Programme Area: Energy Storage and Distribution

Project: Consumers, Vehicles and Energy Integration (CVEI)

Title: D3.1. Battery Cost and Performance and Battery Management System Capability Report and Battery Database

Abstract:

This report represents Deliverable D3.1, Battery Cost and Performance and Battery Management System Capability Report and Battery Database. The purpose of this report is capture the approach proposed to develop cost and performance projections for automotive batteries to 2050. A brief explanation of the battery components and working principles is provided before the overall data collection and modelling methodology are described. This is followed by a presentation of the cost and energy density projections for automotive battery packs. Several scenarios have been developed for use in the wider modelling framework of the CVEI project. The report also includes an assessment of Battery Management Systems (BMS), their current features and potential additional capabilities required to provide tighter integration of electric vehicles (EVs) into the electricity system.

The separate spreadsheet (accompanying this report) provides more detail in the form of the Battery Cost and Performance Database.

Context:

The objective of the Consumers, Vehicles and Energy Integration project is to inform UK Government and European policy and to help shape energy and automotive industry products, propositions and investment strategies. Additionally, it aims to develop an integrated set of analytical tools that models future market scenarios in order to test the impact of future policy, industry and societal choices. The project is made up of two stages:

• Stage 1 aims to characterize market and policy frameworks, business propositions, and the integrated vehicle and energy infrastructure system and technologies best suited to enabling a cost-effective UK energy system for low-carbon vehicles, using the amalgamated analytical toolset.

• Stage 2 aims to fill knowledge gaps and validate assumptions from Stage 1 through scientifically robust research, including real world trials with private vehicle consumers and case studies with business fleets. A mainstream consumer uptake trial will be carried out to measure attitudes to PiVs after direct experience of them, and consumer charging trials will measure mainstream consumer PiV charging behaviours and responses to managed harging options.

Project: Consumers, Vehicles and Energy Integration

Project ID: TR1006

Deliverable D3.1:

Battery Cost and Performance and Battery Management System Capability Report and Battery Database

for

ETI

Version 4

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Executive summary

Background and objectives

This report is part of deliverable D3.1 for WP3 of the ETI Consumers Vehicles and Energy Integration (CVEI) Project. It sets out the approach to develop cost and performance projections for automotive batteries to 2050. A brief explanation of the battery components and working principles is provided before the overall data collection and modelling methodology are described. This is followed by a presentation of the cost and energy density projections for automotive battery packs. Several scenarios have been developed for use in the wider modelling framework of the CVEI project. The report also includes an assessment of Battery Management Systems (BMS), their current features and potential additional capabilities required to provide tighter integration of electric vehicles (EVs) into the electricity system.

Approach

The study built on (and updated) the Element Energy bottom up model of lithium-ion battery pack performance and costs, developed in 2012 for the Committee on Climate Change, and benefitted from industry stakeholder inputs, notably Johnson Matthey's input regarding packing components. The bottom up model combines battery sub-component specifications and costs to 2030, while a top down approach is used for post-2030 projections.

Comparison of recent trends in automotive battery packs and the model's predictions revealed a good match. The model reproduces the cost reduction of ca.10 % p.a. and energy density improvement of ca. 5% p.a. observed over the last 5 years (ca. 40% cost reduction and 15% energy density improvement at the pack level), resulting in today's cost and energy density of ca. £350/kWh (GBP2014) and ca. 100 Wh/kg for a 25 kWh pack.

A detailed review of both lithium-ion chemistries and post-lithium ion technologies was carried out to understand the upcoming improvement in cell energy density (mostly dependent on the active material mAh/g and voltage) and possible transition to cheaper materials. Another key cost driver in the model is the assumption regarding global EV sales, as these are used with learning rates to calculate the future cost of some components.

Automotive battery state of the art and current trends: an overview

The assumptions that underpin the energy density of batteries have been updated following the review of current limitations and recent breakthroughs in this area. For example, the observed shift towards Ni-rich battery cathodes among the major car OEMs helped to define the energy density projection scenarios on a cell level with higher confidence. Equally, the revised assumptions relevant to the pack components, such as the 25% reduction in housing weight suggested by Johnson Matthey, contributed to a better definition of the battery pack energy densities for 2015-2050.

A vast majority of car manufacturers currently use Li-ion batteries for propulsion power in EVs. Various methods have been pursued in recent years to overcome the limitations of Li-ion batteries in terms of energy density, power density, cycle life and safety. Cathode materials continue to be dominated by Li compounds with transition metal oxides. Lithium Nickel Manganese Cobalt Oxide (NMC) was identified as one of the most popular EV battery cathodes at the moment, as the use of Ni and Co leads to higher energy and power densities, whilst Mn ensures better cycle life and safety. Three types of Li-ion cathode materials with different structures that are currently used in the EVs are considered separately in the database that accompanies this report. These are:

- NMC – identified as the most popular cathode material in EVs at the moment and is expected to be used in upcoming EV models. Offers one of the highest theoretical specific capacities (ca. 280 mAh/g), has a relatively high operating temperature window upper limit (210 °C) and a good cycle life.

- Polyanion – Lithium Iron Phosphate (LFP) – identified as an alternative cathode material, currently used predominantly by the Chinese OEMs. Offers a medium theoretical specific capacity (ca. 170 mAh/g), but has one of the highest operating temperature window upper limits (270 °C) and an excellent cycle life.
- Spinel – Lithium Manganese Oxide (LMO) – the material of choice for early EV models (e.g. first generation Nissan Leaf). Often is used as a part of a blended cathode in current EVs. Has a relatively low theoretical specific capacity (ca. 150 mAh/g), and a high operating temperature window upper limit (250 °C), but at the same time has a relatively poor cycle life.

In terms of the anodes, carbon blends with Si have received the most attention recently due to their extremely high gravimetric capacity. However, sufficiently long cycle life for batteries with Si-rich anodes remains to be demonstrated. Thus, for the anode, graphite is assumed in the short term and graphite blends with silicon are assumed from 2020, with the silicon part in the blend being increased with time. Capacity of Si/Gr anodes was revised down from 1,000 mAh/g in 2020 to 650 mAh/g in 2020 based on the current scientific progress.

Emerging technologies for EV batteries

The fundamental advantage of Li-ion batteries over other battery chemistries is that Li has the lowest reduction potential of any element, resulting in the highest achievable cell potential. Li is also the third lightest element, which allows Li-ion batteries to achieve high energy and power densities. This makes Li-ion batteries the technology of choice for the automotive industry and the core of the present report. However the use of composite cathodes and anodes, in order to achieve a good cycle life, results in a significant reduction in practically achievable energy and power densities.

The advantages, the drawbacks and the key characteristics of the emerging Li-based battery technologies are reviewed in the report. In theory, a Li-air system could offer ca. 10 times higher energy density (ca. 3,500 Wh/kg) than the best currently available Li-ion batteries that use composite electrodes. However, the cycle life of Li-air systems was found to be only ca. 100 cycles at present and despite many advances in recent years, the battery community recognises that Li-air systems are still far away from commercialisation. Currently, Li-S is the most promising high-energy density technology, but at ca. 200 cycles before the end of life, it still needs significant improvement before it can be used in automotive applications.

A possible alternative to Li-ion cells are batteries based on alternative metal ions. Specifically, the report discusses high temperature molten sodium batteries that have previously been used in EV prototypes. Current progress in low temperature Na-ion electrolytes and the transition to low temperature Na-ion batteries are described in the report. This technology still has many issues, especially the lower energy density and the inferior cycling stability compared to Li-ion batteries.

Another battery technology that has already found its application in stationary power is flow batteries. Although the main advantage of decoupling power and energy by storing fuel in a liquid form is less relevant for transport applications, other strengths such as very good cycle life and calendar life make flow batteries appealing for use in EVs. The report reviews several types of flow battery chemistries and outlines the advantages and drawbacks of each. The most studied type of flow cell is the all-vanadium system. This system was found to have >13,000 cycle life, but is unsuitable for EV applications due to a very low theoretical energy density (ca. 25 Wh/kg). Other chemistries have the potential to reach a much higher energy density, but are at early stages of development and their cost, cyclability and safety remain to be tested.

Based on the historic rate of commercialisation of new technologies, also discussed in this report, these emerging technologies are not expected to enter the automotive market in the next 10 years. Post lithium-ion technologies are however considered from 2030 in the projections developed for this work.

Cost and performance projections

Several scenarios were developed, to cover a range of outcomes (for use in the wider modelling framework in WP1):

- A **baseline case**, where EVs see a high global uptake (reaching 4 and 35 million cumulative sales by 2020 and 2030, respectively) and R&D delivers cell improvement to the extent that the lithium-ion limits are reached by 2030, and significant blending of silicon in the anode is achieved
- An '**EV push**' case where the same R&D outcomes as above are coupled with a higher global uptake of EVs (15 and 123 million cumulative sales by 2020 and 2030, equivalent to 5 and 14% global EV uptake by 2020 and 2030)
- An '**EV niche**' case corresponding to a lower energy density and higher cost trajectory: R&D efforts are slower to deliver improvements in energy density, and global EV sales are also lower.

The cost and performance projections for post lithium-ion chemistries constitute an alternative scenario for post-2030 values, called 'New battery technologies'.

Results were developed for six battery pack size bands, and the format of these is compatible with the vehicle uptake Electric Car Consumer (ECCo) model. This allows the results to capture the impact of the pack size on cost: because of fixed costs, the larger the capacity, the lower the cost per kWh. This also applies (to a lesser extent) to energy density.

Under the baseline case, a 30 kWh pack would decrease in cost from ca. £320/kWh in 2015 to ca. £215/kWh in 2020 and ca. £150/kWh in 2030, a 35% and 55% decrease respectively. The energy density is projected to increase by ca. 30% in 2020 and ca. 90% in 2030, compared to today's pack level density (ca. 100 Wh/kg).

Taking into account vehicle energy use efficiency improvements and future wider depth of discharge windows, a 30 kWh pack in a medium size car was found to be capable of ca. 190 km driving range at a cost of £9,540 and mass of 280 kg in 2015. According to the results of the model, the range of an equivalent car should be expected to increase to 200 km in 2020, at a cost and mass of £6,430 and 200 kg respectively. By 2030, a 30 kWh pack would have gone further down to £4,400 and 150 kg, providing 230 km of driving range.

Cost and energy density are projected to improve further post-2030 for a lithium-ion pack, through continuous efficiency gains, to reach £109/kWh and 250 Wh/kg (pack level) by 2050 (assuming a 2% p.a. decrease in pack costs 2030 onwards).

Baseline results for a 30 kWh battery pack

30kWh pack	2015	2020	2030	2040	2050
Total pack cost, 2014GBP	£9,540	£6,433	£4,977	£4,407	£3,788
2014GBP/kWh	£318	£214	£147	£126	£109
Wh/kg	108	143	205	226	250
Mass, kg	280	209	147	133	120
Depth of discharge	85%	85%	90%	90%	90%

For the 'New battery technologies' scenario, hypothetical lithium-sulphur and lithium-air batteries were compared to the projected 2030 lithium-ion pack to identify potential cost differences. Although both technologies offer areas where cost reductions could be achieved (e.g. lower electrode material costs), other components would be more expensive (e.g. higher packing costs due to lower voltage). This leads to overall comparable ‘bill of material’ costs (<10% reduction estimated for a 30kWh pack). If remaining challenges are addressed and post-lithium ion cells achieve the automotive cell grade, high volume manufacturing will begin at least 10 years after large lithium-ion cells and thus might not be competitive from the start.

For these reasons, under the ‘New battery technologies’ scenario, post-lithium ion batteries are mostly bringing energy density improvements. The energy density projections are based on theoretical cell densities, typical theoretical to practical ratios and assume new cell technologies would benefit from the streamlined manufacturing process developed for lithium-ion cells. The projected ‘New battery technologies’ energy densities are ca. 290 Wh/kg in 2030 and ca. 360 Wh/kg in 2050.

Battery management system

The report assesses the state of the art for vehicle Battery Management Systems (BMS), and identifies the gaps in the capabilities required to implement the strategies, policy and regulatory frameworks, and commercial arrangements identified in WP1a for the integration of EVs in the electricity system. The three main BMS capability developments that have been identified for the integration of EVs in the energy system are:

- reporting state of health in real-time to optimise charging and usage of EVs
- advanced state of health reporting to allow prediction of availability for demand management
- new algorithms (for example, algorithms that enable the identification of unusual aging trends).

It was found that current state of the art BMS already have the basic capabilities required for the integration into the electricity grid. On the other hand, the evidence indicates that interfaces other than the BMS are required to enable the integration of EVs into the electricity system. That is, the critical components for this system integration, such as algorithms able to gather the needs of different actors and to optimise the use of the battery accordingly, are likely to be embedded in components other than the BMS (e.g. the car Energy Management System). Hence, in addition to the identification of areas of improvement and new capabilities in the BMS itself, this report also comments on other components and capability gaps for the integration of EVs into the electricity system. This is supported by the demonstration projects and relevant funding opportunities discussed in this report. The majority of these projects are led by utility companies in collaboration with car Original Equipment Manufacturers (OEMs), charging point providers and software developers, and are focused on the development and testing of smart charging algorithms. Information gathered from industry stakeholders suggests that in terms of future projects, the value of collaboration is highest where the focus is on standardisation or interactions with the wider EV integration chain (e.g. cloud solutions, apps, data transfer to aggregators or renewable energy generators).

Contents

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Version control

Version number	Submission date	Comments
1	20/01/2016	First version, not including the chapter on Battery Management System (to be submitted at a later date).
2	01/06/2016	This version merges the version 1 report with the BMS section, and addresses the feedback received from ETI on the 03/03/2016 (V1 report) and 13/04/2016 (BMS section).
3	07/10/2016	This version addresses the feedback received from ETI on the 04/07/2016.
4	29/11/2016	This version addresses the feedback received from ETI on the 22/11/2016.

