggressively pursuing battery manufacturing and is promoting EVs in its home market. The IEA has examined the targets set by many countries and estimated that OECD nations and China have set a target of about 4 million EVs in 2020, as shown in Figure 25. Examination of the IEA estimated targets for EV penetration by country shows a mixture of realistic and unrealistic targets – for example, the IEA estimates Spain's target for EV sales is the same as China's target at 500,000 in 2020.

Figure 24 Limotive scenarios for EV sales

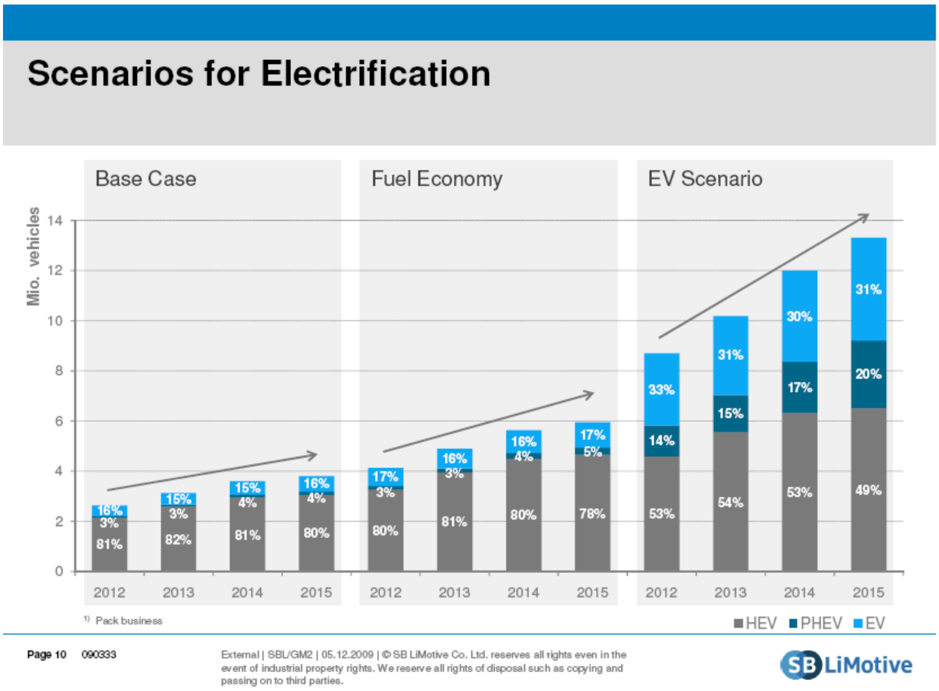
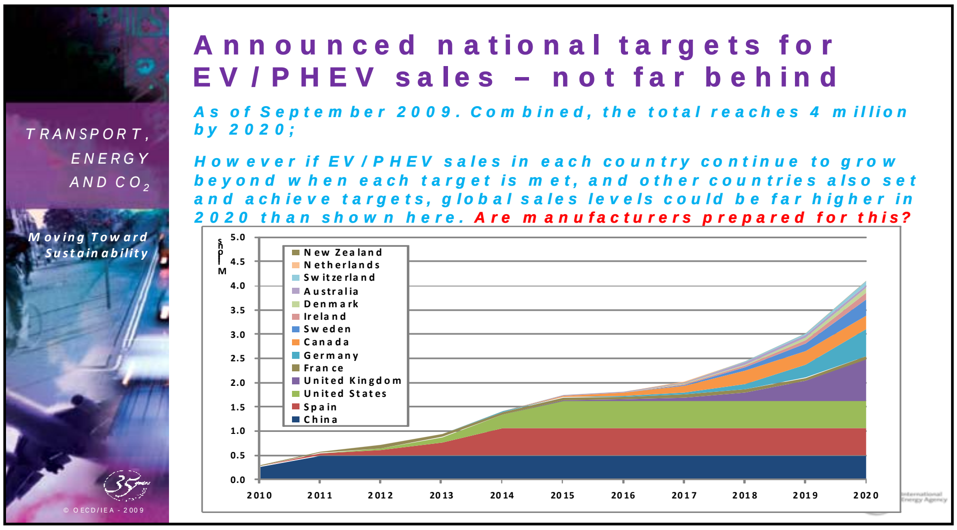


Figure 25 IEA estimate of national targets for EV sales



6.2 Own projection of market shares

It is clear that forecasts of EV and PHEV absolute sales volumes to 2020 are too dependent on parameters that cannot be reliably determined now, such as consumer willingness to pay for green technology and the ability of governments to continue significant subsidies for ten or more years. We have constructed a scenario below that lies between the extremes that is approximately consistent with the Limotive 'fuel economy' scenario, but this should be regarded only as preliminary and in our opinion, optimistic, estimate for determining economies of scale in battery manufacturing globally.

