elementenergy

Cost and performance of EV batteries

Final report

for

The Committee on Climate Change

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Element Energy Limited
20 Station Road

Cambridge CB1 2JD

Tel: 01223 227764
Fax: 01223 353 475

Executive summary

Background

Deep decarbonisation of the road transport sector can only be achieved through the introduction of electrified drivetrains. A key component within an electric vehicle (EV) in terms of overall cost and performance is the battery.

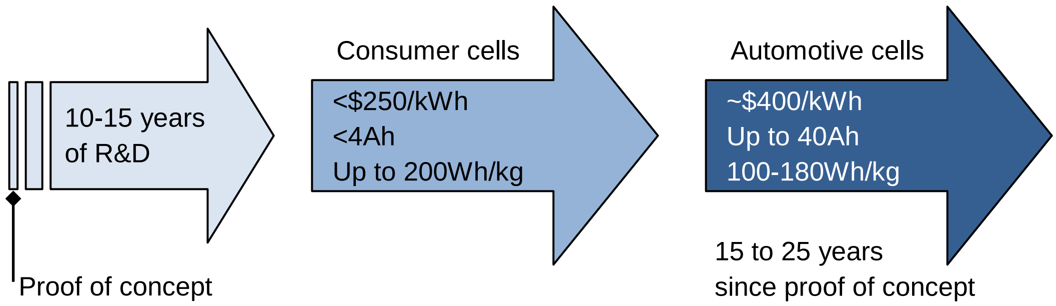
The Committee on Climate Change commissioned Element Energy, Axeon and Prof. Peter Bruce of EastChem to investigate the future trajectory of batteries cost and performance. This report describes the current state of development and cost of batteries, before mapping the future cost and performance of lithium-ion batteries out to 2030. The trajectory of battery technology beyond 2030 is investigated through the study of lithium-air batteries, currently the most promising post lithium-ion battery.

Current lithium-ion batteries: performance

A range of battery chemistries have been deployed in EVs, most notably the use of nickel metal hydride in the Toyota Prius. However energy density has emerged as the most important metric in battery design, leading to lithium family chemistries becoming the dominant chemistry for pure and Plug in Hybrid EV (PHEV) applications.

Currently, cells suitable for transport applications typically have an energy density of 100-180Wh/kg, are available at a capacity of 40 Ah/cell, and (with careful thermal and operational management) may achieve 10 years of life in automotive operation. Automotive cells cost ca. $400/kWh but the actual cost of the battery system is higher due to the need for electronic and thermal management. The whole battery system including cells, structural support, thermal management and electronic balance, is called the battery pack. The cost of a battery pack for a pure EV is approximately $800/kWh, i.e. double the cost of the cells alone.

Automotive cells represent only a marginal share (<5%) of the rechargeable lithium-ion cells market. The largest market is consumer electronics, such as batteries for laptops and phones. Consumer cells are smaller and have less stringent performance specifications than automotive cells in terms of power, battery life and safety. Small consumer cells cost under 250$/kWh, but these figures do not translate directly to automotive cells because of their more stringent requirements and the engineering challenge of manufacturing large cells.



Today's typical lithium-ion cells characteristics and technology development path

Battery chemistry innovations first appear in the electronic consumer market before trickling down to the more demanding automotive market several years later. The time interval between chemistries first being demonstrated in laboratory conditions, and then deployed in vehicles, is observed to be 15-25 years.

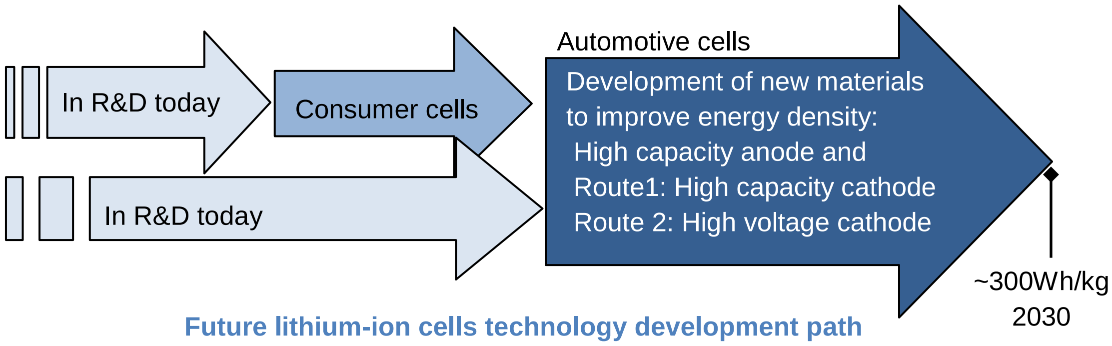
This indicates that out to 2020, step-change improvements in performance of automotive batteries are highly unlikely to occur as there are no “breakthrough” technologies approaching the consumer market today.

Future lithium-ion batteries: performance

Much of the current R&D is on improving the energy density of cells via new chemistries. As well as greater vehicle range, increasing energy density has the potential to reduce costs as a result of less material per kWh and fewer cells to monitor. Two routes are being pursued to improve energy density: developing electrode materials with higher capacity (mAh/g); or developing cells using higher voltage chemistry.

Next-generation technologies delivering higher specific energy are likely to be nickel cobalt manganese and composite cathodes and high capacity anodes (silicon), estimated to be available in a series vehicle ca. 2020. Higher voltage cathode chemistries are expected to follow.

These developments could take the energy density of lithium-ion cells close to 300Wh/kg. As the automotive market grows, new cells will be increasingly developed for that market as well as trickling down from the consumer cell market.



Future lithium-ion cells technology development path

Post lithium-ion batteries: performance

There are several technologies in lab/prototype stage which have the potential to offer superior battery performance. The most notable are lithium-sulphur batteries and lithium-air batteries which have the highest theoretical energy density (greater than 2,500 Wh/kg). However they all have significant technical challenges that must be overcome before practical batteries with acceptable life and safety characteristics are available to the automotive market.

Based on the observed development times for battery technologies and the current challenges lithium-air cells face, practical lithium-air batteries for automotive applications are not expected before 2030.

This report sets out a reasonable basis for predicting future Li-Air performance between 500-1000Wh/kg (at cell level - a factor 2-3 improvement over expectations for Li-Ion in 2030). This is based on historical data on the ratio between theoretical and practical energy of other chemistries and is in accordance with expert opinion.

Battery cost modelling

Following a review of existing battery cost models, a bottom-up component-based approach to cost modelling of lithium-ion cells to 2030 was developed. The cost model contains cell component and pack component costs, where each is designed to be fit for purpose for a set of vehicles over the period to 2030. Within the cell module there are sub models related to cell design, material consumption, manufacturing cost, factory

throughput and overheads. The packing cost module represents physical supports, environmental control, wiring, battery management system and power electronics. Post 2030 cost projections are based on cost estimates of lithium-air batteries.

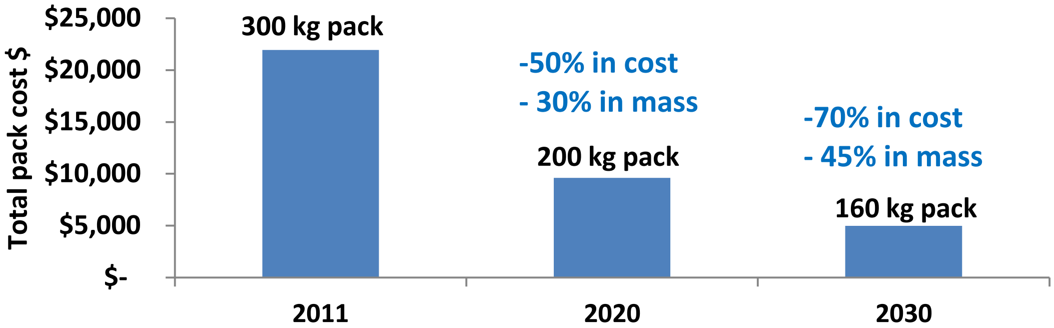
Two main cost drivers have been identified:

The improvement in material properties delivering higher energy densities
The improvement in material properties is represented through a detailed technology roadmap of lithium-ion cathode and anode characteristics up to 2030, developed from a review of current R&D efforts and progress.

The scaling up in production of large cell formats
Cost improvements occur through increased volumes and cell size standardisation. Pack assembly – a large contributor to the total pack cost – is also expected to benefit from increased volume and standardization of components.

Results

Current costs for a pure EV of ~$800/kWh at pack level translates into a pack cost of $21,000 for a 2012 medium sized BEV with a range of 150km. In 2030, under a baseline scenario, this is predicted to drop to $6,400 for a BEV with a range of 250km.



Results for a medium sized pure battery electric car – 30kWh pack

Batteries for PHEVs are more constrained by power density, as the smaller packs have higher discharge rates during acceleration. It results in a higher cost per kWh for a PHEV compared to pure battery electric vehicle.

Lithium air batteries (if successfully deployed) can bring cost savings at the cell level. However this saving is reduced by the increased cost of packing arising from the lower cell voltage and the requirement for more air management. Our cost modelling suggests that in the long term, the deployment of Li-air would not be expected to bring a significant cost reduction on the pack level compared to the advanced lithium-ion batteries expected to be developed by 2030. However the ca. 50% weight saving which may be expected with Li-air would have other benefits such as reduced chassis weight and better performance.

Barriers and key challenges

The technology roadmap assumes that lithium-ion chemistries will reach their highest practicable energy density through the development of high voltage cathodes. There are significant and fundamental technical challenges to be overcome before these technologies can be deployed, such as the development of an electrolyte stable at a high voltage.
The cost benefits brought by high production volume of battery packs are highly dependent on the uptake of EVs. Looking at the announced new production capacity, there is a significant risk of over-capacity in the next 5 years if consumers do not take to the technology; this could stall further investment.

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Authors

For comments or queries please contact:

Celine Cluzel
celine.cluzel@element-energy.co.uk
Tel: +44 (0) 330 119 0984

Craig Douglas
craig.douglas@element-energy.co.uk

Reviewers

Shane Slater, Director, Element Energy

Prof. P. G. Bruce FRS, FRSE, School of Chemistry, University of St Andrews

George Paterson, Director of Sales, Axeon

Dr Valentina Gentili, Electrochemical Engineer, Axeon

Dr Allan Paterson, Senior Electrochemical Engineer, Axeon

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Acronyms and terminology

ANL	Argonne National Laboratory
Anode	The electrode of a cell at which oxidation occurs. By convention this is the negative electrode and is the electrode that electric current flows into (and electrons flow out of) at discharge. It is typically carbon based.
BEV	Battery Electric Vehicle. A pure battery electric vehicle contains a battery and an electric motor only. The vehicle is charged by mains electricity. Examples include the Nissan Leaf and Mitsubishi i-MIEV.
BMS	Battery Management System
BOM	Bill of materials
CAPEX	Capital Expenditure
Cathode	The electrode of a cell at which reduction occurs, by convention this is the positive electrode and is the electrode that electric current flows out of (and electrons flow into) at discharge.
CCC	Committee on Climate Change
CGGC	Centre on Globalization, Governance & Competitiveness
DC	Direct Current
DECC	Department of Energy and Climate Change
DfT	Department for Transport
DLR	German Aerospace Centre
DOD	Depth of discharge
DoE	Department of Energy (of United States)
EastChem	The Edinburg And St Andrews research school of Chemistry
EE	Element Energy
EPRI	Electric Power Research Institute
ESW	Electrolyte Stability Window
EV	Electric Vehicle
FC	Fuel Cell
ICE	Internal Combustion Engine
IP	Intellectual Property
kW	Kilowatt (unit of power)
kWh	Kilowatt hour (unit of energy, 3.6MJ)
LCO	Lithium Cobalt Oxide. Cathode active material
LFP	Lithium Iron Phosphate. Cathode active material
LL	Layered-layered. Type of cathode active material
LMO	Lithium Manganese Oxide. Cathode active material
LMP	Lithium Manganese Phosphate. Cathode active material

Low CVP	Low Carbon Vehicle Partnership
LTO	Lithium Titanate Oxide. Anode active material
MIT	Massachusetts Institute of Technology
MPV	Multi Purpose Vehicle
NEDC	New European Drive Cycle
NMC	Nickel Manganese Cobalt. Cathode active material
OEM	Original Equipment Manufacturer
PHEV	Plug in hybrid electric vehicle. A PHEV can be charged from mains electricity and runs in electric mode until the battery is depleted (or high power is demanded), at which point the ICE takes over. An example of this vehicle is the Toyota Plug-in Prius.
PIV	Plug In Vehicle
R&D	Research and Development
REEV	Range Extender EV
SEI	Solid Electrolyte Interface
SMMT	Society of Motor Manufacturers and Traders
SOC	State of charge
TCO	Total Cost of Ownership
UK	United Kingdom
US ABC	United States Advanced Battery Consortium

1 Introduction

Background

The Committee on Climate Change (CCC) was established in 2008 to advise the UK Government on climate change issues, and particularly the setting of carbon budgets and the scope of those budgets. In its first report published in 2008, the Committee concluded that the UK should aim to reduce Kyoto greenhouse gas emissions by at least 80% below the 1990 levels by 2050.
A key consideration for the CCC in recommending the level of carbon budgets is the cost-effectiveness of the abatement technologies needed to achieve them, relative to DECC's carbon prices.

When looking at the road transport sector, the potential for improvement of internal combustion engines (ICEs) and the potential of biofuels are not enough to achieve deep levels of decarbonisation of the road transport sector. This can only be achieved through the introduction of electrified drivetrains. The battery is the key component within an electric vehicle (EV) which determines its overall capital cost and performance. Therefore, the task of determining the cost-effectiveness of EVs is predominantly one of identifying the future trajectory of battery cost and performance.

Objectives of the work

In this context, the CCC appointed Element Energy to develop a model and thereby a roadmap of battery cost and performance for a selection of EV applications, from now to 2050. This work provides insight on cost reduction drivers as well as barriers. Element Energy leads a team including Axeon and Professor Peter Bruce, Professor of Chemistry at the EaStCHEM.

The findings of this work will be used by the CCC in their analysis of the relative cost of ownership of different types of vehicle over the medium-term (to 2020 and 2030) as well as supporting their recommendations on the types of vehicle that are most likely to deliver cost-effective emissions reductions over the longer term (to 2050).

Methodology

The approach taken is a bottom up, component based model of battery cost, which takes in consideration likely improvements in the current battery technologies, up to 2030. Longer term costs are estimated based on the best – in terms of prospective energy density – future battery technology.

Structure of the report

Section 3 introduces the plug-in vehicles chosen to represent the UK market, and gives a general introduction to batteries and their attributes.
Section 4 presents current automotive batteries in terms of performance and costs. A short presentation of the historical development of lithium-ion batteries, for applications other than transport, is used to give an insight on the potential speed of development of new automotive batteries.
In section 5, prospective battery improvements or new chemistries are presented in terms of key R&D challenges and development status. This review, along with main national research programs and insights gathered from historical battery development, is used to inform the technology roadmap of the model (speed of battery technology improvement).

Section 6 describes the model methodology, which was developed after a review of existing models, as well as key assumptions, while results are outlined in section 7. Detailed model input data and supplementary results data have been placed in the Appendix.

Note on currency: some costs are expressed in US dollars ($) as it is the currency used in international trade and it allows our results to be compared with results published by other sources. An exchange rate of £1=$1.5 is used. Future costs are expressed in today's prices.

About the authors and reviewers

Element Energy is a consultancy specialising in low carbon energy technologies. Element Energy has conducted innovative analyses of low carbon road transport, from cost analysis, recharging infrastructure analysis and consumer preference modelling. Element Energy has led the collaborative team effort involving Axeon and Professor Peter Bruce.

Axeon is Europe's largest independent supplier of automotive battery systems, working with a large number of cell suppliers. Axeon's primary input to this project has been helping to develop cost models for battery assembly, provide data on cost and performance of current batteries as well as provide links with cell manufacturers to ensure the cell cost and performance models are accurate.

Peter Bruce is Professor of Chemistry at the EaStCHEM (Edinburgh and St. Andrews Research School of Chemistry). His group is a recognised leader in the electrochemistry of energy storage devices, with a significant body of research on lithium-based batteries. Prof. Bruce provided the technical insight to understand the scientific challenges limiting battery performance.

2 Plug in vehicles and battery attributes

The Committee on Climate Change (CCC) is carrying out an analysis of road transport technologies in terms of cost of carbon abatement. In this context, the Committee has commissioned two studies. A first team has been modelling the cost and performance of vehicles (excluding the cost of batteries for plug-in vehicles) while a second team – Element Energy, Axeon and Prof. Bruce – has been working exclusively on batteries for plug-in vehicles. This report presents the results of the battery cost and performance modelling exercise.

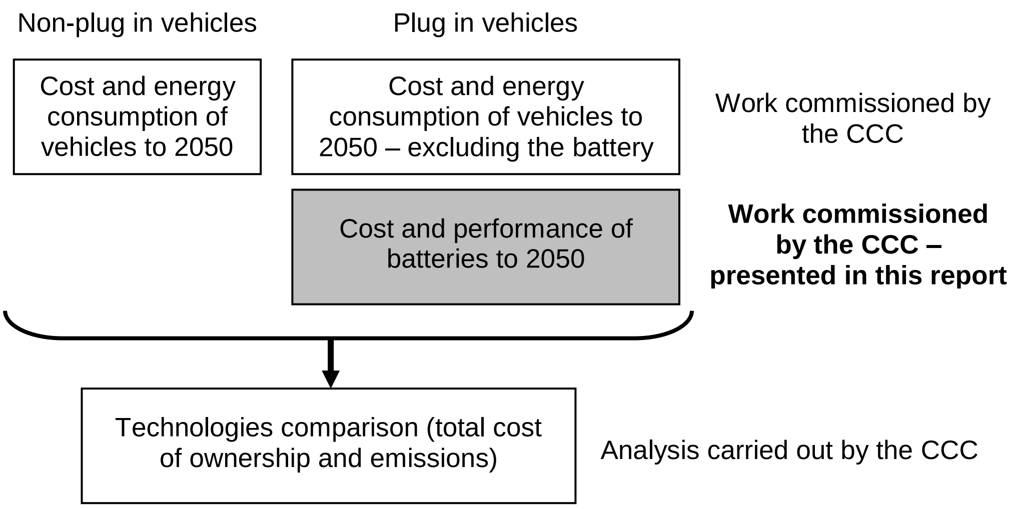


Figure 2-1 Context of the battery cost modelling

This section presents the characteristics of plug-in vehicles representative of the UK market (present and future) as well as their corresponding battery attributes.

2.1 Choice of vehicles to model

The specification (hence cost) of a battery changes significantly depending on the vehicle it powers, as well as the drivetrain (pure BEV or PHEV for example). In this section of the analysis, the UK vehicle market is segmented to develop a limited number of representative vehicle types. A bespoke pack is then designed for each of these for its cost to be modelled. Assumptions have to be made on certain design issues; an example is the EV range requirement. It is lower than ICE vehicles now and is set to increase in the future but is assumed to stay lower than for ICE vehicles. This assumption is based on evidence that consumers value capital cost savings more than range, and so are more prepared to accept range constraints rather than a very expensive vehicle.

The UK road transport market is dominated by cars, with a small contribution from commercial vehicles (vans, buses and trucks). The scope of this work is the car market and the van market (light commercial vehicles, gross vehicle weight under 3.5 tonnes).

The UK car market is traditionally segmented into 9 vehicle classes, from the ‘A segment’ (small city car, e.g. Toyota iQ, Hyundai i10) to the ‘I segment’ (Multi Purpose Vehicle, e.g. Renault Scenic, Ford Galaxy). Figure 2-2 shows SMMT data on the respective sale volumes of each car segment; along with sales of vans.

The plug-in car market is represented in the model through 3 classes: small cars (A&B segments), medium size cars (C&D segments) and high power cars (E&H segments). This is in line with the overall vehicle market modelling conducted in parallel of this work.

The van sector represents <10% of cars and vans sales, and less than any of the 3 car classes defined for the cost modelling. Within the van sector, the large panel van and standard panel van represent 55%[1] of sales. The difference in performance of these van classes is minimal (with less than a 13% difference in gCO_2/km); therefore only one class of van is represented in the model: the panel van (kerb weight ~ 2t, e.g. Ford Transit).

Other small commercial vehicles were not included due to their similarity to C&D and E&H class cars from which they derive.

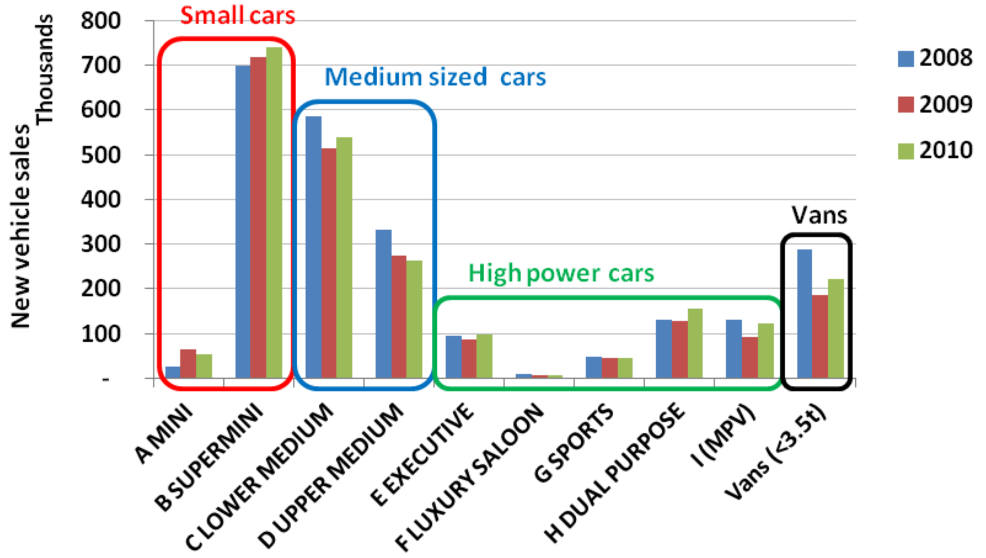


Figure 2-2 Annual vehicle sales by segment in Great Britain. Source: SMMT 2011

Characteristics (engine output, kerb weight etc) of each segment have been aggregated to form vehicle datasets for two powertrains: pure battery electric vehicle (BEV) and plug-in EV (PHEV). Current characteristics have also been projected to the future based on expected vehicle energy consumption improvement. Table 2-1 shows the resulting vehicle dataset for medium sized cars (C/D segment); see Appendix 8.1 for details on the methodology and full datasets.

Table 2-1 C&D BEV and PHEV vehicle attributes in 2011 and 2030 for use in the battery cost modelling

Attribute	BEV		PHEV	
	2011	2030	2011	2030
Range (km)	150	250	30	80
Energy consumption (kWh/km)	0.14	0.097	0.15	0.106
Max pack mass (kg)	300	180	150	120
Motor peak power (kW)	70	70	60	60
Usable energy (kWh)	21	24	4.6	8.5

Usable energy means 'required energy to achieve the target range'; the total energy is actually greater as batteries are generally not fully discharged/charged; this is explained in the next section.

[1] SMMT Motor industry facts, 2010

2.2 Vehicle battery architectures

Figure 2-3 provides an example of an automotive battery pack. A pack is composed of a large number of cells. As cells have a relatively low voltage (between 1.5-4V) and limited capacity, these cells are arranged in series (to increase the overall voltage to a usable level) and in parallel. Cells may be arranged into relatively self-contained modules which themselves are arranged in series and parallel as required by the vehicle drivetrain.

The sections below first provide an overview of cells and their architecture, followed by the rest of the pack elements.

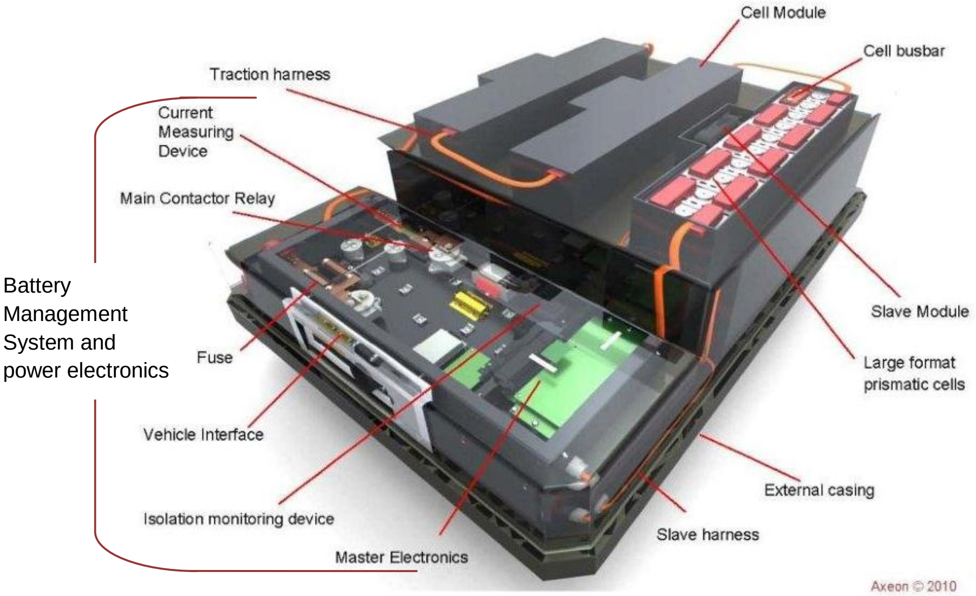


Figure 2-3 Example of a battery pack. Source: Axeon guide to batteries

2.2.1 Introduction to batteries

All batteries consist of:

- **two electrodes**: which supply and collect charge, connected to an external electrical circuit
- **an electrolyte:** this conducts ions which move between the electrodes (cations (e.g. H^+) and anions (e.g. OH^-)) but it does not conduct electrons, which must instead flow through an external circuit.
- **chemical fuel:** two species (elements or compounds) that spontaneously react due to a desire to reach a lower energy state (different electro potentials)

In many common batteries, each of the two chemical fuels (solid) is attached to its corresponding electrode (which is solid), and the two electrodes are immersed in a liquid electrolyte. However, in general: the electrolyte may be liquid (lead-acid) or a polymer in liquid (lithium polymer); and the chemical fuel supplied to the electrodes can be solid (e.g. lead-acid batteries), liquid (flow batteries) or gaseous (Zinc-air or Lithium-Air).

The voltage of the battery is the sum of voltages of the reactions at the anode and cathode. The battery capacity is set by the mass of reactive materials in the battery, the quantity of electrons released per mole of material, and the cell voltage.

Table 2-2 Examples oxidation reactions and resulting specific energy.

	PbO_2	Al	Li	LiCoO2
Molar mass g/mol	239	26.98	6.94	97.87
Electropotential V	1.94	1.66	3.05	4.2
Electron per mol	2	3	1	1
kJ/g	1.57	17.81	42.40	4.41
Wh/kg	435	4,947	11,779	1,150

There are three routes to maximise specific energy at the half reaction level:

- High electro potential: combining a highly electronegative and electropositive species
- High stochiometric transfer of electrons, i.e. electrons per mole of reactants
- Low molar mass of the participating species

The table above shows that certain species (e.g. pure Lithium) have a very high specific energy (ca. 12,000Wh/kg is very close to petrol/diesel). However in practice, the achieved specific energy of a cell may be much less because:

- The reactive element may need to be combined with other, heavier elements to allow the reaction to be reversible (e.g. Li to lithium cobalt oxide $LiCoO_2$)
- Only a fraction of the mass of the battery is the reactants (typically between 25-40%) the rest comprising electrolyte, charge collectors, electrode substrate, physical containment, and unused/unreacted species.

The battery energy density can be increased by:

- Using reacting species with high theoretical energy densities:
  e.g. elemental Lithium or Aluminium (ideally) or Hydrogen (Nickel/Metal Hydride)
- Better battery design: minimise non-reacting components, reducing the quantity of electrolyte, e.g. liquid species and thin solid electrolyte (ZEBRA batteries)
- Sourcing the oxidising species from the battery surroundings, e.g. metal-air cells
- Taking both of the reacting species from the battery surroundings:
  fuel cells, flow batteries (but then the “battery” should include the mass of the reactant container)

2.2.2 Automotive battery technologies

While lithium ion is emerging as the preferred automotive technology, other technologies have been deployed in vehicle application. A brief overview of lead-acid, nickel-cadmium (Ni-Cd), nickel metal hydride (Ni-MH) and molten salt is set out below.

Lead acid

Lead acid batteries are better understood than any other battery types and were used in the earliest traction vehicles. Their benefits are the very low cost and very high reliability. However they are limited by a very low specific energy (a practical upper bound is 50Wh/kg) and this has all but excluded their serious consideration in a practical mass market electric vehicle. This is likely to remain the case, unless users are happy to accommodate low speeds, very limited ranges (less than 100km) and frequent fast charging (which the technology is capable of). Lead acid batteries are currently in use in applications where limited range and speed are not a concern (e.g. golf cart, mobility scooters, forklifts) and in electric bikes. They are also used in small series electric cars such as the 2 seater Norwegian Buddy (20-60km range, maximum 80km/h).

Nickel-Cadmium

Ni-Cd batteries were used in EVs in the 90s and early 2000s but have since been banned for consumer use and vehicle applications by the European Commission in 2006[2] on toxicity grounds. They are authorised only for military and medical applications.

Nickel Metal Hydride

Ni-MH batteries currently dominate the (non plug-in) hybrid market but cannot compete with lithium ion batteries in the plug-in market because of their lower specific energy (<100Wh/kg against 100-180Wh/kg for current lithium ion cells). Ni-MH batteries have been used in the most popular hybrid vehicle model – the Toyota Prius – and have proved reliable. Despite this positive experience, Toyota has turned to lithium-ion chemistries for their plug-in hybrid model, supporting the argument that higher energy densities are required to deliver a fit-for-purpose electric vehicle.

Molten salt

These are batteries which operate at elevated temperatures (ca. 300deg. C), and include sodium sulphur, sodium nickel chloride (e.g. the ZEBRA battery) and lithium iron sulphide. There has been some deployment in commercial vehicles and the THINK and Smart (in the first electric version only) cars.
High temperatures are required to keep the metal-salt electrolyte in liquid form and must be maintained even when the vehicle is not in operation. The energy and CO_2 penalty arising from this can be very substantial, and is a serious drawback to the use of molten salt batteries as a CO_2 reduction technology in vehicles.

Complementary technologies: capacitors and flywheels

A capacitor is an electronic device that stores an electric charge, consisting of one or more pairs of conductors separated by an insulator. Capacitors are found in common electronic devices, and are used in circuit boards e.g. to create a time delay circuit, store a voltage, filter frequencies and block direct current.
Capacitors considered for vehicle applications are much larger and have a much higher energy density than conventional capacitors. They are "electric double-layer capacitors", often called ultracapacitors or supercapacitors.

Capacitors can charge and discharge very quickly; their power density can be 10 times greater than for a lithium-ion battery. This characteristic makes them a good complementary technology: using capacitors in tandem with a battery insulates the battery from high power peaks and helps preserve its life. In practise, the added cost and complexity of capacitors do not make them an attractive solution for plug-in vehicles[3]. They are used in some hybrid vehicles (e.g. BMW 1 fuel cell hybrid vehicle) and there is on-going work to improve their suitability for use in vehicles and decrease their costs.

Table 2-3 summarises the current status of capacitors. Their low energy density (<10Wh/kg currently, 20Wh/kg in development versus 100-180Wh/kg for current lithium-ion cells) disqualifies them as a storage solution for EVs. Although life characteristics are better than for batteries, capacitors suffer from life limitations too; parameters accelerating their degradation include: electrical aspects, temperature, vibrations, pressure and humidity.

[2] Directive 2006/66/CE
[3] EDAG, Future steel vehicle phase 1 report, 2009

Table 2-3 Capacitors current and target characteristics.

	Available capacitors[4]	Under development
Energy	Max 5-6 Wh/kg	15-20 Wh/kg[5]
Life	10^6 cycles	USABC target: 750k / 150,000 miles for HEV
Cost	$10,000/kWh[6]	USABC target: 130$/system (60Wh)

Flywheels, like capacitors, show higher specific power than batteries but lower specific energy (<50Wh/kg). They are not expected to power vehicles on their own but could be complementary technologies to batteries in the future.

Flywheels have been tried on vehicles in France in the 50's, as well as in Switzerland (buses) as engine 'power assist'. They are a good energy storage solution for stationary applications, but in moving applications they need complex stabilization mechanisms, which made them impractical for vehicle applications. Recent developments have seen new flywheel systems entering racing vehicle applications, but again this has been as a hybrid technology rather than an energy storage solution.