Acronyms

AC	Alternative current
ALISE	Advance Lithium Sulphur Batteries for Hybrid Electric Vehicle
ANL	Argonne National Laboratory
APC	Advanced Propulsion Centre
API	Application Program Interface
BMS	Battery Management System
BOM	Bill of Materials
BTRL	Battery Technology Readiness Level
CCC	Committee on Climate Change
CP	Charging point
CVEI	Consumers Vehicles and Energy Integration
DC	Direct Current
DM	Demand Management
DNO	Distribution Network Operator
DOD	Depth of Discharge
ECLIPSE	European Consortium for Lithium Sulphur Power for Space Environments
EIS	Electrochemical Impedance Spectroscopy
EMS	Energy Management System
EPSRC	Engineering and Physical Sciences Research Council
EV	Electric Vehicle
FP	Framework Programme
FR	Frequency Response
HV	High voltage
Gr	Graphite
G2V	Grid to Vehicle
LCO	Lithium Cobalt Oxide
LFP	Lithium Iron Phosphate
LMO	Lithium Manganese Oxide
LMP	Lithium Manganese Phosphate
LTO	Lithium Titanate Oxide
NCA	Lithium Nickel Cobalt Aluminium Oxide
NEDC	New European Driving Cycle
NMC	Lithium Nickel Manganese Cobalt Oxide
NMC/Gr	NMC cathode and Gr anode
OCPP	Open Charge point Protocol
OEM	Original Equipment Manufacturer (i.e. vehicle manufacturer)
PHEV	Plug-in Hybrid Electric Vehicle
REVB	Revolutionary EV Battery Project
SOC	State of Charge
SOH	State of Health
TMH	The Mobility House (smart charging point provider)
ToU	Time of Use
V2G	Vehicle to Grid

Glossary

18650	The most common (in laptops and other consumer electronic goods) and mass produced cell; it is a cylindrical cell, 18 mm in diameter, 65 mm high.
Active material	Constituents of a cell that participate in the electrochemical charge/discharge reaction.
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.
Battery	Two or more cells electrically connected to form a unit.
Battery Management System (BMS)	Set of electronic components that monitors and controls the battery. Its main functions are to protect the battery and cells from damage, to prolong the battery lifetime, to ensure that the battery state is fit for the application purpose and to interface with the host application (e.g. a car).
Battery pack	Battery with the integration of a BMS and other packing components such as power electronics, wiring harness and connectors, internal cell support, housing and a thermal management system.
Capacity	Number of Ah or kWh a fully charged cell or battery can deliver under specified conditions of discharge. It is typically reported in units of amp-hour (Ah) at cell level and kWh at battery pack level.
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.
Cell	Basic electrochemical unit used to store electrical energy.
Depth of Discharge (DoD)	The DoD is used to describe how deeply the battery is discharged (i.e. if a battery has a DoD of 0%, it means that it is fully charged). This concept is an alternative way of indicating the battery's State of Charge (SoC): 100% DoD is equivalent to 0% SoC. In this report, the DoD refers to the window of (dis)charge that is allowed on the pack. Packs based on lithium-ion cells are never allowed to get to either 100% or 0% DoD (to prolong battery life and for power requirements). The 0-100% charging status range an electric vehicle owner sees is different, applying to the useable capacity; it actually corresponds to e.g. 10%-90% over the total pack capacity.
Electrolyte	Medium which provides the ion transport function between the positive and negative electrodes of a cell.
G2V	Grid to Vehicle refers to the case when an EV provides services to the grid through changes in charging (start time, duration, and/or rate).
Intercalation	The principle of intercalation is the reversible insertion of a guest ion (or molecule) into a host structure without inducing a major disruption of the host material. In a Lithium-ion cell, lithium ions shuttle back and forth between the intercalating electrodes.
Ion	An atom or a molecule in which the total number of electrons is not equal to the total number of protons, giving the atom or molecule a net positive or negative electrical charge
Separator	Electrically insulating layer of material which physically separates electrodes of opposite polarity. Separators must be permeable to ions in the electrolyte and may also have the function of storing or immobilizing the electrolyte.
State of Charge (SoC)	Describes the extent to which the battery is charged (100% = fully charged). See also the Depth of Discharge entry.
V2G	Vehicle to Grid refers to the case when an EV provides services to the grid by feeding the electricity stored in the battery back to the grid.

1 Introduction and scope

ETI Consumers, Vehicles and Energy Integration project

The overall aim of the Consumers, Vehicles and Energy Integration (CVEI) Project is to provide a detailed understanding of how the UK's car and van markets and related refuelling infrastructure will need to evolve in the future in order to meet long term CO_2 reductions from the transport sector. In particular, it aims to define internally consistent future scenarios which take account of changes in vehicle technologies and costs, consumer behaviour, policy and evolving commercial models. Given the likely role of electrified powertrains in the future light vehicle parc, a key focus of the project is the interaction between vehicles and the electricity system (in addition to hydrogen and existing liquid fuel infrastructure), both from a technical point of view and in terms of the roles for different actors at each part of the value chain, such as electricity suppliers, grid operators and vehicle manufacturers. During Stage 1, the project is developing an overarching 'analytical framework', a collection of models and tools to quantify these future scenarios and assess their relative strengths. Stage 1 will also map potential configurations for 'managed charging' of electric vehicles to minimise negative impacts on the wider electricity system (and potentially to provide a net benefit). Some of these technical and commercial configurations will be tested in real-world vehicle and charging trials in Stage 2 of the project.

This report forms part of Work Package 3, Vehicle Energy Management Systems and Technologies. The battery pack is a key component of electric vehicles, and the development of its cost and performance attributes over time will have a critical influence on the future uptake and use of electric vehicles. This component is also the link between EVs and the wider energy system, and it has the potential to create new services that benefit several actors across the energy supply value chain (e.g. grid services aggregators, charging infrastructure operators, and energy suppliers). For this reason, vehicle battery packs are the primary focus of WP3. Specifically, the scope includes firstly a technology roadmap of battery costs and performance up to 2050, which will provide a complete set of projections for use in vehicle uptake models in Work Package 1, secondly an assessment of Battery Management Systems (BMS), their current features and potential additional capabilities required to provide tighter integration with the electricity system (and hence opportunities for research and development to address these gaps), and finally the development of an Excel-based State of Health (SoH) model providing evidence on the impact of different battery use patterns on their life. This report, Deliverable 3.1, covers the battery cost and performance projections, and the BMS assessment.

Background

The report builds on Element Energy's extensive battery cost and performance data gathered through previous work carried out for the Committee on Climate Change in 2012 [1]. For that study, a technology and cost roadmap of cell materials up to 2030 was developed, to feed a bottom-up cost and performance model. A top-down approach was taken for the projections from 2030 to 2050, given the higher uncertainties in long term costs and 'post-lithium ion' chemistries. Both the assumptions underlying this model, the selection of technologies post 2030, and the top down approach for the estimation of densities and costs were validated through an in-depth literature review and industry consultation. That study and the resulting cost model were used as a starting point for the updates, literature review and consultation carried out in this D3.1 report.

Scope

The purpose of this deliverable is to summarise the latest evidence on the current and future costs and performance of automotive batteries up to 2050, for use in the WP1 economic modelling and in the vehicle uptake modelling. Specifically, the purpose is as follows:

- Ensure that battery costs used in the project reflect the current state of the art and expected future developments

- Ensure that assumptions on future battery chemistries meet the likely technical requirements of vehicles and demand management services
- Identify potential research and development projects to address any current capability gaps in Battery Management Systems (BMS) and related components

The report is accompanied by a battery cost and performance database (Excel file) containing the following data:

- Costs and energy densities of batteries on a pack and a cell level for 2010-2050 by size (i.e. kWh) for three different cathodes: spinel, Lithium Nickel Manganese Cobalt Oxide (NMC) and polyanion.
- Costs and energy densities on a pack level as used in the model for the following scenarios: base case, niche EV and EV push. Pack level costs and energy densities of batteries for "New battery technologies" scenario for 2025-2050, calculated using top-down approach.
- Description of the assumptions used in each scenario, including assumed cathode and anode chemistries, capacities and voltage.
- Dataset of key battery pack parameters for more than 20 EVs currently on the market (or being introduced in 2016), including the battery pack specific energy density and the cell capacity.
- Cost breakdown for battery packs by cathode type and by size for three scenarios (base case, niche EV and EV push) for years 2010-2050, split by the following components: cell materials, pack components, depreciation/financing, labour, overheads, margin and warranty.

Structure of the report

The report is structured in six main chapters. Chapter 2 presents the approach taken to produce the battery performance and cost projections up to 2050. Chapter 3 reviews those technologies relevant for electric vehicles applications and demand management services. Chapter 4 compares the trends in the battery industry over the last five years with the model results. Chapter 5 presents the key model inputs and updates, preceding the results and future trends, in Chapter 6. Chapter 7 discusses the BMS capabilities required for EV integration into electricity grid and outlines the research gaps in this area. Finally, Chapter 8 covers the conclusions of this work.

All costs are reported in 2014GBP, for consistency with the modelling tools used in the CVEI project. An exchange rate of 1GBP = 1.5 USD has been used to convert USD costs.

2 Approach and key data resources

This section describes the approach to developing cost and performance projections for automotive batteries to 2050. First, the components of batteries are briefly described to set out the terminology used throughout the report. Secondly, the overall data collection and modelling methodology are described. Thirdly, each component of the approach is described, including an overview of the bottom-up cost model employed (pre-2030) and the approach to post-2030 projections, as well as the key data sources from the literature review and consultation.

2.1 Battery components and battery properties

Before entering into the details of specific battery chemistries and costs, and to present the terminology that will be used throughout the report, Figure 1 shows a **battery pack** and its components. A vehicle battery pack is made of **cells**, which are the elements storing the energy, and of **packing components**, necessary for the flow of electricity and to ensure its safety. *Cells* are composed mainly of a cathode, an anode, foils, electrolyte and a separator, and the *packing components* comprise the Battery Management System (BMS), power electronics, wiring harness and connectors, internal cell support, housing and a thermal management system (an air or liquid coolant circulated around the cells). The cost projections presented in this report include costs both of the *cells* and of all of these *packing components*, as well as *other* costs such as margins (10%), warranty (5%), labour cost, depreciation of the plant (capital paid over five years, with a 7% financing rate,) and overheads (30%)[1].

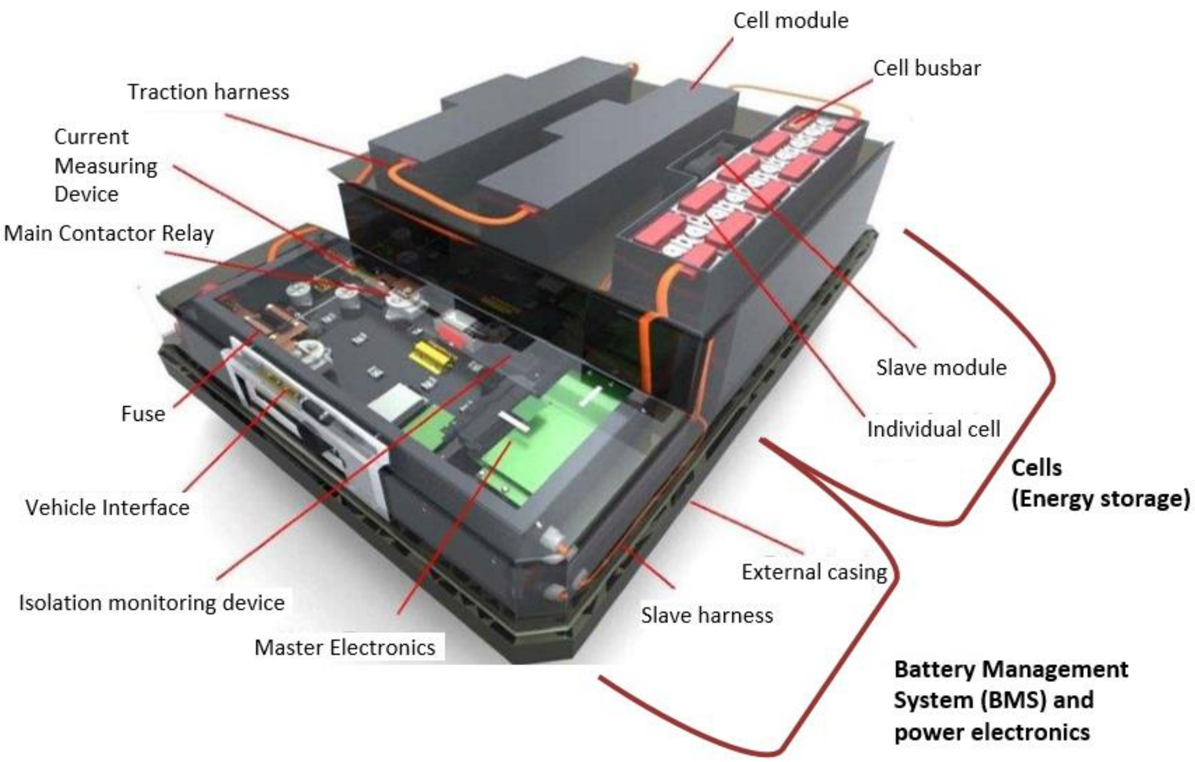

Figure 1. Battery components. The figure originally provided by and reproduced with the permission of Johnson Matthey / Axeon, it is the copyright of Johnson Matthey Battery Systems [2]

[1] Percentages indicated are based on [1]

Introduction to cell components and battery properties

An automotive battery converts, in a reversible way, stored chemical energy into electrical energy. Each cell is composed of **two electrodes**: a **cathode** (positive terminal) and an **anode** (negative terminal). Each of the electrodes contains the **active material** that reacts to provide electricity. The difference in electrical potential between the cathode and anode creates the electromotive force required to energise the vehicle. The **electrolyte** enables the transfer of ions within the cell, and subsequently the chemical reactions at the two electrodes.

Redox[2] reactions, which involve the transfer of electrons between chemical species, underpin the operation of the battery. During discharge the active material at the anode is oxidised, losing electrons that travel through an external circuit whilst the resulting ions travel through the electrolyte towards the cathode. Simultaneously, the active material at the cathode is reduced, where the ions arriving from the anode gain the electrons coming from the external circuit (Figure 2). During charge, the process is reversed. To prevent short circuiting, the electrodes are kept apart via a separator which is permeable to ions.

The active material currently in use in lithium-ion batteries for automotive applications is in solid state. However, it can also be liquid (i.e. flow batteries) and gaseous (i.e. lithium-air). The former state is mainly targeted for grid applications due to the larger size of the required system and is only applied in automotive applications in niche premium prototype cars[3]. Flow batteries and lithium-air batteries will be explored in more detail in Section 3.3.

The electrolyte currently in use in lithium-ion cells is typically liquid (i.e. lithium salt dissolved in organic solvents such as lithium hexafluorophosphate). Solid electrolytes (polymer or ceramic) are under development, presenting safety advantages. In current applications a range of additives, besides lithium salt, need to be included to give the required properties to the electrolyte solution (i.e. to improve the stability preventing dendrite formation[4] and degradation of the solution).