It should be noted that the projections in this report are based primarily on manufacturer and supplier inputs. Deliverable 1 of this project included an overview of sales target announcements and goals set by Governments around the world.

Deliverable 5 of this project has refined both cost and sales estimates for EV and PHEV sales in the EU using a model developed for the EU and taking account the cost levels and structures of various types of EV compared to ICEVs. Our preliminary estimates for 2020 are shown in Table 16.

Table 16 **Global light duty vehicle sales forecast for 2020, in millions of units, with optimistic forecasts of EV and PHEV sales**

	Total light vehicle sales	EV sales	PHEV sales	Hybrid sales
North America	19	0.5	0.5	2.5
South America	4	-	-	0.2
Western Europe	16	0.5	0.15	2.5
Eastern Europe-Russia	3	0.05	-	0.15
India	4	0.05	-	0.15
China	19	0.5	0.1	1.0
Japan and Korea	6	0.5	0.1	1.0
Other Asia/Oceana	7	0.1	0.05	0.4
Middle East and Africa	2	-	-	0.1
Total	**80**	**2.2**	**0.9**	**8.0**

Table 16 assumes that stringent fuel economy regulations will drive sales of Hybrid, PHEV and EV models in all developed countries but PHEV models will mainly be in larger vehicles popular in the US. China's push for EV sales is also reflected in this table. Due to the power shortages in India and Africa, EV or PHEV are not expected to sell well there. South America, particularly Brazil, seems to be investing more in bio-fuels so that EV or PHEV penetration is likely to be small over the next ten years.

Although Hybrid Vehicle sales will climb to about 10% of global sales by 2020 in this forecast, these vehicles will use relatively small batteries of the high power type, which are different in design from EV and PHEV high energy batteries, and are also much smaller, at about 5% the energy capacity of an EV battery. Hence, EV type batteries are forecast to have sales of about 3 million units in 2020 and we anticipate that these sales will be divided among 12 to 15 global battery suppliers by 2020 to estimate production volumes and economies of scale.

Current battery recycling methods are energy intensive. Emissions after-treatment and transportation/handling costs are also high so the industry claims that rough cost for battery recycling is about $ 1,000 to $ 2,000 per ton. There are projections that the costs will decline after new battery streams will become available and new plants are built with optimised large scale processes. Currently, however, the metal recovery alone can not pay for recycling costs. Government and private subsidies are required according to a battery type. In some regions, the subsidy is in the form of tax added to each manufactured cell. Some chemistries such as lead and nickel-based are nearly profitable from metal recovery so subsidies are minimal. The Li-Ion battery receives among the highest subsidies since the cells generally contain little retrievable metal.

7 Conclusions of the EV technology analysis

7.1 Battery technology to 2030

The range of Full Electric Vehicles and the AER of Plug-in Hybrids of either type continue to be a major determinant of costs as it drives the size of the battery and the cost of energy storage continues to be single greatest challenge to the commercialisation of both PHEV and EV models. In this context, the cost of recharging infrastructure is not as large a problem as widely believed in the next five to ten years since most early adopters are those who will have access to home recharging facilities at night. The durability and life of the battery are also major concerns since under the deep cycling of state-of-charge (SOC) of the battery, battery life is impacted.

7.1.1 Battery costs to 2030

By 2011/12, we anticipate that commercial volume production of batteries will start and several battery manufacturers have indicated to us that preliminary production in 2012 will be about 2,000 batteries per month (Nissan-Renault may be higher) or about 25,000 per year. At this volume, battery manufacturers estimated cell costs to be about $ 500 per kWh which is 25 to 30% lower than the 2009 low volume cost estimated by BCG. Nissan has publicly claimed battery costs at $ 500/kWh but they are receiving significant subsidies towards capital equipment and building the manufacturing plant so that this is reasonable as a subsidised cost. Integration to module and battery level have costs that are somewhat less volume sensitive, and we estimate total battery cost at $ 750 to $ 800 per kWh in 2012. At current exchange rates of $ 1.25 per €, we estimate battery cost in 2012 (unsubsidised) to be € 620 per kWh, but there are some small fixed costs for the battery like safety fuses and current leak detection that do not scale with battery size, so that an add on cost of € 200 per battery is utilised that is independent of kWh storage capacity. Subsidised cost may be € 50 to € 100 per kWh lower.