Summary

The above review describes that in automotive battery applications, and as can be seen in the graph below, the primary trend is increasing energy density. This has favoured a move towards lithium chemistries, even though other chemistries can demonstrate greater longevity, and lower specific costs. On this basis, the remainder of this section focuses on lithium chemistries, their operation, potential and their drawbacks.

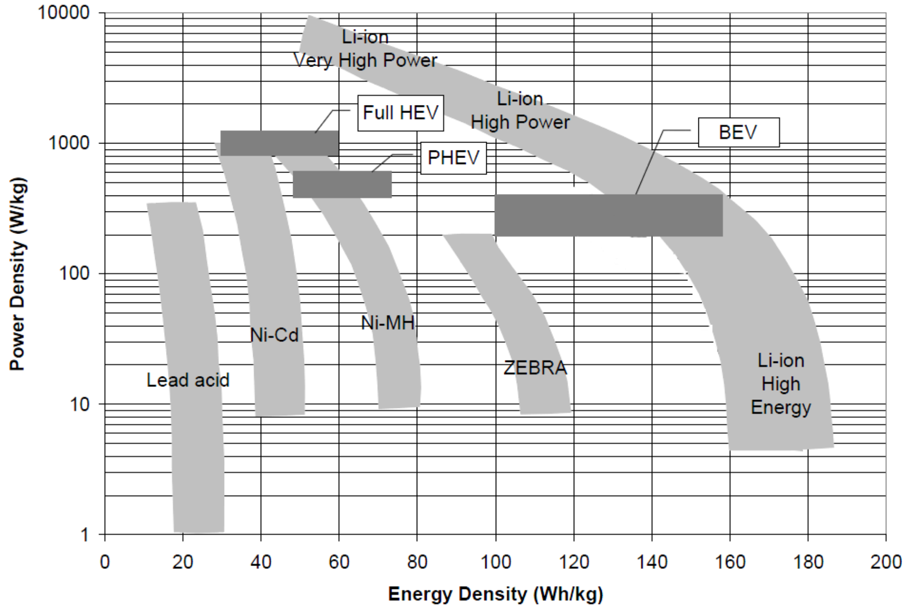


Figure 2-4 - Ragone plot comparing power and energy densities of battery technologies. Source: CARB 2007

[4] Mastragostino M., Lithium-ion batteries and supercapacitors for HEV, International workshop on distributed energy systems, Milano April 2009
[5] Smith P., Jiang T. and Tran T., High Energy Density Ultracapacitors, Annual Merit Review, DOE Vehicle Technologies Program, Washington, D.C, June 2010
[6] Sandia National Laboratories

2.2.3 Lithium ion cells

In a Li-ion cell, lithium ions shuttle back and forth between the intercalating electrodes. The principle of intercalation is the reversible insertion of a guest atom (or molecule) into a host structure without inducing a major disruption of the host material.

This is represented in the figure below. In operation (discharge cycle), the positive (ions) and negative (electrons) charges leave the anode for the cathode: the flow of electrons across a potential difference in the external circuit can be used to do work (e.g. drive a motor) while the ions move across the electrolyte. In this case the guest atom is the lithium ion.

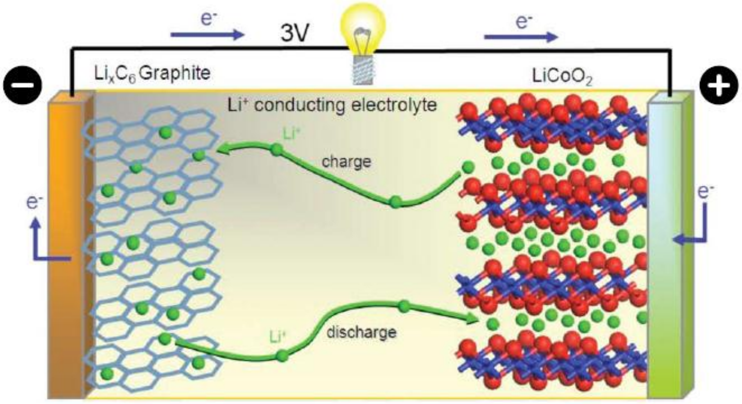


Figure 2-5- Schematic of ions (charge and discharge) and electrons (discharge) movements in a lithium ion cell. Source: Axeon

The next figure depicts cell components in more detail:

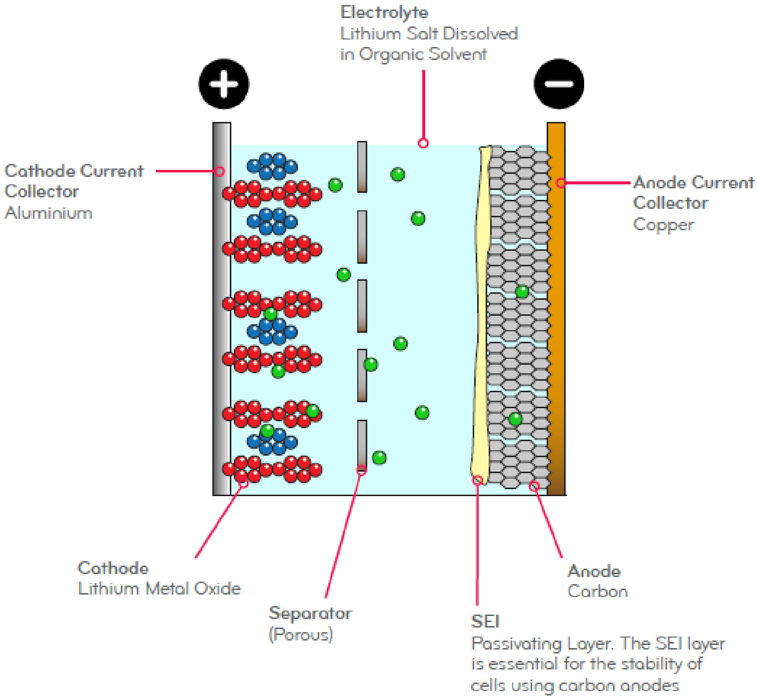


Figure 2-6 Schematic of lithium ion cell. Source: Axeon

The most common active material for the **anode** is graphite. Current anode R&D focuses on developing materials that are safer, and have a higher capacity (charge per unit of weight) than graphite (~300 mAh/g).

The **cathode** active material is currently either a lithium metal oxide or lithium iron phosphate. Current R&D is focussing on improving the reversibility of the active material, and developing new active materials with higher voltages and/or higher capacity (mAh/g). The current highest reversible capacity used in commercial cells is approximately 160mAh/g. This is considerably lower than the anode capacity and therefore there is a greater R&D focus on the cathode than the anode.

Current collectors - also called foils - are made of aluminium at the cathode and copper at the anode. In the case of a lithium titanate anode the current collector is aluminium due to higher electrode potential Vs Li.

The **separator** provides separation of the electrodes while being porous to the conducting lithium ions. A polymer or solid electrolyte could eliminate the need for an additional separator, as these can act as both an electrolyte and a separator.
R&D efforts are directed at improving separator stability for safety and reducing separator thickness. The separator can be coated with a ceramic to improve thermal stability (developed by German company Evonic).

The **electrolyte** is liquid (or a polymer/liquid or gel), most typically a lithium salt (e.g. $LiPF_6$) dissolved in organic solvents that conduct ions. Electrolyte additives can be used to increase performance or improve cell life and safety (life and safety attributes are defined in the next section). The challenge of current R&D is to increase the voltage range the electrolyte can operate over, known as the electrolyte stability window.
Some solid materials could conduct as much as liquid electrolytes, with the advantage of avoiding leaks. One of the big challenges in using solid material is maintaining surface contact between electrodes and electrolyte over a wide temperature range, as the materials in contact have different thermal volume expansion properties.

2.2.4 Battery pack attributes

Cells are assembled in series (to build voltage) and parallel (to build capacity, Ah) into modules, which in turn are assembled into a pack. The total energy of the pack is the voltage multiplied by the capacity. The cell voltage for a given type of battery is more or less constant (e.g. lithium-ion cells are ca. 3-4V), while the capacity will vary based on the cell design and size. For this reason, when pack assemblers are buying cells, they are quoted prices in $/Ah rather than $/kWh and the battery capacity (Ah) is sometimes quoted rather than its energy (kWh).

The pack components ensure the cells are performing at their best, and they are briefly described here:

- Battery Management System (BMS): an assembly of circuit boards that monitor the cells (e.g. temperature, voltage), and monitors the whole pack to determine state of health and state of charge. It ensures the safety of the pack and interfaces with the vehicle electronics and charger. Its cost increases with the number of cells it has to monitor.
- Power electronics distribute the high currents and include safety devices: shunts, fuses, contactors and safety disconnect. Note that these are distinct from the power electronic devices required on the vehicle that outside of the

pack (e.g. DC-DC conversion for managing voltage/current between a pack and a motor driver).

- Wiring harnesses are made to connect the main controller to the slave monitoring boards, wiring and connectors (containing copper). Connectors to the vehicle electronics have to pass automotive standards and sometimes require high ingress[7] protection levels (IP), which contributes to cost.
- Internal cell support: made of plastic and/or metal, it holds the cells together to the correct compression levels and allows a module assembly process. When the pack is liquid cooled, the cell support is more complex as it acts as a cooling matrix, e.g. it has a network of groves for the coolant to circulate through.
- Temperature control: heating, cooling, heatsinks, fans, etc. Maintaining the battery pack in the optimum temperature window is essential to maintaining and extending battery life. For battery packs to be global products, both cooling and heating are needed. Cooling can be active or passive. In active cooling, a fluid (water, another liquid or air) cools the cell surface with forced circulation. In passive cooling, excess heat is dissipated from the side of the cell or pack without forced ventilation.

Delivering energy (kWh) and power (kW) are the first two obvious functions of a battery. There are, however, other attributes crucial to the viability of an electric vehicle. This section gives a short description of a selection of battery pack attributes and how they relate to its cost and performance in the cost modelling.

Energy

In the model, the usable energy (kWh) for a given vehicle is defined by the energy consumption and target vehicle range, for example a segment C&D car is fitted with 23kWh (useable energy) pack to deliver a 150 km range (from Table 2-1, page 4).
The total energy of the pack is however always higher: the full window of charge is not used. A state of charge (SOC) of 100% and a depth of discharge (DOD) of 100%[8] are avoided for several reasons:

- To meet power requirements: batteries have lower discharge power at low SOC and lower charge power at high SOC.
- To reduce safety risks: limiting the maximum SOC avoids overcharge situations.
- To maximise the battery life: lowering the DOD window extends the battery cycle life. Some chemistries (e.g. manganese oxides) degrade when fully charged or fully discharged, due to chemical reactions with the electrolyte or cathode material. Calendar life is also affected by the maximum SOC (see below for definitions of cycle and calendar life).

This is schematically represented in the next figure. The SOC/DOD window is referred as DOD window thereafter for simplicity.

Although the DOD window varies with the battery chemistry and level of thermal management in place, a typical DOD window is 80% for BEV packs and 70% for PHEV[9]. It is lower for PHEV applications as the higher power to energy ratio makes the power requirement more difficult to meet at low state of charge. These are the baseline values used in the cost model. In this report, model results reporting cost per kWh refers to the total kWh rather than the useable kWh.

[7] Such as ingress of water and particulates
[8] SOC and DOD are interchangeable terms in the sense that 0% SOC = 100% DOD and vice versa. DOD is most commonly used when referring to life cycle and battery testing.
[9] Battery DOD windows currently used also vary considerably across vehicle manufacturers

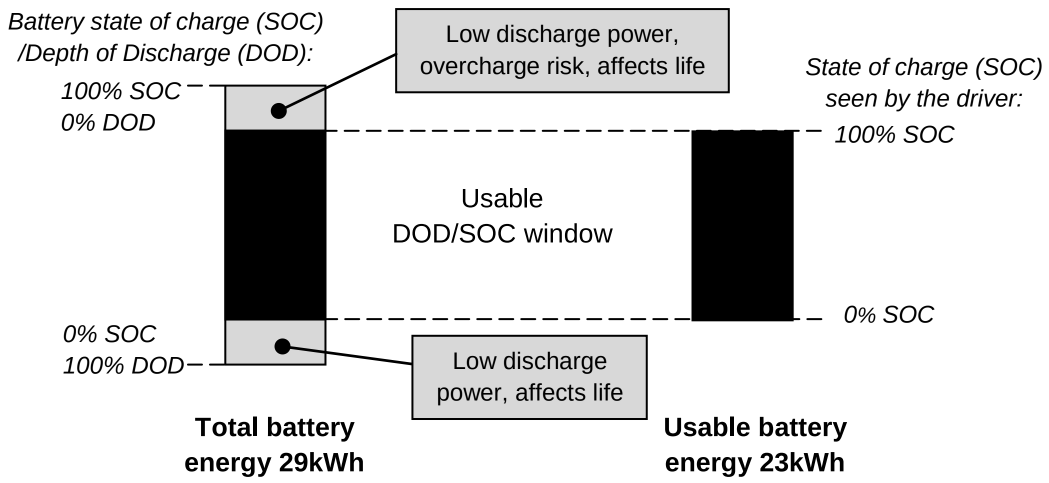


Figure 2-7 Illustration of a battery with 80% DOD/SOC window

Power

The power (kW) a battery can deliver depends on the intrinsic properties of the chemistry (kinetics of particles involved), it varies across the SOC and is defined for different time intervals (continuous and peak, e.g. 2s). Power is the measure of how quickly the battery can release its energy. The battery power output informs the thermal management demand.

In operation, a power based battery may also be used with a constrained SOC window to ensure that the maximum charge and discharge performance is achieved across the entire usable energy window. Different chemistries have different degrees of variation of power capability with state of charge, due to variation in voltage profile and this must be taken into account when deriving SOC window.

For the purpose of a model looking at future costs, the power requirements of the modelled packs are defined by the peak motor output (see Appendix 8.1 for values).

In a BEV pack, the large amount of energy carried for range requirements means the power requirements can be met easily i.e. the required pack discharge current is distributed through many/large cells so the power to energy ratio is low. In smaller capacity PHEV packs, the power to energy ratio is high: the battery cells must discharge at higher rates. This translates into a different cell design and higher thermal management demand and ultimately a higher cost per kWh for PHEV packs.

Voltage

The minimum nominal voltage (V) required from a pack today is typically 300 or 350V for cars, and can be up to 700V for vans. A higher voltage reduces losses in wiring and in the electric motor. Using packs of lower voltage would be cheaper at battery level but would effectively move the cost to other parts of the vehicle, e.g. the motor and electronic control equipment. In the cost model, a 300V pack requirement is assumed in all years.

Battery life

On standing, a battery cell deteriorates even if it is not used; it has a ‘calendar life’. The ageing is due to chemical side reactions occurring between the electrodes and electrolyte and any dissolved impurities. The ageing mechanism cannot be stopped, but can be significantly attenuated through storage at an appropriate temperature range and by the

use of additives. Ageing has two outcomes: impedance growth (resulting in lower current output capability) and capacity (Ah) loss.

A battery also has a 'cycle life': it deteriorates when used; some lithium deposits and reacts, i.e. it will not intercalate at the electrodes and so will not carry charge. The battery capacity (Ah) is thus reduced. Typically the end of life for vehicular application is defined as the point when the battery capacity is less than or equal to 80% of its original capacity.

Mechanisms for influencing battery life are well understood, and are similar for all chemistries, although they affect them to different extents. EV OEMs minimise the temperature impact through thermal management of the battery pack (e.g. forced air, liquid cooled) and they do not allow a full DOD window on the pack, i.e. they oversize the pack.

Table 2-4 lists the parameters influencing battery life and gives the life requirement as defined by the USABC (United States Advanced Battery Consortium, consortium of US car OEMs involved in battery research funding).

Battery life is critical for the economics of EVs both in terms of total cost of ownership but also in terms of the environmental impact[10]; both would greatly be affected if the battery must be replaced before the vehicle end of life.

Table 2-4 Battery life dependencies and typical requirements

	Calendar life	Cycle life
Temperature impact	High temperatures decrease life.	
SOC / DOD Impact	Voltage / SOC A lower voltage is better for life. Battery cells are not stored at full SOC before being assembled into a pack.	DOD Cycle life has a strong relationship with depth of discharge: the lower the DOD, the longer the cycle life.
USABC /DoE goals	15 years PHEV 10 years BEV	1000 to 80% DOD, 1600 to 50% DOD, 2670 to 30% DOD

Safety

Lithium-ion batteries have several failure mechanisms that can lead to thermal runaway[11] and thus cause a safety hazard. A thermal runaway can start from a sufficiently large internal short circuit or, following a shock, from deposited lithium that becomes very reactive. As cells contain combustible materials, in particular the electrolyte, a fire can develop.

There have been incidents in the past with lithium ion cells that have resulted in large scale and costly recalls of laptop batteries. Sony had to recall 340,000 laptop batteries in 2006 in the US alone, after overheating batteries caused property damage and minor

[10] See DOI: 10.1021/es903729a for a life cycle analysis of EVs
[11] Increase in temperature resulting in an increase reaction rate and net release of energy, increasing the temperature further.

burns[12]. No serious injuries have been caused by small battery pack thermal runaway, but with a large vehicle pack the consequences could be more dramatic. This is why the safety of battery cells is a prime concern for car OEMs.

Separators – which separate the electrodes and thus prevent short circuits – play a key role in terms of safety[13]. A lot of improvement work is taking place, for example preventing their softening at high temperatures. Evonik pioneered ceramic coatings to give better temperature stability. However this is not enough to make a cell perfectly safe. The quality of the electrode is the key to minimising the growth of dendrites (lithium deposits) which can push through the separator and thus create an internal short circuit[14].

The Sony laptop battery product recall was not due to inherent safety concerns around Li-ion cells and the materials themselves, but as a result of detection of metallic particles due to manufacturing control issue. The metallic particles resulted in increased probability of dendrite growth and therefore short circuit. Also the chemistry in use at the time suffered from thermal runaway that could occur at lower battery temperatures and could occur naturally during discharge in confined spaces. Other Li-ion chemistries are safer, in that thermal runaway can only happen at more elevated temperatures that are not likely to occur during normal operation.

Quality manufacturing must be employed to ensure the quality of electrodes and thus improve cell safety. The quality of electrode manufacturing is defined by minimal variation of electrode characteristics such as thickness, porosity etc within one batch, and high repeatability, the ability to produce with high degree of uniformity across batches. Scaling up from small cells to large cells for EVs scales up the quality control challenge, because there is the need to control micro particles and ensure uniformity, but over a much bigger electrode area.

Automotive cell safety demands dictate the need for reduced contaminants in finished electrodes, i.e. cleaner working environments. Current best clean standards installed in cell manufacturing are ISO6 (maximum 1million particles ≥ 0.1 µm per m^3) while ISO4 or ISO5 (10,000 and 100,000 particles per m^3) levels are needed for safety demands of automotive cells[15].

Safety concerns at vehicle OEMs level translate into longer vehicle development lead times, due to cell testing. OEMs test cells assembled in pack in real-life conditions, e.g. pilot vehicles, for several months to ensure the final product is safe.

Other parameters

Battery packs have other attributes, briefly summarised here:

- Operating temperature range, e.g. ca. -5°C to +40°C for today's packs. For reference, the USABC minimum goals for long term commercialization are -40°C to +50°C (20% performance loss permitted) and long term goal -40°C to +85°C. The cost of technologies (pack thermal control) allowing for such a wide temperature range are not explicitly estimated in the cost model.

[12] Source: U.S. Consumer Product Safety Commission
[13] One of the reasons for laptop battery recalls were due to poor (thin) separators
[14] Barnett, New safety technologies for lithium-ion cells and batteries, Batteries 2011 conference, Mandelieu, September 2011
[15] Quass J., Benhamou E., Keil A., Advances in Battery Electrode Coating, Drying and Solvent Recovery System Design, Batteries 2010 conference, Mandelieu, September 2010

- Charging rate: continuous charge rate (commanding pack recharge time) and pulse rate (regenerative breaking). Current generation batteries are specified at lower charge rates, but higher discharge rates. This is due to concerns about safety and the very close control that is required during high charge currents while ensuring safe operation. Future batteries might be required to handle charging rates higher than the typical current charging post (3 to 7kW). For reference, the USABC long term goal is 40-80% SOC in 15 minutes. Charging rate capabilities are not explicitly modelled.

- Volume and mass. In the development of the specification of plug-in vehicles to model, an indicative maximum pack volume and maximum pack mass have been defined, see the Appendix 8.1.

Summary

- Battery pack cost will be modelled for a selection of vehicles representative of the UK market: small cars, medium sized cars, high power cars and panel vans. Current vehicles attributes such as energy consumption are defined based on existing models while future vehicles attributes account for the expected light weighting and increased range. Drivetrains considered are pure electric and plug-in hybrid electric.

- The general architecture of a battery has been presented: cells, module, thermal control and electronics controls.

- Among the past and existing automotive battery technologies, lithium-ion has the highest energy density and has replaced other battery chemistries in production vehicles. On this basis, it will be the only technology modelled for the short term.

- Current lithium ion cells work on the principle of intercalation: reversible insertion of a guest atom (lithium) into a solid host structure without inducing a major disruption of the host material (electrode materials).

- Attributes of batteries have been presented. Some, such as safety and life, affects the lithium-ion battery pack design and cost as they require oversizing the pack and integrating an advanced thermal control.

3 Understanding current automotive cells

This section presents current lithium-ion cells, starting with historical development of cells, followed by performance and cost of automotive cells across the existing lithium chemistries[16]. Costs of automotive packs are then introduced, followed by a short description of the battery industry.

3.1 Historical trends of lithium-ion cells

The first commercial rechargeable lithium-ion cell, sold in Japan in 1991, had a lithium cobalt oxide cathode (LCO) and a hard carbon anode. Performance (e.g. Ah, Wh/kg) and the costs of cells have since significantly improved, materials have diversified and the market size has grown. Table 3-1 gives a snapshot of performance, cost change and market size for lithium-ion cells; these are commented in this section.

Table 3-1 Consumer market size and 18650 cell costs & size. Source: Avicenne 2011 and manufacturers' data

		1999	2011
Mobile phones sold (millions)	Li-ion cells	100	1,400
	Ni-MH cells	200	0
Laptops sold (millions) – Li-ion cells		14	225
Tablets sold (millions) – Li-ion cells		0	65
Tons of Li-ion cathode material		4,583	55,000
Li-ion 18650 cell price ($/kWh)		**2,600**	**240**
Typical Li-ion 18650 size (Ah)		1.5	2.2

Performance trajectory and cell markets

From an initial 0.8Ah capacity, 18650 cells (the most common and mass produced model, a cylindrical 18 mm diameter, 65 mm high cell) reached 2.3Ah in 2005 and up to 2.6Ah today, corresponding to a specific energy increase from 90Wh/kg to around 200Wh/kg[17]. This remarkable trajectory is the result of several improvements:

- Moving from a hard carbon anode (~200 mAh/g capacity) to graphite anodes, (~280 mAh/g capacity)
- Introduction of electrolyte additives in 1998, allowing further graphitisation of the anode (from 280mAh/g to 360mAh/g)
- Engineering process improvements, packing efficiencies e.g. reduction of non active materials in the cathode (less carbon and less binder), increasing the weight of active materials from approximately 85 to 95%.

By 2005, engineering process improvements had reached their limit and further improvements in energy density or cost reductions had to come from other sources; new cathode materials (with higher capacity or lower cost) started to be developed. Table 3-2 gives a list of cathode materials used in commercially available lithium-ion cells. While some chemistries are now used in vehicles, the main cell market is still consumer electronics: phones, laptops and cameras etc (see Figure 3-1). Li-ion cells market share exceeded the cumulative share of Ni-Cd and Ni-MH cells by 2004, and now they account for 80% of the rechargeable battery market.

[16] Usually referenced by the chemistry at the cathode
[17] 2.9Ah cells are due to enter the market soon, based on silicon/carbon anode, they correspond to 230Wh/kg

Table 3-2 Current or close to market cathode materials for automotive cells

Cathode active material name	Material	Abbreviation	Short form	Maturity for EV?
Lithium cobalt oxide	$LiCoO_2$ (60%Co)	LCO	Li-cobalt	Used in the original Tesla car but rejected on safety concern grounds by series car OEMs
Lithium manganese oxide	$LiMn_2O_4$	LMO	Li-manganese or spinel	Already in series car (e.g. Leaf, Volt, iMiEV)
Lithium iron phosphate	$LiFePO_4$	LFP	Li-phosphate	Already in series car (e.g. Fisker EV)
Lithium nickel manganese cobalt oxide	$LiNiMnCoO_2$ (10-20% Co)	NMC	NMC	Used in consumer goods and EV prototypes
Lithium nickel cobalt aluminium oxide	$LiNiCoAlO_2$ (10-20% Co)	NCA	NCA	Already in series car (e.g. plug-in Prius)

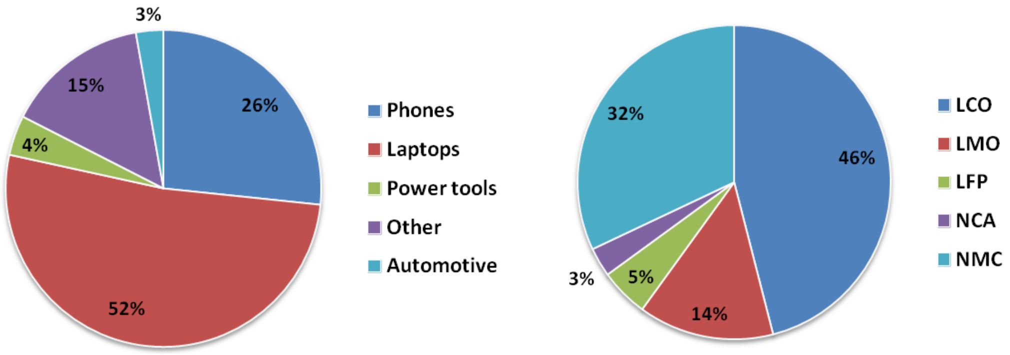


Figure 3-1 Market application of rechargeable lithium-ion cells in 2010 (total 28,400MWh) and cathode chemistries split Source: Avicenne 2011

Cost trajectory

The cost of 18650 cells was reduced mainly due to high volume production as well as some manufacturing efficiency gains. However, the cost of cells for EVs does not benefit directly from the small cell production optimisation. Scaling up the processes to make larger cells brings new challenges, especially around quality control, and the industry does not have the volume production experience yet. Interviewed cell manufacturers are of the opinion that the cost of large cells cannot go down to the cost of small mass produced cells, at least not without a decade of experience.

Development time

New chemistries developed for the consumer electronics market find their way to the vehicle market, typically many years later[18]. Table 3-3 provides some examples.

The industry consensus is that this lag between consumer cells and vehicle cells will remain constant because the development of a new product is easier (less stringent requirements, especially in terms of battery life) and lower risk in small battery sizes where the market is larger.

This means chemistries that are not already in use in consumer applications today are not expected to penetrate the automotive market for at least 5 years. The next chemistry in line to be used in series vehicles is the NMC cathode, already used in prototype vehicles.

As the published literature search reveals no chemistries demonstrating a step-change in performance increase entering the consumer cell market today, it is reasonable to assume there will be no step-change in automotive cell performance by 2020. Instead we expect a gradual performance improvement. In the longer term, as the automotive market increases, cells will be increasingly developed for that market.

The time lapse between proof of concept in lab and commercialization for successful battery chemistries is at least 10 years, and as the table below shows, may be significantly greater. This is the time it takes to go from one promising electrode chemistry, finding a compatible opposite electrode, and refining the cell (structure of materials, electrolyte etc) into a product with rate and life characteristics appropriate for consumer electronics.

This has profound consequences for the landscape of batteries for vehicles in the years to come: any new chemistry that is still at the proof of concept stage in the laboratory will not be expected to penetrate the automotive market for at least 10-15 years.

Table 3-3 Development time of chemistries from proof of concept to commercial cell

Chemistry	First paper / patent	First commercial rechargeable cell	First use in series car *(small series)*
Lithium LCO	1979	1991	*2008 (Tesla)*
Lithium LMO	1983	1996	2009 (iMieV)
Lithium LFP	1994	2006	*2007 (MODEC van)*
Ni-MH	1967	1990	1997 (Prius)

[18] The only exception is the nano-structured lithium titanate anode which was developed by Altairnano for power applications other than small consumer cells such as grid support, uninterruptable power supply, military and transport.

3.2 Cost and performance of current lithium ion cells

The previous section introduced the general and historical lithium-ion cell market whereas this section focuses on describing the current lithium cells characteristics.

Cathode chemistries

As introduced earlier, several cathode materials have been developed since the original lithium cobalt oxide (LCO). Table 3-4 summarises the strengths and weaknesses of the current 5 cathode chemistries type[19].

As mentioned earlier, LCO cathodes are not considered appropriate for automotive applications due to the safety risk they would present. Their high cobalt content, a material of high and volatile price, was a driver for developing alternative cathode materials.

Table 3-4 Comparison of performance of current lithium ion cells

Cathode	LCO Lithium Cobalt Oxide	LMO Lithium Manganese Oxide	NCA Lithium nickel cobalt aluminium oxide	NMC Lithium nickel manganese cobalt oxide	LFP Lithium iron phosphate
Type	Metal oxides				Polyanion
Energy					
Power					
Safety					
Expected cost	*High (Co)*	*Low*	*High (Ni, Co)*	*Medium to High (Ni, Co)*	*Low*
Low temperature					
High temperature					
Cycle life					
Calendar life					

LMO cathodes – also called spinel in reference to their structure – have the advantage of being based on non toxic and cheap manganese. The main limitation of LMO is the dissolution of manganese in the electrolyte, which translates into a shortened life, especially at high temperatures. Batteries based on LMO cathodes need advanced thermal management to mitigate this sensitivity to high temperature.

The NCA and NMC cathodes have had wide adoption in the laptop and power tool markets, taking market share away from the LCO cathodes, thanks to their lower cobalt content and overall good performance. NMC cathodes present more advantages in terms of both safety and potential for improvement of the reversible capacity mAh/g and voltage. They will therefore be taken forward to the cost model.

Poly-anion type cathodes, such as LFP, are considered intrinsically safer than metal oxide cathodes that can release their oxygen more readily and fuel a potential thermal

[19] Note that the exact composition of the cathode material varies across suppliers and can be a mix of chemistries described here, e.g. Boston Power has developed a 'LMO-LCO' cathode.

runway. LFP is more stable at high temperatures than most chemistries, but its kinetics (i.e. power) are poorer at low temperatures; this is mitigated by processing the LFP into nano-sized particles, although this compromises the volumetric energy density.

Figure 3-2 plots the volumetric and gravimetric energy and power densities for a selection of currently available lithium-ion cells. While the energy density is clustered by chemistries, the power density shows a greater spread of values within each electrode type; this is linked to the internal design of the cell which can be adapted to be more power intense, e.g. by changing the way the active material is loaded on the electrode.

There is a trade-off between high energy and high power: cells dedicated to power applications, i.e. PHEVs, are more power dense and less energy dense than cells designed for BEVs. Currently metal oxide cathodes are seen as the more likely candidates for BEVs whereas LFP is perceived as better for PHEV applications.

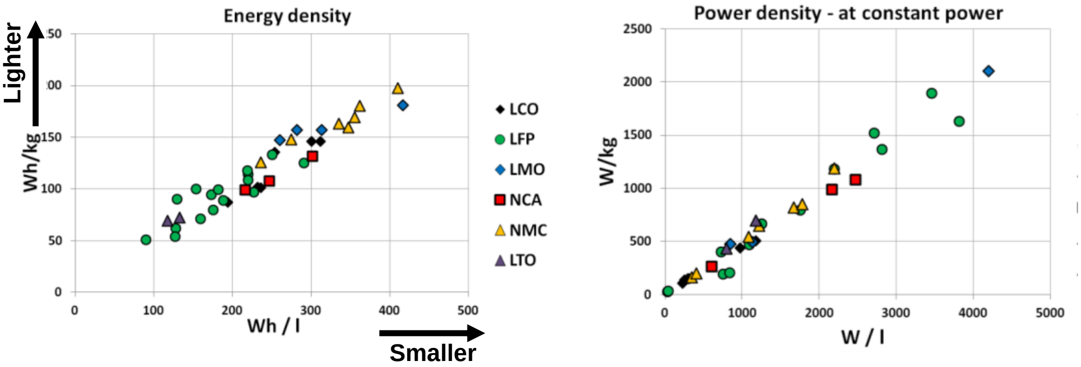


Figure 3-2 Energy and power densities of currently available lithium-ion cells. Compiled from manufacturer data

Expected life

Quality automotive cells can achieve today, in laboratory conditions[20]:

- 1,000 cycles or over at 100% DOD. There are variations across chemistries, with LFP being noticeably better.
- 5 to 10 years (or over) but this is very temperature dependent and varies across chemistries. This translates in the need for a very good thermal management in the car, especially for LMO, the most temperature sensitive chemistry in terms of calendar life. Cells with LTO (lithium titanate oxide) anodes show excellent life, possibly exceeding 20 years at ambient temperature.