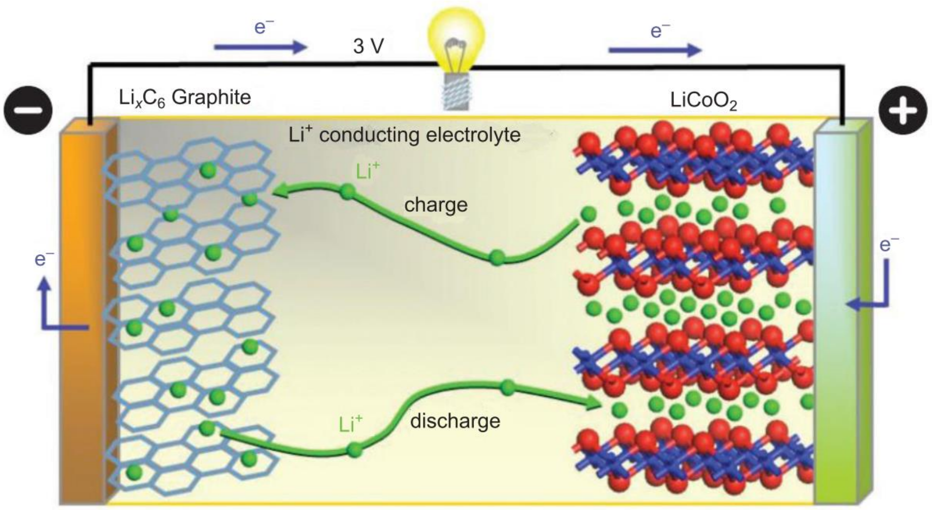

Figure 2. Working mechanism of a typical lithium cell (intercalation: reversible insertion of the lithium ion into the electrodes), showing the electron flow under discharge and lithium ion flow under both charge and discharge. The figure originally provided by and reproduced with the permission from Johnson Matthey / Axeon and is the copyright of Johnson Matthey Battery Systems [3]

[2] Redox is an abbreviation of reduction-oxidation. In chemistry, oxidation refers to the loss of electrons of a molecule, atom or ion, and reduction to the gain of electrons

[3] NanoFlowcell has presented prototype cars based on flow batteries (i.e. Quant)

[4] Lithium deposits. Over the charge/discharge cycles, microscopic fibres of lithium (dendrites) arise from the surface of the lithium electrode. An electrical current passing through them can short-circuit the battery, causing its overheat, and in some cases to catch fire

A battery's capacity, which is an important concept for understanding battery performance, is the amount of electric charge it can deliver at the rated voltage. It is typically measured in units of amp-hour (Ah, units of charge) at a cell level and kWh (units of energy) at a battery pack level. It is key to the **specific energy density** of the cells **(Wh/kg),** the result of the product of the mass weighted cell capacity and its **voltage (V).** The levers underpinning a high energy density are a high voltage, a high number of electrons released per mole of active material (i.e. $1e^-$ for Lithium and $2e^-$ for Magnesium) and a low mass of the active materials.

Depth of Discharge (DoD), is used to describe how deeply the battery is discharged (i.e. if a battery has a DoD of 0%, it means that it is fully charged). This concept is an alternative way of indicating the battery's **State of Charge** (SoC): 100% DoD is equivalent to 0% SoC. In this report, the DoD refers to the window of (dis)charge that is allowed on the pack. Packs based on lithium-ion cells are never allowed to get to either 100% or 0% DoD[5]. The 0-100% charging status range the EV user sees is different, applying to the useable capacity; it actually corresponds to e.g. 10%-90% over the total pack capacity.

2.2 Overview of the approach

The battery review has been carried out in the following steps:

- A detailed review of available battery chemistries and a shortlisting of those able to meet vehicle and demand management requirements. This review draws on published data from battery and cell suppliers (and OEM data on batteries used in vehicles currently on the market), as well as consultation and interviews with suppliers (including developers of new chemistries, active material suppliers, battery pack providers and vehicle OEMs)
- A comprehensive update of Element Energy's existing component-based cost model for batteries based on the review above
- A 'top-down' analysis of long term battery costs and novel chemistries based on expected improvement rates
- Generation of a battery cost and performance database for use in the Electric Car Consumer (ECCo) model to calculate projections of future vehicle uptake and powertrain mixes for Work Package 1
- An assessment of the current capabilities and future requirements of Battery Management Systems, and hence the capability gaps that can be addressed through defined research and development projects
- Generation of a report with all the supporting evidence and assumptions, with detailed cost and technical data for each battery chemistry and year (in the Appendix)

The workflow is summarised in Figure 3.

[5] For several reasons: to meet power requirements, to reduce safety risks, to maximise the battery life

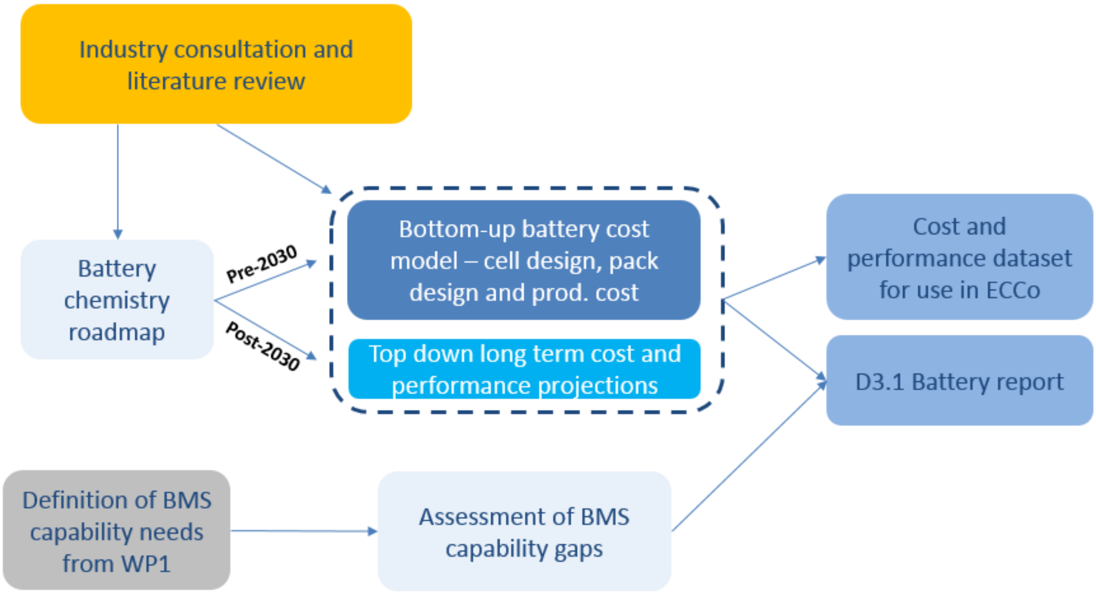

Figure 3. Overview of approach to the battery and BMS analysis

2.3 Overview of the component-based battery cost and performance model

Figure 4 presents a summary of the bottom-up approach taken for the projection of battery cost and performance up to 2030, highlighting those parameters that vary with the proposed scenarios. These scenarios are presented in Section 5.1, as well as their underlying R&D paths (i.e. the degree to which technological advances are achieved) and EV uptake scenarios (i.e. global deployment levels of plug-in electric vehicles). A full description of the cost and performance model is available in the public report for the Committee on Climate Change, and hence will not be repeated here. Instead, only the key characteristics will be presented.

Overview of model to 2030

The model is run using inputs to define chemistry (i.e. which active material is used in cathode and anodes) and battery pack requirements (i.e. total battery kWh, motor kW, battery pack voltage, and maximum mass and volume). With this information, the **cell design module**, based on design parameters imported from Argonne National Laboratory's (ANL) BatPac model (see Box 1 for background information on this model) outputs the Bill of Materials (BOM) for a single cell (i.e. grams or m^2 needed per component) and the number of cells. Here, the active material properties and costs are dependent on the selected scenario. The **pack design module** calculates the packaging costs (i.e. BMS, housing, wiring harnesses, etc.), the pack mass and volume, based on its kWh, the total number of cells (in series and in parallel) and the type of vehicle. It is based on Johnson Matthey data and uses learning rates to project the costs of different components (see Appendix 10.2 for detail). Subsequently, the costs of pack components are linked to assumptions of global EV uptake. Finally, the **cell production module** projects the plant capex and labour costs using ANL's modelling framework (i.e. bottom-up estimation of the plant area, machinery and labour requirements for those processes needed for the battery assembly), but calibrated against data from real plants. The plants are sized based on the anticipated annual production volume required (i.e. number of packs manufactured per year and total kg or m^2 of active material or electrode needed).

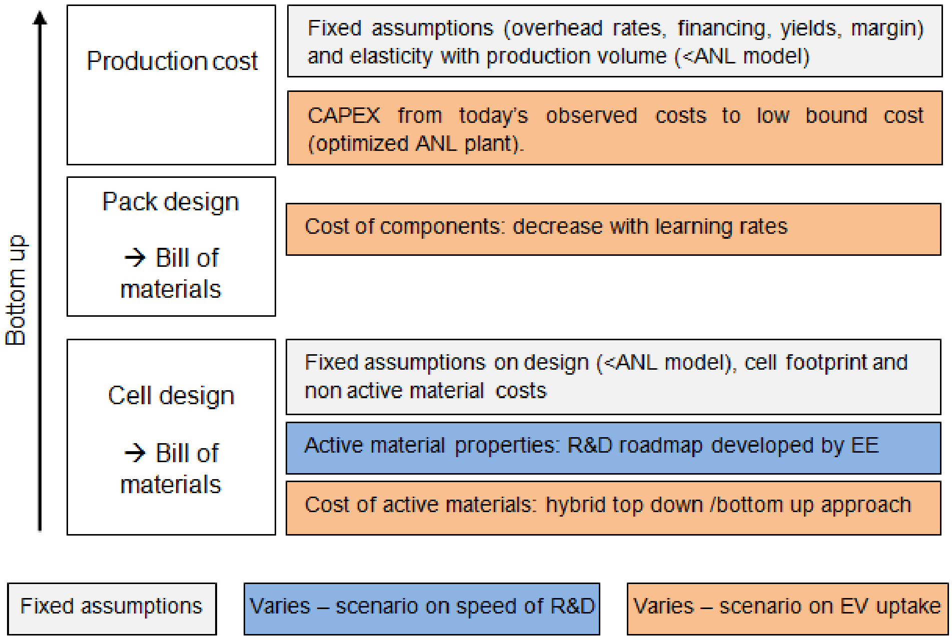

Figure 4. Bottom-up approach summary and assumptions

Cell format and size

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, 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. For equivalent cell capacity, the cost difference between cell formats is negligible and not investigated in our model, as recommended by cell manufacturers in our previous work [1] and in line with ANL's findings [4]. The model assumes that cells are prismatic.

Beyond the cell format, the cell size (which is related to its capacity in Ah) also varies between vehicle models and OEMs. A commonly used cell type in batteries across all applications (i.e. including consumer electronics) is the cylindrical 18650 low capacity cell (18 mm diameter by 65 mm high cells with capacities under 5 Ah, referred to as 18650 cells, commonly used in consumer applications such as laptops). This is a standard format, that is to say it is produced by (and thus can be purchased from) different manufacturers.

In terms of cell design for automotive batteries, two broad approaches have been developed:

- When the production of lithium-ion based EVs started (ca. 2010), several established car OEMs (e.g. Nissan with the Leaf, GM with the Volt, Mitsubishi with the iMiEV and Toyota with the plug-in Prius) opted to use larger cells (>20 Ah), to reflect the large battery pack needed in an EV (typically >60Ah) compared to consumer electronic applications (typically <6Ah). **Large cells were new and did not follow a standard format** (a standard format for large cells still does not exist) but presented the advantage of a more practical packing than small cells: fewer cells to connect and monitor (leading to cost reductions in the BMS, wiring harness and interconnectors) and fewer cells to handle and test on the production line.
- Departing from this approach, Tesla chose to use the **existing 18650 cells**, and assembles over 5,000 of them in the BEVs they sell[6]. This was perceived as a short term approach that would stay niche. However, while it is still niche in terms of the adoption among car OEMs, that

[6] Small 18650 cells are also the choice of other EV start-ups, as they are more readily available for purchase at low volumes and cheaper on a £/kWh basis

solution has endured with Tesla who has since become one of the world top EV OEMs in terms of sales and has invested in a 'gigafactory': the largest battery manufacturing site in terms of GWh capacity to date, based on standard small cells[7]. Packs from this factory are intended to be used both in EVs and for stationary power (grid) applications.

Views from industry stakeholders consulted for this work vary, with some believing that the small cell approach will continue to be a side/short term case, while others think some car OEMs could adopt this approach[8]. Interestingly, all consultees agree that large cells should deliver lower cost at pack level once mass-produced. Reinforcing the point that the cost advantage of small standard cells is short lived, industry contacts report that, due to production overcapacity of large cells, pricing of automotive cells is currently strategic (lower than the profit-making price) and thus comparable across cell sizes[9].

An advantage of the standard cells is that, being used in sectors other than automotive, they benefit from innovation quicker than cells made for a (currently) more restricted market. The aforementioned packing disadvantage (more cells to connect etc.) is partly compensated by the fact that small cylindrical cells are easier to thermally manage than larger cells. However, the key decision point around small standard vs large non-standard cells for car OEMs is the value placed on the advantages of a standard format, namely the ability to change cell supplier.

The model used in this study does not aim at predicting OEMs' choice of approach in terms of cell format (small standard vs. large non-standard). Considering the cost differences are expected to disappear between the approaches (and artificially has already, because of pricing strategies), the battery model used for the cost projections considers only large format cells. The model assumes that cells are 300 x 210 mm, reaching capacities over 60Ah by 2025. Among large cells, this is aligned with the current observed trends towards higher capacity cells[10].

Box 1 About the BatPac model

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 [1]. 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 today [5]; it has been industry peer-reviewed and comes complete with detailed documentation.
This model allows for 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.

The key advantages of the BatPaC model are the bottom up approach of the cell design as well as the links between production costs and cell design and volume.
The restrictions 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). These restrictions have been addressed in the EE model as it has a time dimension and future cell material improvements are modelled.

[7] 35 GWh capacity, expected to start production by the end of 2016; https://www.tesla.com/gigafactory

[8] To a certain extent this is supported by the fact that several car OEMs have a dual approach today: using large cells in some models, and using small cells in others, e.g. Toyota worked with Tesla to develop the RAV4 EV but uses large cells on the plug-in Prius.

[9] One consultee mentioned typical prices of $200-250/kWh for all cell sizes, with deals as low as $150/kWh (£133-166/kWh and £100/kWh using 1GBP=1.5 USD), another mentioned a slight wider range, with an average at $250/kWh

[10] See Figure 16 on page 44 for examples of size of cells used in PHEVs and BEVs

Post-2030 projections

The bottom-up model is used for projections to the year 2030, where detailed roadmaps of changes in chemistries and electrode design can be defined based on industry feedback. Beyond 2030, there is significantly more uncertainty in costs and performance, particularly in disruptive 'post-lithium-ion' technologies such as lithium sulphur or lithium air, where the latter still requires numerous fundamental breakthroughs to be viable for use in automotive batteries. Hence for projections beyond 2030, a less detailed, 'top down' approach is used, which applies annual improvement factors to cost and energy density to the end point reached in the bottom-up model in 2030.