Battery manufacturers also indicated that each battery generation is likely to be in production for four to five years at least to recoup capital investments and R&D costs, so that 2011/2012 introduction of the first generation of automotive lithium-ion batteries implies that the second-generation batteries could be commercialised in 2016/17 and third-generation batteries in the early 2020 time frame.

Based on our survey of battery technology development, we anticipate the following developments relative to a 2010 battery:

1. Improvements of 20 to 25% in specific energy with a similar reduction in cost by 2016 primarily due to improved battery design and packaging.
2. Improvements of 70 to 75% in specific energy and 50% reduction in cost per kWh by 2020 to 2022 with the introduction of advanced materials for the anodes and cathodes, such as silicon anodes.
3. Potential for a tripling of specific energy and 70% cost reduction per kWh by 2030 with the introduction of lithium-sulfur batteries.

Within the next five years, cells for small devices using a silicon graphite alloy anode are expected to come to market because even though it does not realise silicon's 4,200 mAh/g theoretical capacity, silicon will still improve the energy density of the battery. There is much promising research in the ability of nanostructures to take advantage of silicon's high capacity potential but this technology may still be ten years away from commercialisation in automotive batteries since high volume manufacturing techniques have not yet been developed. We expect the first such automotive batteries to be introduced around 2020, and we anticipate that energy density will increase by 75% relative to *current* Li-Ion cells and may improve further with improved cathode chemistry. Researchers interviewed for this analysis stated that silicon's cost per gram will be highly competitive with graphite's cost, and they anticipate that battery costs per unit weight will be similar at similar levels of manufacturing maturity. This implies that costs per kWh will decline by the same percentage as the inverse of energy density (i.e., 1/1.75) when production reaches the same level of maturity.

With a theoretical specific energy capable of achieving the energy density of hydrocarbon fuels, research in lithium-air batteries will likely increase over the next few years. However, lithium-air is still at a very experimental stage and many obstacles hinder the practicality of this chemistry, so it could take at least 15 to 20 years to make a commercially viable product for portable electronics and perhaps 25 to 30 years before a vehicle battery is developed. At this point, we have not included this technology in any cost calculations but recognise that such a battery could change the entire vehicle transport system.

Based on available analysis and current battery data, it appears that current (2010) battery life should exceed seven years and may be around ten years for 'average' use. However, there is still much uncertainty regarding battery calendar life at more severe ambient temperatures such as those encountered in North Africa or Scandinavia. In the EU, the more moderate temperatures may allow real world battery life to be around ten years on average, and we anticipate continued improvement to 2020 by which time, expectations are that average life may be in the thirteen to fifteen year range.

7.1.2 Battery recycling and lithium supply

It is generally understood that, unlike cadmium and lead based batteries, current known formulations of the Li-Ion battery materials do not present significant environmental concerns beyond fire safety and landfill utilisation. There is some concern with nickel metal hydride batteries commonly used in current generation of Hybrids but these batteries are highly recyclable.

Because lithium-based batteries are considered more environmentally benign compared to the nickel metal hydride batteries, there are indications that battery manufacturers themselves will be in a position to recycle the EOL vehicle batteries together with their internal battery scrap. For example Renault and Nissan just announced intent to establish a joint venture with the French Energy Commission (CEA) and the French Strategic Investment Fund (FSI) to produce Li-Ion batteries in France. The venture is envisioned to develop, manufacture and recycle the FEV batteries in one facility. Similar battery recycling capabilities exist in other parts of Europe. Umicor has decided to build an industrial scale recycling facility for the EOL rechargeable batteries in Hoboken, Belgium. As a result, we believe that are no major concerns that would distinguish recycling Li-Ion batteries relative to current lead acid and nickel metal hydride batteries.

According to the Rechargeable Battery Recycling Corporation, if a steady stream of batteries, sorted by chemistry, were available at no charge, recycling would be profitable[21]. Our analysis show that the Li-Ion batteries with high value content, such as MS/titanate, would approach the process cost break-even at high historical LC prices. For the low lithium content chemistries, such as MS/graphite, recycling economics would be poor. The economics would drastically improve for cell chemistries that contain other high value metals, especially nickel and cobalt. Lower value metals such as iron and manganese would improve recycling revenue but not enough to alter the overall economics. Knowing that the metal prices will remain volatile, the battery recycling economics appear to be difficult and hard to predict ten years into the future but will likely require government mandates or subsidies to be economical.