Based on this, the cost model includes the cost of advanced thermal management in the packing costs, even in future costs.

The temperature impact on battery life is recognized by car OEMs; they provide guidelines on this to drivers, and caveat their warranty. For instance the Nissan Leaf warranty booklet stipulates, amongst other conditions, that the 8 years/100,000miles warranty on the lithium-ion battery “does not cover damages or failure resulting from or caused by exposing a vehicle to ambient temperatures above 49°C for over 24hours or storing a vehicle in temperatures below -25°C for over 7 days”.

[20] Based on an independent third party analysis on competitive products.

Cell size

Cells for consumer markets are relatively small, with capacity lower than 10Ah. Driven by vehicle, grid support & IT markets, larger cells are entering the market. Figure 3-3 shows capacity and voltage of a selection of currently available lithium-ion cells. Each chemistry has a specific voltage band but can be manufactured in various sizes.

Large cells allow a reduction in the number of (parallel) cell strings in a car and thus bring pack assembly cost reductions. They are however more difficult to manufacture; the mechanical integration in pick and place, stacking and winding stages are more difficult to do accurately to ensure critical alignment of electrode stack with high uniformity. High capacity cell manufacture currently results in typically lower cell yield and slightly higher cell to cell variation compared to smaller format cells. As discussed earlier, the quality control in large format cells is more difficult when trying to prevent manufacturing problems such as the ingress of small particles that could lead to cell defects, given the large surface area of electrode per cell.

Our industry contacts consider that cells up to 40Ah are safe today for vehicle applications and that the 40-60Ah band is mostly of good quality. Cells above 60Ah are currently not generally dedicated to car applications, with the exception of converted vans that tend to use very large cells.

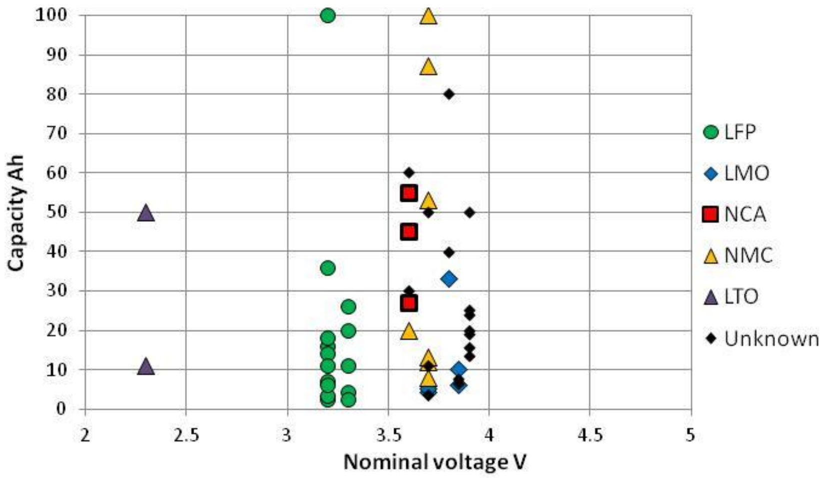


Figure 3-3 - Voltage and capacity of currently available lithium-ion cells. Compiled from manufacturer data.

Cost

Data on cell cost was collected through a survey of cell manufacturers; see Figure 3-4 for quoted cost of EV cells of comparable characteristics. There is no evident correlation between chemistries and price across quotes obtained from different suppliers.

One might expect that NMC cells (cathode based on expensive raw materials such as cobalt and nickel) and LMO (cathode made from cheap manganese) cells to reflect the difference in cathode material cost.

The feedback from project partners is that, in theory, there ought to be a difference but it is small and currently masked by strategic pricing: cell suppliers adapt their price to the customer or project depending on the size of the opportunity. There is no clear visibility on the real cost of lithium-ion cell chemistries. A predominant Japanese cell manufacturer currently providing cells for car OEMs revealed they have a client target of $300-350/kWh by 2015, without specifying the cathode chemistry.

The wide range of prices (330-550 \$/kWh) quoted for LFP might reflect different product quality or specifications. LFP cathodes are based on cheap raw materials (Mn, Fe, PO_4) but have higher processing costs to turn the raw materials into the final cathode material. These higher processing costs result in part from the inert atmosphere needed for synthesis, and in part from the nano-particles size required to enable LFP as an electro active material with significant power capability.

In conclusion, while recognizing the observed price range is currently large, today's average cell price can be approximated at \$400/kWh.
High power cells, i.e. for HEV or PHEV applications, are typically 30% more expensive (approximately \$520/kWh) according to our industry contacts, but it is harder to generalise on price here as it is very sensitive to the power performance and total pack size.

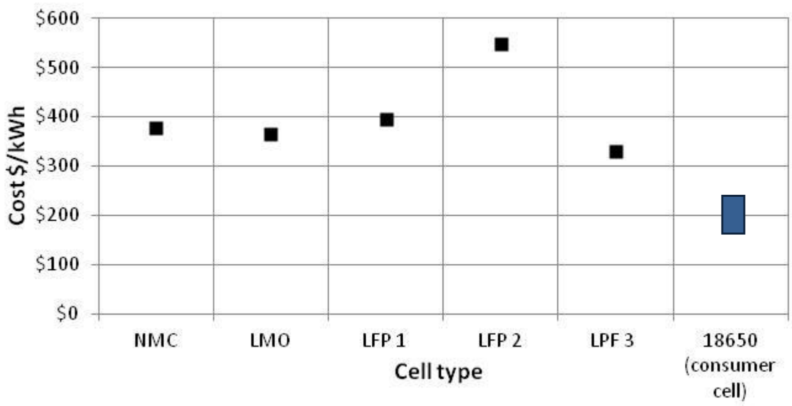


Figure 3-4 Cell prices, based on quotes for 10million cells or survey answers

Cell format

Cells come in different formats, typically: prismatic, cylindrical or pouch. Pouch cells can be made of different shapes but are generally rectangular and their casing is made of soft polymer[21], which gives them a higher specific energy than the other hard case formats for the same chemistry. This weight advantage is however lost at pack level, as they require more packaging for strength. Each format presents some advantages and disadvantages in the context of vehicle application, Table 3-5 sets out a comparison. It is not clear which format will emerge as dominant in vehicle applications. The cost difference between cell formats is negligible and not investigated in our model, as recommended by the surveyed cell manufacturers.

Table 3-5 Cell formats comparison in vehicle application context

	Prismatic	Cylindrical	Pouch
Heat rejection/ cooling	Good	Good – space between cells can be used for cooling	Good
Stacking	Easiest	Requires extra parts	Requires extra parts
Assembly in module	Good	Requires integration	Hardest: requires more housing to add rigidity

21 Pouch cells are sometimes referred to as polymer cells but it is usually in reference to the casing not the electrolyte.

Recycling/Disassembly	Good	Good (depending on how they are held in place)	Can be difficult, if tabs are laser welded
Use of space/ packing efficiency	Good	Worse	Best
Casing	Aluminium, steel or hard plastic	Steel/aluminium	Polymer
Used in vehicles?	Pre-production	Yes, e.g. Panasonic cells in first Tesla car	Yes, e.g. LG cells in Chevrolet Volt

3.3 Cost of automotive packs

Pack components were introduced in section 2.2.4. Table 3-6 gives an illustrative bill for materials, with costs and mass, for a BEV 22kWh pack produced today in a facility capable of producing 20,000 packs per annum. The components costs are based on actual quotes for each component, for batches equivalent to 20,000 packs.

The table on the right gives our estimate of total pack cost, based on a cell cost of $400/kWh. The resulting $792/kWh compares well with information collected through surveys of pack suppliers, considering the small production volume assumed. They all quoted large price ranges, stressing that price is very volume dependent and the overall range was $450 to $800/kWh for 2013-2015.

As for cells, the costs for PHEV pack components are more expensive than for BEV due to the higher power to energy ratio: the BMS has to have extra components and architecture to be able to shuttle energy, and this comes at a significant cost overhead.

Table 3-6 Example of pack BOM and total pack cost estimates for 2012

Pack Bill of Materials (BOM) – excluding cells	Cost ($)	Mass (kg)
Battery Management System (BMS)	$1,483	8
Power electronics	$1,079	9
Wiring harnesses, interconnections and connectors	$923	11
Internal cell support	$791	15
Housing	$649	34
Temperature control (forced air)	$302	11
TOTAL	**$5,227**	**88**

Estimation of total pack cost

	$/kWh
Cells	$400
Pack BOM excl. cells	$238
Pack overheads, depreciation and labour	$ 54
Margin and warranty	$100
Total pack	**$792**

Based on 22kWh pack (246 25Ah cells). 20,000 packs per annum

The cost of the BMS increases with the number of cells to monitor. Standardisation of this component – currently customized for each vehicle model – is expected to strongly decrease the cost in future. Wireless monitoring could in future reduce the amount of wiring between the BMS and the cells and thus reduce cost and weight.

The pack housing is the component with the biggest potential improvement in cost and weight. It can be made of steel, aluminium, plastic, composite components or even carbon fibre to save weight. Some racing car batteries currently use carbon fibre housing, but this comes with a considerable cost premium. In the cost model, it is assumed the pack housing is made of steel.

3.4 The rechargeable battery industry

Asia (Japan, South Korea and China) dominates the battery manufacturing market, both in terms of historical production of consumer cells, and projected volume of large automotive cells. Figure 3-5 shows a list of the main cell and battery manufacturers. Recently South Korea has been gaining on the incumbent Japan on battery production volume, however Japan remains the leader in lithium ion battery patent applications; see Figure 3-6.

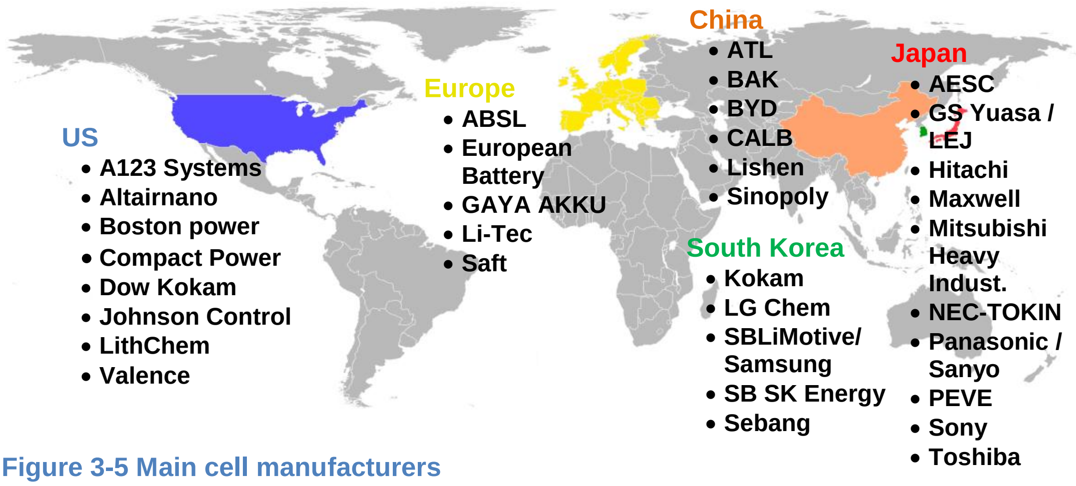


Figure 3-5 Main cell manufacturers

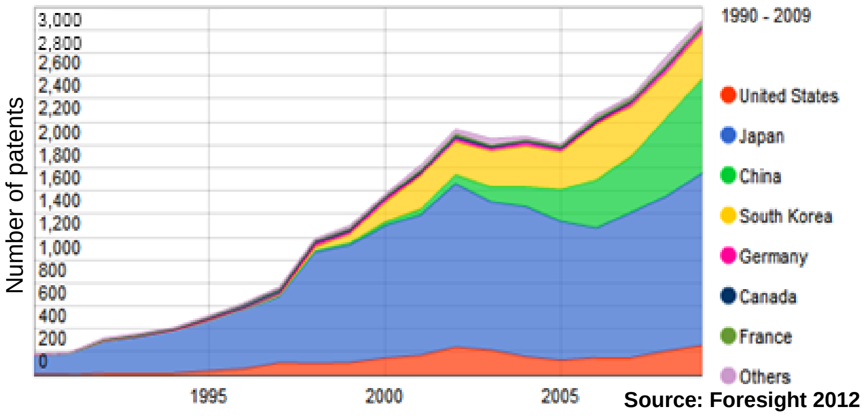


Figure 3-6 - Lithium ion patent activity by country.

Table 3-7 shows that Asian countries also lead the cell supply chain. For more detailed information on cell manufacturers and their supply chain, see the CGGC report[22].

[22] CGGC, Lithium ion batteries for electric vehicles, 2010

Table 3-7 Main players on the cell supply chain[23]

Component	Cathode	Anode	Separator	Electrolyte
Market share of top 3 suppliers	**61%**	**65%**	**78%**	**65%**
Top 3 suppliers	Toda Kogyo	BTR Energy Materials	Tonen/Toray	Mitsubishi Chem.
	Nichia Chemical	Nippon Carbon	Celgard	Ube industries
	Umicore	Hitachi Chemicals	Asahi Kasei	Cheil industries

Country colour code:

USA	BELGIUM	CHINA	JAPAN	SOUTH KOREA

Governments see the automotive battery supply chain as a key future 'green' industrywith large growth potential. As such, governments are giving industry significant incentives to locate to their county. For example the US has allocated $1.5bn[24] for investment into lithium battery manufacture. In the UK, there is only one large scale battery assembly plant planned (Nissan, in Sunderland, from 2013), which received a £20.7 million grant from the government.

In response to developed countries supporting the uptake of EVs and car OEMs planning new EV models, large investments in battery manufacturing has been announced. Cell manufacturers in Japan, South Korean and China are investing ~70% of the announced new 50GWh capacity; see Figure 3-7 for the split of investment between producing countries. A capacity of 50GWh is more than today's total rechargeable lithium-ion cells market (~30GWh).

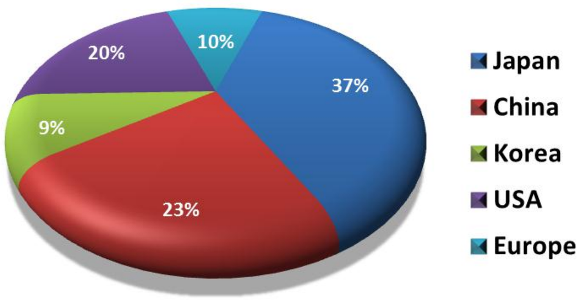


Figure 3-7 Split of the announced $12billion investment in cell manufacturing for 2011-2015. Source: French embassy in Japan, 2010

This large global investment in battery manufacturing would correspond to an EV demand of 2-3.3 million PIVs by 2015[25] representing a high risk of overcapacity if the expected EV demand does not materialise.

Furthermore, the investment in cell manufacturing is not being followed by the necessary investment in the supply chain, i.e. the processing of cell materials such as cathode & anode active materials, electrolyte and separators[23.] . This implies that EV battery plants will not all run at full capacity and adds to the risk of production overcapacity in the short term.

[23] Roland Berger, Lithium-ion batteries for automotive applications – value chain and costs perspectives, Batteries 2011 conference, Mandelieu, September 2011

[24] DoE, *Progress of DOE Materials, Manufacturing Process R&D, and ARRA Battery Manufacturing Grants,* 2011

[25] Based on average pack size of 15 to 25kWh, depending on the HEV, PHEV and BEV market shares

Summary

- The predominant market for lithium-ion cells is consumer applications, mainly phones and laptops. Since the first Li-ion cells sold in 1991, their cost has dropped (to under 250$/kWh) and performance has improved (up to 200Wh/kg) for small consumer cells.
- Cells for automotive applications are however different from consumer cells, with harder to achieve requirements in terms of size, power, life and safety. They translate into a new manufacturing challenge that does not directly benefit from the consumer cell manufacturing cost curve.
- The quickly expanding and competitive cell consumer market has driven innovation, with several new cathode materials developed in the last 7 years. Automotive cells do benefit from this innovation but with a time lag of several years, due to their more demanding requirements. Historical development times indicate that any new chemistry to come in cars in the next 3-5 years must already be in consumer cells today.
- Cells suitable for transport applications today have an energy density of approximately 100-180Wh/kg (200-350Wh/l), have a capacity up to 40 Ah and require continuous thermal management to reach 10 years of life.
- Large cells are not a commodity yet and as such there is no visibility on their cost. A cost approximation would be $400/kWh for BEV cells. At pack level, the cost can double.
- Both automotive cell and pack production volumes are low today, but considerable investment in production capacity indicates a cost reduction potential in future. There is however a risk of overcapacity if the EV demand does not increase significantly within a few years.
- Asia (Japan, South Korean and China) dominates the current battery market and lead on the investment in automotive battery production capacity.

4 Looking ahead: chemistries of the future

Current battery technologies are both too expensive and bulky to make EVs competitive compared to conventional vehicles. The considerable R&D focus and funding is expected to bring improved, lighter and cheaper batteries to the market. This section presents the battery technologies that are being researched and the key R&D challenges currently hindering their development and mass manufacture. The funding and scope of national R&D programs working on addressing these challenges are also briefly presented. Finally, the technology roadmap, i.e. which cell chemistries will be used in cars in the future, used to model the costs of future cells is presented.

4.1 Battery taxonomy

This section presents a brief list of the mechanisms in use or considered for large cells for transferring charge, with their expected advantages over the incumbent technology.

Intercalation

Current lithium-ion cells are based on intercalation: ions intercalate at the electrodes (see 2.2.3 for more details). The theoretical capacity limit associated with intercalation materials (with a single valance change) is approximately 300mAh/g; it corresponds to the number of ions a host material can accept without collapsing. This would translate into a theoretical cathode energy density of 1200 Wh/kg in a 4V cell.
Current intercalating cathode materials are still far from this theoretical ceiling, for example the LMO cathode is around 550Wh/kg. Research to develop cathode materials with higher capacities is on-going and will deliver improvements.

Even the maximum practical energy of intercalating cathode cells (1200 Wk/kg) is however much lower than that of other types of cells, as illustrated in Table 4-1.

Table 4-1 Theoretical energy densities of some battery technologies (based on cathode theoretical capacity) and estimates of practical energy density

Type	Example battery	Cell voltage	Theoretical Wh/kg [26]	Theoretical Wh/l [26]	Practical [1] cell Wh/kg
Intercalation	Today's LMO-Gr	3.8	550		110-165
Theoretical max intercalation			*1,200*		*240-300*
Reaction - sulphur	Li-Sulphur	2.2	2567	2200	*300-800*
Reaction - Metal-air	Li-O_2 (non-aqueous)	3.0	3505	3430	*700-1000*
Reaction - Metal-air	Li-O_2 (aqueous)	3.2	3582	2230	*700-1000*
Reaction - Metal-air	Zn-air	1.65	1086	6090	*220-330*

1 *Not achieved today - approximation for indication purposes only*

Reaction – Metal-sulphur

In a reaction cell based on sulphur, the sulphur reduces at the cathode and ultimately combines with the metal. The metal can be lithium, sodium (Na) or magnesium (Mg).
The expected advantages over current intercalation cathodes are a higher energy density and the utilisation of low costs materials, e.g. sulphur.

[26] Adapted from Peter G. Bruce et al., High energy storage li-O2 and Li-S batteries

Reaction – Metal-air (Metal-O_2)

In this type of cell, part of the active material is not carried in the battery but received from the air: oxygen from the air enters the cathode to be reduced. Lithium-air has the greatest theoretical energy density, see previous table; this level of energy density would mean a 500km driving range EV could become practical. The other expected advantage over Li-ion is the use of non-toxic and lower cost material.

Zn-air batteries have two advantages over Li-air batteries: zinc is cheaper than lithium and (when compared with non-aqueous Li-air) water entering the cells does not cause problems. However decades of work on rechargeable Zn-air have not delivered a rechargeable battery. Their low voltage is also a disadvantage for the automotive market. They are therefore excluded from the cost modelling. Other possible options for metal-air cells include sodium and aluminium. These are excluded from the modelling as well, in favour of lithium-air, the most promising metal-air battery as of today.

Alloying reactions

Elements used or considered for alloying anodes are silicon (Si) and tin (Sn). They present much greater capacity (mAh/g) than intercalating anodes.

The development status and scientific challenges of these technologies are presented in the next section.

Other technologies, not considered in this work

Some non-rechargeable batteries rely on conversion reactions (also called displacement) but there is nothing commercial to date for the rechargeable market. One of the big barriers is the significant gap between charge and discharge voltage. R&D in this field has been abandoned in favour of alloying reactions.

Divalent batteries – where the anode is lithium metal and the intercalating cathode is based a divalent metal, e.g. magnesium – might deliver higher energy density (the divalent metal allows for 2 electrons to be released for each ion) but have low voltage, low cycle life and safety issues. They are only a lab concept at this stage and will not be considered in the model due to their overall low advantage over existing technologies.

Other technologies that show promising performances but are not appropriate for the automotive market in the foreseeable future include flow batteries and redox batteries. They show lower energy and power density than lithium-ion and need pumping solutions to refuel the electrolyte. They are suitable for other markets with stationary applications such as grid support and Uninterruptible Power Supply.

4.2 Key R&D challenges and development status

Publically funded R&D programs and research papers have been reviewed to understand the current development status of the technologies presented in this section. Information from private entities has been gathered from specialist conferences, direct conversations with cell manufacturers and from the public domain (e.g. press releases).

4.2.1 Intercalating cathodes

Current cathodes such as LMO and LFP (see Table 3-2 for full chemistry names) have a reversible capacity (i.e. usable capacity) under 150mAh/g while in theory the maximum intercalation capacity could be as high as c.300mAh/g. The tables below show current

values along with the potential improvements in terms of capacity and/or voltage that chemistries under development now could bring in the future. The most promising work in the short term is around the optimisation in the NMC triangle which could reach high capacities (200mAh/g).

Table 4-2 NMC cathode development potential

	Current NMC	Adv. NMC potential
Theoretical capacity (mAh/g)	280	300
Reversible capacity (mAh/g)	140	200
Voltage vs Li/Li+ (V)	3.7	3.7

NMC cathodes are already in use in cells for electronic goods but do not reach their full potential. Numerous R&D projects are on-going, with many combinations and blends under investigation to get the reversible capacity closer to the theoretical maximum.

The main challenges of NMC cathodes are around the volumetric density (particle packing), improvement of cyclability and rate capability, and cost of raw materials (cobalt being the most expensive). These problems are being addressed through control of particle morphology by new synthesis techniques and also by reducing the amount cobalt to a minimum. Cobalt is essential for power capability; it is estimated that 10% (by mass) of Co would be the minimum amount possible.

Table 4-3 Lithium spinel development potential

	Current LMO	LMNO potential
Theoretical capacity (mAh/g)	150	150
Reversible capacity (mAh/g)	100	120
Voltage vs Li/Li+ (V)	3.9	4.7

Lithium manganese nickel oxide (LNMO) cathodes are being developed by both private companies and through several US DoE funded projects. They suffer from poor stability of the electrode electrolyte interface, related to their higher voltage (4.7-5V) compared to LMO or NMC. This will require either electrode coatings or electrolytes that are stable to high voltage ranges.

In the polyanion family, lithium metal phosphates cathodes ($Li(M)PO_4$, M= Mn, Ni or Co) have the same theoretical capacity (mAh/g) as the currently produced LFP but would bring higher energy density through their higher voltage. Several metals are being investigated in the lab with $LiMnPO_4$ (LMP) showing the most promise amongst the polyanion family for future introduction into mass market cells.

Table 4-4 Polyanion cathodes development potential

	Current LFP	LMP potential	Li(M)SO4F potential
Theoretical capacity (mAh/g)	170	170	170
Reversible capacity (mAh/g)	130	150	150
Voltage vs Li/Li+ (V)	3.4	4	5

The challenges to overcome are a poor capacity retention and slow kinetics, attributed to low intrinsic ionic and electronic conductivity (using Mn results in a more insulating material than Fe). Solutions developed include doping and nano-structured materials such as mesoporous materials. For example, the Japanese cell manufacturer Yuasa is working on a $LiMnPO_4$ cathode, using a carbon layer (3-4nm) and a carbon network to compensate for the poor electronic conductivity[27].

[27] Junichi Maruta, High performance lithium-ion batteries for electrified vehicle application with various chemistries and cell dimensions, Lithium Energy Japan, Batteries 2011 conference, Mandelieu, September 2011

Further away in the development timeline, fluorophosphates (PO_4F) and fluorosulphates (SO_4F) cathodes present the advantage of a higher voltage than LFP, and better ionic and electronic conductivity. The better conductivity means there would be no need for nano-sizing and carbon coating, and this could bring a cost advantage over LFP.
However it is expensive to synthesise SO_4F materials, as their sensitivity to water makes them difficult and expensive to handle. There are R&D programs investigating new synthesis routes with lower cost than the current solvothermal, ionic liquid method.

Another development worth noting is the high capacity layered composite cathode (referred as layered-layered or LL thereafter). LL cathodes could have a capacity higher than 230mAh/g but fundamental problems still need to be solved to make them viable.

The LL material is first activated by charging; it releases oxygen in this process that can react with the electrolyte and degrade it. This oxygen loss changes the material structure and allows increased lithium insertion.

LL cathodes also suffer from poor kinetics, and the cathode has to be cycled over a large voltage range to get the full material capacity.

The Argonne National Laboratory (ANL) and BASF are working on such LL materials (xLi_2MnO_3•$(1-x)LiNiO_2$) with the support of DoE funding[28] (LG Chemical is also a licensee). They can produce the materials in kg batches, with particle spheres of high homogeneity. They are studying surface modification to stabilise the material for cycle life and using coating oxides to improve conductivity. Their cathode material can achieve around 50 cycles without significant capacity loss.

Sodium-ion chemistries (Na-ion)

The basic concept for Na-ion cathodes is the same than Li-ion, and they are now at early laboratory stage in terms of development. There are no compatible anodes at the moment, so this technology is far from practical implementation.
Na-ion presents two advantages over Li-ion: sodium is cheaper than lithium and this research opens the possibility of finding new high voltage/high capacity cathodes. It might be easier to find high capacity Na-ion cathodes than to improve Li-ion cathodes. However the power capability might not be as high as with Li-ion.
Na-ion cathodes are the subject of a number of research projects in 2012, with Argonne National Laboratory in the US, St Andrews University in the UK and the French national research centre all dedicating funding to the topic.

4.2.2 Intercalating anodes

Intercalating anodes can be split into categories: low and high voltage versus Li/Li+.

Low voltage anodes (<1 V vs. Li/Li+)

This is the type of anode currently in use. They are carbonaceous; with soft carbon, hard carbon or graphite. The disadvantage of low voltage anodes is the risk of lithium plating and dendrite formation, leading to safety issues. On-going work to address this issue includes anode coatings and surface treatments.

At this low voltage, lithium is corroded by the electrolyte salts and solvent. A layer (called solid-electrolyte interphase, SEI) forms at the anode and passivates the lithium, preventing further chemical degradation. Additives are introduced to condition the SEI, improving its properties and ensuring the electrode stability and thus cell safety.

[28] Argonne National Laboratory, Engineering of High energy cathode material, 2011

Graphite anodes (theoretical capacity 372mAh/g, reversible ~330mAh/g) are the most commonly used anodes at the moment. Hard carbon anodes (theoretical capacity 480mAh/g and cheaper than graphite) are already used in some applications and could be ready for series cars by 2020 but they suffer from volume expansion problems; development might instead be directed to alloying anodes; see next section.

Another material being investigated is lithium vanadium oxide (LVO). It has the same capacity as graphite but is twice as dense; it would thus result in a greater volumetric density (Wh/l).

High voltage anodes (~1.5 V vs. Li/Li+)

Thanks to the higher voltage, these anodes (lithium titanate oxide, LTO) have very good characteristics in terms of safety, cycle life, low temperature performance and power rating, permitting fast recharge.
The use of LTO anodes enhances the safety of Li-ion cells due to their thermal stability, no anode SEI and ability to absorb O_2 released from unstable cathode compounds in abuse conditions, therefore preventing thermal runaway.
But the higher voltage at the anode comes with a significant drawback: the resulting cell has a lower voltage and thus low energy density, see Figure 3-2 and Figure 3-3 for illustration. LTO anodes are also more expensive than graphite anodes and are prone to stability problems (reactions) with the electrolyte at elevated temperatures.

Due to their limited energy density, LTO-based cells are perceived as more appropriate for HEV applications than for plug-in vehicles. Nevertheless LTO anodes are coming to the EV market , e.g. in the Honda Fit EV announced for summer 2012[29].

LTO anode capacity is limited (175 mAh/g) while a titanate oxide (TiO_2) anode would have almost double this capacity. TiO_2 anodes are being investigated but are still at an early stage of development.

LTO and TiO_2 anodes will not be modelled, due to their energy density, the improvement prospects and costs.

4.2.3 Alloying anodes

Silicon (Si) alloying anodes offer theoretical capacities more than 10 times that of intercalating anodes, see Table 4-5. But there are some significant challenges to their use.
During the alloying/de-alloying reactions, there is a large volume expansion (up to 300%) that can break up the electrode, resulting in reduced capacity and a short cycle life (<200 cycles). Solutions under development or investigation include the use of nano particle-Si, Si nano-wires, porous Si and Si Graphite blends. The full capacity of silicon will never be usable with the high cycle life requirements of the EV market. Instead, silicon will instead be blended with carbon.

Silicon/carbon blend anodes are starting to penetrate the high end consumer cells. In 2010, Panasonic announced the commercialisation of 18650 cells based on Si anodes for 2012. They claimed 500 cycles and 80% capacity retained with a specific energy of 252Wh/kg at cell level. This corresponds to around 1,100 mAh/g of reversible capacity.

Nexeon, a UK based silicon anode manufacturer, claims their first nanostructure anode achieved 1,000mAh/g and that their second generation will achieve up to 3,600mAh/g.

[29] The Honda Fit EV will be fitted with the Toshiba SCiB battery that uses LTO anodes. The battery has been tested since Dec 2010 by Honda and officially qualified in Nov 2011.

The production is still at pilot level and there is no evidence yet that their product can achieve a life cycle matching the EV market needs.

Table 4-5 Comparison of anode properties

	LTO	Graphite	Silicon
Type	Intercalation	Intercalation	Alloying
Theoretical capacity mAh/g	175	330	4200
Voltage vs Li/Li+ (V)	1.5	0.1	0.1
Current collector	Aluminium	Copper	Copper
Main drawbacks	Low voltage & low energy density cell	Safety issues	Volume expansion (up to 300%), poor cycling ability
Development status	New product, in series car in 2012	Commonly used	Si/C alloys used in some consumer cells

4.2.4 Electrolyte

Current electrolytes are liquid (or polymer/liquid), typically a lithium salt (e.g. $LiPF_6$) dissolved in organic solvent. Additives are introduced into the electrolyte to enhance its stability and hence the cell life and safety. A major challenge of current R&D is to increase the electrolyte stability window (ESW), i.e. increase the upper voltage range it can handle. The current upper end of the ESW is around 4.5V.

Developing an electrolyte that is stable at 5V and hence suitable for high voltage cathodes is a formidable challenge. Polymer electrolytes can be used to higher voltages but two barriers have to be overcome: they have lower conductivity than liquid electrolyte, and the volume/interface problem (the need to ensure contact at the interface considering the materials have different volume changes with temperature).

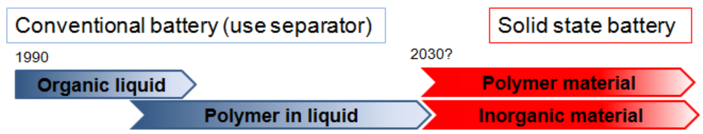
Solid electrolytes have the advantage of avoiding leaks and enhanced safety too but face the same challenges as polymer materials.

Both polymer and solid material electrolyte would dispense with the need for the separator. Some cells are currently labelled ‘polymer’, but this is either in reference to the polymer casing or a polymer in liquid electrolyte, which needs a separator.

All cell manufacturers investigate electrolyte additives to improve stability. Gel-polymer electrolytes are also being investigated, both at lab level and by cell suppliers. Some car OEMs are already working on solid electrolyte R&D (e.g. Toyota); a lot of research is being carried out on this topic in Japan.

Although there has been some progress in terms of polymer conductivity[30], it is still very uncertain when functional polymer electrolytes will enter the cell market. Figure 4-1 provides a high level comparison of electrolyte types.