2.4 Literature review and consultation

The battery roadmaps and cost projections described in this report reflect the latest published evidence available in the literature. Key references are set out below, with a comprehensive list in the References section (from page 100).

- **Public reports:**
  - PwC, November 2013. Battery update Can the Lithium-ion industry satisfy the growing demands of the auto market?
  - Peter Miller, 2015. Automotive Li-ion batteries. State of the art and future developments in Li-ion battery packs for passenger car applications. *Johnson Matthey Technol. Rev.*, 2015, 59, (1), 4–13
  - US battery R&D programme
- **Academic journals:**
  - Björn Nykvist and Måns Nilsson, 2015. Rapidly falling costs of battery packs for electric vehicles. Nature, DOI: 10.1038/NCLIMATE2564
  - Oliver Gröger, Hubert A. Gasteiger, and Jens-Peter Suchsland, 2015. "Review. Electromobility: Batteries or Fuel Cells?" J. Electrochem. Soc. volume 162, issue 14, A2605-A2622
- **Industry announcements and news related to battery developments**
  - Specialist websites, such as Greencarcongress.com, chargedEVs.com, US Energy Efficiency and Renewable Energy website, chemical and engineering news
- **Argonne National Laboratory (ANL) BatPaC model**
  - The Element Energy bottom-up model is partly based on BatPac approach
  - BatPaC v3B 4May2015 and BatPaC v2.1 inputs were compared to track the developments of battery components cost and performance in the last three years
- **Conferences and webinars:**
  - BATTERIES, Avicenne conference, Nice, October 2015
  - UK Energy Storage conference, Birmingham, November 2015
  - IDTechEx webinar, October 2015. Advanced and post lithium-ion batteries 2016-2026
  - Batteries2020 external workshop, Brussels, May 2016
- **Research and development (R&D) projects:**
  - European COmpetitiveness in Commercial Hybrid and AutoMotive PowertrainS (Ecochamps) project aimed at extending the functionality of EVs (EU Horizon2020 funded, 2015-2018)
  - Practical Lithium Air Battery project to develop a lithium air battery cell with improved performance (EPSRC funded, 2013-2016)
  - Battery Characterisation and Management - the key to Smart Grids and the Integration of Electric Vehicles project (EPSRC funded, 2013-2016)
  - Proving Integrity of Complex Automotive Systems of Systems (PICASSOS) project aimed to develop embedded software systems for the increased uptake of EVs (UK Advanced Manufacturing Supply Chain Initiative (AMSCI) funded, 2013-2015)

- Materials for Ageing Resistant Lithium-ion energy Storage for the EVs (Mars EV) project that develops materials for high energy and cycle-life Li-ion battery cells (EU FP7 funded, 2013-2017)
- Stable Interfaces for Rechargeable Batteries (SIRBATT) project intended to improve battery lifetime and includes development of improved BMS (EU FP7 funded, 2013-2016)
- Lithium Sulphur Superbattery Exploiting Nanotechnology (LISSEN) project to identify and develop nanostructured materials for implementation in lithium-sulphur battery (EU FP7 funded, 2012-2015)
- Smart and Compact Battery Management System Module for Integration into Lithium-Ion Cell for Fully Electric Vehicles (SMART-LIC) project (EU FP7 funded, 2011-2014)

The literature review was complemented with face to face and telephone discussions with selected industry experts. These provided access to more sensitive data not available in the public domain, and resulted in valuable commentary on public claims, some of which are influenced by marketing strategy as much as by fundamental technical roadmaps. Most consultees preferred to stay anonymous (this option was offered if it allowed more open discussion of confidential or sensitive data offered), in which case the input is referenced as ‘source that wants to be anonymous’. They included developers of new chemistries, active material suppliers, battery pack providers, vehicle OEMs, researchers and other industry experts. Oxis Energy (developer of lithium-sulphur batteries) have provided detail inputs on their technology and were happy to be referenced. Johnson Matthey, as a sub-contractor to the research, also provided inputs and reviewed the findings.

3 Review of battery technologies relevant to electric vehicle applications

A review of the battery technologies likely to be relevant to the automotive industry up to 2050 was carried out and is presented in this section. Two principal battery groups can be distinguished, in terms of the timescales for penetration in the automotive market: the currently used **intercalated lithium-ion**, based on univalent intercalation processes[11] (Figure 2) and **post-lithium chemistries**, currently under development, with potential to increase battery energy density and reduce costs, and based on several processes such as univalent intercalation (e.g. lithium-air), multivalent intercalation (e.g. magnesium-ion), chemical reaction (e.g. lithium-sulphur) or redox couples (flow batteries). Additionally, **molten sodium batteries** that have been employed in early EV prototypes are discussed.

3.1 Battery development timescales and impact on future technologies

From new unproven battery technologies to commercial cells

The process of translating a scientific breakthrough to a commercial prototype is complex and lengthy, particularly due to the stringent demands of the automotive industry – a fact generally not highlighted in articles reporting "breakthroughs" related to battery technologies. Based on a publication from the US Joint Centre for Energy Storage Research [6], Figure 5 shows the steps for the introduction of a new concept into the market, where the synthesis of new materials can take 1-2 years, its test in half cells 2-5 years, proof of performance in laboratory scale full cells an additional 2-5 years, and scale up 5-10 years, and where the iterative nature of the process might translate into ever longer timescales. This is in line with a recent UK Energy Research Centre report on the topic of commercialisation of different technologies, which concludes that Lithium-ion rechargeable batteries experienced a relatively quick rate of innovation, taking just 19 years [7]. A more detailed timeline and the main tasks involved in developing new battery chemistries can be found elsewhere [8].

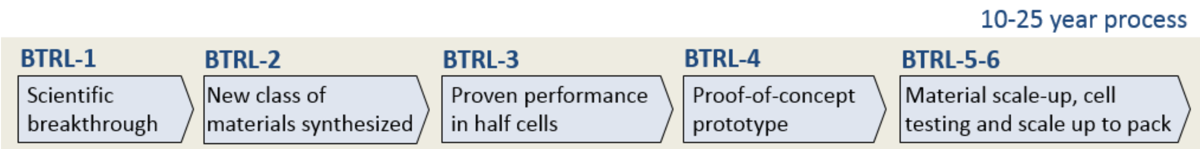

Figure 5. Battery Technology Readiness Level (BTRL) scale [6]

Development time of cells for automotive applications

The process of introducing battery innovations in the automotive sector is an iteration between cell and prototype development and their integration and testing in cars, as shown in Figure 6. In addition – or increasingly partly in parallel – to the BTRL timescale is the prototype development cycle and the integration of the innovations into the battery pack. Discussions with material and cell developers indicated typical prototype development cycles of 10-12 years, within which the prototype is refined (BTRL 5-6) and different iterations are introduced at the pack level by OEMs until the final product is reached. In other words, a post-lithium ion technology at BTRL 5-6 (such as lithium sulphur) and starting the process of developing a prototype for car OEMs is still ca. 10 years away (or more) from the automotive market.

This development time also applies to variations/improvement to lithium-ion cells: the time between the idea (e.g. new process, new compounds) to getting cells including this innovation into a car adds up to 10-12 years.

[11] Univalent means that only one electron (e-) is transferred

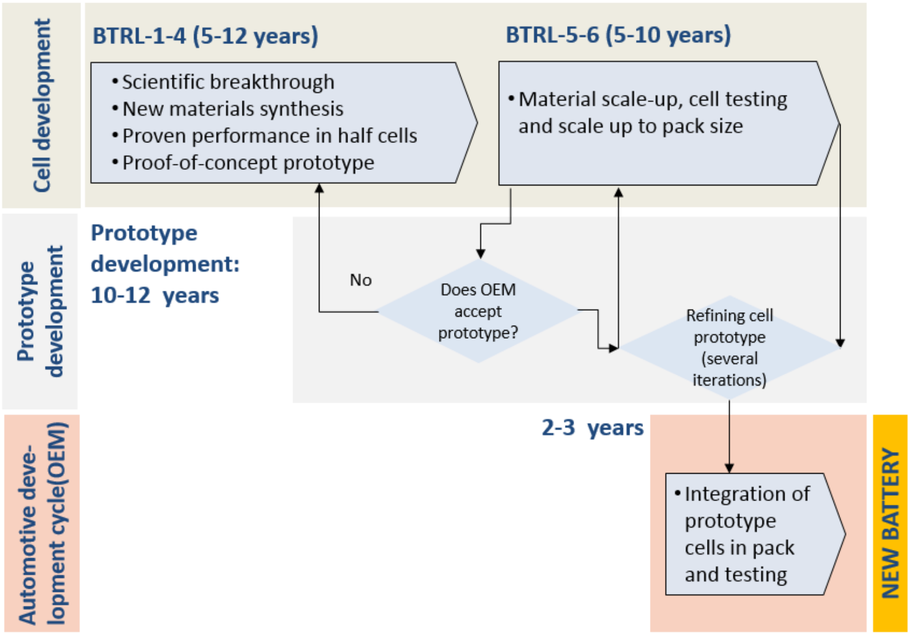

Figure 6. BTRL and OEM battery integration timescales

Impact of development timescales

These timescales have the following implications, developed further next:

- **Over the next 10 years there is no currently foreseeable 'step change' automotive battery technology to be available and ready for use in vehicles. Instead, an improvement in lithium-ion cells is expected.** Many improved lithium-ion cells are currently at different stages of the prototype cycle and will bring incremental improvement over time.
- Breakthroughs reported today in post lithium-ion technologies might not reach the automotive market before 10-20 years' time (and requirements for further fundamental breakthroughs mean it is not yet certain that post lithium-ion technologies will be successfully commercialised even in the long term).

Battery pack update cycle

On average vehicle models have a platform change (i.e. of its main components) every 6-8 years (and are refreshed with a face-lift 2-4 years after a platform change) [9]. Battery industry stakeholders interviewed report that the battery pack would not change on a given platform (but report a slightly shorter cycle time of 5-6 years) beyond the cell packing, and possibly a slightly improved set of cells from the same chemistry and/or supplier. However, in the next five to ten years shorter battery platform cycles of 3 years are expected (supported by standardisation of several pack components), so that OEMs capture constant pack improvements and stay competitive in the pack performance their products offer.

3.2 Lithium ion chemistries and molten salt batteries

Li-ion batteries have a currently unmatchable combination of high energy and high power density and therefore presently dominate the automotive industry. This section is focused on Li-ion technology. However, Li and some of the transition metals used in Li-ion batteries (e.g. cobalt) are relatively expensive. This provides the motivation for the development of batteries based on low cost components, such as molten sodium batteries, a review of which is also included in this section. Refer to Table 25 in the Appendix for the comparison of the key characteristics of Lead Acid and Nickel-metal hydride batteries with Li-ion batteries.

3.2.1 Lithium ion chemistries

In the past five years improvements in pack energy density have been incremental, with an increase around 15% between 2010 and 2015. Currently, **intercalated lithium-ion** cell densities of 90-200 Wh/kg [3] and pack densities of 80-100 Wh/kg[12][10] are achieved. In the following 10-15 years, it is expected that lithium-ion chemistry will be prevalent, given the length of the process to implement new breakthroughs in final applications and the stringent demands (life, power, size, safety) of the automotive industry.

The shortlisted chemistries for *lithium-ion automotive batteries*, which will likely dominate the industry for the next 10-15 years, are presented in this section. They apply to both BEVs and PHEVs, although no example of PHEVs using LFP cells has been found among EVs sold in Europe. The chemistries for the cathode and the anode are presented separately, and the evidence informing the selection is described alongside the tables.

Cathode

Table 1 presents the cathode chemistries shortlisted to be modelled up to 2030, and their performance and costs underpin the results presented in section 6 . The performance of each chemistry varies as a function of the mass of the active material, the voltage at which the cell is stable and the extent to which the practical cell energy densities approach their theoretical potential. The costs of the cathode active material depend on the raw material (i.e. nickel and cobalt are expensive and their price can be very volatile) and processing costs (i.e. certain active materials might require more expensive equipment or more extreme conditions for their processing).

Three main cathode chemistries have been shortlisted: Lithium Manganese Oxide (LMO, also referred as spinel due to its structure), Lithium Nickel Manganese Cobalt (NMC) and Lithium Iron Phosphate (LFP, also referred as polyanion, due to the ionic nature of iron phosphate compared to the metal oxides of the other chemistries). Refer to Table 26 in Appendix for some of the key characteristics of the batteries with different cathodes. However, the technical improvements within each family are captured through time (described in Section 5). Despite the fact that the cathode active materials currently in use in automotive applications might be a mix of several chemistries (i.e. LMO and NMC), for simplicity, only pure active materials are modelled[13].

In Europe, currently and for the next five years, NMC and mixed NMC and LMO cathodes seem to be dominating the BEV and PHEV market, with examples such as BMW i3, Mitsubishi Outlander or VW models using this chemistry. The use of Ni and Co leads to higher energy and power densities, whilst Mn ensures better cycle life and safety [11]. Manganese spinel (LMO) has one of the highest thermal runaway onset temperatures among currently employed EV cathode materials [11]. The weakness of spinel cathodes is insufficient long-term cyclability which can be improved by blending with other cathode materials, e.g. NMC or NCA. Nissan is using LMO blend with Lithium Nickel Cobalt Aluminium oxide (NCA), whilst Tesla and Mercedes B-class are using NCA batteries. However, NCA is less safe (with thermal runaway temperatures of 150 degree Celsius, compared to 210 degree Celsius for NMC). Conversely, Chinese battery manufacturers tend to use LFP as the cathode material for automotive applications [12]. This fact, together with China's support for electric vehicles, has promoted the rapid increase of the country's demand for LFP (by the end of 2014, over 80% of global LFP originated from China). However, in the future, it is expected that the low energy density of LFP will result in the diversification of cathode chemistries for use in the Chinese automotive industry [13].

[12] The higher end corresponds to 2016 Nissan Leaf with a 30 kWh and 315 kg pack

[13] This means the model might overestimate or underestimate some trade-offs, e.g. a blend of chemistries might be more expensive but might yield a higher energy density and vice versa. However the magnitude of the over or underestimate is a few percent, which is small in the context of other drivers of battery costs/performance, in particular pack size (discussed in more detail in Section 5.5.

Between the selected cathode chemistries, NMC offers the highest potential energy density, whilst polyanion and spinel are the best cathode materials from the safety perspective. The weakness of spinel cathodes is insufficient long-term cyclability, whilst LFP has a relatively low energy density. In terms of the anodes, carbon blends with Si have received most attention recently due to their extremely high gravimetric capacity, however sufficiently long cycle life for batteries with Si-rich anodes remains to be demonstrated.