The use of lithium batteries for EV and PHEV fleets in large numbers has raised concerns about lithium supply and future availability of lithium in large quantities. Some observers have suggested that the developed world would be trading dependence on the OPEC oil cartel to a new lithium cartel of Bolivia and Chile, where most of the current lithium mining activity is centred. Such concerns have been proved to be false by detailed studies of lithium production and reserves. In typical scenarios, lithium demand is 3,000 to 5,000 tons which represents 10 to 20% of current production and there should be no major issues concerning supply expansion by this amount especially given the current excess supply. Only in very high EV penetration scenarios does lithium demand become sizeable compared to current production, but ICF does not consider these scenarios to be realistic. In addition, even these concerns are related to current production but in comparison even to known global reserves, the demand from EVs is very small. If, as an extreme example, by 2040, all of the world's 2 billion cars are EVs, the total lithium used would be ~3 x 2 billion kg, or 6 million tons, which is equivalent to less than 25% of the world's known reserves. Hence, there does not appear to be any case for supply shortages.

7.1.3 Battery cost and weight summary

The current costs of lithium batteries are based on battery manufacturer quotations to car manufacturers at rates of about 20 thousand per year for supply starting in 2011/2012. A number of vehicle manufacturers are starting volume production of EV and PHEV models in this time frame and we have obtained battery costs on a confidential basis from several battery manufacturers. These costs are the ones paid by car manufacturers to battery manufacturers, and are not the retail price to consumers. Many of the contracts for the near term appear to be around $ 500 to $ 550 per kWh for the battery cells. Nissan executives have publicly claimed a cost of 'less than $ 500 per kWh' for the battery but we believe that this cost includes some of the subsidies received by Nissan from the US and Japanese governments to set up battery manufacturing facilities. We have used an *unsubsidised* cost of $ 525 per kWh, equivalent to € 420 per kWh for cells supplied at volumes to build 25,000 batteries per year in 2011/2012. Based on the mark-up for the relationship of cell cost to battery cost, this works out to € 620 per kWh for a battery. In addition, there are some costs independent of battery kWh associated with battery safety and cooling that are estimated at about € 200 per battery.

21 Rechargeable Battery Recycling Corporation (RBRC). Website http://www.call2recycle.org/case-studies.php?c=1&d=82&e=358&w=1&r=Y.

Future costs to 2020 and 2030 are based on using current cost numbers and accounting for effects of volume, scale and in the case of the battery, new technology, as shown in Table 17.

Table 17 Unsubsidised battery costs over time

	Sp. Energy Wh/kg Battery 1	Cost € to OEM* Battery 1	Sp. Energy Wh/kg Battery 2	Cost € to OEM Battery 2
2012 lithium Mn spinel	105 ± 5	€ 200 + 620*kWh		
2020 Li Mn spinel (Battery 1) 2020 silicon lithium (Battery 2)	125 ± 5	€ 180 + 310*kWh	160 ± 5	€ 200 + 350*kWh
2025 silicon lithium (Battery 1) 2030 silicon Li-S (Battery 2)	190 ± 10	€ 180 + 185*kWh	300 ± 20	€ 200 + 200*kWh

* Cost of 20 kWh battery will be € 200 + 620*20 or 12,600 € in 2012.

7.2 Other major components

There are a number of other components on an EV or PHEV that are unique to such a vehicle and different from those in a conventional ICE-powered vehicle. Of course, the motor, inverter and controller are the most expensive components after the battery and special attention is paid to these components. The other components of interest include the DC/DC converter for 14 V supply for the lights and ignition (in a PHEV)high voltage wiring harness, the special HVAC unit and the regenerative brakes.

7.2.1 Motors and controllers

The technology for motors is relatively mature now and we do not anticipate large cost reductions or performance increases in permanent magnet motors. We have assumed that the motors will be of the high RPM type (about 13,000 RPM max.) and will require a boost converter for increasing the voltage as RPM increases to enable the very high RPM operation. However, the power control unit will likely employ silicon carbide/gallium nitride technology and will reduce weight by a factor of 2 from current levels where silicon and silicon carbide are used. The inverter will likely use trench gate IGBT technology and we expect specific power and cost for both the inverter and boost converter to improve by 20% per decade based on the historic record of the last five years. Coat data were obtained for a recent US National Academy of Sciences study by ICF interviewing the technical staff of Toyota, Honda and Hitachi (in 2009) and have been used as the baseline 2012 values for this study. The cost and performance estimates are shown in Table 18.