[30] Masquelier C., Solid electrolytes: Lithium ions on the fast track , Nature Materials, Volume 10, p649–650, 2011



Type	Organic liquid	Polymer liquid	Polymer solid	Inorganic solid
PROS	Currently used	Less leak prone	High safety Cell can be flexible Easy to manufacture	High safety Wide V window Solid (strength)
CONS	SAFETY ISSUES (can combust) Limited voltage window		Under R&D: lower conductivity and volume/interface problem	

Figure 4-1 Electrolyte types comparison

4.2.5 Sulphur metal

Although the concept of the sulphur cathode was demonstrated in the 60s, there are still no commercial rechargeable metal-sulphur cells delivering the high energy density and low cost that they were expected to deliver.

Lithium-sulphur (Li-S) cells are the most advanced metal-S cells. Three main companies are working on their development today: Sion Power/BASF, Samsung, and Oxis Energy. Polyplus used to work on Li-S but sold their patents to Sion Power to concentrate on lithium-air.

Fundamental challenges of Li-S cells to be overcome are the poor rate capacity (i.e. low power), high self-discharge and safety issues with electrolyte stability and use of lithium-metal anode. The loss of capacity is due to the loss of sulphur following the formation of soluble polysulfides that 'shuttle' between the electrodes and can eventually lead to deposition of Li_2S_2 or Li_2S at the anode and elsewhere[31]. This is represented schematically in the figure below.

Although Li-S cells do not use toxic materials, there is a risk of hydrogen sulphide (H_2S, highly toxic) forming if water were to leak into the cell. Another disadvantage of Li-S cells in the context of automotive application is their low voltage (2.2V).

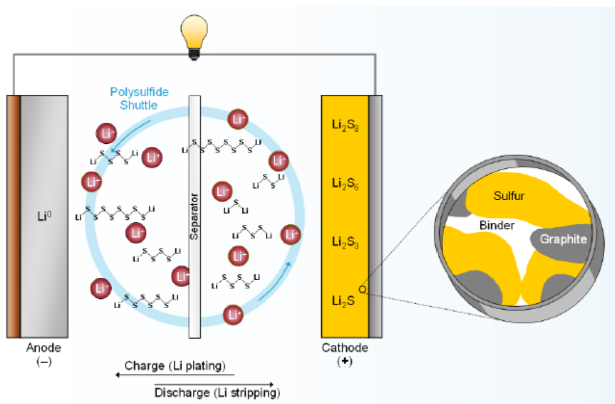


Figure 4-2 Schematic of lithium-sulphur cell. Source: BASF

US-based Sion Power has successfully fitted a Li-S battery in an unmanned aerial vehicle (UAV) in 2010 with a reported specific energy of 350 Wh/kg, but lifecycle performance was not reported. Although Sion Power were targeting small electronics, their area of

[31] Peter G. Bruce et al., High energy storage li-O2 and Li-S batteries

focus might change since BASF, which is targeting the automotive marke, invested $50million to acquire an equity ownership position (January 2012).

Oxis Energy, based in the UK, seems closer to commercialisation with several European supply contracts for e-bike batteries secured. Oxis Energy has numerous patents on Li-S batteries. They claim to have developed a technology that renders their lithium-metal anode safe, as well as having developed an inherently safe electrolyte, two of the greatest challenges the battery industry is facing. They claim their Li-S cell achieves 300 cycles and an energy density of 300Wh/kg. Their product will be independently tested for the first time this year, for homologation for the EU market.

They are partnering with an existing lithium-ion cell supplier in China to manufacture the Li-S cells and packs. Li-S cell production is overall similar to Li-ion cell production and they expect 70% of the existing equipment can be used without or with little modification.

Oxis Energy is also targeting the automotive market. They have been selected to supply Li-S packs for a small series city BEV that currently being developed by French robotic company Induct. Their pilot vehicle is due to be demonstrated next year at the Geneva motor show. In parallel to this pilot vehicle project, Oxis Energy has also started approaching series car OEMs, but the life cycle of their product is not high enough yet for this market. The table below summarises their targets and commercialisation path.

Table 4-6 Li-S battery plans and targets of Oxis Energy

	Commercialisation path	Announced / *target* performance
2012	Testing for homologation of e-bikes batteries for EU market	10Ah 60x120 mm, 2.1V cell. 300Wh/kg (cell) 200Wh/kg (pack) 300 cycles
2013	Production (with Chinese partner) of e-bike batteries (40,000 packs). Demo of Li-S pack in BEV at the Geneva Motor show	*460 Wh/kg cell level* *500 cycles*
2014-2017	Li-S pack in small series BEV (developed by Induct, France) Pack in series car?	*600Wh/kg within 3-5 years* *1,500 cycles by 2014*

Other metal-sulphur batteries include Na-S and Mg-S. There are two types of Na-S cell, high and low temperature. Low temperature Na-S operates similarly to Li-S. Following an accident with high temperature Na-S (grid support application) in Japan, work on this technology has stopped. Na-S cells are susceptible to release the highly toxic hydrogen sulphide and they are not being considered for automotive applications.

Toyota has announced they are starting work on Mg-S batteries, which in theory present fewer safety problems (no polysulphides and hydrogen sulphide).

4.2.6 Lithium-air

Introduction to lithium-air cells

At its purest, a lithium battery relies on the oxidation of lithium ions to release energy. It takes 1kg of pure lithium metal oxides to produce 11,780Wh of energy – a figure very close to that of petroleum. The much lower energy densities achieved in practical Li-ion batteries arise because the weight of the oxidant must be included, heavier elements

(e.g. cobalt) are required to support recharging, and the weight of non-reactive battery components must also be included.

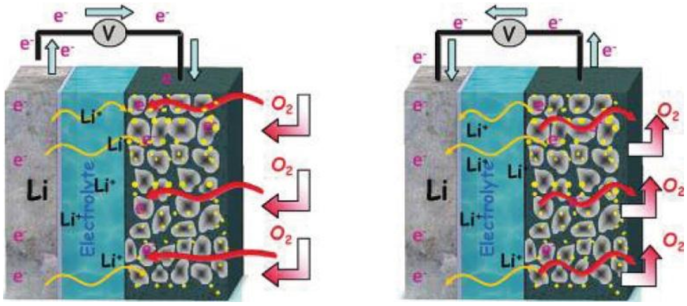


Figure 4-3 Operation of a Li-Air cell under discharge (left) and charge (right).[32]

A common feature of all the lithium battery chemistries introduced in this document is that the electrodes contain all the active material that participates in the charge/discharge reactions. In a lithium-air battery, the oxidant at the cathode is oxygen which is taken from the air around the battery. During discharge:

- Lithium metal from the anode is reduced,
- The lithium ions travel to the cathode,
- Gaseous oxygen from the surroundings is drawn into the cell through the porous cathode, dissolving in the electrolyte inside the cell,
- Oxygen combines with the ionic lithium to form solid Li_2O_2 which precipitates out onto the porous cathode.

The main features of a Li-Air (or more accurately, Li-O_2) cell that increase the energy density relative to a Li-Ion cell, are: (1) the amount of lithium per unit mass of Li_2O_2 is much higher than in lithium metal oxide, (2) the graphite anode is replaced with (generally) pure lithium (3) the cathode electrode is porous, permitting transfer of oxygen from outside of the cell to the inside where it is reduced and binds with Li+ ions to form Li_2O_2 at the cathode.

There are certain practical considerations which arise with a Li-O_2 battery:

- During discharge a Li-O_2 cell will take in oxygen from its surroundings. Therefore, as well as the thermal control issues which Li-ion packs require, packs of Li-O_2 cells will need a sufficient volume of air passing by each cathode, to avoid oxygen starvation. As a guide, a 70kW Li-O_2 pack will require roughly the same volume of air as a 70kW IC engine.
- The porous cathode will require a high throughput air breathing system/membrane which will pass O_2 but keep out water and environmental contaminants such as CO_2.
- During charging, a Li-O_2 cell will release gaseous oxygen. This leads to implications for recharging in confined spaces and avoiding elevated oxygen levels.
- While Li-O_2 has the potential for high energy density, the diffusion of oxygen through the porous cathode is a reaction rate limiting step; the power density of Li-O_2 cells is not expected to be higher than Li-ion cells.

There are two types of Li-O_2 chemistry depending on whether they use an aqueous or non-aqueous electrolyte. The former has been studied since the 1970s and the latter,

[32] Source: G. Girishkumar et al., Lithium-Air Battery: Promise and Challenges, J. Phys. Chem. Lett. 2010, 1, 2193–2203

although first reported in 1996, has only been investigated more intensively since 2006. Some of the challenges to be met are the same for both technologies and some are distinct. Currently, the major performance limitations are capacity fading and voltage gap. These are detailed below (for the non-aqueous type), along with issues to be solved to make a practical Li-air battery.

Scientific advances required for a practical Li-air battery

The success of lithium batteries, combined with the recognition of their long-term limitations, has kindled recent interest in the reversible Li-O_2 battery. The technology has only recently come under sustained study. Recent industry announcements have come from BASF and IBM. Global chemicals company BASF has recently founded a science network composed of academic experts from Germany, Switzerland, Israel and USA to work on the topic. While BASF labels Li-O2 a long term R&D goal, IBM announced more ambitious plans: they will have a prototype Li-air battery for 2013, aiming for commercialisation in 2020.

Many fundamental scientific and technical issues remain to be solved before a practical Li-O_2 battery is available. The most important challenges to the development of a practical battery are outlined below. When considering the potential role for Li-O_2 technologies in an energy system, it is important to bear in mind that it is too early to tell whether these fundamental challenges will in fact be overcome, and a practical Li-O_2 battery will emerge.

Capacity fading

A significant challenge to practical Li-O_2 cells is the considerable fading of cell capacity with cycling.

The example shown here is from a recent paper by Bruce et al. It shows that after 30 cycles the capacity has dropped from circa 2500mAh/g to a level approaching 500mAh/g. In some cases 100 cycles have been achieved, but significant fading still occurs.

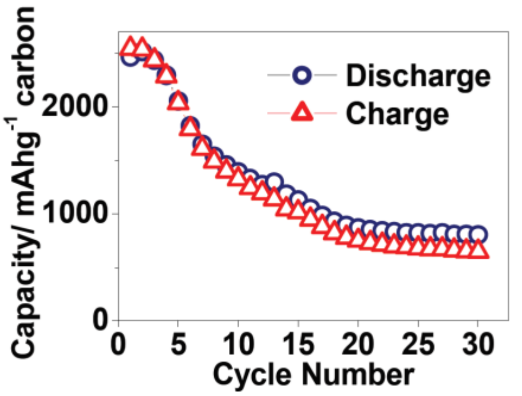


Figure 4-4 Example of Li-O_2 cell capacity fading[26]

Capacity fading is due to the gradual consumption of Li metal in (largely irreversible) side reactions during charging and discharge. Mechanisms for lithium consumption include:

- Side reactions with the electrolyte
- Morphological changes during deposition of Li onto the anode during charging, which can result in lithium dendrite formation and some lithium becoming electrically insulated from the anode.
- Reactions with reduced O_2 from cathode.

A variety of approaches are being investigated to address this issue. For example, the anode may be coated in a Li+ conducting solid layer, insulating the anode from the electrolyte and from reduced O_2. New electrolytes which result in lower Li loss have been announced by IBM.

Overloading the cell with excess lithium at the start of its life is thought to be a pragmatic approach, and this is one factor accounted for in estimates of the reduction of theoretical energy density to practical energy density.

Overvoltage/voltage gap

The graph here shows that during constant current charge and discharge, there is a significant difference in the charging voltage (overpotential) and discharge voltage for a Li-O_2 cell. Therefore the electrical efficiency for a charge discharge cycle is only 65%. If not improved, this would be highly detrimental to the economic and environmental performance of a practical battery.

Currently, the use of electrocatalysts to narrow the gap between the overpotentials is being studied.

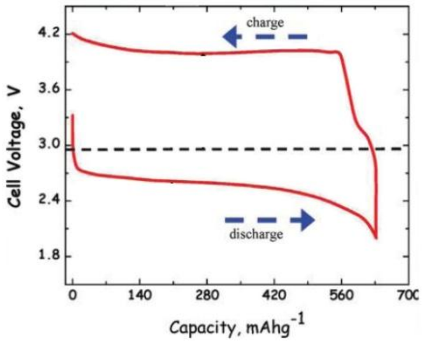


Figure 4-5 Example of discharge-charge cycle for an Li-O_2 cell[32]

Cathode and specific power

The cathode in a Li-O_2 cell has a very complex task, permitting the diffusion of gaseous O_2 through to an interface with the Li+ containing electrolyte. The diffusion of O_2 is thought to worsen with deposition of Li_2O_2 in the porous electrode. The specific power (i.e. mA/cm^2) of Li-O_2 is low at present, thought to be due to the kinetics at the cathode.

Specific challenges of the cathode are:

- The development of a membrane which will pass oxygen but keep out contaminants such as CO_2.
- The development of a porous cathode structure with pores small enough to give high surface area, but large enough to limit the effects of clogging due to the deposition of Li_2O_2.
- Improving O_2 transport - oxygen transport is currently limiting the cell rate.

Safety

Thermal runaway due to overcharging is not possible in Li-O_2 cells because of the rate-limited reaction at the cathode surface. However the use of lithium metal anodes is a possible hazard, with both the potential for pure lithium to be exposed to the air in a serious cell bursting incident, as well as the growth of pure lithium dendrites during charging, possibly leading to short-circuits.

4.3 National programs and international research

International support for battery R&D and industry development is considerable. The split of funding between R&D and industrial development varies by country; government support for these activities also varies widely.

National R&D programs are a relatively small proportion of the total investment in battery R&D worldwide; a single battery manufacturer can invest the equivalent of an entire country's R&D budget. This is true even in the US where the government budget for battery R&D was $76million[33] in 2010; by comparison GS Yuasa (a Japanese battery manufacturer) invested $76million[34] in 2011.

Most of the US national funding is channelled into improving existing lithium ion intercalation chemistries, with the 2009 Recovery Act allocating $1.5 billion for

[33] DoE, Annual Merit Review and Peer Evaluation Meeting, Energy Storage R&D, 2011
[34] Company accounts 2011

manufacturing and material improvement[35] ; Figure 4-6 shows the corresponding funding split.

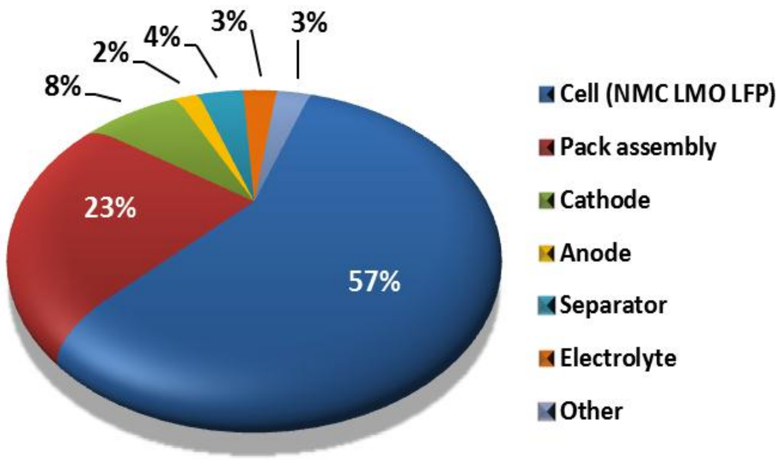


Figure 4-6 DoE funding split for manufacturing and material improvement of lithium-ion batteries

Industry funded R&D is highly secretive and often a new technology (R&D stream) is only known about in press releases before mass manufacture, or through patent applications. A large proportion of world battery R&D is carried out in this way by companies such as; Panasonic/Sanyo, Samsung, Sony, Toshiba, LG Chem, Mitsubishi, Hitachi, Toyota, GS Yuasa, Lishen, BYD and 3M. Due to their secretive nature, the R&D spent on automotive batteries for the majority of these companies remains difficult to estimate.

The US and Japan lead the world in national battery R&D funding. The US research program is transparent and we have collected significant detail about the funding distribution and research areas[36]. This, combined with other inputs has been used to inform the model technology roadmap (presented in the next section).

The US, Japan and Europe have considerable national battery R&D programs and more recently South Korea and China have been setting up government and industry funded research labs. Although the US may lead in national funding, Japan leads in industry R&D funding as many of the established battery manufacturers are Japanese companies. Most research programs have specific cost and performance targets and roadmaps that the funding is meant to accomplish, these can of course vary between countries. An example of a roadmap (Japan's) is shown in Figure 4-7.

The main countries within Europe funding battery R&D programs are France and Germany, with a future vehicle R&D funding worth up to €60million p.a. per country. Germany's Fraunhofer Institute has created a detailed roadmap for battery technology development and implementation for Germany. There is, as yet, no Europe wide roadmap or program.

[35] DoE - NETL, Progress of DOE Materials, Manufacturing Process R&D, and ARRA Battery Manufacturing Grants, 2011
[36] Especially DoE merit review papers that can be found at http://www1.eere.energy.gov/vehiclesandfuels/resources/proceedings/2011_merit_review.html

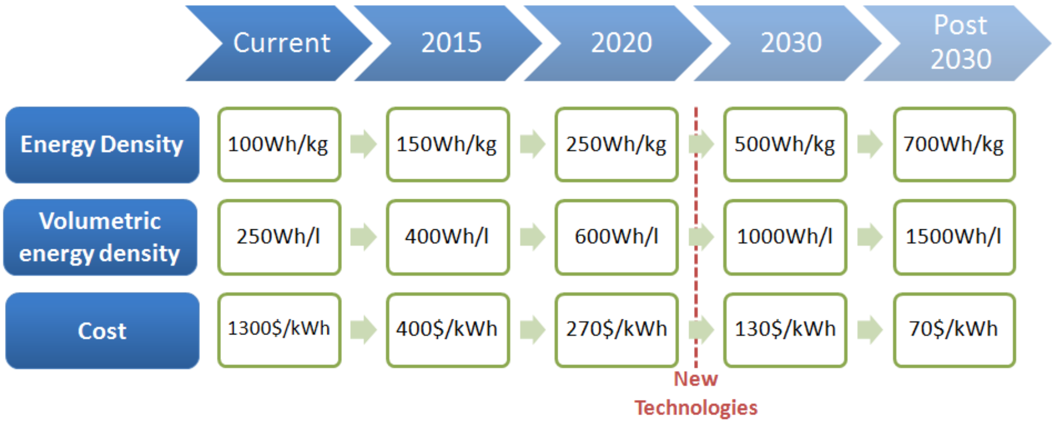


Figure 4-7 Japans EV battery roadmap. Source: French embassy in Japan 2010, yen prices converted using $1=75¥

South Korea, an increasingly large player in the battery production market, had set aside $2.7billion[37] for R&D related funding for vehicle electrification technologies in 2010, more than the current U.S. funding ($2billion in total for vehicle electrification[35]). However there is no public report on spending and progress.

4.4 Technology roadmap

A review of key challenges to improvement of current chemistries and development of post-lithium-ion chemistries shows there is scope for energy density improvement with intercalating cathodes, and that this is a more realistic target in the short/medium term than post-lithium-ion technologies. This is reflected in international research programs; they stage their targets according to the level of difficulty associated with each technology.

Lithium-ion cells (intercalation cathode)

A detailed technology roadmap has been developed for Li-ion cells, based on this predicted continued dominance of lithium-ion chemistries. The technology roadmap is a trajectory of electrode materials type and performance (reversible capacity, mAh/g and voltage), and will be used as an input for the cost modelling. It has been informed by a review of research papers and R&D plans of surveyed cell suppliers, and developed with the help of our academic partner. The roadmap has 4 milestones: 2015, 2020, 2025 and 2030.

The year of entry in the roadmap corresponds to a judgement on the date of maturity of a given technology for vehicle applications, i.e. when it can answer power, safety and life requirements of EVs. Lessons learnt from past data on development time from proof of concept R&D to a product that is vehicle compliant have been taken into account.

Several technology roadmaps have been developed, corresponding to three scenarios on spend and progress of R&D: a baseline case, a 'slow R&D' case and 'fast R&D' case.

In the baseline case, current materials improve (mAh/g and/or V) and new materials get developed for the vehicle market. Electrolytes allowing for 5V cathodes become possible and high voltage cells (>4.5V) enter the market by 2025. The anode capacity will improve greatly with the introduction of silicon alloy anodes in automotive cells by 2020. These will have 1000mAh/g reversible capacity, increasing to 1750mAh/g by 2030.

[37] Pike Research, Green Car Race in Asia: Two Fast Runners, 2010

The increase in material capacity and/or voltage translates into a greater energy density and – because the volume of active material is assumed constant – cells with a greater capacity (Ah) in the case of increased mAh/g. The expected cost reductions brought by greater energy density are outlined in Appendix 8.3.2.

The slow R&D scenario is conservative, and some scientific challenges are not solved, such as electrolytes that allow for high voltage cathodes. Overall there is slow improvement in materials, and silicon anodes make their way into automotive cells from 2025 only. On the other hand, the fast R&D case is an optimistic scenario: material breakthroughs are introduced as soon as 2015 and silicon anodes from 2020. Slow and fast R&D roadmaps are illustrated in Appendix 8.3.2.

Figure 4-8 shows the cell gravimetric energy density resulting from the materials used in the baseline scenario. In the polyanion cathode family, it is assumed that LiMnPO4 (LMP) replaces LFP by 2020 bringing the voltage to 4V, while 5V Li(M)SO4F cathodes are assumed to be ready for the car market from 2025. In the spinel family, 4.5V LMNO cathodes would supplant LMO by 2020. By 2025, layered-layered cathodes (labelled 'LL' on the graph), with capacities greater than 200mAg/h, would take the cell energy density above 200Wh/kg. The optimisation of NMC type of cathodes could see their reversible capacity increased to 200mAh/g (for 3.7V).

Table 4-7 Cell density targets

Cell Wh/kg	2015	2020
Supplier A	180	220
Supplier B	250	-
Supplier C	150	200

These cell energy density results are more conservative than other published battery performance roadmaps – mostly because they are specific to the demanding automotive market. High energy densities will be achieved sooner in the consumer cell market. Table 4-7shows the cell energy density targets of three surveyed cell suppliers. With the exception of the supplier B in 2015, the other targets match the baseline roadmap.

It is worth noting not all chemistries included in the roadmap would be suitable for both BEV and PHEV. For example, todays composite cathodes (layered-layered) show poor power capability and are thus unlikely candidate for PHEV cells.

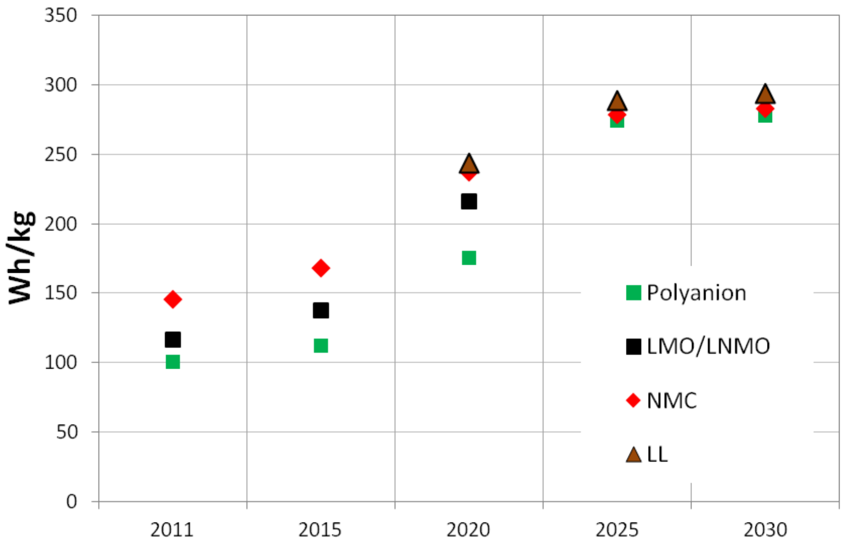


Figure 4-8 Lithium-ion energy density (Wh/kg) at cell level in the baseline R&D scenario for different types of cathodes

Post lithium-ion cells

Post lithium-ions have great challenges to overcome (briefly outlined in section 4.2) before they reach the automotive market if they do at all. Assuming a maturity date is very speculative.

Nonetheless, based on recent progress of Li-sulphur cells (presented in previous sections) and if their life cycle properties were to be improved, a base scenario would see their entry in the car market in 2025 with an energy density of 350Wh/kg, increasing to 500Wk/kg by 2030. A more aggressive scenario would see 300Wh/kg Li-S cells by 2020, increasing to 500Wh/kg by 2030.

Batteries using lithium-air cells have a greater energy density potential (see Table 4-1, up to 1,000Wh/kg for cells) and are receiving the most R&D of any of the post Li-ion batteries. Lithium-air batteries are used as the only proxy for post-lithium technologies in the long term cost modelling (post 2030).

Summary

- The current research emphasis is on improving lithium-ion batteries (intercalation). The main R&D challenges are around life, safety and power requirements.
- Through the development of high voltage cathodes or high capacity cathodes, the specific energy of lithium-ion cells has the potential to increase from ~170Wh/kg today to ~290Wh/kg by 2030. High voltage cathodes however require overcoming a substantial challenge: developing an electrolyte that can withstand a voltage at which organic materials breakdown.
- A detailed technology roadmap of lithium-ion cathode and anode characteristics was developed, to be used in the cost modelling, for up to 2030.
- Post lithium-ion technologies have the potential to deliver much higher specific energies, up to 1,000 Wh/kg in the case of lithium-air, and could therefore deliver a 500km driving range, something that will not be possible for Li-ion. They however are still far from commercialisation in the automotive market with several fundamental R&D challenges to be resolved.
- Estimating a date of technology readiness for various post-lithium-ion technologies would be very speculative, and has not been not attempted. Instead, only the technology with the greater theoretical energy (lithium-air) will be used to model longer term (post 2030) costs.

5 Cost and performance model

The objective of the cost and performance model is to answer the following questions and produce the following outputs:

1. predict the cost of different battery packs through time (out to 2050)
2. allow the performance of battery packs to vary in line with key uncertainties
3. show the key drivers behind the costs of batteries
4. identify the largest cost components of battery packs
5. identify the key areas requiring R&D to reduce battery costs

5.1 Review of existing models

There are a large number of battery cost models used world-wide. To ensure that the model incorporates state of the art techniques, an extensive review of over fifteen of the most referenced battery cost models was undertaken. EPRI[38] (Electric Power Research Institute) in 2010 undertook a similar review of seven of the most used models with an in-depth review of two of the bottom up models. The conclusions of this study and its grading criteria were used to inform the larger, more general, review of existing models undertaken in this study. The three key cost dependencies identified in the EPRI report are: cell size, cell production volume and standardization.

5.1.1 Modelling methodologies

There are three main approaches to modelling battery costs, each with their own merits and limitations.

Table 5-1 Merits and limitations of modelling approaches

Model Attribute	Bottom up	Top down	Hybrid
Can produce long term time dependent forecasts easily?	No	Yes	Yes
Allows the performance of the batteries to be modelled from explicit improvements	Yes	No	No
Level of detail of the key drivers behind costs	High	Medium	Medium
Level of separation of the cost components	High	Medium	High
Level of R&D needs identifiable	High	Low	Medium
Number of inputs	High	Low	Medium
Detail of outputs	High	Low	Medium
Takes into account specific improvements in manufacturing techniques	Yes	No	No
Allows the effect of battery cell capacity and structure to be modelled directly	Yes	No	No
Non direct costs modelled	Yes	No	No

- **Bottom up (component based)**

This method is based on a detailed set of inputs, uses a specified manufacturing process (with associated costs) and specifies a design of a battery pack. The EPRI study concluded this was the most informative and useful model format, with assumptions generally more explicit and better documented than the 'top down' approach.

38 EPRI, Large-Format Lithium-Ion Battery Costs Analysis - Critical Review of Existing PHEV Lithium Ion Battery Cost Studies, 2010

- **Top down**

This is the preferred method used by financial institutions. From a starting reference year, learning rates are applied to the different battery cost components, using historical learning rates or primary analysis with industry consultation. This kind of analysis is very good for identifying overall patterns of developments in industries, but often does not have the explanatory power to identify the origin of changes, or fundamentals which might constrain such changes in the future.

- **Hybrid**

This uses a combination of the two models, starting from a bottom up model but with industry informed trajectories on costs and performance improving the validity of the results through time.

To ensure that no important models were overlooked in our review the following process was used:

- A search of all the major battery research programs and institutions worldwide,
- Consultation with battery industry experts and private discussions with manufacturers,
- A recent publications search including conference proceedings and merit reviews.

A summary of a selection of reviewed models is shown in Table 5-2; some comparative fields are also explored in this table.

Table 5-2 Summary of attributes of different battery cost models used worldwide

	Time dimension	Allows performance changes?	Shows key drivers?	High level outputs	Detailed outputs	Bottom up model?	Level of access to inputs	Detail of process	Production volume effect
ANL	No	Yes	Yes	Yes	High	Yes	High	High	Yes
DLR	No	Yes	Yes	Yes	Low	Yes	Moderate	Moderate	-
TIAX	No	Yes	No	Yes	Moderate	Yes	Moderate	Moderate	-
Roland Berger	Yes (2020+)	No	Yes	Yes	Moderate	No	Moderate	Low	No
Avicenne	Yes (2020)	No	Yes	Yes	Moderate	Yes	Low	Low	-
Boston Consulting	Yes (2020)	-	No	Yes	Moderate	No	Low	Low	-
CARB	No	No	Yes	Yes	Low	No	High	High	Yes
Deutsche Bank	Yes (2020)	No	No	Yes	High	No	Low	Low	Yes

5.1.2 Review of state of the art battery cost models

From the initial review, further interrogation of two state of the art models was carried out: a bottom up model and a top down model, both developed in 2011. They stand out from other models by the transparency of the assumptions and thus usefulness.

Bottom up model – ANL's BatPaC 2011

Argonne National Laboratory (ANL), in the US, has extensive knowledge of the battery industry and is a leading research entity, with the 5th largest number of international

research papers on lithium battery topics of any institution in the world[39]. Over the past 10 years they have performed extensive bottom up analyses of lithium ion batteries. They have produced the most detailed bottom up model available[40] today; it has been industry peer-reviewed and comes complete with detailed documentation.
This model allows performance changes; several different battery chemistries are modelled and **measured chemical properties** of different materials are core inputs. Each stage in the manufacturing process is modelled separately; it assumes a highly optimised manufacturing plant built for production in 2020 to provide for a consolidated EV market. Due to the detail of the model the key drivers behind battery cost and performance can be derived – some are detailed in Appendix 8.3.

The key advantages of the BatPaC model that match our model requirements are the bottom up approach of the cell design (it designs a cell from first principles) as well as the links between production costs and cell design and volume.
The restrictions compared to our model requirements are the lack of a time dimension (outputs values for 2020 only) and the limitation to chemistries that can currently be measured in the lab (in terms of power, capacity and physical properties).

Top Down model – Roland Berger 2011

This is one of several top down models used in market and performance projections in the battery and financial industries. The Roland Berger model is regarded highly by some industry players and has the advantage of showing cost trends over time. It explains the key drivers behind cost reductions, but not explicitly how these will change through time.

One of the advantages of this approach which matches our model requirements are the explicit change in costs of cell materials through time as the industry grows. The main limitation of the Roland Berger model is that it cannot distinguish between different battery pack capacities and properties.

Figure 5-1 compares the aforementioned model results for 2020 (ANL) and long term (Roland Berger). The ANL cost is significantly lower, mainly because highly optimised manufacturing is assumed, along with very low pack component costs (BMS, housing etc). Cell manufacturers interviewed for this work view the ANL results as too optimistic for 2020 but recognise the approach in terms of cell design and link between production cost and volume is sound.

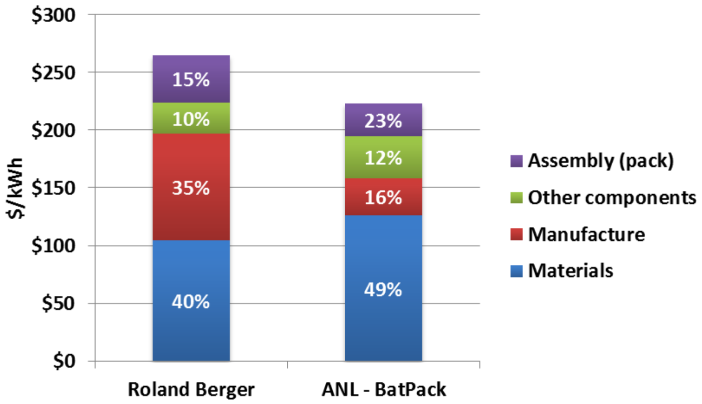


Figure 5-1 - Comparison of Roland Berger model 'long-term' results and ANL – BatPaC model 2020 outputs (20kWh NMC)

[39] METI 2009 (papers published between 1998-2007, 241 papers)
[40] Available at http://www.cse.anl.gov/batpac/

5.2 Chosen methodology

Based on our review of existing state of the art models we have chosen to use a bottom up model for intercalation cathode cells (similar to existing cells) out to 2030, with cost and performance inputs derived from a technology review, and top down analysis including learning rates. The model incorporates the state of the art methods from some of the existing models and has been expanded and modified to create an extensive bottom up model that has time, chemistry and application dimensions.
Post-lithium ion cells for long term cost projections are dealt with differently, due to their uncertain architecture.