The advantage of batteries with LFP cathodes is very good thermal stability leading to superior safety. This advantage stems from the polyanion structure of the cathode, where large $(PO_4)^{3-}$ polyanions stabilise the lattice [11]. However, the cathode material has a relatively low voltage during discharge – plateau at ca. 3.5 V compared to ca. 4.1 V for the cells with LMO or LCO cathodes [14]. In order to increase the operating voltage, much attention has been focused on substituting iron with other transition metals such as Manganese. $LiMnPO_4$ (LMP) cathodes offer ca. 0.4 V increase in average operating voltage, but at the expense of lower conductivity [11]. Further improvements are required for the commercialisation of this cathode material.

Table 1. Shortlisted cathode chemistries up to 2030

Chemistry	**In use in automotive** (examples) [1], [15]–[17]	**Potential use in vehicles**	**In scope for modelling**
Lithium Manganese Oxide (LMO, spinel)	YES (Nissan Leaf - blended with NCA; Mitsubishi i-MiEV, Mitsubishi Outlander, Chevrolet Volt – blended with NMC)	Already	Yes
Lithium Nickel Manganese Cobalt Oxide (NMC)	YES (Daimler Smart, BMW i3, Ford C-Max, VW e-Golf and Golf GTE, Kia Soul)	Already	Yes
Lithium Iron Phosphate (LFP, polyanion)	YES (mostly in China, e.g. BYD e6)	Already	Yes
Lithium Manganese Phosphate (LMP, polyanion)	Under R&D	Under R&D	Yes
Lithium Cobalt Oxide (LCO)	*NO (except first Tesla)*	*NO*	*NO – not used in automotive sector, due to cost and safety*
Lithium nickel cobalt aluminium oxide (NCA)	*YES (Tesla, Mercedes B Class PHEV, Toyota Prius)*	*Already*	*NO – similar costs and energy densities than NMC and safety issues*

Another technology used in the market but not considered here is the lithium metal polymer chemistry used in Bolloré cars. This is restricted to captive applications where vehicles can be plugged-in when not in use because of its high self-discharge rate (50h or less) and high operating temperatures.

Anode

Table 2 presents the shortlisted anode chemistries to be modelled: firstly, **graphite**, currently in use and based on an intercalation reaction, that is, the reversible insertion of an ion (i.e. Li^+ in lithium-ion batteries) into compounds with layered structures. Secondly, **silicon**, already in use in consumer cells, under development for the automotive industry and announced to be introduced in small proportions in automotive battery graphite anodes (e.g. new Tesla Model X equipped with a 90kWh pack). Lithium titanate oxide (LTO) provides high rate and stability because of a very low expansion upon lithiation, additionally, using LTO also has calendar life advantages. However, its theoretical capacity is less than half that of carbon, which translates into a low energy density at cell level. This, and the high equilibrium potential leading to a reduced cell voltage, significantly limits its potential application in EVs.

Table 2. Shortlisted anode chemistries up to 2030

Chemistry	In use in automotive	Potential use in vehicles	In scope for modelling
Graphite	YES (all BEVs and PHEVs)	Already	YES – in EE model
Silicon-graphite	NO (Tesla soon, very low blend of silicon in graphite)	YES	YES – in EE model
Lithium titanate	*NO*	*Low (low energy density)*	*NO – density and cost issue*

Silicon anodes are based on an alloying reaction (as opposed to graphite's intercalation), in which different intermetallic compounds are formed when silicon reacts with lithium, allowing the incorporation of a higher number of lithium ions in the anode. This is because lithium can react with silicon to form a $Li_{22}Si_5$ alloy, where a silicon atom is able to bond four lithium atoms, but with graphite can only form a LiC_6 alloy, where six carbon atoms are needed for each lithium atom. There is a consensus that a breakthrough in anode capacity (mAh/g) can be achieved by moving from graphite to a blend of silicon into carbon, which has the *theoretical potential* to increase fivefold the current anode capacity (i.e. currently graphite has a capacity of 330 mAh/g, compared to a potential to achieve ca. 1,700 mAh/g for a ca. 40% Si/C blend[14]). Additionally, this blend of silicon presents safety advantages in comparison to graphite.

However, there are significant **challenges** that need to be overcome for the successful introduction of silicon in anodes. **Cycling stability is very poor**, causing capacity losses at a low number of cycles. This is mainly due to the large volume expansion of the silicon anode (up to 300%), which increases the internal resistance, may cause the electrode to break, and which also reduces the contact area between the anode active material and the current collector, resulting in poor transport of electrons. A secondary cause of the problem is the formation of an unstable Solid Electrolyte Interphase[15] (SEI), which may increase the anode impedance and reduce its chemical reactivity [18].

At the moment there is **a large number of researchers/groups working on the development of future anode chemistries**, with several alternatives being explored such as silicon nanostructures (i.e. nanoparticles, nanowires or nanofibers), Si/M composites (where M is an active/inactive conductive material, i.e. $CoSi_2$ or SiC) and hollow and yolk-shell structure composites. New binders, which attach

[14] The full theoretical capacity of silicon (i.e. 4,200 mAh/g) will not be realised at the high cyclability required by the automotive industry, and silicon will be blended in carbon instead of being used pure
[15] A film that forms at the anode and passivates the lithium, preventing lithium chemical degradation by the electrolyte salts and solvent at low potential

the active material to the collectors, are also being investigated, as studies show that stability and irreversible capacity losses are critically dependent on the binder's properties [19], [20].

Silicon nanostructures have the potential to improve capacity retention but face the intrinsic low electrical conductivity of silicon and their production needs to be cost-effective and scalable. The buffering effect of *silicon nanoparticles* (i.e. <100nm) on volume change has been reported in academic publications [21], [22]. The University of Southern California has developed a cost-effective anode using *silicon nanowires* with a stable capacity of 1,100 mAh/g for 600 cycles at the half-cell level [23]. The University of California Riverside has developed a coin type half-cell with a capacity of 800 mAh/g stable for 660 cycles using *silicon nanofibres* [24]. However, significant developments are needed for application in the automotive industry, where cycle lives of 1,500 cycles at 80% Depth of Discharge (DoD) are required, and the new anodes need to be manufactured at scale and low cost.

Si/M composites are intermetallic compounds hosting and supporting silicon. Recent work has been conducted on SiC composites, with carbon, graphite or graphene as matrices. The latter is regarded as a promising candidate to host active Si nanoparticles due to its high surface area, high electrical conductivity and good mechanical flexibility. The University of California Riverside has developed an anode based on carbon nanotubes hosting the silicon with a capacity of 1,200 mAh/g, stable for 230 cycles [25]. The University of Waterloo and General Motors Global Research and Development Centre have developed a graphene-based anode with 1,000 mAh/g stable for 2,275 cycles at the coin type half-cell level. Despite the positive advances in cyclability, the concept still needs to be developed for cells with the large capacity (Ah) expected for automotive applications, and with scalable and affordable mass production methodology.

However, the problem of an unstable Solid Electrolyte Interphase at the lithium surface still remains for nano-sized silicon. Recent studies on **hollow and yolk-shell structures** of silicon composites, where the silicon nano-particles are encapsulated by carbon and coated with conductive materials, might overcome this problem [26]–[28].

Outside of academia, there is a significant amount of activity amongst companies in developing silicon anodes. *Nexeon*, a UK based silicon anode manufacturer, is currently using 1,200 mAh/g silicon carbon for consumer applications with 500 cycles. *Hitachi*, one of the anode industry leaders, demonstrated in 2014 a SiC 30Ah cell with an energy density of 335Wh/kg at the cell level (2.6 times previous performance), for 50 charge/discharge cycles, and expects its deployment by 2020 – a target which seems optimistic on the basis of the currently low cycle life. *OneD material* produces SiNANOde, an anode made of silicon nanowires with several grades of Si:C (8-50%) with a scalable manufacturing process, achieving 850 mAh/g and ca. 500 cycles at the coin cell level and 600 mAh/g and ca. 1000 cycles at 80% retention capacity in a SiNANOde/NCA cell [29], [30]. They have licenced the technology to EaglePicher, who will scale up production and incorporate the anode into its new cells and batteries for defence applications. *Amprius* is another US start-up working on silicon anodes. They have introduced their use in mobile phone applications (with 580Wh/l) and they plan to enter the automotive market (with targets of >400 Wh/kg and 1,000 cycles).

Taking into account this level of research, the results achieved so far and the remaining challenges, the assumptions presented in Table 3 are used in the bottom-up model. The 2020 baseline value is 650 mAh/g reversible capacity, a revision down from 1,000 mAh/g in Element Energy's previous study [1]. This is supported by the evidence that a current state of the art commercial SiC anode with good capacity retention (ca. 1000 cycles) has a capacity of 600 mAh/g (OneD material, described above). Given that the technology needs several years to transition from the consumer cell into the automotive cell market, only a slight increase in Si content in the blend (and therefore the energy density increase) may be expected in 2020. Several consulted industry stakeholders still view the baseline values as too optimistic (too high) in the face of remaining challenges to obtain long life in an automotive cell with a high silicon blend. For this reason, lower values are tested in the model, under the 'Slow R&D scenario'.

Table 3. Assumptions on anode capacity and levels of silicon blended

R&D Scenario*	Parameter	2015	2020	2025	2030
Baseline	mAh/g	330	650	1,500	1,750
Baseline	% silicon blended	0%	8.5%	30%	37%
Slow	mAh/g	330	370	840	1,050
Slow	% silicon blended	0%	1%	13%	19%

** Details on scenarios are presented in section 5.1*

3.2.2 Molten Sodium batteries

There are two main types of commercially available molten Sodium ion batteries – Sodium-sulphur and Sodium-nickel-chloride batteries. Both require ca. 270-350 °C for the employed materials to be sufficiently conductive for the Sodium ions (Na^+) that are used as charge carriers in these types of battery. Sodium-nickel-chloride batteries are safer than sodium sulphur batteries and will be discussed in more detail in this section.

In Sodium-nickel-chloride batteries, rock salt (NaCl) and nickel (Ni) are transformed into nickel-chloride ($NiCl_2$) and molten sodium (Na) during operation. Electrodes are separated by a ceramic wall ($NaAl_{11}O_{17}$ beta-alumina electrolyte) that is conductive for Na^+ but an insulator for electrons. Cells are hermetically sealed and typically packaged into modules of about 20 kWh each [31]. There are two main suppliers of these type of batteries – GE and FIAMM SoNick [32]. GE acquired their core technology from a UK company Beta R&D who developed ZEBRA batteries [33].

Specific energy density of Sodium-nickel-chloride batteries is ca. 80-125 Wh/kg with a cycle life of 1000-3000 cycles [34]–[36]. ZEBRA batteries were used in early BEV prototypes in 1990s and early 2000s – Mercedes A class, BMW 3 series, Renault Twingo, as well as in buses in Lyon (France) [34], [35]. These types of batteries continue to be considered for certain EV applications with a recent study reporting positive results for ZEBRA battery testing in a commercial urban delivery vehicle [37]. A summary of the key parameter of this technology is shown in Table 4.

Table 4 Key parameters of molten sodium batteries [34]–[36], [38], [39]

Parameter	Value
Theoretical cell energy density (Wh/kg)	~ 300
Practical (realised) cell energy density (Wh/kg)	80-125
Round trip efficiency (%)	85
Maximum discharge rate	3-4C
Cycle life	1000-3000
Voltage (V)	2.6 (ZEBRA)
Safety	Good, short circuit does not cause complete failure of the battery
Maturity - technology (BTRL)	6
Maturity - manufacturing	Available from GE and FIAMM SoNick for stationary applications
Theoretical advantages over lithium-ion	Tolerant to short circuits, wide temperature window for safe operation
Inherent disadvantages over lithium-ion	High operating temperature, high manufacturing cost. Suitable for large capacity only (>20 kWh).

The major disadvantage of molten sodium technology in terms of automotive applications is the requirement to maintain the elevated temperature (over 250 °C) at all times [1]. This leads to a high level of self-discharge during storage in the absence of an external energy supply. If shut down, the reheating process lasts 24 hours [2]. This excludes molten sodium batteries from the automotive market, unless restricted to applications where the vehicle is almost always plugged-in when not in use (e.g. captive fleets with ability to plug-in at a depot/main location).

Cradle-to-gate life-cycle CO_2 emissions for ZEBRA batteries were found to be 6 times higher than for Li-ion batteries [35]. The technology is relatively expensive on a small scale at more than 1 000 £/kWh for an 80 kWh system [31]. This is likely to remain unchanged on a short to medium timescale as there are only two suppliers, and there is no major external driver for growth. In fact, GE is currently significantly scaling back production of sodium-nickel-chloride batteries due to weak demand from the grid-scale energy storage market [40].

3.3 Post lithium ion chemistries

Alternatives to the lithium-ion battery and to its intercalation process are being explored in a series of **post-lithium ion chemistries**. These have the potential to dramatically increase battery energy density, with theoretical cell densities of 3,500 Wh/kg for lithium-air and 2,600 Wh/kg for Li-sulphur batteries, compared to 550 Wh/kg for a conventional lithium-ion LMO/Gr[16] battery (used in the first generation of li-ion EV packs) [41] – see Box 2 for an explanation on theoretical densities. However, the extent to which these theoretical cell energy density advantages will translate in terms of practical pack energy densities is yet to be determined, and the challenges they currently face rule them out of the car market until at least 2025 for lithium sulphur and 2030 for others.

Box 2 About the calculation of theoretical energy density of cells

The theoretical energy density of a given cell chemistry can be calculated from the fundamental properties of the reactants e.g. in terms of the energy released for a given reaction. This theoretical maximum will never be achieved in a practical cell as the masses of essential components of the cell are ignored: only a proportion of the mass of the battery is the reactants (typically between 25-40%), with the rest comprising the electrolyte, charge collectors, electrode substrate, physical containment, and unused/unreacted species [1]. Theoretical values are nonetheless a valuable and commonly used way to compare the potential of different chemistries, regardless of their current state of development.

More details on the calculations for lithium-ion, lithium-air and lithium-sulphur are provided below.

The value of 1,200 Wh/kg for lithium-ion cells is based on the theoretical capacity limit associated with an intercalation cathode and a conversion anode. For Li-ion cathodes the capacity limit is approximately 300 mAh/g [11]. This corresponds to the number of ions that a host material can accept without collapsing. Assuming the theoretical specific energy capacity of 3,500 mAh/g for silicon, the mass of the anode would add ca. 8% to the total weight. This would translate into a theoretical cell energy density of ca. 1,200 Wh/kg in a 4.2 V cell.