Table 18 **Costs of motor/controller systems**

Motor	kW/Kg, 30 second peak	kW/Kg, Continuous	Cost € per peak kW
2012	1.6	1.25	€ 50 + 8.0*kW
2020	1.8	1.40	€ 40 + 6.40*kW
2030	2.0	1.60	€ 32 + 5.1*kW

Inverter	Peak kW/kg	Peak kW/L	Cost
2012	9.5	12.0	€ 50 + 10*kW
2020	11	14.5	€ 40 + 8.0*kW
2030	13	17	€ 32 + 6.40*kW

Boost Converter	Peak kW/kg	Peak kW/L	Cost
2012	4.5	8.6	€ 10 + 3.0*kW
2020	5.5	10	€ 8 + 2.4*kW
2030	6.5	12	€ 6.4 + 1.9*kW

The control unit size and weight are only weakly dependent on motor power output and we suggest using a fixed weight of 8 kg and a cost € 150 in 2012, declining to 5 kg and € 120 in 2020 and staying constant thereafter.
In addition, EVs will require a high voltage to 14 V uni-directional DC-DC converter for lights and convenience items, and we estimate the cost of these converters at € 65 per kW, with the typical requirement being a 1.2 to 1.5 kW unit. Depending on design, PHEV models will need either a unidirectional or bidirectional unit, and the latter type is expected to cost € 100 per kW in high volume production. The converters are already in volume production and are mature technology so no change in cost expected over the forecast period.

Table 19 **Cost and weight of motor controller**

Control unit	2012	2020	2030
Weight	8 kg	5 kg	5 kg
Cost	€ 150	€ 120	€ 120

7.2.2 High voltage harness and battery safety

The high voltage wiring harness weighs about 12 kg in a Hybrid Camry that has two electric motors with a combined peak rating of about 100 kW. This can be used as a default value for the weight of a harness for a small car since the actual weight will depend on battery placement and exact motor location in the body. A wiring harness for midsize EV is estimated at 14 kg and for a large EV at 16 kg. Battery leak current detection and wiring harness disconnects in case of accidents will add another 3 kg. Total cost of the harness and safety equipment is estimated at € 120, € 150 and € 180 for small, midsize and large cars, respectively. These are mature products and no cost reduction is expected at the same volume.

7.2.3 HVAC units

We expect that both the FEV and PHEV will need to use heat pump during operation on pure electric mode since resistance heating is too inefficient. The electric heat pump will add a 10% weight increase over a current air-conditioning system, and is a mature product. Cost by vehicle size assuming volume production is shown below and we estimate a 10% decrease in cost per decade for this product.

Table 20 **Cost of HVAC system for Electric Car in €**

Heat pump	2010	2020	2030
Small Car	900	810	730
Midsize car	1,000	900	810
Large Car	1,100	990	900

7.2.4 Regenerative brakes

The regenerative braking system apportions the braking force to the electrical motors and mechanical brakes so that as electric braking energy decreases, the mechanical energy absorption increases for a desired total braking level. Such brakes are used in all current hybrid products, and their costs for midsize car (C or D class in Europe) has been estimated at $ 300 or € 240 increment to the current mechanical brakes, assuming high volume production.
We anticipate a 10% cost reduction per decade so that the cost will decline to € 215 in 2010 and € 193 by 2030. However, braking requirements for all cars will have to be enhanced in 2012 to meet new European safety requirements, and this may reduce the marginal cost of regenerative brakes to much lower levels relative to a post-2012 ICEV.

7.3 Safety issues

There are concerns expressed by various safety groups that 'silent' vehicles present a safety hazard for visually impaired, cyclists, runners, small children, and other pedestrians. Furthermore, some motor vehicles, such as Electric Vehicles and Hybrid Vehicles, may not be audibly detectable by the visually impaired when a vehicle's internal combustion engine is not operating and vehicle is moving at low speeds. The problem can be especially acute at urban intersections with loud background noise and where blind pedestrians make decisions about crossing streets based on what they can hear in their environment.

In response to the 'silent' vehicle issue there were several recent studies performed to better understand the issue and a number of technical solutions were proposed. The solutions can be broadly classified into the following technology types:

- Infrastructure-based. Examples include intersection rumble strips and audio warnings at intersections.
- Communications-based, which include personal proximity warning transmitters, electronic travel aids.
- Vehicle-based, which include artificial vehicle sounds when approaching intersections or moving at low speed.