Bottom up model – lithium-ion technologies

A bottom up approach gives the highest resolution of data and the highest level of interpretation of the sensitivities while a top down analysis of inputs is necessary to bring a time dimension to the model.
Existing models have been used to identify key cost drivers to integrate in our model, in particular the ANL model for cell design, production cost and volume effect on production costs. We also used the Roland Berger model approach to consider cell material cost trends.

The schematic below summarises the model approach and inputs that change with time:

- The active material properties (mAh/g, voltage) are an input that changes with time, in line with expected material improvement brought by current R&D effort. This is detailed in section 4.4.
- The active material cost inputs are based on top down analysis that takes into account the expected production difficulty of future materials.
- The cost of purchased pack components (BMS, housing etc) is decreased using learning rates.
- The production plant CAPEX is decreased from today's observed cost to the lower bound values, based on the ANL plant.

All model inputs and assumptions are detailed in Appendix 8.3.

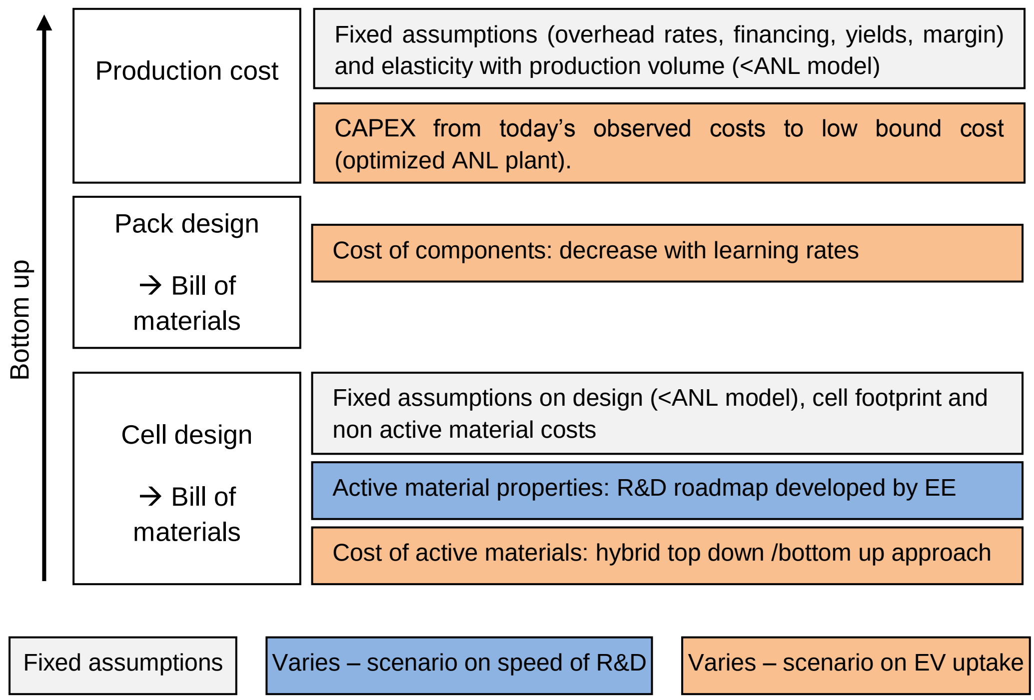


Figure 5-2 Summary of the bottom up approach and type of assumptions

A detailed flow diagram of the model is included in Appendix 8.2, a simplified and annotated version of the flow diagram is shown in Figure 5-3.

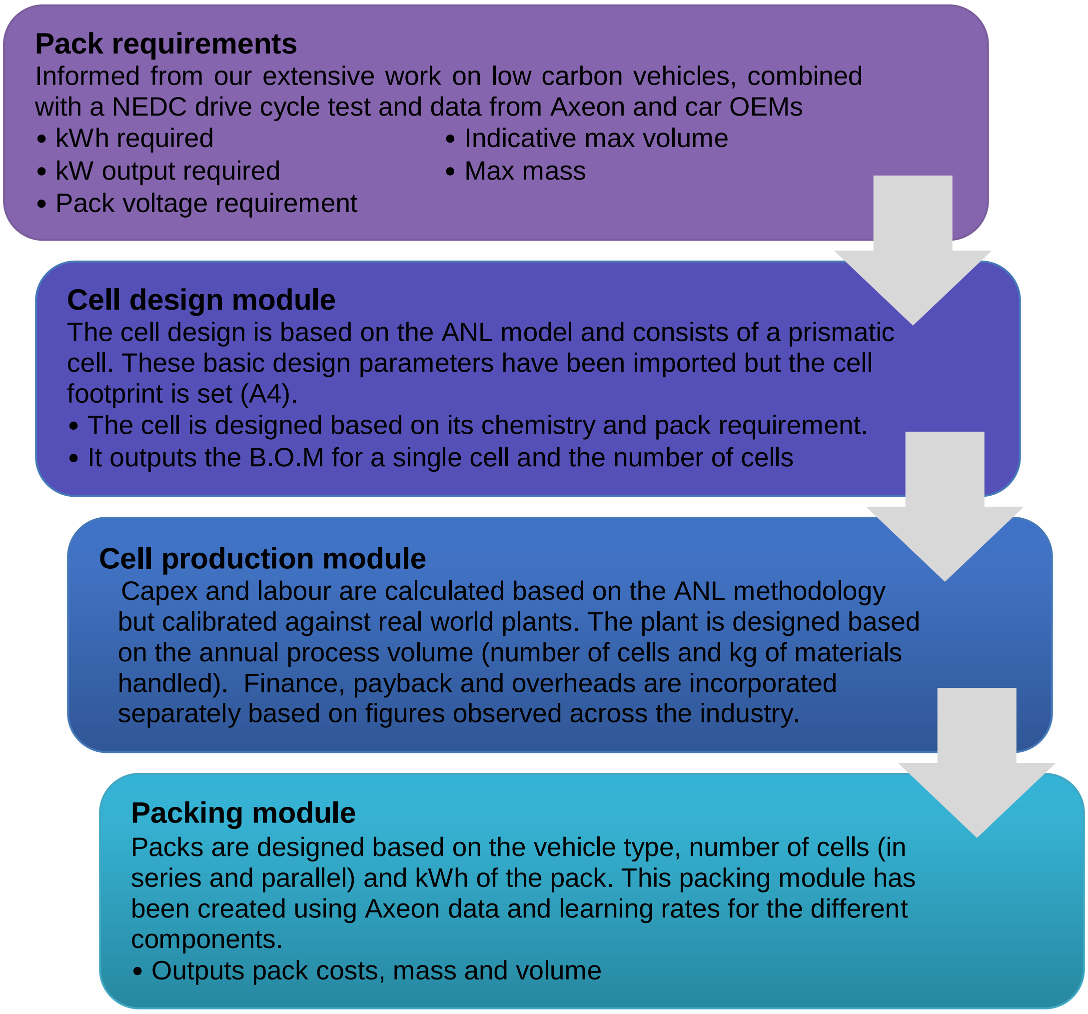


Figure 5-3 – Simple bottom up model module diagram with explanations

Long term cost – post-lithium-ion technologies

Using the bottom up model results from 2030 as a starting point, long term costs are estimated for lithium-air cells. The costs of the main components of the 2030 lithium-ion cells are projected for Li-air cell based on judgement of the new materials needed. The process is described along with results in section 7.

5.3 Key assumptions and scenarios

Key assumption - Standardisation and manufacturing of large cells

At the core of the model is the assumption that some degree of standardisation in large cell manufacturing will emerge in the coming decade, in line with the CCC transport roadmap that envisages policy support that stimulates electric vehicle uptake.

It is assumed that manufacturing improvements will make standardised quality large cells achievable, at high production yields, by 2015. The adjective ‘quality’ refers here to the high standard of consistency, safety and life that automotive packs require.

EV uptake and production volumes

In the model, three cost areas are affected by standardisation and learning brought by cumulative production: cell material costs, cell production (plant capacity and CAPEX), packing costs.

The production costs are based on the methodology developed by ANL for their BatPaC model. It reproduces the relationships between volume (e.g. quantity of material handled, number of cells produced) and manufacturing cost. The ANL BatPaC plant costs are used as the lower bound of our CAPEX plant costs; it assumes a highly optimised plant, producing one type of cell, operating after a large adoption of EVs.

This lower bound manufacturing cost, corresponding to a consolidated EV market, is assumed to be reached by 2025 in the base case. This would correspond to a global EV uptake following the same trajectory as HEVs since 2000, thanks to policy support in developed countries, to reach around 1% of global sales by 2020 (~4million cumulative sales).

Cell production assumptions, material costs and packing costs are detailed in section 8.3.

Material improvement

It is expected that the current R&D on cell materials will deliver increased energy density and bring new, cheaper materials into cells. Several R&D scenarios have been developed around this theme, presented in section 4.4.

In the baseline scenario, lithium-ion cells answering the automotive market needs (safety, power, life) exceed 200Wh/kg by 2020 and reaches 290Wh/kg by 2030.

Post-lithium-ion chemistries, represented by lithium-air, would deliver up to 1000Wh/kg.

Scenarios

The baseline technology roadmap together with the central EV uptake constitutes the base case of the lithium-ion battery model. The central EV uptake scenario represents a successful trajectory for EVs, i.e. their uptake, supported by policy, increases steadily and advances in materials bring high energy density cells.

Two other scenarios have been developed to represent alternative narratives. A more conservative scenario (‘Niche EV’) sees slower material improvements and no EV uptake beyond niche or localised markets while the third scenario is very optimistic (‘EV push’). In the ‘Niche EV’ scenario, progress on materials is made, and cell production costs do decrease over time, despite the globally low uptake of EVs. It is assumed other emerging large cell markets (e.g. grid back up) will grow and contribute to innovation and cost reduction.

The 'EV push' scenario corresponds to quick EV uptake and material improvements, bringing the production costs to their optimized level as early as 2020. The table below summarises the scenarios.

Table 5-3 Main model assumptions and scenarios

Scenario	R&D path	EV uptake
Niche EV	**Slow R&D** This is a conservative scenario. Some scientific challenges do not get overcome (5V electrolyte, capacity cathode >200mAh/g). Overall little/slow material improvement, silicon blend anode from 2025. Cells at 200Wh/kg by 2020 and 260Wh/kg by 2030.	**Low uptake** Lack of strong policy support and no rapid improvement in cost/performance of EVs means EVs stay a niche product for at least a decade (<1% global sales by 2020). This corresponds to 3 million cumulative sales by 2020. Learning brought by cumulative production drives the cell production cost (CAPEX) down. The low EV uptake means the production cost are not optimized before 2030.
Baseline case Steady EV	**Baseline R&D** Baseline scenario. Existing materials improve and new materials get developed. 5V cells become possible. Silicon blend anode from 2020. Cells at 250Wh/kg by 2020 and 290Wh/kg by 2030.	**Baseline uptake** Plug-in vehicle uptake follows the same path as hybrid vehicles since 2000, thanks to policy support in developed countries. This corresponds to 4 million cumulative sales by 2020. Learning brought by cumulative production means production costs are optimized by 2025.
EV push	**Fast R&D** This is an aggressive/optimistic scenario. Faster introduction of the baseline R&D. Material breakthrough introduced as soon as 2015. Cells at 280Wh/kg by 2020 and 300Wh/kg by 2030.	**Stretch uptake** In line with the CCC central scenario of uptake in the UK – this corresponds to a strong global policy push, delivering over 5% EV uptake at global level by 2020. This corresponds to 16 million cumulative sales by 2020. The fast uptake means production costs are optimized by 2020.
More details on assumptions provided in:	Section 4.4 Appendix 8.3.2	Appendix 8.3.3 for cell material costs Appendix 8.3.4 for production costs Appendix 8.3.5 for packing costs

Caveat on PHEV results

PHEV cells differ from BEV cells in their relative power requirements, with PHEV cells having a higher power to energy ratio. This makes their cost very sensitive to defined vehicle power requirement. Results shown for PHEV cells are therefore very dependent on the definition of the modelled vehicles and are by no means applicable to all kinds of PHEVs. Power capability of future materials is also poorly documented. While the energy content is an intrinsic characteristic property of a given material, i.e. the theoretical energy density can be calculated from the molecular weight of material, power (speed of release of the energy) must be measured and varies with parameters such state of charge of the cell and cell design parameters. PHEV results have therefore been run only for existing cathode chemistries (LMO, LFP) or chemistries with similar power capability to existing chemistries (LMNO).

Summary

- Based on a review of existing models, a bottom up approach to cost modelling of lithium-ion cells was selected. Key cell design assumptions and the elasticity of production costs to the volume of material handled are based on the state of art, peer-reviewed model, developed by Argonne National Laboratory.
- Key cost inputs feeding the bottom up model are developed through a top down approach, e.g. learning rates are applied to pack components.
- At the core of the model is the assumption that some degree of standardisation in large cell manufacturing will emerge in the coming decade, in line with the CCC transport roadmap that envisages a policy support that stimulates the uptake of electric vehicles.
- Scenarios have been developed around the anticipated main cost reduction drivers: the improvement in material properties delivering higher energy densities (based on technology roadmaps) and the speed of cost reduction of manufacturing & material cost (based on EV uptake assumptions).
- Costs of long term post lithium-ion technologies cannot be modelled directly with a bottom-up approach. Their cost is modelled on an estimate of lithium-air battery cost that takes into account the technology barriers to be overcome.

6 Battery cost and performance to 2050

Battery cost and performance results presented here are split between 2012-2030 outputs of the bottom up model approach (lithium-ion batteries) and longer term results based on an approximation of lithium-air battery cost.

6.1 Bottom up model results to 2030

The lithium-ion battery costs and specific energy to 2030 have been modelled for both BEV and PHEV vehicles. The results presented focus on the medium size car (C&D class) and van battery packs. Results for other vehicles types are available in the Appendix.

Note: the model results between 2015 and 2030 are in 5 years intervals. Values shown between time steps are simple linear interpolated values.

6.1.1 Baseline outputs

6.1.1.1 BEV results

In the baseline case, battery pack costs decrease to \$320/kWh in 2020 and \$215/kWh in 2030 at pack level for a C&D car (30kWh total energy). Costs are lower for a van as the pack is bigger (69kWh total energy), as shown in Figure 6-1.

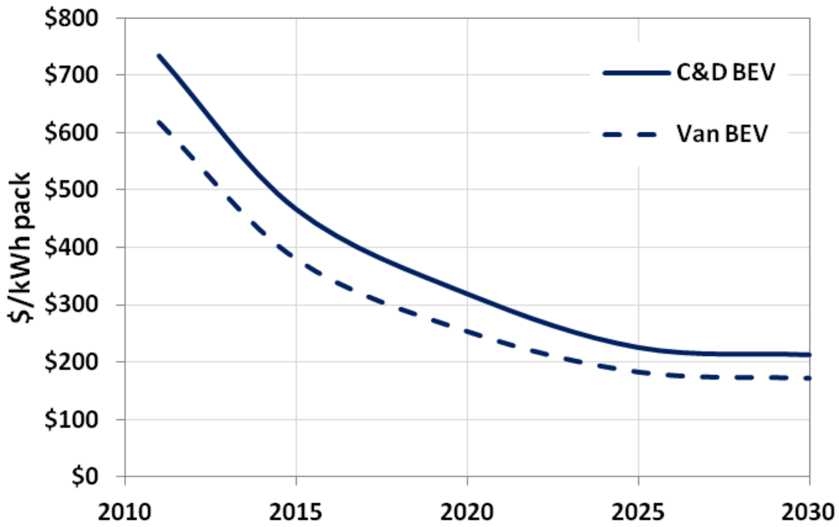


Figure 6-1 Baseline cost results (\$/kWh pack) for 2011 BEV C&D car and van

The price advantage (per kWh) of larger packs is due to two factors: reduced cell costs resulting from larger cells (>100Ah by 2030) and reduced packing costs as fixed costs (such as housing and power electronics) are spread over a larger total of kWh. This is illustrated in Figure 6-2; the packing cost component represents a larger share of the cost in the smaller pack.

The lowest costs achieved by the chemistries of the technology roadmap - presented above – correspond to spinel cathodes in 2015, high capacity cathodes in 2020 (LL), high voltage cathodes from 2025 (e.g. $Li(M)SO_4F$) and silicon alloy anodes from 2020.

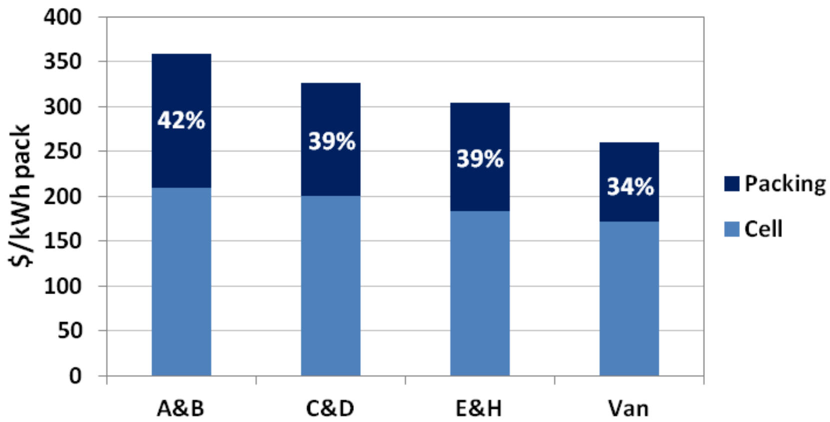


Figure 6-2 Cell and packing cost split in 2020 for the four defined BEV types

The specific energy of battery packs increases from around 100Wh/kg today to 150Wh/kg in 2020 and 185Wh/kg from 2025 at pack level for a C&D car. As with costs, bigger packs are at an advantage because the packing weight overhead is spread over more kWh; see Figure 6-3.

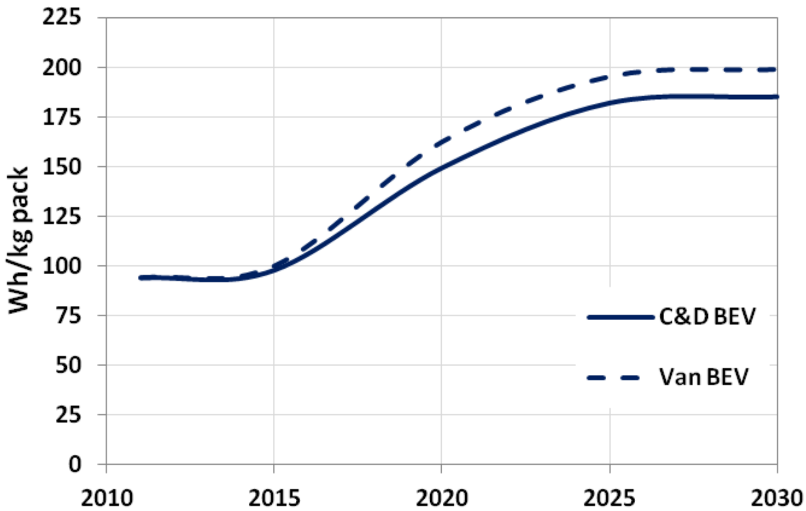


Figure 6-3 Baseline specific energy results (Wh/kg pack) for BEVs

Life expectancy

Today's cells can achieve a 10 year life and over 1,000 cycles at 100% DOD in laboratory conditions (albeit with variations in life performance across the different cathode chemistries, see 3.2). In the field, these figures should be achievable under temperate climates and provided a thermal management system keeps the cells at their optimum temperature range. In the model, advanced thermal management costs are accounted for, even in the long term.

Based on the expected improvements in thermal control and management, it is reasonable to assume that future cells will achieve a 12 year lifetime (temperate climates) and at least 1,000 cycles at 100%DOD[41] from 2020.

If the packs are oversized to restrict the useable DOD/SOC window to 80%, this cycle life can increase to 1,500 cycles[42]. For a 2020 C&D car this translates to a distance limit of

[41] Reminder: 100% DOD is used for cell testing/benchmarking but not on cells used in vehicles.

250km x 1,500 = 375,000 km. This is a theoretical value as, in practice, the time to achieve over 1,000 cycles with an EV pack might exceed the calendar life of the pack.

An 80% DOD window corresponds to today's typical BEV pack design. Improvements in material power capabilities and life characteristics could see this value increase to 90%; more of the carried energy (kWh) will be useable and the total pack cost lower.

Results at pack levels for a C&D car are shown below, for both 80% and 90% DOD/SOC windows. For comparison the cost of a 150km C&D car pack is estimated at $21,000 in 2011. Results for other vehicles are available in Appendix 8.5.

Table 6-1 Pack costs ($) for C&D BEV (~250km range) for 2 pack design approaches

BEV C&D car	2020	2025	2030
80% DOD/SOC window - 30kWh Conservative life characteristics – recommended assumption			
Pack cost ($)	$9,620	$6,790	$6,400
90% DOD/SOC window - 27kWh Optimistic life characteristics			
Pack cost ($)	$8,960	$6,330	$5,975

6.1.1.2 PHEV results

PHEV packs are less generic than BEV packs in terms of power requirements; OEMs can choose different drivetrain strategies (e.g. develop power focused and energy focused cells in the pack; combine power of IC engine and motor). Also, the costs per kWh of PHEV packs are very sensitive to the power to energy ratio, i.e. the chosen range and vehicle power. Figure 6-4 illustrates this sensitivity to total energy; it shows baseline model results for a C&D PHEV 60kW pack, for different total pack sizes.

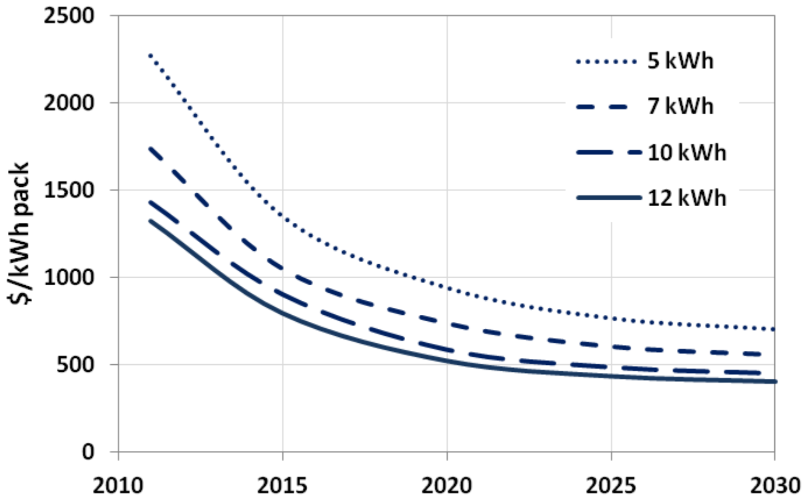


Figure 6-4 PHEV pack cost ($/kWh) for C&D 60kW pack for various pack sizes

[42] Based on an independent third party analysis on competitive products carried on cells. This varies with chemistries. Pack assembler Detroit Electric claims the LFP cells they use achieve 3,000 cycles at 80%DOD.

The cost per kWh of small 5kWh packs[43] is 80% higher than for 12kWh packs in 2020 ($940/kWh Vs. $525/kWh), i.e. small packs are relatively uneconomical. Doubling the pack size to 10kWh comes at only a 25-30% premium on the total pack cost, at $14,335 for 10kWh compared to $11,370 for 5kWh in 2011.

This mitigates against one of the proposed advantages of PHEV's, that the smaller battery capacity leads to proportionally lower cost. This indicates that plug-in hybrid drivetrains might not be appropriate for small city cars that have low energy consumption but might rather be more suited to upper end car segments. It also means PHEV pack costs should always indicate the pack size assumption and not be linearly scaled from BEV pack costs and capacity.

Figure 6-5 shows the specific energy trajectory for two PHEV packs. As for BEVs, larger packs have both an energy density benefit and cost benefit, in part due to the lower packing cost per kWh of larger packs; see Figure 6-6.

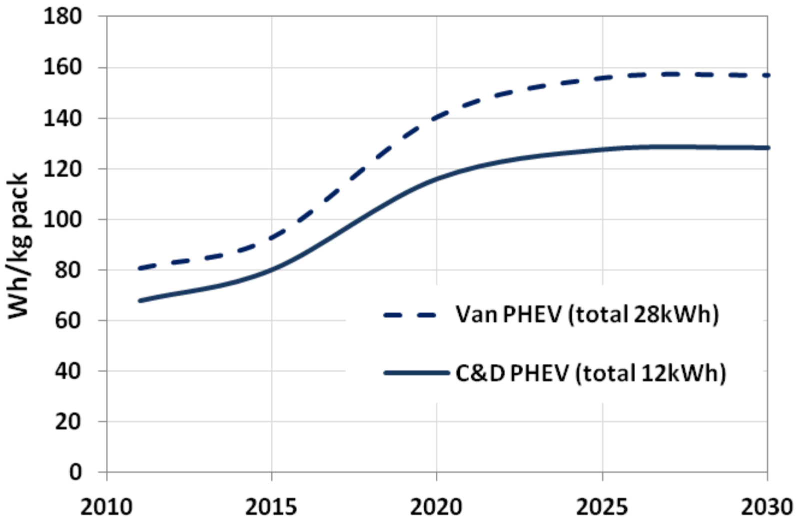


Figure 6-5 Baseline specific energy results (Wh/kg pack) for PHEVs

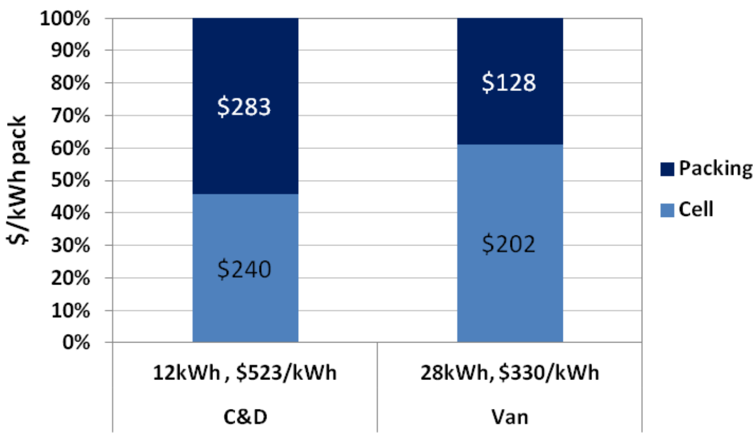


Figure 6-6 Cell and packing cost split in 2020 for PHEVs packs

[43] A 5kWh pack with a 70% usable window corresponds to 20-25km electric range based on today's vehicle estimated energy consumption of 0.155 kWh/km for a C&D class vehicle.

Life expectancy

Achieving a 12 year life time and ensuring good power capabilities over this lifetime will require limiting the usable DOD/SOC window. Table 6-2 shows pack cost results for two different assumptions on usable window: 70% which is observed today and 80% which assumes an improvement in life and power characteristics of packs compared to today.

Table 6-2 Pack costs ($) for C&D PHEV (~80km range) for 2 pack design approaches

PHEV C&D car	2020	2025	2030
70% DOD/SOC window – 12.2 kWh Conservative life and power characteristics – recommended assumption			
Pack cost ($)	$6,350	$5,280	$4,900
80% DOD/SOC window – 10.6 kWh Optimistic life and power characteristics			
Pack cost ($)	$6,025	$4,990	$4,625

6.1.1.3 Comparison of BEV and PHEV results

This section compares the results on BEV and PHEV packs from the previous sections, to highlight and comment on the cost difference. The PHEV pack comes with a significant cost premium, between 70 to 90% more expensive in $/kWh compared to the BEV pack; see table below.

Table 6-3 Baseline pack cost results for C/D car BEV and PHEV

Total pack size and type		2020	2025	2030
BEV 30 kWh	$/pack	$9,620	$6,790	$6,400
	$/kWh	$320	$225	$215
PHEV 12 kWh	$/pack	$6,350	$5,280	$4,900
	$/kWh	$525	$435	$405

The reason for this premium is a core difference between the power requirements of PHEV and BEV packs. It translates in:

- Higher cost of PHEV cells (~$50-70/kWh premium at cell level for 2020-2030). This comes from the use of smaller cells which results in higher cell production costs per kWh and the use of chemistries which are better suited to the higher discharge rate. PHEV results have been run only for existing cathode chemistries (LMO, LFP) or chemistries with similar power capability to existing chemistries (LMNO). This is because the power capability of other future cathode materials is either poorly documented or not expected to be high enough for a PHEV cell.

  The 2020 results shown above are based on LMNO cathode (120mAh/g) for the PHEV whereas the modelled BEV cells are fitted with a cathode of high capacity (200mAh/g). This difference in cell design results in distinct energy densities: 205Wh/kg for the PHEV cells vs. 240Wh/kg for the BEV cells.

- Higher cost of pack components for PHEVs, a consequence of the higher power to energy ratios, as PHEV cells discharge more quickly. This is the main source of

added cost as shown by the comparison of cost breakdown ($/kWh) for BEV and PHEV packs in Figure 6-7.

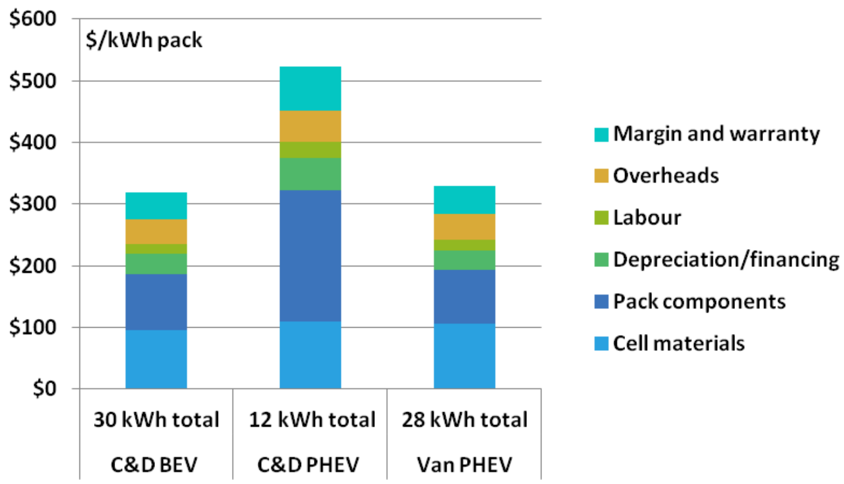


Figure 6-7 Pack cost ($/kWh) comparison in 2020 for BEV and PHEV applications.

Figure 6-8 gives a cost breakdown of the pack components. The main difference between the BEV and PHEV are:

- Power electronics: the smaller PHEV packs have to provide the same overall power, and so the specific discharge rate per cell (‘C rate’) is higher. The higher rated connectors and cables in a PHEV translate into a higher cost per kWh.

- Thermal management and cell internal support: the cells of the PHEV pack are placed in a more complex cooling matrix; they are liquid cooled whereas BEV packs are currently air cooled and are assumed to remain so in the future. Liquid cooling is more appropriate for both power reasons (the higher discharge rates generate more heat) and for space constraint reasons: it requires less space between the cells and so the IC engine can also be accommodated in the PHEV. Liquid cooling offers a better temperature control than forced air but however comes at a cost premium.

- The battery management system (BMS): both the hardware and software are more expensive, as a result of the more complex balancing[44] required by PHEV packs. The lower charge/discharge requirements (‘C rating’) of BEV packs means they can be balanced during recharging while stationary. With PHEVs, the operational cycle (requiring the battery to be charged while the vehicle is in motion) combined with higher C ratings, requires the pack to be actively balanced throughout charging and discharging. This means that the balance leads (required for each of the cells in series) will need to be rated more highly and therefore be more expensive in a PHEV pack.

For both the BEV and PHEV packs, some components have a fixed cost element e.g. power electronics, housing. The voltage of the modelled pack is constant (regardless of

[44] Lithium-ion packs need to be frequently balanced i.e. cell voltages are equalised across the pack. The cells level of energy is balanced to ensure homogenous performance and ageing among the cells. Cells with higher level of capacity left can be discharged (passive balancing) or energy can be transferred between cells (active balancing)

the pack size in kWh), which means that the components which have a cost proportional to the number of cells (e.g. BMS) will have approximately the same cost in $/pack.