The calculation of the theoretical energy density for lithium-air and Li-sulphur batteries quoted in the academic literature (and used to derive the figures quoted in this report, 3,500 Wh/kg for lithium-air and 2,600 Wh/kg for Li-sulphur) includes a number of simplifications [41]. The theoretical energy density of the lithium-air battery is calculated based on the assumptions that the cathode is composed only of Li_2O_2 (that is, no porosity, or carbon, or binder) and assuming a stoichiometric quantity of lithium in the anode (i.e. expecting that all lithium will be oxidised upon discharge). The mass of the electrolyte is also ignored for this calculation. Equally, the theoretical energy density for Li-sulphur does not take into account any porosity, carbon, or binder on the cathode, neither it does provide for the additional weight of the electrolyte. The energy density calculation for Li-sulphur cells is based on the energy obtained per unit mass from the following cell reaction:

$$2Li + S \leftrightarrow Li_2S$$

[16] Name of the active material at the cathode and anode: Lithium Manganese Oxide (cathode)/ Graphite (anode)

Among the post lithium-ion chemistries currently under research and development, the most promising technologies in terms of market readiness and theoretical energy density have been selected. The selection presented here is later used for the post-2030 cost and performance projections.

The shortlisted chemistries for the *post lithium-ion automotive batteries* showing the highest potential to reach the automotive market are presented in Table 5. The first column names the technology: either a battery family (e.g. Li-Sulphur), or a particular component different from today's (e.g. solid electrolyte, liquid electrode), or a complementary battery technology (e.g. capacitors).

Four technologies were selected for the modelling of battery cost and performance from 2030-50: **sodium-ion, lithium-sulphur and lithium-air batteries, and solid electrolytes**. They present different Battery Technology Readiness Levels and are currently being widely explored by research and industry organisations to tap into the opportunities to overcome lithium-ion limits on battery energy density, improve safety and reduce costs.

Table 5. Post lithium-ion battery technologies under R&D (shortlisted technologies for long term cost projections in black)

Technology	**BTRL**	**Greatest challenge for deployment**	**Theoretical cell Wh/kg** [1], [42]	**In scope for modelling**
Na-ion	5-6	Low life (300 cycles), prototype stage	400-500	YES
Li-sulphur	5-6	Poor rate capacity (i.e. low power), high self-discharge and safety issues with electrolyte stability and Li metal anode	ca. 2,600	YES
Metal-air	2-4 (Li-air) *2-4 (Zn-air)*	Poor cycle life, poor rate capability, low efficiency and safety issues with electrolyte stability and Li metal anode (for Li-air)	ca. 3,500 *ca. 1,100 (Zn-air)*	YES *NO*
Solid electrolytes	2-4	Lower conductivity, volume interphase issues, fabrication methods	N/A	YES
Magnesium anode	*2-3*	*Slow reaction kinetics, imply a low discharge power/C-rate*	*400*	*NO*
Supercapa-citors	*4*	*Complementary to battery, would provide extra capabilities. At current costs, not viable*	*20 (commercial)*	*NO*
Flow batteries	*5-6 (aqueous)* *0-1 (hybrid)*	*Low energy density* *Early prototype stage of hybrid technologies*	*ca. 50* *ca. 3,500*	*NO* *NO*

3.3.1 Lithium sulphur

Lithium sulphur cells are the most advanced metal sulphur cells. Under a BTRL 5-6, a proof-of-concept prototype has been demonstrated (e.g. Oxis Energy[17] has developed cells with 220 Wh/kg achieving

[17] OXIS Energy is a UK company based in the Culham Science Centre in Oxfordshire that has been developing Lithium Sulphur technology since 2005. The company has a portfolio of 58 patents (to date) and has developed

1,400 cycles), and current efforts are towards material scale-up, cell testing and scale-up to pack for automotive applications.

Figure 7 is a schematic description of a typical lithium-sulphur cell and of the phenomena occurring during its discharge, where the pure lithium of the anode is oxidised, lithium ions travel towards the cathode and the electrons pass through the external electric circuit. During this process, lithium is involved in a series of reactions with sulphur, resulting in the creation of soluble polysulphides (Li_2S_x, 4 ≤ *x* ≤ 8) and solid insoluble products that deposit at the anode and electrolyte (Li_2S_2 or Li_2S). Sulphur is embedded in porous carbon at the cathode and the electrolyte is liquid.

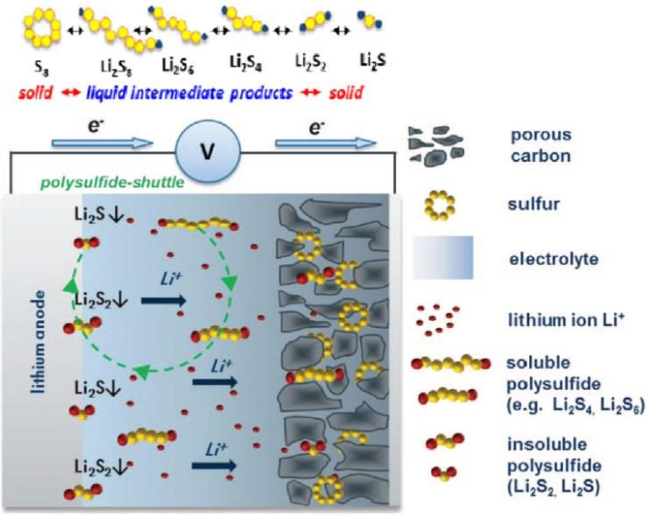

Figure 7. Li-S cell scheme and reactions taking place within it, under discharge [43][18]

The main **advantage** of this technology is its **higher gravimetric energy density**, in theory five times that of lithium-ion batteries *at the cell level* (i.e. 2,600 Wh/kg for Li-S vs 550 Wh/kg for a LMO/Gr Li-ion battery). In practice, density at the cell level is twice that of lithium-ion cells, with an Oxis Energy Li-S cell achieving 325 Wh/kg in comparison to a 170 Wh/kg for NMC/Gr (Li-ion) cell. This ratio is expected to be the same in 2030 and on the order of 2-3 by 2050, where the Li-ion battery would have reached its practical limit (i.e. 280 Wh/kg for NMC/Gr at cell level), and it is projected that Li-S cells will reach 800 Wh/kg[19]. This energy density advantage is achieved due to the replacement of graphite with a pure lithium anode that acts both as electrode and lithium supplier, and also the replacement of metal oxides by lighter sulphur at the cathode. The gravimetric energy density advantage *at the pack level* might be lower when other parameters, such as larger number of cells in Li-S batteries or their lower volumetric energy density, are factored in. A second advantage is the fact that **Li-S batteries can be used at a 100% Depth of Discharge (DoD), as opposed to ca. 80% for Li-ion batteries**[20], and they cannot be damaged by over-discharge. This means that for the same range, the kWh required by a Li-S battery is lower than for a Li-ion one. Together with their higher gravimetric energy density, this translates (in theory) into a **lower battery weight and pack cost for equivalent ranges**. Finally, Li-S batteries benefit from the use of **sulphur** instead of nickel or cobalt, a **cheaper, more abundant** material. Additionally, the international prices for sulphur show relatively low volatility – with a standard deviation of 22.6% between 1900 and 2007 [44]. This compares to the standard deviation of 49.3% for Cobalt and 17.6% for Nickel for the same period.

several prototype batteries. The company works closely with a range of partners across the industry to augment the commercial production of Li-S battery systems.

[18] Figure reprinted under the terms of the Creative Commons Attribution 4.0 License, © O. Gröger, H. A. Gasteiger, and J.-P. Suchsland 2015, http://jes.ecsdl.org/lookup/doi/10.1149/2.0211514jes

[19] See chapter 6 for further details

[20] 100% DoD is avoided in Li-ion batteries to meet power requirements (i.e. low discharge rate at high DoD and low charge rate at low DoD), for safety reasons and to maximise battery life

However, several **challenges** face lithium-sulphur technology, to the extent that its application in automotive applications is not envisaged until 10-15 years' time:

- **Poor rate capacity (low power)** is particularly challenging for those applications with a higher power to energy ratio requirement (i.e. PHEVs). The insulating nature (electrical) of sulphur and lithium sulphides on the cathode surface decreases the utilisation rate of active material, leading to poor high-rate capacity.
- **Low cycling capability** is still one of the main barriers to overcome. Capacity is lost due to the formation of soluble polysulphides that 'shuttle' between electrodes and lead to deposition of Li_2S_2 or Li_2S at the anode or elsewhere, resulting in a loss of active material, the formation of electrically insulating products, and the blockage of the electrodes.
- **Li-S cells operate at low nominal voltages** (i.e. 2.1 V compared to 3.5-4 V for Li-ion), which translates into a larger number of cells and subsequently larger packing costs (i.e. BMS, wiring or interconnectors) for a given pack voltage.
- Additional disadvantages are their **low volumetric energy density** (McCloskey has recently concluded that lithium sulphur batteries may never compete with lithium ion batteries in terms of volumetric energy density)[45], **high self-discharge** when not in use[21] and **safety concerns** (due to dendrite growth at the pure lithium anode, electrolyte stability and H_2S formation if water leaks into the cell).

Figure 8 presents three strategies to increase the cyclability of Li-S batteries. One option is the use of a solid electrolyte as a diffusion barrier to the polysulphides, preventing their shuttling between electrodes, hence avoiding the loss of sulphur in the form of precipitated Li_2S at the anode. Another strategy consists of development of novel cathode architectures that avoid polysulphide mobility, such as embedding sulphur in carbon spheres or adulterating the cathode with graphene oxide binders. Finally, a silicon anode might be used instead of pure lithium to avoid the shuttle effect and its negative consequences. Solutions are also being developed to create electrolytes in which sulphur compounds are less soluble and which reduce the self-discharge.

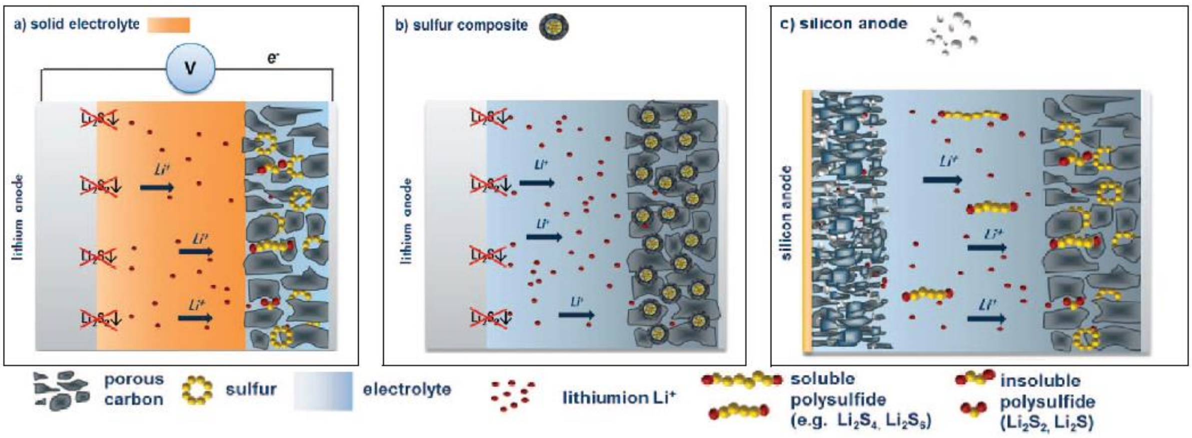

Figure 8. Different Li-S battery configurations to overcome limited cycle life: a) use of solid electrolyte, b) encapsulated sulphur particles, c) silicon anode (shown under discharge) [43][22]

Several research organisations and companies are developing Li-S batteries. *Polyplus*, a US start-up, will initially commercialise them with a focus on high margin applications where light weight comes at a premium and has prospects of achieving >400 Wh/kg at the cell level (at the moment they are able to cycle on the hundreds scale). *Solid Power*, another US start-up, is developing a battery consisting of a

[21] Due to an internal polysulphide shuttle effect, where soluble long-chain polysulphide species continue to dissolve and migrate to the negative side to react with metallic lithium

[22] Figure reprinted under the terms of the Creative Commons Attribution 4.0 License. Adapted, the stacking of the a, b and c figure blocks has been changed from vertical to horizontal, © O. Gröger, H. A. Gasteiger, and J.-P. Suchsland 2015, http://jes.ecsdl.org/lookup/doi/10.1149/2.0211514jes

sulphur cathode, a lithium anode and a solid electrolyte. They recently constructed a 65m[2] dry room facility that will translate to production scale and will allow the first large-scale prototypes to begin production in 2016. *Sion Power/BASF* has developed a 350 Wh/kg cell, with an unreported number of cycles. *Toyota* is working on a new structure of sulphur cathodes at the coin cell level, achieving a capacity of 675 mAh/g at 2C and 500 cycles [46]. The *Fraunhofer Institute* is involved in several projects related to Li-S storage for automotive applications. The *Lawrence Berkeley National laboratory* has demonstrated coin cells achieving 1,500 cycles of life with ca. 50% decay and an initial estimation of cell density of 500 Wh/kg.

In the UK, *Oxis Energy* is leading work in this field. They claim to have addressed several of the challenges mentioned above, such as reduced shelf-life (i.e. claiming no charging is required over long periods to prevent failure), safety (through lithium-sulphide passivation layer and non-flammable electrolyte) and, despite current low cycle life, they are targeting 1,500 cycles by 2020. They claim 125 cycles for their 325 Wh/kg cells, and they have set a target of >200 Wh/kg and 1,500 cycles by the end of 2016 and 2020 respectively. However, the issues of low nominal voltage, low rate capacity and low volumetric energy density still need to be resolved.

Figure 9 shows the achievements of Oxis Energy over the last three years and their targets in the next years. Since 2013, they have become part of several UK and EU funded projects, among which two are dedicated to the development of an automotive Lithium-sulphur battery (Advance Lithium Sulphur Batteries for Hybrid Electric Vehicle, ALISE and Revolutionary EV Battery Project, REVB).