The current trend appears to be moving toward the vehicle-based solutions as the most practical implementation measure. However, there appears to be little agreement over what the artificial vehicle sound should be, how loud, and whether manufacturers should be allowed to create their own distinctive audio tracks.

Japanese car manufacturers have an early electrified vehicle lead and have achieved mass production volumes of some popular Hybrid Vehicles. Honda has patented a simulated sound generator concept in the mid-1990s. Toyota, the leader in Hybrids, and Nissan/Renault which announced mass production of FEVs, are studying the issue and technical solutions will be announced as vehicles are launched in near term. The Nissan Leaf FEV will generate a sine-wave sound resembling a 'whistle' while the vehicle is travelling at less than 19 mph. The Leaf system will sweep the sound frequency from 2.5 kHz to 600 Hz through a loudspeaker device located in an engine compartment.

Car manufacturers and their trade associations generally recognise that 'silent' vehicles can present a safety hazard to pedestrians, especially those who are visually impaired. The industry is advocating a regulatory solution to make sure that the issue is addressed in a consistent manner among various markets. Government regulators also believe that the electrified vehicles, such as Hybrids, have reached substantial market penetration and sufficient anecdotal evidence exists to warrant a regulatory action. In conclusion, there appears to be sufficient regulatory efforts and adequate low cost solutions to address this problem in OECD countries.

7.4 Vehicle production energy use and GHG emissions, life cycle issues

When looking at GHG-emissions of EVs during their entire life cycle, impacts can come from (apart from vehicle use):
- Energy carrier production (fuels and electricity).
- Vehicle production and end-of-life processes.

On average, on a well-to-wheel basis, EVs produce less GHG emissions compared to conventional internal combustion engine vehicles (ICEVs), although this strongly depends on the electricity mix. However, the division of emissions over the life cycle is somewhat different for EVs. The share of emissions in the production phase is higher due to higher energy use for vehicle production because of the production of the battery and lower energy use in the vehicle use phase.

However, also for EVs, the share of vehicle production in total life cycle emissions is still quite limited. The lion share of GHG emissions come from the use phase. The energy required for battery production depends on the battery type: NiMH batteries which are mostly used for current HEVs require more energy to produce than the next generation, the Li-Ion batteries used for PHEVs, EREVs and FEVs.

7.5 Market forecast

The size of the market for pure battery Electric Vehicles and Plug-in Hybrid Electric Vehicles is a major driver of costs of these vehicles since economies of scale and scope are possible with large markets. Unfortunately, there is little or no consensus on the size of the EU and global markets for EV and PHEV models. However, we can bracket the forecasts and the reasoning behind some of the forecasts to provide a forecast with internally consistent assumptions about battery developments, reliability, cost and market size.

It is clear that forecasts of EV and PHEV absolute sales volumes to 2020 are too dependent on parameters that cannot be reliably determined now, such as consumer willingness to pay for green technology and the ability of governments to continue significant subsidies for ten or more years. We have constructed a scenario below that lies between the extremes, but this should be regarded only as preliminary and in our opinion, optimistic, estimate for determining economies of scale in battery manufacturing globally. Future reports under this project will refine both cost and sales estimates for EV and PHEV sales in the EU. Our preliminary estimates for 2020 assume that stringent fuel economy regulations will drive sales of Hybrid, PHEV and EV models in all developed countries but PHEV models will mainly be in larger vehicles popular in the US. China's push for EV sales is also reflected in our analysis. Due to the power shortages in India and Africa, EV or PHEV are not expected to sell well there. South America, particularly Brazil, seems to be investing more in bio-fuels so that EV or PHEV penetration is likely to be small over the next ten years. Based on global light-duty vehicle sales of 80 million, we expect sales of 8 million Hybrid Vehicles, 2.2 million EV and 0.9 million PHEV in 2020.

Although Hybrid Vehicle sales will climb to about 10% of global sales by 2020 in this forecast, these vehicles will use relatively small batteries of the high power type, which are different in design from EV and PHEV high energy batteries, and are also much smaller, at about 5% the energy capacity of an EV battery. Hence, EV type batteries are forecast to have sales of about 3 million units in 2020 and we anticipate that these sales will be divided among twelve to fifteen global battery suppliers by 2020 to estimate production volumes and economies of scale.

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