For these reasons, increasing the total PHEV pack kWh brings the cost $/kWh down, as shown in Figure 6-4. In the model, it is assumed OEMs will take advantage of this cost curve and favour relatively large packs: an 80km electric range is modelled for future PHEVs.

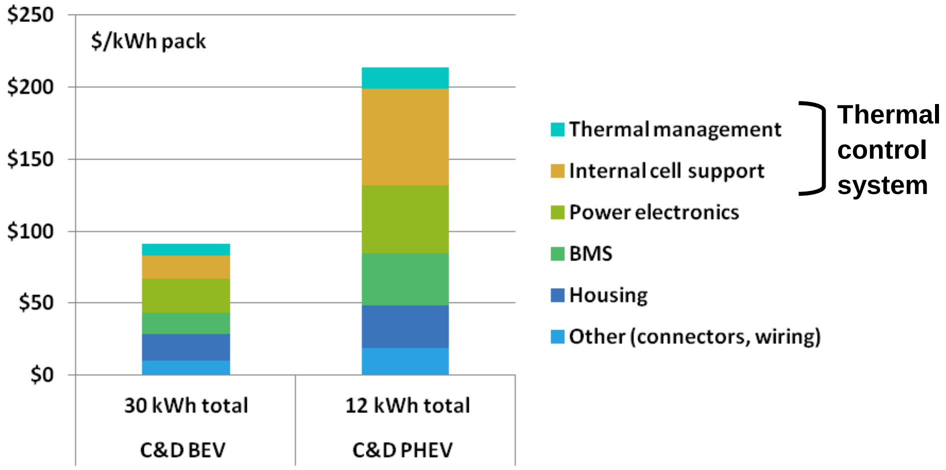


Figure 6-8 Comparison of cost of pack components ($/kWh) in 2020

This cost reduction with size, as well as the large cost premium of PHEV pack over BEV pack (see Table 6-3), seem to imply that a very large pack could be fitted in a PHEV for little extra cost. Certainly it is the case that the model indicates that the optimum PHEV pack size is hard to define, and that in practice, the assumptions made here about PHEV pack size could be challenged.

Currently OEMs are developing PHEVs with relatively small pack sizes, to limit overall vehicle costs. The modelling indicates that PHEV pack size could increase without significant cost impact. As pack size increases, it is the case that certain cost elements such as air/liquid cooling, or passive/active balancing, bring “step changes” in costs. An optimum PHEV pack size may be near to one of these step changes. (Similarly, the cost optimum BEV size could be less than indicated here, i.e. reduced towards a threshold beyond which liquid cooling would be required). In consultation with our packing experts, we conclude that the baseline 12kWh pack is far from one of these thresholds, but with 16kWh and beyond it may be the case that the pack could be fundamentally redesigned.

Figure 6-9 compares the PHEV results for the baseline 12kWh pack and 16kWh[45], the size beyond which we estimate our PHEV model becomes invalid. The graph also shows the cost of a BEV 20 kWh pack (energy cells, air cooled) to give a perspective on the cost premium.
We do not suggest OEMs would choose to fit such a large pack in a PHEV; in fact based on our knowledge of vehicle powertrain costs and exchange with industry players, it seems that, currently, beyond a certain pack size, a BEV architecture will be preferred over the PHEV configuration.

[45] See in Appendix page 87 for details on cost breakdown.

It is also worth noting that plug-in hybrid cars are constrained in the amount of space that can be dedicated to the battery pack, as both an ICE system and electric drive train must be accommodated. This suggests the air cooled temperature management might never be adequate for PHEV.

Vans are less volume constrained and a large pack is modelled (28kWh total); this is estimated to be beyond the threshold of the power to energy ratio that requires an expensive packing architecture. The plug in hybrid van pack is comparable to a BEV pack both in energy and power requirements. Furthermore, the management of the ICE heat source is easier on a van than on a medium sized car due to the larger volume of the van glider. For these reasons, BEV packing component costs have been used for the PHEV van, making its cost comparable to a BEV pack[46] (see Figure 6-7).

In the future, new design strategies such as the combination of high energy and high power packs (which could use cells or ultracapacitors) might bring further cost reduction for PHEV packs; such combinations were not studied in this work.

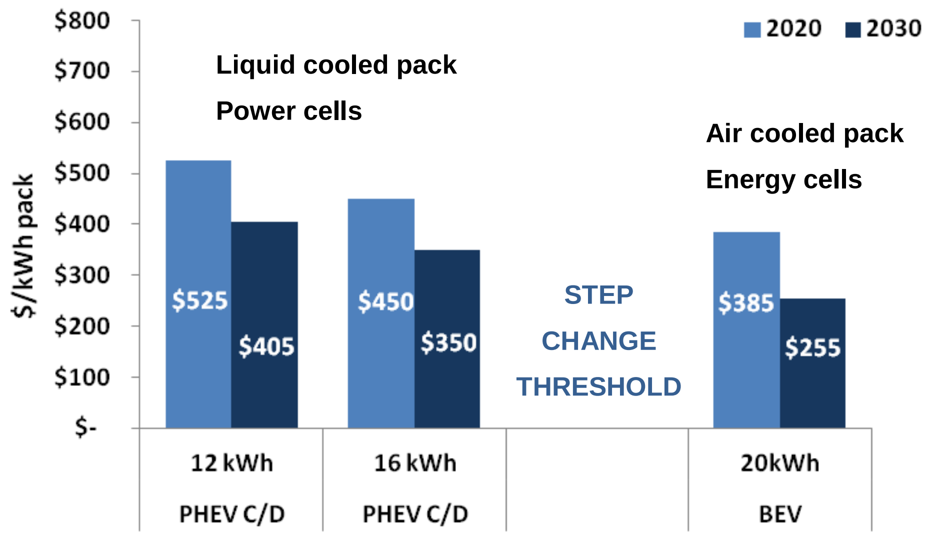


Figure 6-9 PHEV cost results in the valid kWh range and comparison with small BEV pack

6.1.2 Conservative and optimistic outputs

Figure 6-10 and Figure 6-11 show a comparison of the baseline results with two alternative scenarios. The 'Niche EV' scenario corresponds to a conservative approach to material improvements and manufacturing cost reductions. In contrast the 'EV push' scenario assumes aggressive manufacturing cost reductions driven by high PIV uptake (16 million cumulative sales globally by 2020 against 4 million in the base case) and R&D work delivering improvement in automotive cells in the short term; see Table 5-3 for a description of scenario assumptions.

[46] It is assumed that the monitoring and cell balancing in the PH van would be similar to the BEV pack (no active balancing and vehicle recharged when the battery is depleted) i.e. there is no cost premium for packing components of the PH van. Note that, for the safe guard of life, packs used in vans today with an ICE use a higher power version chemistry and air cooling is more aggressive than in a pure BEV pack. This carries a 10-15% premium over the same capacity BEV.

In the 'EV push' scenario, results for cost and energy density that are equivalent to those in the baseline scenario are obtained earlier: $245/kWh and 165Wh/kg (pack level) by 2020 against approximately 2023 in the baseline case. Both baseline and EV push scenarios plateau at the same values (although costs are slightly lower in the optimistic scenario as material costs decrease further due to the higher cumulative production) because both scenarios get to the limit of intercalation in terms of energy density. Reaching this cost plateau relies on the development of high voltage cells, a scientific challenge not guaranteed to be overcome.

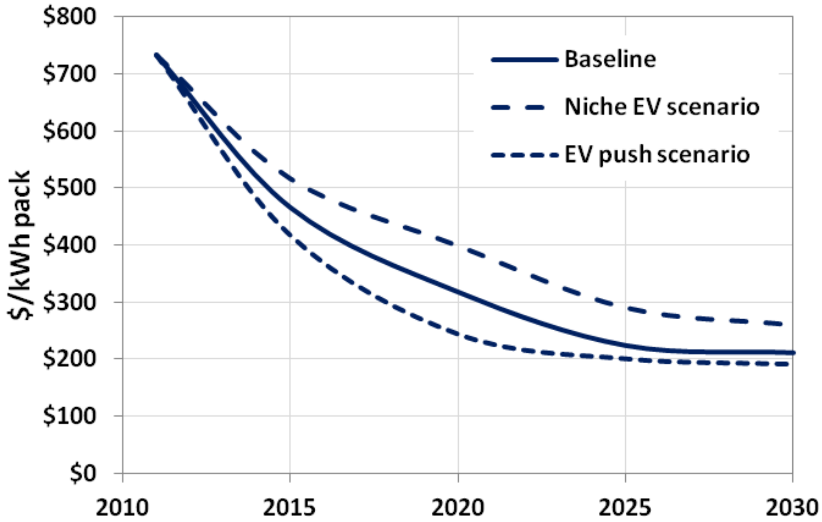


Figure 6-10 Pack costs ($/kWh) for C&D BEV for various scenarios

The niche EV scenario assumes more modest technology development and so represents a lower risk future. Results ($/kWh and Wh/kg) equivalent to those from the baseline in 2020 are in this case delayed to approximately 2024.

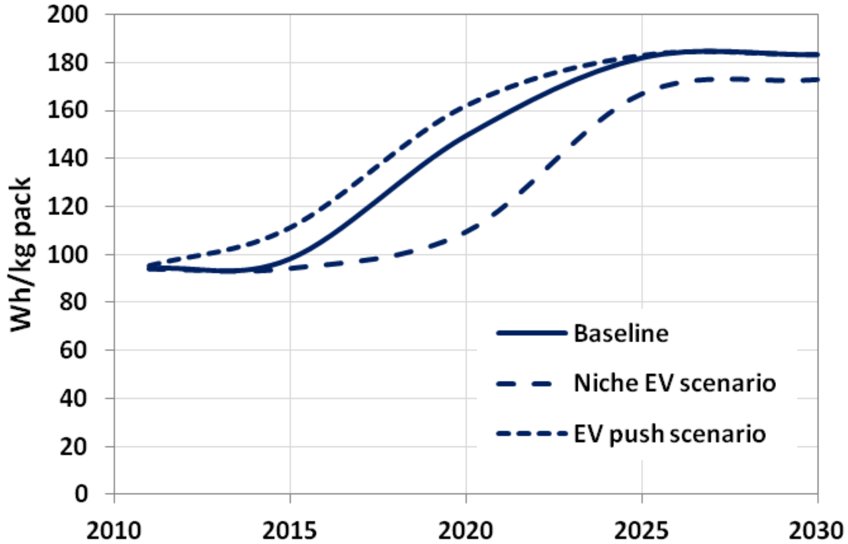


Figure 6-11 Pack specific energy (Wh/kg) for C&D BEV for various scenarios

Note that the cost ranges created by the conservative and optimistic scenarios and presented here do not imply lower and upper cost bounds. Rather each scenario represents a reasonably realistic set of conclusions following changes in market uptake and speed of technology development. Many of the cost improvements rely on the practical deployment of technology improvements, which may not occur in practice. For illustration of cost sensitivity and alternative costs, see Appendix 8.4.

6.2 Long term cost and performance

A lithium-air battery is used to represent post-lithium-ion technologies and estimate long term battery costs.

From the presentation of lithium-air cells and their key challenges (section 4.2.6) it should be clear that the fundamental scientific uncertainty in the production of a practical Li-air cell will limit the confidence in any projection of cost and performance, particularly when the actual production of a practical cell is many years away. In developing the model approach, we have adopted a relatively transparent and defensible methodology.

Performance

Based on the observed ratio of practical to theoretical specific energy for a range of batteries (typically 30%, range of 20-40%), a practical Li-air cell specific energy can be estimated to be 500 - 1,000Wh/kg. The lower estimate would correspond to high lithium overloading (to replace the lost material consumed during operation) while the high estimate assumes better lithium cycling efficiency.

The practical volumetric energy density is particularly sensitive to the amount of excess lithium needed. This could range from 500Wh/l to 800Wh/l. These speculative ranges are wide as Li-air cells are currently only laboratory experiments.

The range of 500-1000Wh/kg is in line with most academic predictions. It should be noted that many commercial predictions are much higher. It is possible that they incorrectly quote figures of energy density of the reduction of pure lithium, or the production of Li_2O, or not count the oxygen as a component in the system.

Cost

A practical Li-air cell has yet to be constructed; hence estimates of practical cell cost must be treated with caution. Similar chemistries and electrochemical devices such as Li-ion cells, and fuel cells (FC), are reasonable proxies for some elements of a future Li-air cell and pack; they are used to estimate future cost.

Comparing a 2030 high performance Li-ion cell and a Li-air cell, the main differences are:

- The Li-ion cell may use lithium metal oxide or polyanion cathode – Li-O_2 requires a much more complex porous carbon substrate, with a layer impermeable to CO_2.
- Li-ion anodes may use carbon or silicon alloy – Li-O_2 uses lithium metal.
- Li-O_2 will require the development of more exotic electrolytes, possibly with a cost premium.

On a pack level, a Li-O_2 system will require an air management system while a Li-ion does not (except indirectly when air cooling). This would require air systems similar to those required in fuel cells. Furthermore, the lower voltage of a Li-O2 cell results in the need for more cells to maintain overall pack/system voltage, with an increase in cost.

The two tables below represent a reasonable lower and an upper-bound to the projected costs for a Li-air battery pack.

Table 6-4 Cost projection for Li-air battery pack – low cost case

Component	Cost 2030 L(M)SO_4F- Si/C	Li-O_2 2030 cost estimate (low)	Comment
Cathode and anode	25$/kWh ~ 35% of cell materials cost	Assume more efficient Li loading, (x3.5 improvement in Wh/kg)	Reduction in cell material cost from $70/kWh to $52/kWh ***-$18/kWh pack level***
Electrolyte	$9kWh ~13% of cell material costs	Assume constant electrolyte cost	No change
Cell voltage	5V	3.2V	
Cell Wh/kg	285 Wh/kg	1000 Wh/kg	3.5x better - cell level
Packing-electronics	Electronic components ca. 30% of total pack cost	+30% in electronics cost due to increase in number of cells for same pack voltage	***+$20/kWh pack level***
Packing – air management	Required for thermal control	No extra complication arising from O_2 supply	No cost change
Total	$215/kWh (30kWh pack)		$217/kWh (30kWh pack)

Table 6-5 Cost projection for Li-air battery pack – high cost case

Component	Cost 2030 L(M)SO_4F- Si/C	Li-O_2 2030 cost estimate (high)	Comment
Cathode and anode	25$/kWh ~ 35% of cell materials cost	Assume more efficient Li loading, (x2 improvement in Wh/kg)	Reduction from $70/kWh to $58/kWh ***-$12/kWh pack level***
Electrolyte	$9kWh ~13% of cell material costs	Double electrolyte cost (more exotic, electrode protection)	***+$9/kWh pack level***
Cell voltage	5V	3.2V	
Cell Wh/kg	285 Wh/kg	500Wh/kg	1.8x better - cell level
Packing-electronics	Electronic components ca. 30% of total pack cost	+30% in electronics cost due to increase in number of cells for same pack voltage	***+$20/kWh pack level***
Packing – air management	Required for thermal control	Extra system complexity arising from O_2 supply requirement	15% extra system cost in line with long term FC projections ***+$20/kWh pack level***
Total	$215/kWh (30kWh pack)		$252/kWh (30kWh pack)

While reiterating that such estimates must be treated with extreme caution, it is important to observe the following points involved in the previous estimates:

- The anode/cathode materials of high performance Li-ion cells account for 35% of cell material cost, and cell materials account for c. 30% of final pack cost in the modelled 2030 Li-ion pack. Therefore, the cost reduction on electrode material brought by a Li-air technology with very efficient lithium loading is expected to benefit a relatively small proportion of the overall cost.
- Although the high energy density of lithium air could translate in high capacity cells (in Ah/cell), the low voltage of each cells means the overall number of cells will be greater than for a 2030 lithium-ion pack to achieve 300V. Therefore lithium-air packs are not likely to benefit from the cost reductions in production line and packing usually expected from a reduced number of cells per kWh (outlined in Table 8-4, page 74). As mentioned in section 2.2.4, lowering the system voltage requirement would enable some cost reduction at the pack level but would effectively displace the cost to other part of the vehicle (e.g. electric motor). This trade-off was not studied here.
- There is the potential for cost increases in some system elements arising from Li-air, including battery BMS and air management.

Overall therefore, while it is reasonable to expect that a successful Li-air pack could provide significant weight savings for a fixed kWh of stored energy, we cannot find a reasonable basis for expecting $/kWh pack costs to be significantly different from projected 2030 (high performance) Li-ion figures. The overall cost and performance trajectory result is shown on the graph below. Li-air cell energy density has been converted to pack level density by adding the same pack component weight as observed in for Li-ion packs in 2030.

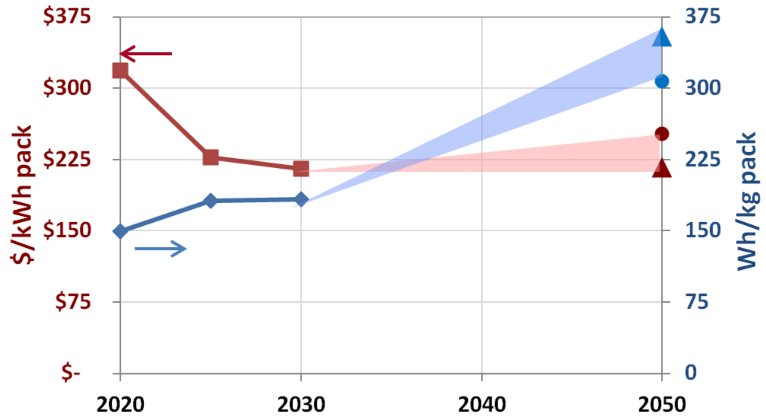


Figure 6-12 Long term cost and performance trajectories for BEV 30 kWh pack

Projections of timescales for the achievement of such outcomes are exposed to as much uncertainty as projections of cost and performance. In developing temporal estimates, we note the following:

> *"Automotive propulsion batteries are just beginning the transition from nickel metal hydride to Li-ion batteries, after nearly 35 years of research and development on the latter. The transition to Li-air batteries (if successful) should be viewed in terms of a similar development cycle.*[47]*"*

[47] Lithium-Air Battery: Promise and Challenges G. Girishkumar,* B. McCloskey, A. C. Luntz, S. Swanson, and W. Wilcke, IBM research 2010.

It is reasonable to assume that projected developments in practical Li-air batteries in automotive applications should arise in the period 2030-2050.

6.3 Interpretation

The baseline results show that incremental improvements of lithium-ion batteries and production cost reduction through volume production could cut the pack cost of a medium size car down to $215/kWh by 2030; this is a ca. 70% reduction compared to today's costs.

Cost reductions due to improvements in materials (higher energy density)

The main driver behind this cell cost reduction is the improvement of active materials – i.e. higher energy densities – which reduces the amount of both active and non active material needed per kWh.

The effect of improvement in active materials is illustrated in Figure 6-13; it shows the cell cost reduction for the three technology roadmaps when material costs and production parameters are kept constant, and so only the material properties such as voltage and capacity mAh/g change with time.

Delivering the assumed material improvements requires overcoming several scientific challenges, such as developing an electrolyte compatible with high voltage cathode. The consumer electronics market for cells is driving innovation and will continue to bring incremental material improvement. However requirements for automotive cells are more challenging in terms of life, power and safety. The amount of R&D effort focused on designing improved Li-ion automotive cells suggests the modelled material improvements will enter vehicle applications. There is however uncertainty around the speed of development of improved materials, represented in the model by the 'Slow R&D' path which sees a slower and less ambitious increase in material energy density.

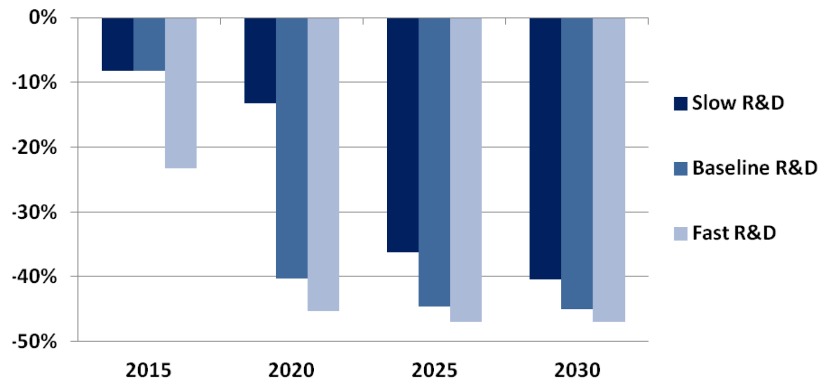


Figure 6-13 Cell cost reduction due to material improvements (other parameters kept constant) compared to 2011

Cost reductions due to cumulative production/EV uptake

Cost reductions due to cumulative production – linked to EV uptake scenarios in the model – have less effect on cell costs than material improvements but have a very significant impact on the cost of pack components excluding cells: housing, power electronics, BMS etc. For illustration, Figure 6-14 shows the cell cost reduction compared to 2011 when material properties and all input costs are kept constant. This shows the effect of the reduced CAPEX cost and increase in annual pack production per plant. In

the baseline EV uptake case, the cell cost is reduced by 12% against 40% from material improvement.
Figure 6-15 shows the impacts of cumulative production on packing costs; they are much greater than for cell cost as packing is done in low volumes today. Most components (e.g. housing, temperature control systems) are designed for each vehicle model and will benefit greatly from standardisation and volume production.

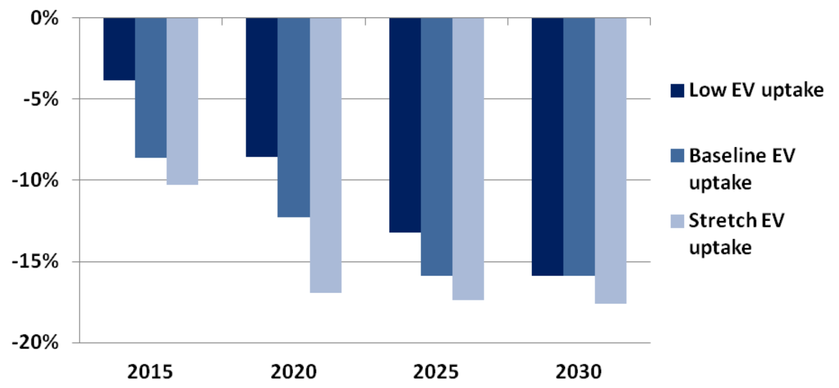


Figure 6-14 Cell cost reductions due to learning rates/EV uptake assumptions (other parameters kept constant) compared to 2011

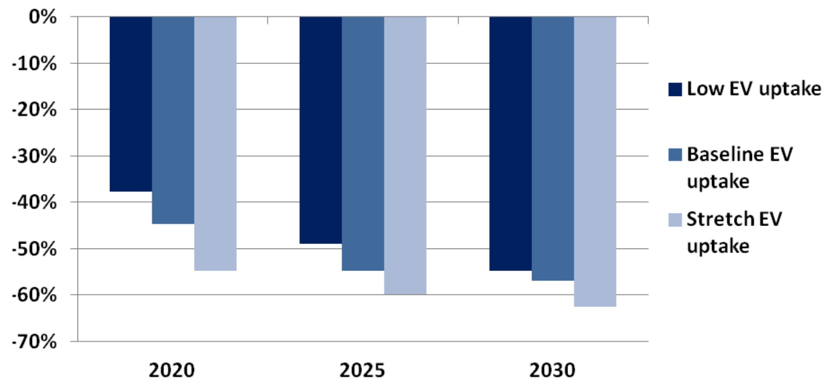


Figure 6-15 Packing cost reductions due to learning rates/EV uptake assumptions (other parameters kept constant) compared to 2011

The risks around realising cost reductions for large cell production are lower than for pack assembly: new markets are emerging for large cells (e.g. grid support, IT back up) whereas pack assembly for the automotive market does not have comparable markets to support scale-up and spread investment risks.

Long term projections

The baseline results show that incremental improvements of lithium-ion batteries could take the pack specific energy of a medium size car to 185 Wh/kg. Although this is an 85% improvement on today's pack, this would translate into a battery pack of more than 300kg to achieve a 500km range.

Only post-lithium technologies, with densities higher than 300Wh/kg at pack level, would make a long range electric vehicle practical. Taking post-lithium-ion technologies from their current lab or prototype stage will require many years of development work and the date when this will be achieved is uncertain.

7 Conclusions

The objective of this report is to predict the cost and performance of automotive drivetrain batteries, over the medium and long term, for a set of vehicles representative on the UK market, for both pure electric and plug-in hybrid electric drivetrains.

Following a review of automotive battery cost models, a bottom up model approach was developed for cost and performance up to 2030. This is a component based approach which allows packs to be bespoke designed to meet the specifications of each vehicle.

In determining future vehicle specifications, the modelled pack voltage is assumed to remain constant at 300V. This high voltage limits losses in the power electronics and motor, but there is a cost to assembling a high voltage string of Li-Ion cells, requiring extensive pack monitoring. We have not explored the potential for packing savings arising from lower system voltages. For other vehicle specifications such as pack size in kWh, the expected improvement in vehicle energy consumption (brought by a series of efficiency measures such as better aerodynamics and light weighting) is taken into account.

Battery developments

A range of historical, current and future chemistries were examined. A clear theme which emerges is that energy density is the most important parameter for battery design (more so than price). In practice this means that while cheaper technologies are available, OEMs have chosen to deploy high cost high performance (based on Wh/kg) technologies, which at present are represented by lithium-ion family chemistries.

Observation of the time lag between cells demonstrated in the laboratory and technologies deployed in automotive applications shows that a period of 15-25 years is representative. This pattern may not hold in the future – as the automotive battery drivetrain market expands, accelerated technology deployment may occur. Nevertheless, it is reasonable to assume the next decade will not see step change technology improvements arriving in series production electric vehicles. New technologies do provide improvements, but these are expected to be gradual.

The longer term cost and performance predictions, summarised below, can only be achieved if a number of significant technical improvements can be integrated together into a practical battery pack. This includes the use of significantly higher energy density cathode materials, which in turn requires electrolytes stable at higher voltage, as well as higher performance anodes. There are many significant fundamental scientific uncertainties which must be overcome before all of these advances can be demonstrated in a rechargeable lab cell. For example, a 5V electrolyte which does not break down in a cell is not yet available. It must be acknowledged that in developing these cost predictions we have taken a position not only on scientific advances, but also on certain cell, pack and vehicle design parameters, all of which are inherently uncertain.

Cost and performance of battery packs to 2050

Under the baseline results, a C/D BEV pack cost could decrease to $320/kWh in 2020 and $215/kWh in 2030, from over $700/kWh today. Roughly half of the battery pack cost is in the cells, and the remainder is packing cost. Pack specific

BEV 30 kWh pack	2011	2020	2030
Pack cost $/pack	$21,950	$9,620	$6,400
Pack cost $/kWh	$725	$320	$215
Pack mass kg	320	200	165

energy increases from around 100Wh/kg today to 185Wh/kg in 2030. Future battery packs are expected to have a life matching the average vehicle life in the UK.

Note that this would require the successful development and deployment of high energy cathodes, high voltage electrolytes, and e.g. silicon anodes. If high energy cathodes were not to become available then the resulting cost is closer to $250/kWh in 2030 – this figure represents a cost prediction with a lower technical delivery risk.

By 2020, a medium size car can be fitted with a 200kg pack, delivering 30kWh of energy, with a range of 250km, an expected lifetime of 12 years, for a total cost of $9620. By 2030, the same pack could weigh 165kg and cost $6400. Despite performance improvements by 2030, we do not expect that BEVs will deliver range equivalence to IC cars, because of weight limitations.

The PHEV cost and performance model involves a greater number of specifications and design constraints, so the figures provided are less definitive. However we predict that a PHEV pack cost for a C/D vehicle would reach $4,900 for a 12kWh pack (80km) in 2030.

PHEV 12 kWh pack	2011	2020	2030
Pack cost $/pack	$16,130	$6,350	$4,900
Pack cost $/kWh	$1,330	$525	$405
Pack mass kg	180	105	95

The costs of PHEV packs are significantly higher than for BEV on a $/kWh basis. Reasons for this include 1) the use of different chemistries which have higher power density but lower energy density than for BEV cells; 2) the use of smaller cells, which results in higher cell production costs per kWh, and mainly 3) additional packing costs due to the higher discharge rate per cell.

It should be noted that where high costs are predicted, innovative design strategies could be deployed, such as the combination of high energy and high power packs. In practice therefore, PHEV pack costs could be brought lower than indicated. Exploring such architectures was outside the scope of this report.

Of the longer term technologies that could replace Li-ion, Li-air emerges as one with the greatest promise. Small Li-air cells have been demonstrated in laboratory conditions, but cycle life and charge deterioration are a key issue. Also, the difference in the charging and discharge voltage for a Li-air cell means that the electrical energy efficiency is low.

Li-air cells are expected to deliver cost reductions due to the efficiency of use of active materials (relative to Li-ion). However some elements are much more complex than in a Li-ion cell. An example is the porous air cathode, which is open to the air, allowing oxygen to diffuse through and dissolve in the electrolyte next to the electrode, but at the same time preventing diffusion of CO_2. Also an active air management system would be required as well as thermal management. This may impact on pack size, but will certainly have an impact on cost.

Long term predictions of Li-air cost and performance need to be treated with caution. Pragmatic estimates of the key performance metric (energy density) suggest an x2 or an x3 performance improvement factor over high performance Li-ion. For a fixed battery capacity, the weight reduction arising from Li-air use could improve vehicle efficiency (kWh/km), certainly in a stop-start urban cycle, but this is not explored.

An estimate of Li-air costs, using existing proxies of Li-ion cells and fuel cells, has indicated that there is no basis for expecting significant cost reductions relative to a high performance Li-ion cell in 2030. While this may seem surprising, the 2030 Li-ion cell is

already very cost efficient, and the loadings of the active materials (which Li-air can reduce significantly) are a small percentage of the overall pack cost.

Key drivers behind cost reductions

While noting that overall cost reductions arise from multiple sources, the ca. 70% reduction in pack costs predicted by 2030 arises primarily through the improvement in material properties delivering higher energy densities, and the scaling up of production of large cell packs.

In practice these issues will be linked. Continued and sustained uptake of automotive electric drivetrains will support the R&D investments required to develop new chemistries. The same market pull will be required to support investments in the development of high quality, large format cells, at the production volumes necessary to make these cost effective.

These cost predictions indicate that electric drivetrains will, for ca. 20 years, cost a premium to produce. It is highly debateable whether the mass market and late adopters will accept a price premium for such a long period of time. To sustain the uptake required, it would seem necessary to have either regulations focusing on OEMs (i.e. fleet average emissions targets favouring some EV production) or incentives (such as grants to reduce the cost difference to consumers).

If the combination of regulation/incentives were not in place over the time period – in the UK and beyond – then the predictions given in this document may be very optimistic. While material improvements are more likely to emerge (because there are other, larger markets for these high performance cells), the production of large format cells, and the learning rate improvement in packing costs, will not emerge if EV uptake stalls.

References

ANL, Modelling the Performance and Cost of Lithium-Ion Batteries for Electric-Drive Vehicles, 2011

Avicenne, The rechargeable battery market past and future, 2011
Axeon, Our guide to batteries, 2011

Barnett, New safety technologies for lithium-ion cells and batteries, Batteries 2011 conference, Mandelieu, September 2011

Boston Consulting, Batteries for electric cars, 2010

Roland Berger, Lithium-ion batteries for automotive applications – value chain and costs perspectives, Batteries 2011 conference, Mandelieu, September 2011

Peter G. Bruce et al., High energy storage li-O2 and Li-S batteries

CARB, Status and Prospects for Zero Emissions Vehicle Technology, 2007

CGGC, Lithium ion batteries for electric vehicles, 2010

Deutsche bank, ElectricCarsPluggedIn2, 2009

DLR, Assessment of Future Li-Ion Battery Production Costs, 2009

EDAG, Future steel vehicle phase 1 report, 2009

Element Energy, Influences on the Low Carbon Car Market from 2020-2030, 2011

Element Energy, Ultra Low Emission Vans study, 2012

EPRI, Large-Format Lithium-Ion Battery Costs Analysis - Critical Review of Existing PHEV Lithium Ion Battery Cost Studies, 2010

French embassy in Japan, Etat de la R&D dans le domaine des batteries pour véhicules électriques au Japon, October 2010

Junichi Maruta, High performance lithium-ion batteries for electrified vehicle application with various chemistries and cell dimensions, Lithium Energy Japan, Batteries 2011 conference, Mandelieu, September 2011

Quass J., Benhamou E., Keil A., Advances in Battery Electrode Coating, Drying and Solvent Recovery System Design, Batteries 2010 conference, Mandelieu, September 2010

Prayion, Strategic approach from an industrial point of view as new advanced active materials supplier, Batteries 2011 conference, Mandelieu, September 2011

Sartorelli G., Ultracapacitors: some view about the life duration and performances over the time, Batteries 2010 conference, Mandelieu, September 2010

TIAX, PHEV and LEESS Battery Cost Assessment, 2011

Yoshio M., Brodd, R.J.m Kozawa A., Lithium-ion batteries: science and technologies, Published by Springer, ISBN0387344446, 9780387344447, 2009

8 Appendix

8.1 Vehicle and pack attributes

Two previous reports by Element Energy[48] detail vehicles attributes and how these are projected to change through time, with performance and design improvements. We built on these original data with new, announced and existing packs for PHEVs and BEVs[49]. Our partner Axeon reviewed our results, based on their experience of OEM requirements and battery pack assembly.