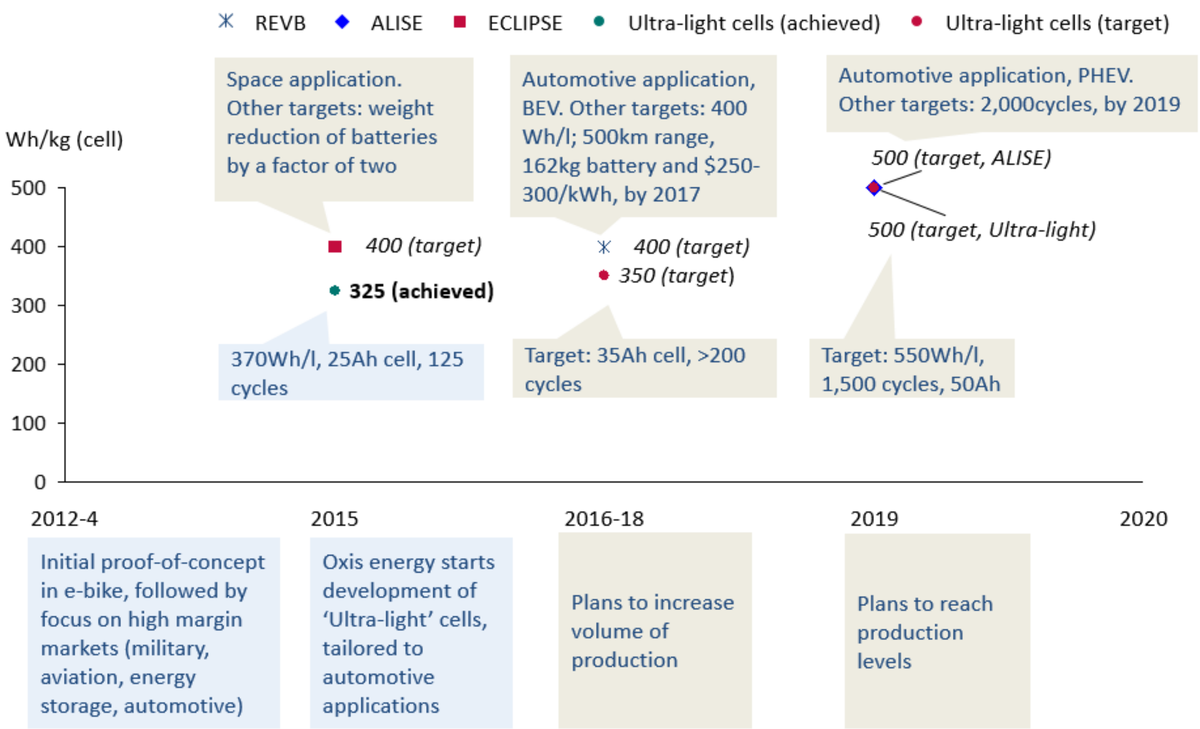

Figure 9. Oxis Energy achievements and targets for Li-S cell energy density

REVB: Revolutionary EV Battery Project; ALISE: Advance Lithium Sulphur Batteries for Hybrid Electric Vehicle project; ECLIPSE: European Consortium for Lithium Sulphur Power for Space Environments

3.3.2 Metal air batteries

The two metal-air batteries with the most promising outlook and greatest research efforts are discussed here: lithium-air and zinc-air.

Lithium-air

Lithium-air cells lag behind lithium-sulphur ones, at BTRL 2-4, covering research and synthesis of new materials and the development of the first proof-of-concept prototypes. An example of a prototype is a cell announced by the University of Cambridge in October 2015. Full cells were tested in sealed flasks in operation with pure oxygen and moisture present (rather than air, whose CO_2 content has a very negative impact on the anode) [47].

Figure 10 shows a lithium-air battery during its discharge cycle. Lithium is oxidised at the anode and travels through the electrolyte to the cathode, with the difference being that the cathode does not contain the active material, which is instead extracted from/expelled to the surrounding air. That is, during discharge oxygen enters the cell through a porous cathode, which dissolves in the electrolyte and then reacts with the Li^+ from the anode to create solid Li_2O_2, which precipitates in the cathode. The anode is usually pure lithium.

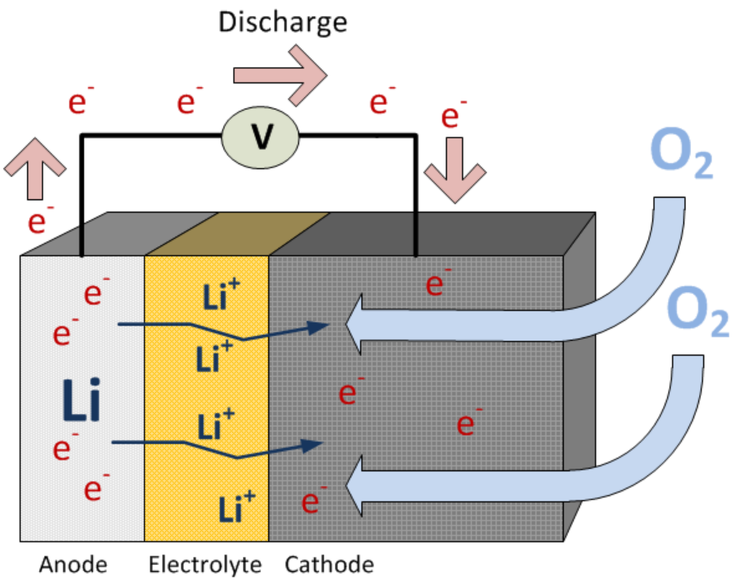

Figure 10. Lithium-air battery during a discharge cycle.

Lithium-air cells have theoretical gravimetric densities of ca. 3,500 Wh/kg (six times the 550 Wh/kg of a LMO/Gr spinel battery), and *Polyplus* has demonstrated a 10 Ah 800 Wh/kg cell, with the number of cycles unreported, and aims to commercialise it at 1,000 Wh/kg (3.5 times the 280 Wh/kg for NMC in 2030). **Hence, the main advantage of lithium-air cells is a high potential to increase gravimetric energy density.**

However, multiple remaining challenges mean that the lithium-air technology will not enter the market until 2030 (and the requirement for fundamental breakthroughs means it is not yet certain that it will be successfully commercialised in automotive applications even in the long term):

- **High capacity fading is an important challenge** which limits the operating cycles of these batteries, and is caused by side reactions and incomplete removal of the discharge product**.** Reduced oxygen from the cathode reacts irreversibly with the electrolyte, resulting in its gradual and irreversible consumption and low cycle life. Additionally, high overpotential has to be applied during the charging cycle to remove the insulating discharge products, which otherwise accumulate and clog the cathode. **This hysteresis process** results in voltage differences during the charge/discharge processes of over 2V, which limit the efficiency of the battery.
- Additionally, the practical reversible capacity at the cathode (mAh/g), and hence, its **practical energy density (Wh/kg), is limited** by the complexity of the cathode design. An equilibrium must be found between small pores leading to high specific areas enabling high capacities, and pores large enough to avoid their clogging.

- **Moisture and CO_2 have a very negative effect on the anode** and precautions need to be taken accordingly.
- Additional challenges include the **need for air control** to regulate the intake and expulsion of oxygen and to limit the moisture and CO_2 entering the system, and the **optimisation of the cathode design** to improve the diffusion of oxygen through the porous cathode, which currently limits the reaction rate, and hence the power density.

Overcoming some of these challenges, the University of Cambridge has very recently demonstrated a lithium air cell achieving more than 2,000 cycles and with a voltage gap of the charge/discharge cycles of 0.2V [47]. However, to put into context the extent to which further development is needed, it has reported that its commercialisation is at least ten years away, in particular as long life results are generally obtained for very low C-rate, with higher C-rates substantially shortening cell lifetimes. This sensitivity to C-rates must be reduced before the cells are suitable for automotive applications.

Illustrating the challenges presented by lithium air batteries, the Joint Center for Energy Storage Research[23] decided in 2015 to de-emphasise work on Li-air batteries due to practical issues, to instead focus more on Li-S technologies.

Zinc-air

In the Element Energy 2012 report, zinc-air batteries were not considered to have a potential in the automotive sector as “decades of work on rechargeable Zn-air have not delivered a rechargeable battery” [1]. Their inherent low voltage and numerous challenges – most in common with lithium-air batteries described above – indicate neither a rapid nor easy pathway to the automotive market. However, remarkable progress has been made in recent years and Zinc-air batteries have reached BTRL2-4. AZA laboratory (a team of 8 people across Armenia and France) achieved a proof of concept in 2014. They have delivered a pilot battery tried in a scooter (e-bikes and scooters are their first target market). Their product can cycle 100 times (300 cycles target for 2017) and achieves 150Wh/kg at cell level.[24]

Key advantages are much cheaper materials than used in lithium-ion cells[25] and safety. It is however unclear if they will ever be suitable for the automotive market, that requires at least 1,000 cycles capability.

3.3.3 Sodium ion batteries

The recent development of room temperature Sodium ion conductive electrolytes lead to the re-emergence of Na-based batteries as a potential alternative to lithium systems [48]. These types of cells do not employ Sodium as the negative electrode; they are comprised of hard carbons or intercalation compounds.[26] Sodium ion cells have a BTRL of 5-6, as a proof-of-concept prototype of an e-bike powered by a Na-ion battery was demonstrated in 2015 (by Faradion), and the focus is now on the material scale up for applications. This chemistry is the focus of a number of research organisations and companies such as Faradion (UK), Aquion Energy (US), Sumitomo Chemicals (Japan) and RS2E,

[23] A public-private partnership that “aims to overcome critical scientific and technical barriers and create new breakthrough energy storage technologies.” It includes the Argonne National Laboratory, the Lawrence Berkeley National Laboratory, Sandia National Laboratories, Dow and many others

[24] Based on conversations with researchers from AZA as well as their presentation at the BATTERIES 2015 conference in Nice, October 2015

[25] Zinc (98% pure) was between $1,500 and $2,400 /t between April 2011 and April 2016 (http://www.indexmundi.com/commodities/?commodity=zinc&months=60). Lithium carbonate (99% pure) was $4,000 to $5,000 /t in 2011-2015 with a recent increase to $13,000t, http://www.economist.com/news/business/21688386-amid-surge-demand-rechargeable-batteries-companies-are-scrambling-supplies

[26] This chemistry is based on the intercalation principle that was presented in section 2.1 (Figure 2).

a French consortium of universities and companies. At the moment, most of the development is targeting grid energy storage applications.

Sodium ion batteries present several advantages such as lower material costs (sodium carbonate is less than 10% of the cost of the equivalent lithium salt), cheaper collectors (sodium ion cathode and anode collectors are made of aluminium, instead of the more expensive copper of lithium-ion ones) and benefit from the same processing of materials and the use of existing lithium ion manufacturing lines. At 140 Wh/kg at a cell level, the energy density of Sodium-ion batteries remains somewhat lower than that of the state of the art Li-ion cells (e.g. 240 Wh/kg for NCA) [49]. Equally, the cycling stability of this technology is inferior compared to Li-ion batteries (e.g. Faradion demonstrated only 350 cycles before the end of life was reached) [50]. Both of these characteristics will need to improve before the technology can be fully commercialised.

3.3.4 Solid electrolyte

"Solid electrolyte" refers only to the electrolyte and does not indicate the electrodes' chemistry, which could be lithium-ion or post-lithium-ion.

The development of batteries using a solid electrolyte is at BTRL 2-4, as progress is different among industry actors. As an example, the Lawrence Berkeley National Laboratory (Berkeley Lab) and the University of North Carolina, BTRL 2, have demonstrated a new material, and plan to incorporate it at the half cell level as the next stage. Seeo, a US start-up recently acquired by Bosch, claims to be at BTRL 4, with sample cells developed in September 2015, combining an NCA cathode and pure lithium anode with a solid electrolyte. The Department of Energy's Oak Ridge National Laboratory and Solid Power have also developed a proof-of-concept battery based on a sulphur cathode, a pure lithium anode and a solid electrolyte, and large-scale prototypes have been announced for 2016.

The main **advantage** of solid-electrolyte batteries is **safety**, as they lack volatile or flammable liquid components. This may also save costs through the elimination of safety features typically associated with liquid electrolyte lithium-ion batteries – although this could be mitigated by a higher material cost for solid-electrolytes. They also benefit from **longer lives**, as the degradation is much lower than for liquid electrolytes, and they have high electrochemical stability. Additionally, they operate at a wide temperature window, ca. 0-200 °C, although the conductivity at the lower end of the window needs to be improved [51].

One of the main **challenges** in the development of solid/polymer electrolytes is to achieve sufficiently high **ionic conductivity** at low temperatures (i.e. they have at least 10-15% lower conductivities than liquid electrolytes), which limits their power rates. Recently, MIT, scientists from the Samsung Advanced Institute of Technology, the University of California at San Diego and the University of Maryland have reported an analysis of the factors that enable high ion conduction in solids, focusing on a class of materials known as superionic lithium-ion conductors, and they claim they could overcome the low conductivity problem [52]. The solid state electrolyte Li_2S-P_2S_5 was found to have a conductivity of 0.0017 S cm^{-1} at room temperature, marking a significant breakthrough in this field [53]. This conductivity is even higher than that of the typical liquid electrolytes used in commercial Li-ion cells, e.g. 1 M $LiPF_6$ in ethylene carbonate–diethyl carbonate has a conductivity of 0.0011 S cm^{-1} [53]. A problem with this electrolyte is that it needs to be heat-treated in the cell before the initial use, promoting a reaction between the electrolyte and the oxide cathode, leading to high interfacial resistance. Suppression of this reaction is the next challenge to realize high-performance solid-state batteries [53].

3.3.5 Flow batteries

There is evidence that flow battery vehicle prototypes are being developed [54], [55]. Therefore, this technology is reviewed in detail with the view to understand its potential in transportation.

All liquid aqueous systems

A flow battery is a rechargeable battery in which the active material (redox couple) is dissolved in a liquid electrolyte (a dilute acid) and stored in external tanks. The active material is pumped through a half cell (the entire cell is divided by a membrane) where the electrochemical exchange reaction occurs, leading to charging and discharging. The active material is in a liquid form and is stored in separate tanks. This leads to decoupling of power (determined by the size of electrochemical device – single cell to a large stack) and energy (determined by the size of electrolyte tanks). This makes this technology particularly attractive for large scale applications. In addition to the highly modular design, current state of the art flow batteries offer fast response times (milliseconds), high depth of discharge, high round-trip efficiency (ca. 85%) and long cycle life (>13 000 cycles) [56].

There are several types of flow batteries using different active materials. Early concept of the flow battery was developed by NASA and relied on Fe^{2+}/Fe^{3+} and Cr^{2+}/Cr^{3+} redox couples in hydrochloric acid [57]. During battery charge, Cr^{3+} ions are converted to Cr^{2+} at the negative electrode through the acceptance of an electron. Meanwhile, a charge carrier (e.g. H^+) is transferred from the positive to the negative electrode through the membrane and Fe^{2+} ions are converted to Fe^{3+} ions at the positive electrode by releasing an electron to the external circuit. During discharge, the reactions run in the opposite direction. Fe/Cr flow batteries have been commercialised and are used for large energy storage applications, e.g. 1 MWh system offered by EnterVault [58]. However, the Fe/Cr system displays relatively low output voltage (1.2 V) and efficiency, and is prone to cross-contamination, i.e. the membrane is not completely impermeable to iron and chromium ions [59]. A major milestone in flow battery development was the introduction of the all Vanadium system which eliminated cross-contamination problems (as Vanadium is used on both the positive and the negative electrodes) and offered higher efficiency and reliability [60]. Systems using this technology are commercially available for stationary storage applications from a number of manufacturers – e.g. PrudentEnergy [61], redT [62] and Gildemeister [63].