Current vehicles

The following process was used to generate the existing vehicles characteristics:

1. From SMMT data the five most popular vehicle models in each vehicle class by sales in 2010 were selected.

2. The properties of these vehicles (weight, power, etc.) were taken from What Car? The vehicle models selected were the lowest cost versions of the smallest and largest engines in the model range[50], for both petrol and diesel versions of the model.

3. The vehicle properties for the petrol models and diesel models were averaged to give petrol and diesel model averages. The average petrol and diesel models were subsequently averaged, using the sales weighted average of petrol and diesel vehicles in the vehicle class.

4. Representative vehicle properties by vehicle class were averaged and weighted according to model sales figures. This generated a single average vehicle for each SMMT vehicle class.

5. The properties of each vehicle class were directly averaged between classes to provide three hybrid classes of vehicle to give illustrative vehicle classes. These were defined as A&B, C&D and E&H class. Other car classes were not included due to their small market share.

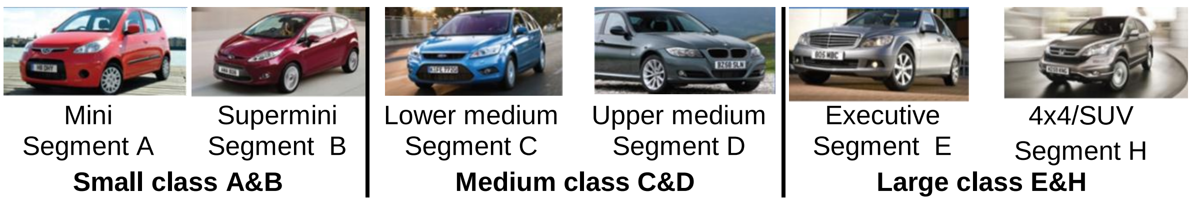


Figure 8-1 Aggregation of car SMMT classes and vehicle properties into three car classes

[48] Influences on the Low Carbon Car Market from 2020-2030, Element Energy, 2011
Ultra Low Emission Vans study, Element Energy, 2012

[49] For cars: iMiEV, Renault Zoe, Renault Fluence, Nissan Leaf, Toyota Prius, Volvo V60, BlueCar, OEMs announced targets for future cars and target of US DoE for medium size cars. For vans: eExpert, eBoxer and Edison models

[50] This approach was designed to avoid biasing the results towards the smallest engine in a model range (which is usually not the best-selling model), while avoiding biases due to high performance and high specification variants.

SMMT sales data and Vans123 data on van characteristics were used to generate a generic van class using a similar approach to cars.

Future vehicles

The expected improvements in the conventional ICE vehicle are used to predict the characteristics of future low carbon vehicles. This approach provides future vehicle properties, against which other powertrains can be compared. It also allows improvements outside the powertrain, such as aerodynamic improvements and vehicle ‘light weighting’, to be quantified and applied across vehicle types.

Table 8-1 represents how these improvements change the energy requirements of the different vehicles types from 2011 to 2030. (For a full description of the individual improvements in vehicles over this time frame please view the reports; *Influences on the Low Carbon Car Market from 2020-2030*, and *Ultra Low Emission Vans study*, both by Element Energy). The indicated energy consumption is based on assumptions on kerb weight mass (which includes battery pack mass).

Battery capacity is set using the vehicle range. The range is a trade-off between issues such as cost and weight, and the need to provide sufficient utility (range) to meet drivers’ needs. In practice, electric ranges of future BEV and PHEVs will be set by user requirements, cost considerations and OEM marketing decisions. The purpose of this study is not to attempt to predict OEM decisions on range offered, so instead simple rules have been used to provide illustrative range estimates for each powertrain to generate pack requirements.

Existing (2011) vehicle ranges are set by vehicles currently on the market. Future vehicle ranges are set according to the expected range requirements of each vehicle class based on travel statistics and OEM discussions. For example A&B class vehicles are used as city cars and have fewer long distance trips; they therefore have a lower range requirement than the other vehicle classes.

Peak power requirement is based on the ICE model engine output and checked along with the assumed pack mass with the Element Energy vehicle modelling of the NEDC drive cycle, Element Energy analysis of SMMT vehicle data, and Axeon data on OEM pack requirements.

The tables below show the resulting plug-in vehicle datasets. The maximum pack volume is given only as an indication; it is harder to estimate as the volume envelope dedicated to the battery pack will depend partly on the shape / modularity of the pack.

Table 8-1 Definition of current and future BEVs for pack cost modelling

Attribute	BEV 2011				BEV 2030			
	A&B	C&D	E&H	Van	A&B	C&D	E&H	Van
Range (km)	150	150	150	150	200	250	300	250
Energy consumption (kWh/km)	0.12	0.14	0.18	0.28	0.084	0.097	0.13	0.22
Max pack mass (kg)	240	300	460	500	110	180	360	400
Max pack volume (L)	180	270	360	550	100	130	280	375
Motor peak power (kW)	50	70	120	60	50	70	120	70
Assumed kerb mass (kg)	1270	1700	2300	2250	920	1280	1790	1800
Usable energy (kWh)	18	21	27	42	17	24	40	55

Two categories of plug in hybrid are currently on the market: the series hybrid (Range Extender EV) and parallel hybrid (PHEV). RE-EVs have an internal combustion engine generating electricity that charges the battery and the drivetrain is purely powered by an electric motor. In PHEVs, engine and motor run in parallel and their power outputs are added.

In practice, all plug-in hybrid vehicles have combined architectures: they can run on pure electric mode as well as 'power mode' where the electric motor output is used to either boost the torque generated by the ICE or to allow the ICE to run at its most efficient level. The main difference in terms of battery is that RE-EVs generally have longer electric range and thus larger packs.

The Toyota Prius is an example of parallel hybrid (~20km electric range) while the Chevrolet Volt is an example of RE-EV (~60km electric range). The cost/performance model developed here does not explicitly differentiate between these two hybrid drivetrains, and only one type of hybrid, labelled PHEV, is represented. The table below shows the definition of PHEVs used in the battery cost model.

PHEV packs need to meet a greater set of specifications than BEVs- an example being the larger discharge currents experienced by PHEV packs due to their smaller size. This restricts chemistries to those with higher acceptable mA/cm2. A greater number of assumptions need to be made to design PHEV packs and so we considered it more appropriate to limit the cost/performance model to the medium sized car and van, to match the vehicle types developed by the parallel vehicle cost modelling work.

Table 8-2 Definition of current and future PHEVs for pack cost modelling

Attribute	PHEV 2011		PHEV 2030	
	C&D	Van	C&D	Van
Range (km)	30	40	80	80
Energy consumption (kWh/km)	0.15	0.3	0.11	0.24
Max pack mass (kg)	150	300	120	300
Max pack volume (L)	120	400	80	400
Motor peak power (kW)	60	60	60	80
Usable energy (kWh)	4.6	12	8.5	19.4

8.2 Model diagram

The figure below shows a schematic representation of the model calculation steps and input/outputs modules.

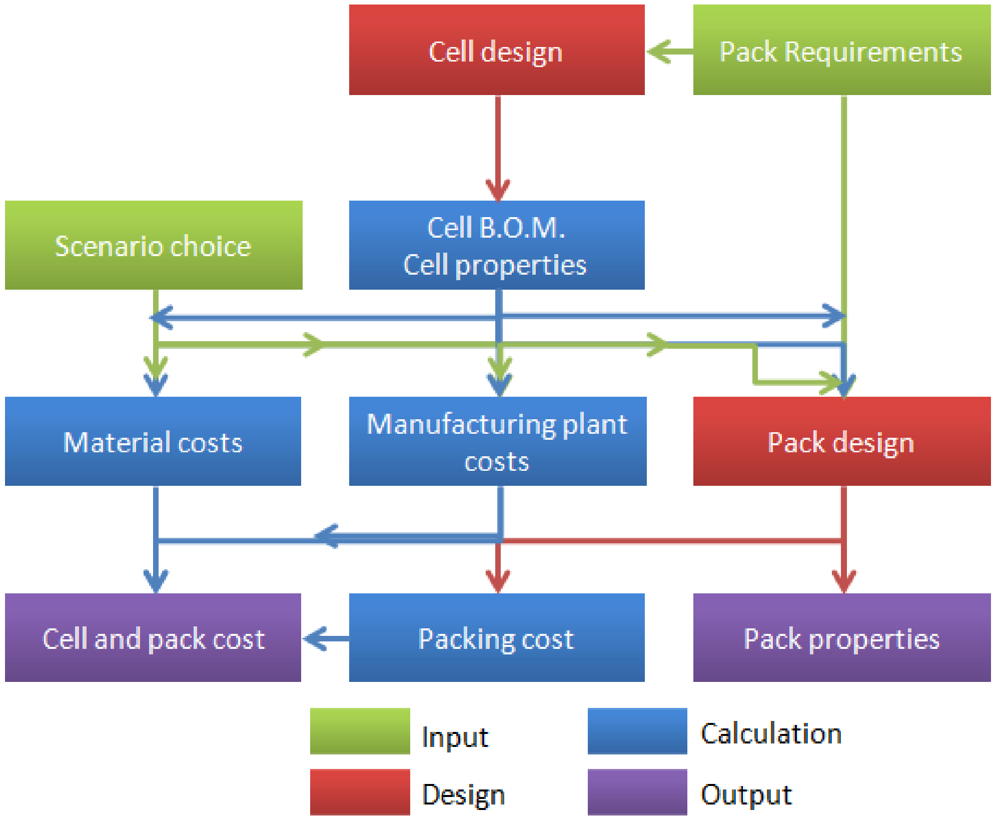


Figure 8-2 Model diagram

8.3 Model inputs and assumptions

The model main assumptions and inputs are presented here, along with results, and insights from existing battery cost models that have been used to understand parameters affecting battery cost.

8.3.1 Cell design

Designing a new cell is an iterative process, and it takes between several months to over a year from qualification of material suppliers to final optimisation in the design (foil thickness, electrode active material thickness, porosity & area, electrolyte additives etc). The cost model cannot and does not aim to reproduce the multitude of possible cell designs. A set of design rules have been kept constant through time; the model shows cost reduction opportunities brought by the improvement of materials and production learning rates only. Our view is that this is sufficient to capture the most important issues while avoiding unnecessary detail.

Based on previous work by ANL and confirmed by industry consultation, the exact cell format (cylindrical, prismatic, etc) does not have a significant effect on the cost per kWh for a given chemistry. In line with the most common large format batteries for automotive applications, the model is based on a prismatic cell format. Most cell component dimensions (e.g. current collector thickness and material, terminal dimensions, etc) are based on the ANL BatPaC model, with the exception of the cell footprint. BEV cell maximum thickness is set at 12 mm while a PHEV cell is limited at 8mm; PHEV cells are thinner because they require more heat rejection (due to their higher discharge power).

Cell footprint

In line with the assumption that automotive cells will become a mass produced commodity, it is assumed that a standard cell footprint (electrode area) will emerge. Most cells today are close to the A6 or A5 format but some manufacturers already make A4 cells for some chemistries (e.g. NMC). It is assumed in the model that A4 is the standard footprint by 2020.

Cell footprint dictates the size (Ah) and thus to a large degree the number of cells required per pack: larger cells reduce the number of cell required per pack. This is in addition to the cost benefits of producing more kWh with fewer cells.

The cost benefit for moving to large cells is not – today – as strong as the illustrative results suggest (Table 8-3) because making large cells requires more complex and precise engineering or results in lower cell yield (quality rejects). In the future, when the manufacturing process has improved and volume production is achieved, cost differences arising from cell format are likely to increase.

Table 8-3 Model results, NMC cells, 2011

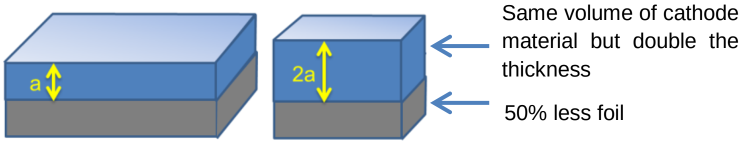
Cell footprint	Cell Ah	$/kWh cell
A6 (150 x 105 mm)	22	470
A5 (150 x 210 mm)	44	410
A4 (300x 210 mm)	87	375

Electrode thickness

Active material thickness is an area of cell design that has been identified as having the largest effect of the cell cost[51]. Thicker electrodes mean more active material (capacity) per unit area. The active material thickness is determined by two main factors, firstly the

[51] TIAX, PHEV and LEESS Battery Cost Assessment ,2011;
ANL, Modelling the Performance and Cost of Lithium-Ion Batteries for Electric-Drive Vehicles, 2011

maximum thickness that that can be deposited evenly on the current collector (engineering limit), secondly the power requirement of the cell.



The electrode thickness affects cost because it controls the amount of non-active material used in a cell battery: the thicker the electrode, the smaller the cell area and the lesser the quantity of inactive material (foil, electrolyte, separator, casing etc) to use.

The kinetics of the active material chemistry determine the maximum power that can be drawn from a cell with a specific active material thickness. This relationship varies with electrode material chemistries.

In the cost model, the active material thickness is set at 100µm; this thickness meets the power (rate) requirements of all vehicles modelled. Following consultation with our partners we have decided to keep this value constant through time to limit assumptions.

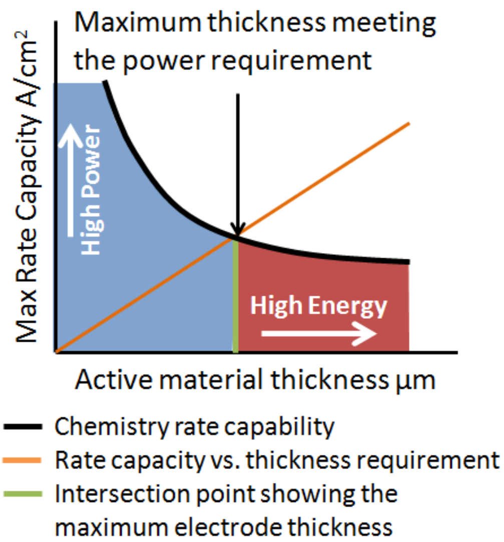
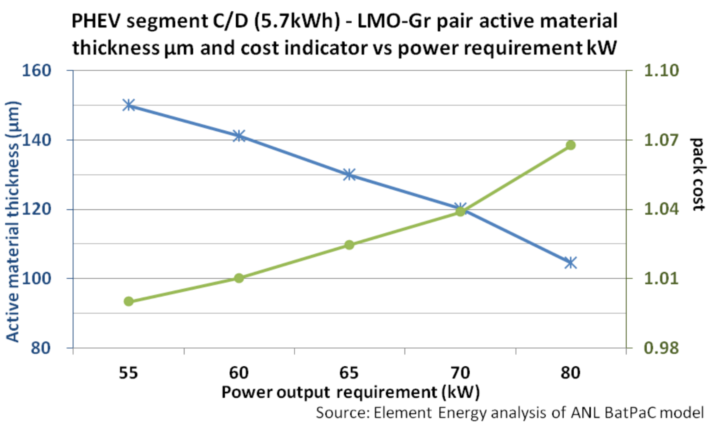


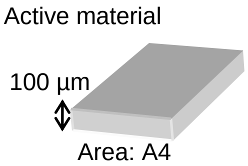
Figure 8-3 Active material rate capability example

Cells developed for PHEV applications have greater power to energy ratios, which translate into thinner electrodes and more expensive cells because of the greater use of inactive material. As a consequence, PHEV cell costs are more sensitive to the vehicle power requirement, as illustrated by the ANL BatPac model results (graph in the right).



8.3.2 Technology roadmap of active materials

The electrode active material properties (reversible capacity mAh/g and voltage) are input into the model while the cell footprint and electrode thickness are kept constant. Future cathode materials, under development now, have greater capacity and/or voltage, i.e. cells will have a greater energy density - this is illustrated in the figure below.



Changes in active material:

- Higher reversible capacity mAh/g → higher cell capacity Ah → might reduce the number of cells in parallel.

And/or

- Higher voltage → higher cell voltage V → reduced number of cells in series.

Both cases result in higher energy density and cost reduction in $/kWh.

Constant assumptions | **Assumptions varying with time according to technology roadmap**

Figure 8-4 Effect of the technology roadmap assumptions on cell Ah and V

This is expected to reduce battery cost for the reasons outlined in the table below. Increasing the material capacity reduces the amount of active material used to generate the same battery capacity. Given the same cell footprint, increasing the active material capacity increases the total capacity of a single cell and can help reduce the number of cells placed in parallel. This is also true of increasing the cell voltage; this reduces the number of cells required in series to meet the pack voltage requirements.

Table 8-4 Cost reductions brought by fewer cells per kWh and increased Wh/kg

Pack production	Cell materials	Pack components
Cheaper as fewer cells to handle and test per kWh on the production line. Greater active material Wh/kg (mAh/g and/or voltage) also means less cell material to handle in the plant.	A greater active material Wh/kg means less material to purchase per kWh. This translates in a cost reduction *if the material cost per kg does not increase when mAh/g and/or V increase.*	Fewer cells to connect and monitor: cost reduction in BMS, wiring harness and interconnectors. Smaller pack volume reduces the housing cost.

Based on a review of material under development, a technology roadmap was developed. Future materials considered are:

- Anode: graphite and in future silicon alloy (blended with carbon)
- High capacity cathode: NMC, layered cathode
- Medium to high voltage cathode: LMP, LNMO, L(M)SO_4F

The resulting baseline cell energy density was presented in section 4.4. The figure below shows how the best baseline energy density available compares to the other roadmaps (‘Fast R&D’ and ‘Slow R&D’). Table 8-5 shows the assumptions in terms of date of entry of new technologies or new performances for the three R&D scenarios.

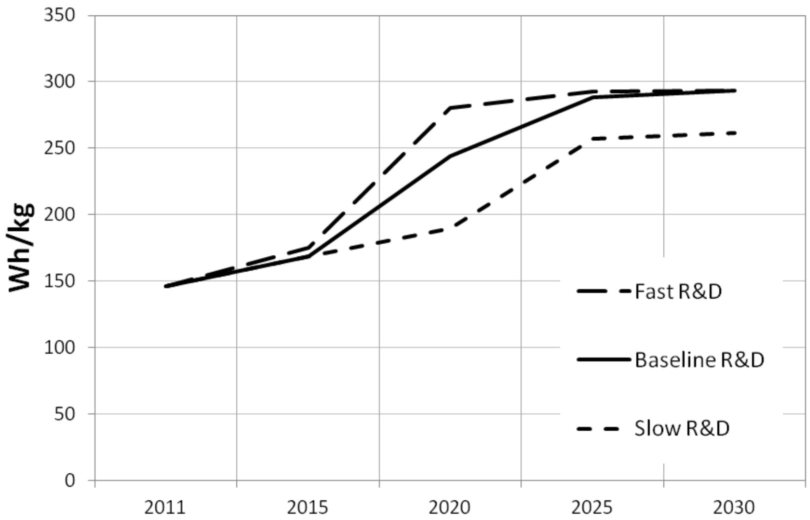


Figure 8-5 Best cell energy density available in the model for each R&D scenario

Table 8-5 Comparison of R&D scenarios - reversible capacities of electrodes

	Slow R&D	Baseline R&D	Fast R&D
High capacity cathode NMC - 200 mAh/g, 3.7V	-	2025	2025
High capacity cathode LL - 230 mAh/g, 3.5V	*2030 (200mAh/g)*	2025	2020
High voltage cathode 150 mAh/g, 5V	-	2025	2025
Silicon blend anode	2025 (1500mAh/g)	2020 (1000mAh/g)	2020 (1200mAh/g)
	All: 1750 mAh/g in 2030		

8.3.3 Cell material costs

The cell material costs in the immediate future could decrease due to competition in raw material prices, commoditisation of some of the processes materials, and increased competition between processed materials suppliers. Based on these assumptions, the Roland Berger[52] model applies significant cost reduction to cell materials in the short term; see graph on the right.

Over the longer term the cost may decrease due to new materials (with reduced raw material costs) and economies of scale.

In the model, the active materials costs (anode and cathode materials) are handled differently than non active materials costs.

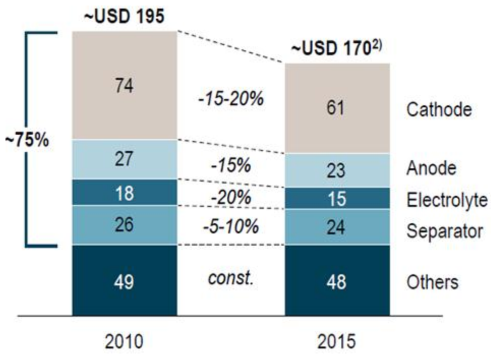


Figure 8-6 Excerpt from Roland Berger cost model of NMC cell (2011)

Active materials

Cost of current active materials have been researched by reviewing existing models and, whenever possible, by obtaining figures directly from the battery industry. The ANL and TIAX models are useful references as they both study various chemistries.

[52] Roland Berger, Lithium-ion batteries for automotive applications – value chain and costs perspectives, Batteries 2011 conference, Mandelieu, September 2011

Active material costs are influenced by:

- The cost of raw materials. Nickel and cobalt are expensive and their price can be very volatile. On the other hand, manganese, iron, sulphur and lithium are abundant and currently relatively cheap.
- The cost of processing. Some materials require more expensive equipment or conditions, for example lithium iron phosphate cathode active material (LFP) is synthesised in an inert atmosphere.

Processing costs present more cost reduction potential than raw materials, through production volume and learning. The prospective active materials cost reduction is therefore dependant on the ratio of raw materials to processing costs.

Modelling future chemistries brings the challenge of estimating the cost of materials that are not yet mass produced. This was done in consultation with our industry partners and by taking into consideration the expected raw material composition and processing level of difficulty. The resulting active material cost assumptions are detailed below.

For each material family type (polyanion, NMC, spinel, layered cathode materials and anode materials), a baseline as well as two other cost trajectories were developed: a 'Low EV uptake' case where the cost reductions are slower, and a 'Stretch EV uptake' case that sees deeper cost reductions.

For each electrode material, a high price was developed to reproduce high raw material costs and/or licensing costs of advanced materials. This price was used in a sensitivity analysis.

Polyanion cathodes: LFP, LMP and L(M)SO4F

According to a cathode supplier we consulted, today high quality LFP materials cost 22$/kg (with raw material costs representing ~6$/kg) and prices close to 15$/kg are already achieved by some manufacturers in Asia but for "low quality" material. Achieving prices under 10$/kg for LFP by 2020-25 would be impossible for anyone, according to the industry.

It is assumed that LMP material would be produced with the same process and would come at the same cost than LFP (Mn and Fe are of about the same cost).

L(M)SO4F raw materials are cheaper but the processing is more expensive today than LFP. When L(M)SO4F cathodes enter the automotive market (assumed 2025), they are assumed to 20% more expensive than LFP/LMP materials would be by then.

Based on a 2011 cost of 22$/kg, the following cost decrease rule is applied in the base case: -1% p.a. on raw materials and -6% p.a. on processing costs. Under this rule, LFP cost reaches ~15$/kg in 2020, i.e. reaches today's low manufacturing costs by 2020 for high quality LFP.

In the low EV uptake scenario, a lower processing cost reduction is assumed (-2% p.a.). In the stretch EV scenario, -2% p.a. on raw materials and -10% p.a. on processing take the cost to the capped value of 10$/kg.

For the high price sensitivity, the cost is kept at 22$/kg. For comparison, the TIAX model uses a cost range of 15-25 $/kg for 2015 for LFP, the ANL model uses 20$/kg for 2020.

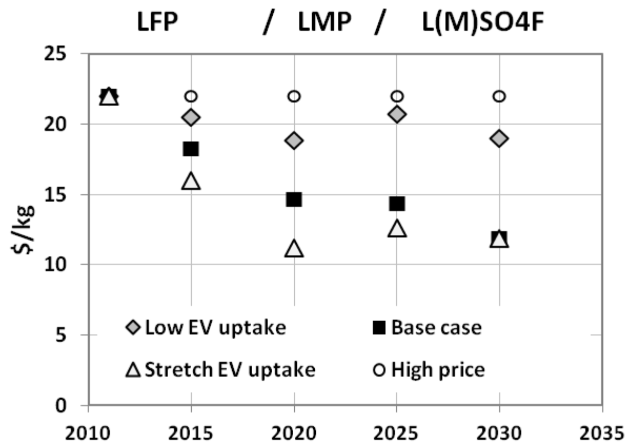


Figure 8-7 Cost inputs for polyanion cathode materials. Based on observed values for 2011 and scenarios developed by Element Energy for future years and materials

NMC cathodes

Today NMC costs are taken to be 42$/kg based on recommendation from industry contacts. For comparison, the Tiax model uses a base value of 45$/kg (40$/kg for low and 53$/kg for high case), the ANL model assumes 39$/kg for 2020, and Deustche Bank modelled NMC cells are based on 39$/kg in 2009.

The expected 15% cost decrease (Roland Berger analysis) reduces NMC cost to $35.7/kg. This is staged according to the EV uptake scenario: by 2015 in the Stretch EV case, by 2020 in the base case and by 2025 in the Low EV uptake scenario. A decrease of -1% p.a. is applied thereafter.

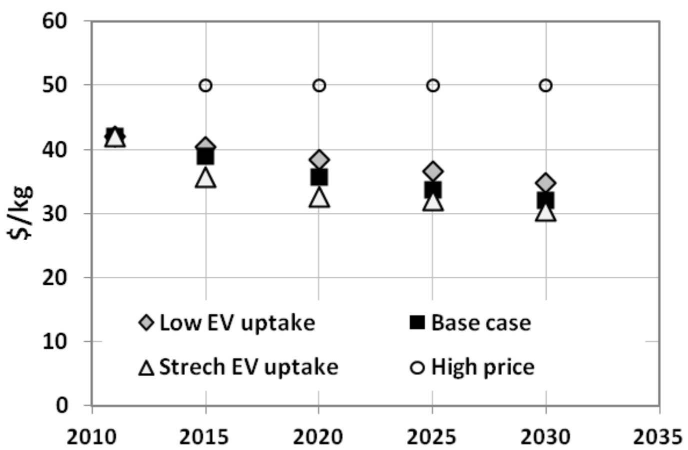


Figure 8-8 Cost inputs for NMC cathode material. Based on observed values for 2011 and scenarios developed by Element Energy for future years

Spinel cathodes (LMO, LNMO)

The TIAX model base value of 16$/kg for LMO is used for 2011. LNMO – replacing LMO from 2020 in the model – is expected to be more expensive because on the addition of nickel and more expensive process (LNMO is more difficult to synthesise than LMO and needs to the coated for high voltage stability). Figure 8-9 below shows the assumed costs trajectories.
For comparison, the ANL model assumes 10$/kg for 2020 and the TIAX model low and high costs are 12 and 20 $/kg for LMO.

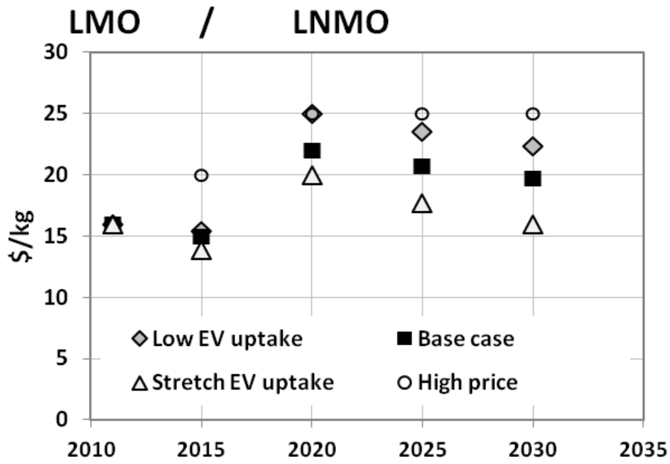


Figure 8-9 Cost inputs for spinel cathode material. Based on observed values for 2011 and scenarios developed by Element Energy for future years and materials

Composite cathodes (LL)

LL cathode materials, entering the model in 2020 in the base case, are assumed to cost the same than LNMO (22-20$/kg). This is a conservative estimate as it is expected to be easier and hence less expensive to synthesise LL than LNMO.

Anode active materials (Graphite, Silicon/C)

Based on conversations with anode material suppliers, the cost of graphite is assumed to 30$/kg in 2011; this is the mid value of the current 20-40$/kg observed range (this range would correspond to variable capacity densities). Graphite anode material is assumed to decrease to 19$/kg by 2020 – in line with the baseline cost used in the ANL model.
For comparison, the TIAX model baseline value is 20$/kg; low and high costs are 17$/kg and 23$/kg.

Silicon alloy anode material is not mass produced today, however several companies are making sample batches and building commercialisation plans. Based on conversations with the industry, a good estimate of today's Si/C cost would be to assume a similar cost per Ah as for graphite, with a 10% premium. It results in a theoretical cost of Si/C of 120$/kg (for 1200mAh/g) in 2011. The table below shows the cost assumptions over the years..

Table 8-6 Anode material cost inputs, including high price used for sensitivity analysis

$/kg	2011	2015	2020	2025	2030
Graphite	30	24	*19*	*19*	*19*
Si/C	*120*	*79*	46	34	34
High price	30	30	60	60	60

Non active materials

Costs of non active materials have been set to the same values as used in the ANL model, see Table 8-7. They are kept constant with time. The more important cost components such as the separator and electrolyte, are kept constant in line with the assumption that future cells will have different active materials and high safety standards, which will require developing new separators and electrolytes, leading to a commensurate increase in cost that would mitigate the cost reduction brought by volume

production. The cost of electrolyte is increased for high voltage cathodes, in line with the scientific challenge it represents.

Table 8-7 Cost of non-active materials used in model

Component	Unit	Marginal cost	Fixed cost	Comments
Carbon (conductor)	$/kg	6.8		
Binder (PDEF)	$/kg	10		
Al foil	$/kg	14.8		
Cu foil	$/kg	16.8		
Separator	$/m^2	2.0		USABC objective is ≤1$/m^2
Electrolyte	$/dm^3	21.6		20% premium added when cathode voltage is >4.9V
Solvent (NMP)	$/kg	3.2		
Positive terminal	$/kg	4	0.25	
Negative terminal	$/kg	6	0.25	
Cell Container	$/kg	3	0.20	

8.3.4 Cell production cost

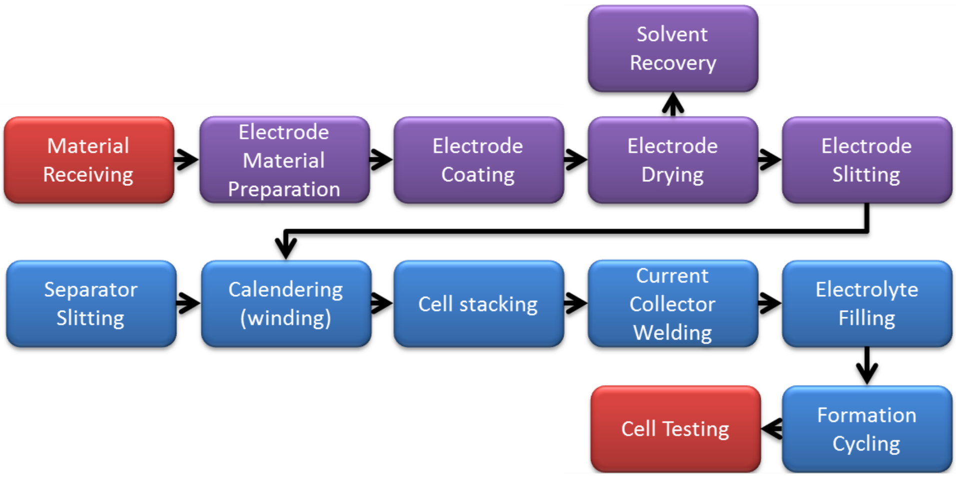


Figure 8-10 Cell production plant processing steps

We have researched investment costs of current and announced battery manufacturing plants worldwide. These plants use similar processes to produce cells (see Figure 8-10). This process, although complex, can be separated into its component parts and the cost dependence of each part can be separated. The plant costs depend mainly on the types of cells manufactured and annual production capacity[53]. This dictates how many machines are required in the plant and to a lesser extent the cost of these machines. We use the methodology developed by the ANL team to represent the elasticity between cell design/ cell volume and CAPEX costs.

[53] The number of cells and cell type combine to give the volume, area and kWh of material processed, these few inputs dictate the production costs.

The ANL calculations have been calibrated using our real world plant cost research. The plant cost / pack volume relationship generated using this method is shown in Figure 8-11 with real world plant cost included.

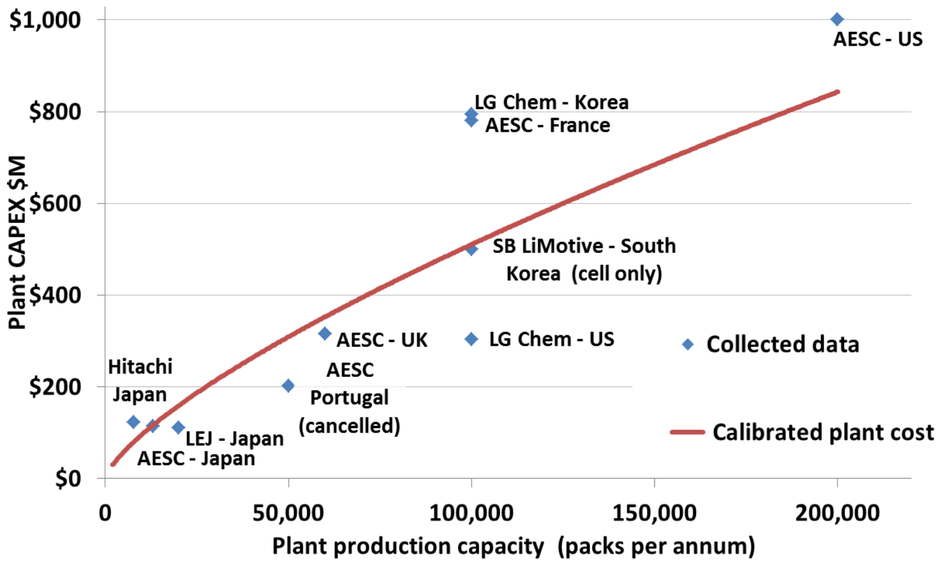


Figure 8-11 Investment costs ($million) of current and planned battery manufacturing plants dedicated to the automotive market. Publically available data collected by Element Energy

The ANL BatPaC plant costs are used as the lower bound of our baseline CAPEX plant costs, as the ANL model assumes a highly optimised plant operating in 2020 after a large adoption of EVs. The rate at which this cost is reached is dependent on the scenario on uptake of EVs: 2025 in the base case, 2030 in the conservative scenario ('Niche EV') and as early as 2020 in the optimistic scenario ('EV push').

There are several other costs that are included as part of the manufacturing costs. These include financing (rate and period), direct labour and overheads. We use a finance rate of 7% (all plant CAPEX costs are financed) and a payback period of 5 years, this is consistent with industry figures and peer review[54]. Direct labour is a small component of the cell cost as the production process is highly automated. Labour rates are set at $18/h. Cell yield is set at 95%.

Plant overheads include; R&D, sales and administration, maintenance (and other indirect labour), utilities and insurance. The overhead is set at flat rate of 30% of all direct costs (amortised plant CAPEX, direct labour and cell material cost); this has been checked against the battery manufactures company accounts[55] and quoted overhead rates[56].

The figure below shows the 2011 baseline cell cost and its variation with changing production parameters. The blue shaded area is the range of quoted cell costs. The modelled cost stays within this range when varying the production parameters, indicating the choice of baseline values is reasonable.

[54] A payback period of 5 years was one of the recommendations on the public consultation of the ANL BatPaC model.
[55] E.g. GS Yuasa and 3M
[56] Deutsche bank, ElectricCarsPluggedIn2, 2009

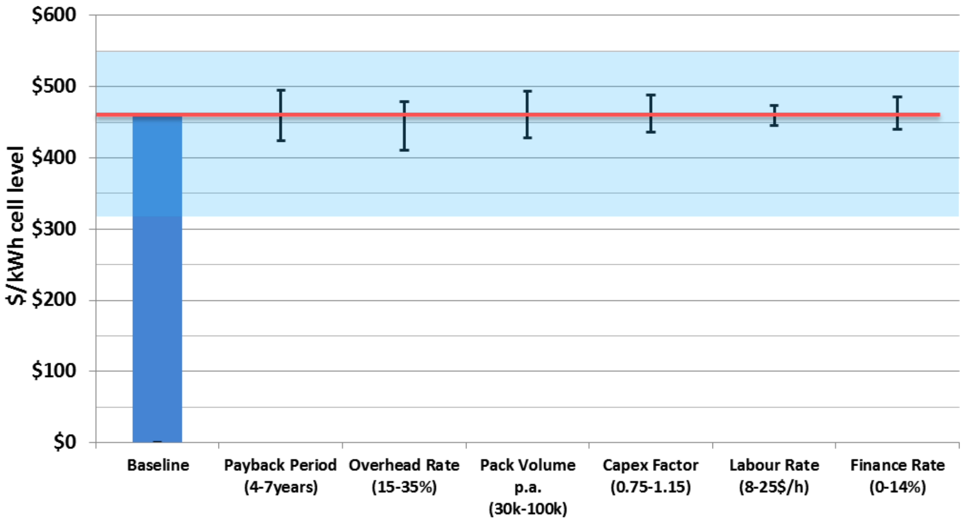
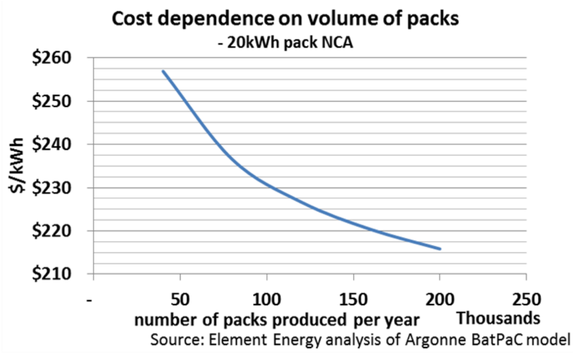


Figure 8-12 – Cost variations with alternative production parameters. 2011 cell costs, based on a C&D BEV pack (22kWh, NMC cathode)

Production volume



There is a large dependence between cost and production volume. The ANL model can reproduce the volume/cost relationship. Most other models state a single production volume and work only from this.

The ANL methodology to model cell production has been imported in our model to reproduce the volume effect as there is an expected change in production volume per plant with time. Currently there are no individual plants with an operational output volume above 50,000 packs, but some plants have a theoretical operational capacity of above 100,000 packs. The table below shows the production volume assumptions, per scenario, used in the model.

Table 8-8 Modelled plant production volumes - scenario and time dependence

Scenario	2011	2015	2020	2025	2030
Niche EV	50,000	50,000	100,000	100,000	100,000
Baseline	50,000	100,000	100,000	100,000	100,000
EV push	50,000	100,000	150,000	180,000	200,000

8.3.5 Pack assembly

Production lines

The table below shows the pack assembly production line costs used in the model; they are based on observed costs today and projected costs accounting for expected decrease. The future low costs are reached in 2025 in the baseline (in 2020 in the 'Stretch EV uptake' and 2030 in the 'low EV uptake' cases).

Pack assembly currently involves testing the pack at each assembly stage. Tester line costs are assumed to come down thanks to a reduced need for testing (e.g. 1 pack/hour)

as cells and pack components improve and are standardised. The cost of the assembly line equipment has the potential to be standardised; it is reduced by half over time in the model arising from an assumption of increased volume production.

Table 8-9 Pack assembly production lines costs

	2011	2015	Future low cost
Number lines needed	9	25	25
Production volume (packs p.a.)	20,000	100,000	100,000
Tester line cost	$450,000	$450,000	$150,000
Assembly line cost	$750,000	$750,000	$375,000

Cost of components

Vehicle battery packing is a more isolated application than production of large cells (that have other applications than the automotive market). Given the limited data we have applied learning rate theory to the pack component costs. The table below shows the cumulative EV sales scenarios. The cumulative production is assumed to be 25,000 packs in 2011.

Table 8-10 Cumulative EVs sales scenarios

Millions EVs	2020	2030
Low	3	23
Base	4	29
Stretch	16	223

Learning rates vary across components used in the pack assembly and the expected rates depend on how manual an operation is, and how novel it is. Rates have been estimated for each element according to typical learning rates observed across industries[57] and resulting component costs have been reviewed by our partner Axeon.

Table 8-11 shows the learning rates applied to pack components. They result in an overall learning rate of approximately 90% of pack purchased parts: a doubling of cumulative production reduces the cost by 10%. Figure 8-13 provides an example of the resulting cost trajectories, for one of the cost components (the fixed cost part of the power electronics).

Table 8-11 Learning rates applied to pack component costs

Component	Rate applied	Comments
BMS	90%	Fairly repetitive electronics
Power electronics	90%	If standardised parts are used
Wiring harnesses	85%	Very manual operation
Cell interconnections	85%	Very manual operation
Internal cell support	97%	Dominated by machine and raw materials
Housing	91%	Dominated by machine and raw materials

[57] See NASA Learning Curve Calculator http://cost.jsc.nasa.gov/learn.html for useful references

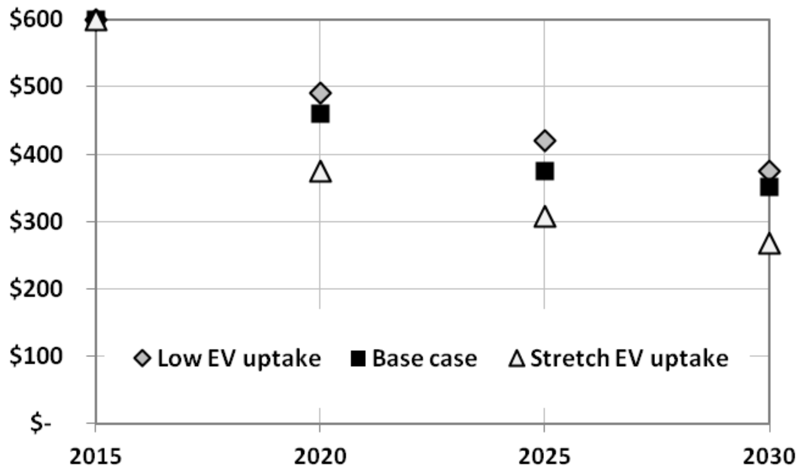


Figure 8-13 BEV power electronic fixed cost ($1,140 in 2011)

8.3.6 Other costs (inc. margin and warranty)

Margins in the manufacturing industry usually range from 5%-15% once the goods have become widespread commodities. We set our margin value at a fixed 10%, the average for manufacturing. This can be seen as conservative for future costs when car OEMs might squeeze battery suppliers' margins towards 7%, like other suppliers.

Warranty figures are set at 5%. This is to cover any defective cell replacement, cell recalls and claims resulting from defective cells.

Product transport costs are not considered in the model due their low value. It is worth mentioning that battery production is a global market and cells are often shipped worldwide, which comes at a low cost (1-2% overhead). Contrary to this, pack transport is more expensive as Dangerous Goods regulations apply more stringently to packaged cells. There will be an interest in having pack assembly plants in the same region as EV assembly plants. Transport costs are not explicitly included in the cost model.

8.4 Cost sensitivity

Table 8-12 on the next page illustrates the main cost sensitivities. The last column shows the percentage change in pack costs in 2020 when applying a +/-5% change in the indicated input parameter value[58]. It shows the cost is sensitive to active material properties (electrode active materials voltage and capacity, highlighted in purple); this is an expected result as these properties determine the battery energy density – a key parameter. The higher the electrode capacity, the higher the cell energy density and the less material needs to be purchased and handled per kWh. A higher cell voltage brings cost gains mainly at pack level: fewer cells are needed to reach the pack voltage requirement, meaning fewer cells to wire up and monitor.

Out of the production plant parameters (highlighted in green), the cell yield is the most influential. It is kept at 95% through the model, i.e. 5% of cells made in the plant are rejected at the end of the production line, for quality reasons. This rate can be seen as conservative for future plants.

The pack size effect has already been illustrated in the results section: the cost per kWh for a van pack (>50kWh) is lower than for a small car pack (<25kWh). The electrode thickness controls the ratio of active to inactive material in a cell and thus influences the energy density and cost of a cell – this effect has been well documented in other models and is commented on in section 8.3.1.

Several levels of cost inputs (highlighted in orange) have been developed, represented by the EV uptake scenarios (the higher the EV uptake, the quicker costs decrease). The greatest uncertainty is probably around the active material costs. For this reason, a high cost trajectory has been developed for them (detailed in section 8.3.3). The figure below shows the baseline results for several cathode chemistries. The dashed lines show the pack cost corresponding to the high active material costs; they can be seen as an indicative cost upper bound, e.g. $242/kWh against $212/kWh in the base case (for L(M)SO_4F cathode).

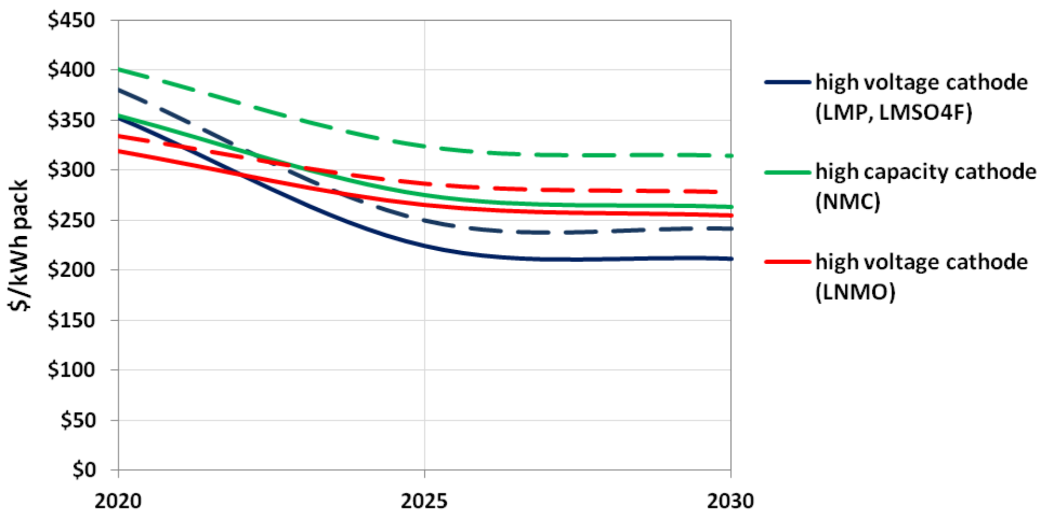


Figure 8-14 Baseline pack cost ($/kWh) results for base active materials costs (solid lines) and high active materials costs (dashed lines) for a selection of cathodes - C&D car BEV pack

[58] Cost deviation = square root (high – low deviation)^2. High/low deviation calculated by applying +/-5% to an input parameter. Cost change = cost deviation/base cost.

Table 8-12 Change in pack costs in 2020 for a +/-5% change in parameter value

Parameter	Units	Base value	% change in pack cost
Cathode voltage	V	4	8%
Cell yield	%	95%	6%
Cathode capacity	mAh/g	150	5%
Total pack size (DOD window)	%	80%	4%
Cathode active material density	g/cm3	3.45	3%
Maximum electrode thickness	µm	100	3%
Overhead rate	%	0.30	2%
CAPEX cost factor	-	1.00	1%
Pack voltage	V	300	1%
Factory load factor	%	95%	1%
Payback period	years	5	1%
Cathode active material cost	$/kg	14.65	1%
Margin	%	10%	1%
Anode capacity	mAh/g	1000	1%
Electrolyte cost	$/dm3	21.6	1%
Anode active material cost	$/kg	46	1%
Labour rate	$/h	18	1%
Pack housing cost	$/pack	325	1%
Warranty	%	5%	1%
Power electronics cost	$/pack	307	0.5%
Number of packs produced	p.a.	100,000	0.5%
BMS cost	$/cell	3.2	0.4%
Anode voltage	V	0.1	0.4%
Labour time factor	-	1	0.3%
Finance rate	%	7.00%	0.2%

Production plant parameters
Cost inputs, linked to EV uptake
Material properties < R&D roadmap

Base cost: $352/kWh,
LMP cathode Si/C anode

8.5 Model results to 2030

8.5.1 Baseline results

Cost breakdown 2011

Figure 8-15 shows the cost breakdown for the baseline mid-size car BEV pack in 2011 (graphite anode, NMC cathode). The main cost components are cell materials and pack components. Their cost breakdown is detailed in Figure 8-16. The cathode is the most expensive cell component and it represents around 12% (43%x27%) of the cost at pack level. The 'Other' cell material includes the cost of terminals, container and material wastage.

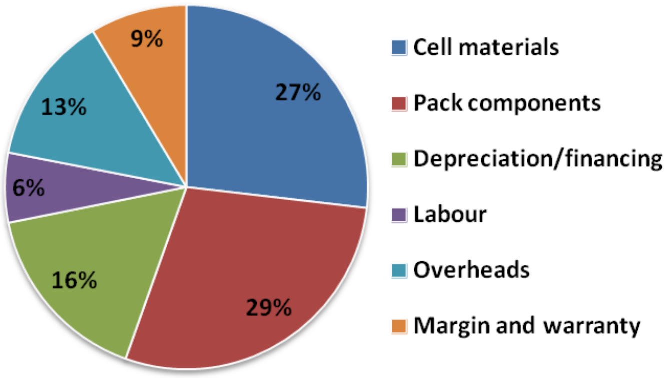
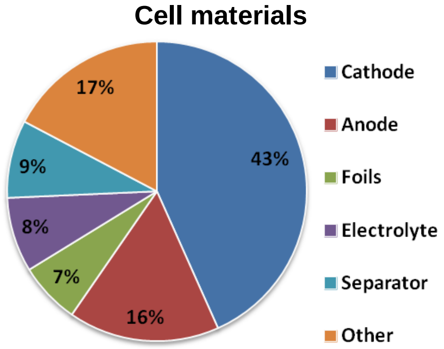


Figure 8-15 Cost breakdown in 2011 for a 26kWh BEV C&D pack. NMC cathode, graphite anode - $777/kWh



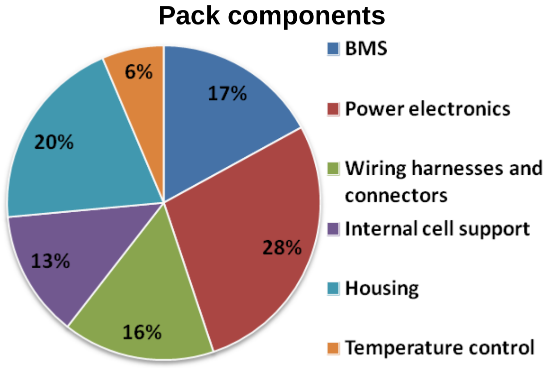


Figure 8-16 Cell materials and pack components cost breakdown - 2011 BEV C&D car pack

Cost breakdown 2030

The next figure gives the cost breakdown for the baseline mid-size car BEV pack in 2030 (silicon anode, high voltage cathode). Cell materials and pack components/assembly are still the main cost constituents, making 64% of the pack cost. Their cost breakdown is detailed in Figure 8-18. The cathode is still the most expensive cell component but it has dropped to only 9% of the pack cost.

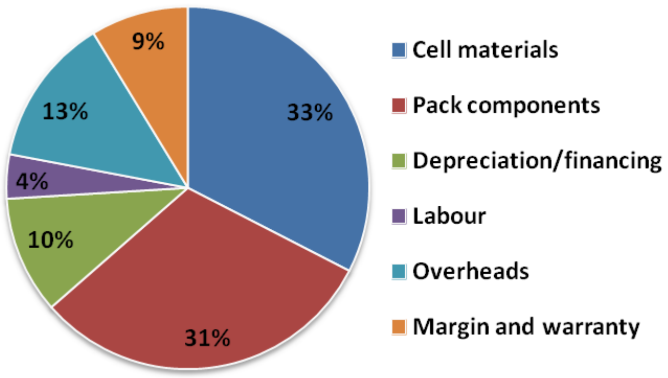


Figure 8-17 Cost breakdown in 2030 for a 30kWh BEV C&D pack. High voltage cathode, Si/C anode - $212/kWh

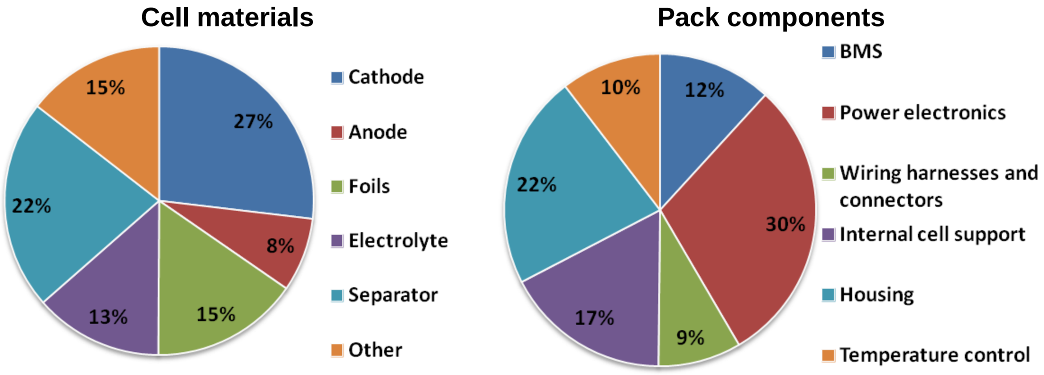


Figure 8-18 Cell materials and pack components cost breakdown - 2030 BEV C&D car pack

Pack results

The next table shows the model baseline results for BEV and PHEV applications. Several cathode chemistries were run; only the one delivering the lowest cost is reported here.

Results for 2011 have been reviewed and validated by our industry partners but they should be viewed as indicative only. As explained earlier in the report, current automotive packs are built at low production volumes, and a wide range of costs is observed, especially at cell level. The element of strategic pricing is certainly an important determinant of costs at the present time, and it is challenging to remove this signal from the market data.

The model results for 2015 already indicate a substantial cost decrease. This is mainly driven by assumptions on cost reductions of pack components and cell footprint standardisation, both in line with the announced investment in battery production capacity. However if demand for EV stalls, and if the announced production capacity is not fully utilised by 2015 (there are indications this may be the case), then the 2015 results should be interpreted as optimistic. Under such circumstances, it may be that a 2020 time horizon is more realistic for achieving the beneficial effects of volume production.

Table 8-13 Baseline pack cost results

		2011	2015	2020	2025	2030
BEV	Pack cost $/pack	$17,499	$11,474	$7,805	$5,533	$5,232
A&B	Pack cost $/kWh	$829	$544	$370	$262	$248
	Pack mass kg	269	231	158	124	123
21kWh	Pack Wh/kg	78	91	134	170	171
	Cell cost $/kWh	$473	$305	$211	$143	$136
BEV	Pack cost $/pack	$21,944	$14,595	$9,619	$6,789	$6,403
C&D	Pack cost $/kWh	$726	$483	$318	$225	$212
	Pack mass kg	317	320	202	166	165
30kWh	Pack Wh/kg	95	94	149	182	183
	Cell cost $/kWh	$454	$299	$187	$134	$127
BEV	Pack cost $/pack	$31,409	$20,348	$13,109	$9,427	$8,860
E&H	Pack cost $/kWh	$634	$411	$265	$190	$179
	Pack mass kg	592	501	307	256	254
50kWh	Pack Wh/kg	84	99	161	194	195
	Cell cost $/kWh	$432	$279	$173	$125	$118
BEV	Pack cost $/pack	$40,336	$26,708	$17,384	$12,512	$11,765
Van	Pack cost $/kWh	$587	$388	$253	$182	$171
	Pack mass kg	808	688	423	352	349
69kWh	Pack Wh/kg	85	100	162	195	197
	Cell cost $/kWh	$417	$278	$176	$127	$120
PHEV	Pack cost $/pack	$16,126	$9,692	$6,353	$5,280	$4,900
C&D	Pack cost $/kWh	$1,327	$798	$523	$435	$403
	Pack mass kg	179	152	105	95	95
12kWh	Pack Wh/kg	68	80	116	127	128
	Cell cost $/kWh	$600	$362	$240	$202	$198
PHEV	Pack cost $/pack	$20,621	$13,923	$9,123	$7,579	$7,284
Van	Pack cost $/kWh	$746	$503	$330	$274	$263
	Pack mass kg	343	298	197	178	176
28kWh	Pack Wh/kg	81	93	140	156	157
	Cell cost $/kWh	$454	$306	$202	$173	$169

The pack size in kWh is the total energy. It is assumed 80% of the total capacity will be available for use in the BEV packs and 70% in the PHEV packs, to ensure packs maintain sufficient energy and power over the vehicle lifetime (see section 2.2.4 for details).

Improvements in cell materials and pack thermal and electronic control could take these available capacity numbers to 90% and 80% - these would be upper bounds.

Results presented above were obtained when running the model for a target usable energy (kWh), as defined in Appendix 8.1.

It has been shown that the cost per kWh varies with the pack size, especially for small PHEV packs. The tables below show alternative results, when modelling a bigger pack to reduce the cost per kWh, while staying in the range of input validity.

Note that in the case of the plug in hybrid C/D car, the cost premium is mostly down to the thermal and electronic management of the pack (see page 57). Increasing the size of the pack decreases the power to energy ratio and thus reduces the $/kWh of packing. The model reproduces this – see Figure 8-19 – but does not reproduce a step change (such as a change in thermal control method or cell type) that might occur in practice when reducing the power to energy ratio.

Table 8-14 PHEV C/D car results when increasing the pack size

	Unit	2020	2025	2030
12 kWh total (baseline)				
Total pack cost	$/kWh	$523	$435	$403
	$	$6,353	$5,280	$4,900
16kWh pack				
Total pack cost	$/kWh	$448	$375	$350
	$	$7,170	$5,995	$5,585

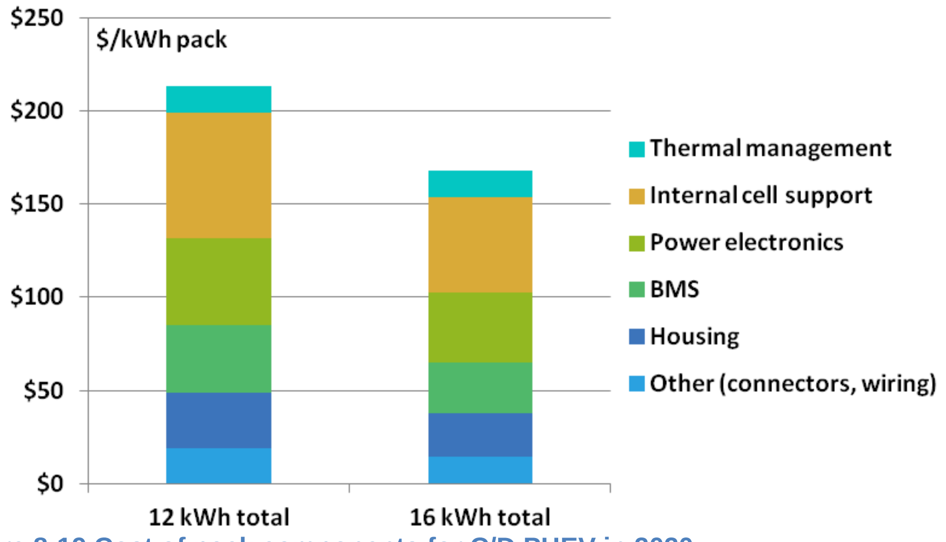


Figure 8-19 Cost of pack components for C/D PHEV in 2020

8.5.2 Conservative scenario results

This scenario corresponds to a lower risk of delivery. See sections 5.3 and 6.1.2 for details on assumptions. As before, the indicated pack size in kWh is the total energy.

Table 8-15 Conservative pack cost results (EV niche scenario)

		2011	2015	2020	2025	2030
BEV	Pack cost $/pack	$17,499	$12,257	$9,301	$7,267	$6,446
A&B	Pack cost $/kWh	$829	$581	$441	$344	$305
	Pack mass kg	269	231	207	135	134
21kWh	Pack Wh/kg	78	91	102	156	157
	Cell cost $/kWh	$473	$340	$248	$186	$169
BEV	Pack cost $/pack	$21,944	$15,612	$12,065	$8,791	$7,875
C&D	Pack cost $/kWh	$726	$517	$399	$291	$261
	Pack mass kg	317	320	276	179	177
30kWh	Pack Wh/kg	95	94	109	169	171
	Cell cost $/kWh	$454	$331	$253	$172	$157
BEV	Pack cost $/pack	$31,409	$21,683	$16,633	$11,981	$10,873
E&H	Pack cost $/kWh	$634	$438	$336	$242	$220
	Pack mass kg	592	501	449	272	269
50kWh	Pack Wh/kg	84	99	110	182	184
	Cell cost $/kWh	$432	$305	$230	$159	$146
BEV	Pack cost $/pack	$40,336	$28,455	$21,754	$15,916	$14,505
Van	Pack cost $/kWh	$587	$414	$316	$232	$211
	Pack mass kg	808	688	616	374	370
69kWh	Pack Wh/kg	85	100	112	184	186
	Cell cost $/kWh	$417	$302	$228	$162	$149
PHEV	Pack cost $/pack	$16,126	$10,360	$7,769	$6,220	$5,402
C&D	Pack cost $/kWh	$1327	$853	$639	$512	$445
	Pack mass kg	179	152	135	99	95
12kWh	Pack Wh/kg	68	80	90	123	128
	Cell cost $/kWh	$600	$414	$283	$235	$205
PHEV	Pack cost $/pack	$20,621	$14,912	$11,574	$8,780	$7,668
Van	Pack cost $/kWh	$746	$539	$418	$317	$277
	Pack mass kg	343	298	270	184	176
28kWh	Pack Wh/kg	81	93	102	150	157
	Cell cost $/kWh	$454	$340	$258	$199	$176

8.5.3 Optimistic scenario results

This scenario corresponds to a rapid deployment of new cell materials and high EV uptake. See sections 5.3 and 6.1.2 for details on assumptions. As before, the indicated pack size in kWh is the total energy.

Table 8-16 Optimistic pack cost results (EV push scenario)

		2011	2015	2020	2025	2030
BEV	Pack cost $/pack	$17,499	$10,002	$6,082	$4,935	$4,687
A&B	Pack cost $/kWh	$829	$474	$288	$234	$222
	Pack mass kg	269	197	142	123	123
21kWh	Pack Wh/kg	78	107	149	171	171
	Cell cost $/kWh	$473	$250	$152	$131	$128
BEV	Pack cost $/pack	$21,944	$12,609	$7,394	$6,091	$5,806
C&D	Pack cost $/kWh	$726	$417	$245	$202	$192
	Pack mass kg	317	272	186	165	165
30kWh	Pack Wh/kg	95	111	162	183	183
	Cell cost $/kWh	$454	$245	$142	$124	$121
BEV	Pack cost $/pack	$31,409	$17,422	$10,149	$8,522	$8,163
E&H	Pack cost $/kWh	$634	$352	$205	$172	$165
	Pack mass kg	592	423	281	254	254
50kWh	Pack Wh/kg	84	117	176	195	195
	Cell cost $/kWh	$432	$229	$132	$116	$114
BEV	Pack cost $/pack	$40,336	$22,737	$13,503	$11,358	$10,915
Van	Pack cost $/kWh	$587	$331	$196	$165	$159
	Pack mass kg	808	581	387	350	349
69kWh	Pack Wh/kg	85	118	178	197	197
	Cell cost $/kWh	$417	$228	$135	$118	$115
PHEV	Pack cost $/pack	$16,126	$8,457	$5,338	$4,622	$4,311
C&D	Pack cost $/kWh	$1327	$696	$439	$380	$355
	Pack mass kg	179	130	104	95	95
12kWh	Pack Wh/kg	68	94	117	128	128
	Cell cost $/kWh	$600	$297	$200	$182	$175
PHEV	Pack cost $/pack	$20,621	$12,045	$7,615	$6,749	$6,374
Van	Pack cost $/kWh	$746	$436	$275	$244	$230
	Pack mass kg	343	253	195	177	176
28kWh	Pack Wh/kg	81	110	142	157	157
	Cell cost $/kWh	$454	$251	$174	$157	$151