In terms of automotive applications, an additional advantage of flow batteries is that the active material could be easily refilled at the station, instead of charging the battery. However, the limitation of all liquid aqueous flow batteries is their low energy density when compared with conventional batteries. This is due to the maximum concentration of the active material (e.g. Vanadium) that can be dissolved in the electrolyte. In the case of the all Vanadium system, the maximum achievable energy density is 25 Wh/kg (and <10 Wh/kg for Fe/Cr) [59], compared to currently available 80-100 Wh/kg for Li-ion battery packs used in EVs. More recently, a flow battery technology that employs Vanadium bromide solution in both half cells was introduced. This technology has the potential to increase the specific energy density of the system up to 50 Wh/kg [64]. However, it is not yet mature and its disadvantage is the formation of bromine vapours during charging which requires the use of expensive agents [64].

Hybrid systems

More recently, flow battery systems that store part of their active material in a solid form have been investigated. These have the potential to increase the energy density of flow batteries. The $ZnBr_2$ flow battery stores Zn in a solid form when charged and has the potential to offer an energy density up to 70 Wh/kg.[64]. However, the currently available commercial $ZnBr_2$ system (from RedFlow) offers a somewhat lower energy density of ca. 35 Wh/kg in an 8 kWh system [65]. This product is targeted for grid and backup power applications.

Another demonstrated prototype of a hybrid flow battery uses nanoparticle suspensions and relies upon the same materials as Li-ion batteries. This is a semi-solid Li flow device that relies on conducting inks (e.g. suspension of LCO nanoparticles) and has a theoretical energy density of ca. 300 Wh/kg [66].

Another hybrid flow battery concept employs Li metal as the anode and flowing-through aqueous solution (e.g. $Fe\text{-}(NO_3)_3/Fe(NO_3)_2$) as the cathode. It has the potential to reach a system energy density on par with Li-air systems [67]. In principle, Li metal can be dissolved in either solvent and the aqueous solution on the opposite electrode can be substituted with the O_2 dissolved in an electrolyte [68]. At this point, the flow battery concept would converge with the concept of Li-air batteries. Note that such a system would require a solid-state Li-ion conducting electrolyte, therefore any advances in the development of such electrolyte would be beneficial.

Summary

Hybrid systems that utilise Li metal face similar problems to Li-air batteries whilst being at an even lower development stage. The reliability, safety and cost of such systems still remains to be demonstrated [69], [70]. Based on the review of academic literature it is concluded that all liquid aqueous flow batteries do not have sufficiently high energy density potential to be used in transport applications. The recent introduction of novel active materials for flow batteries and the demonstration of hybrid systems leads to an increase in their potential energy density. However, all of these have a very low technology readiness level and the research of these has not yet gained momentum. Ultimately, the concept of such technologies converges with that of the Li-air battery, and therefore these are not included separately in the shortlisted post-lithium technologies for transportation.

3.4 Summary of modelled post lithium–ion technologies

Table 6 presents a summary of the main characteristics of post-lithium ion technologies and their comparison with lithium ion ones. “Solid electrolyte” has not been included as it does not constitute a post lithium ion technology per se – it is rather a component (the electrolyte) that may be integrated into certain lithium or post-lithium ion technologies. Solid electrolytes present a high potential to increase battery safety and lifetime. Flow batteries are not included as per discussion in section 3.3.5.

Table 6. Summary of post-lithium ion technologies characteristics and comparison with lithium-ion (in grey)

		Lithium sulphur [1], [43], [71]	Lithium air [1], [43], [47]	Sodium ion [49], [72], [73]	Lithium ion (intercalation) [1], [43]
Theoretical gravimetric cell energy density (Wh/kg)		~ 2,600	~ 3,500	400-600 (cathode specific)	1,200
Practical realised (or potential where indicated)	Gravimetric cell energy density (Wh/kg)	325	800	140 (today) – 200 (potential)	170 (today) – 400 (potential, with Si anode)
	Volumetric cell energy density (Wh/l)	310	780	380	460 (today)
	Cycle life	200	<100	10-100s	>1,000
Voltage (V)		2.1	2.9	3.2 (Faradion)	4.2
Safety/ abuse tolerance		Dendrite growth leading to short circuit and H_2S formation if ruptured	Anode dendrite formation issue, electrolyte decomposition	Can be transported totally discharged	Medium (NMC higher than NCA,LCO, lower than LFP)
Maturity – technology(BTRL)		5-6	2-4	5-6	6
Maturity – manufacturing		Pre-production cells (1000s 25Ah cells made in 2015, 39Ah prototype achieved)	Development of proof-of-concept	Very similar to Li-ion. Incremental CAPEX (<1000 3Ah cells made so far)	Large production (over 300,000 li-ion based light duty EVs sold)
Theoretical advantages over lithium-ion		Cost, higher Wh/kg, cheaper, more abundant and less volatile sulphur	Cost, higher Wh/kg	Cost, safety	
Inherent disadvantages over lithium-ion		Low voltage, poor rate capacity, low cycling capability, relatively low volumetric energy density, high self-discharge*	High capacity fading, poor rate capability, need of air control, challenging optimisation of cathode design	Lower energy density may restrict their usage to electricity grid applications	

*Oxis Energy claims to have overcome this issue

4 Comparison of modelled battery improvements with market trends

In this section the trends in battery pack densities and costs over the last five years are discussed, as well as the underlying drivers of these trends. These trends were compared with the performance roadmap in the Element Energy bottom-up model to validate the input assumptions before generation of future cost projections.

Modelled market projections for 2015 were found to match the market values. The key findings presented are:

- Projected 2015 battery pack costs fit the values within the literature, and the model reproduces the ca. 10% annual reductions observed over the last 5 years.
- Over the past years pack densities have seen annual increases of ca. 5% per annum.
- The bottom-up model reproduces current energy densities observed in the market and for the next 2-3 years, it shows values 10-15% lower than some values claimed by car OEMs.
- The incremental changes in pack density and cost over the last years are driven by a combination of cell and pack level improvements.

4.1 Pack costs

Figure 11 presents the modelled cost (in 2014£/kWh) results at pack level for 2011 and 2015 for a 30 kWh pack and its comparison with reported values in the literature.

Firstly, it can be observed that in the model **average annual pack cost reductions of ca. 10% occur between 2011 to 2015.** This is consistent with a recently published Nature article that reviewed over 80 battery cost estimates reported between 2007 and 2014, finding 14% and 8% annual reductions industry-wide, and for market-leading EV manufacturers, respectively [74].

Secondly, the figure shows **that modelled 2015 pack costs are consistent with those found in the literature**. The wide range of battery costs observed for a particular cathode chemistry in the literature are due to differences existing at the cell and pack level (i.e. in the type of active materials used, cell and pack design, type of BMS and thermal management systems used, etc.). The red square presents costs achieved by Tesla batteries (with a small cylindrical 18650 format and a NCA cathode), which are below the other 2015 modelled values. This is due both to the fact that this manufacturer is using 18650 cells, those used in the consumer electronics market, that are manufactured at mass scale, and to the large size of Tesla battery packs (i.e. 60-90kWh), that is able to capture the benefits of large packs on costs (see section 5.5 for details).

It should also be noted that the Tesla pack costs are inferred by the battery replacement costs [75] and thus might hide some pricing strategy where the battery is undersold. This issue of the lack of visibility between ‘real costs’ and pricing decisions apply to some extent to all costs reported in the literature; this is why a range of sources are presented in the comparison graph. This being said, the pack cost inferred from the Tesla/NCA pack (£250/kWh) is comparable to the modelling results for a pack over 60kWh (£255/kWh).

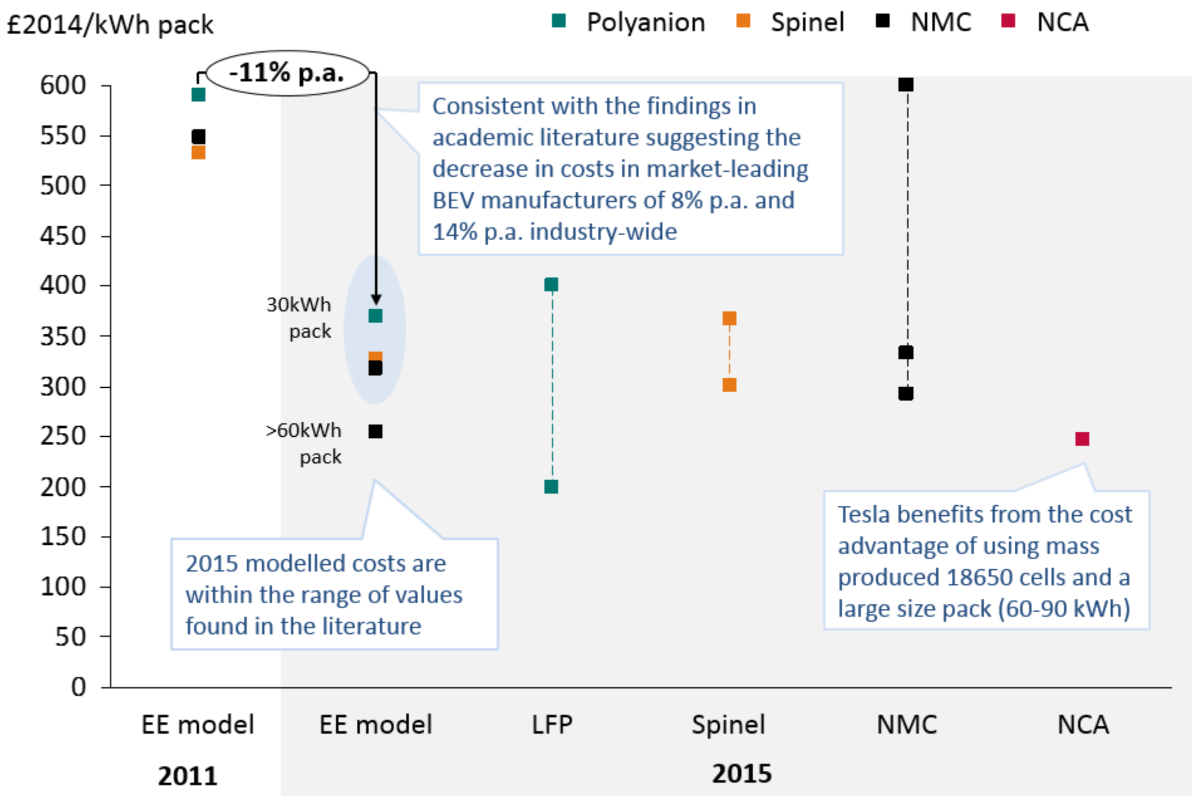

Figure 11. Observed and modelled pack costs and comparison with other sources [3], [74]–[76]. **Modelled pack sizes: 30kWh (25-35 kWh band) and >60kWh, among other sources most do not specify the pack size but it is expected to be around 25-30kWh.**

4.2 Pack energy density

Observed trends

A trend of gradual increase in the average battery pack energy density with time is shown with a dashed grey line in Figure 12 (for BEVs and REEVs) and Figure 13 (for PHEVs). Energy density increases mainly due to the following reasons: a) battery manufacturers shift to more energy dense cathode materials and b) larger battery packs are installed in EVs. Nissan Leaf's announced 2017/18 new model is also included in the graph [77]. Figure 14 shows the relationship between pack density and pack size; in this case the large packs are in line with the overall trend.

Taking Nissan as a representative example, average annual improvements of 3.5% are observed for the period between 2011 and 2016. The new Nissan Leaf model (2016) will benefit from improvements in cell design (i.e. with an increase in Ah per module), and chemistry improvements (new cathode chemistry has not been fully disclosed yet but the LMO fraction is likely to be brought down in favour of NMC, based on conversation with industry stakeholders). The Nissan Leaf model (2017/18) announcement suggests an ambitious 53% improvement in battery pack energy density, partly achieved through doubling the battery pack capacity from 30 kWh for the 2016 Model to 60 kWh for the announced 2017/18 model. On the other hand, the Tesla Model S battery pack is already at 85 kWh, and Tesla has recently announced that it expects annual increases in pack energy density of ca. 5% [78].

As mentioned, several factors explain the differences in pack densities amongst manufacturers, one of these reasons being the distinct energy density shown by different chemistries, where NMC and NCA cathodes present higher values. LMO cathode blends are now almost phased out in BEVs, due to their relatively low energy densities, in favour of more energy dense NMC and NCA cathodes; this is highlighted in Figure 12. The Nissan improvements from 2011 to 2013 (same pack capacity, 4kg lighter) are due to a reduction in battery weight by modification of its components and the streamlining of the case structure.

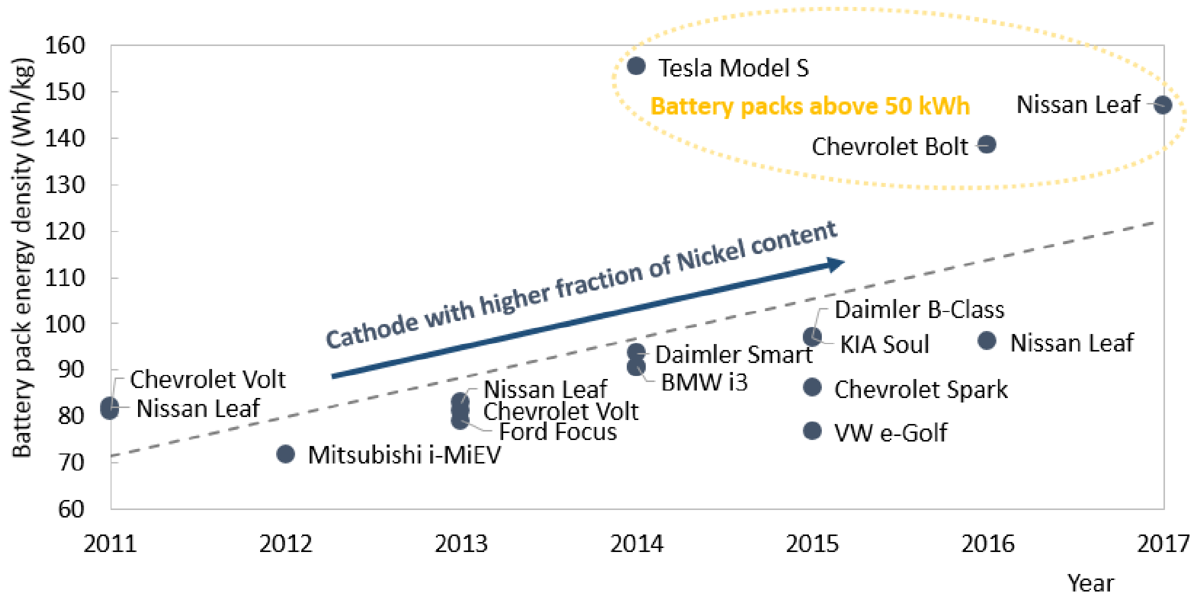

Figure 12 Observed and announced annual pack density improvements for BEVs and REEVs[27]

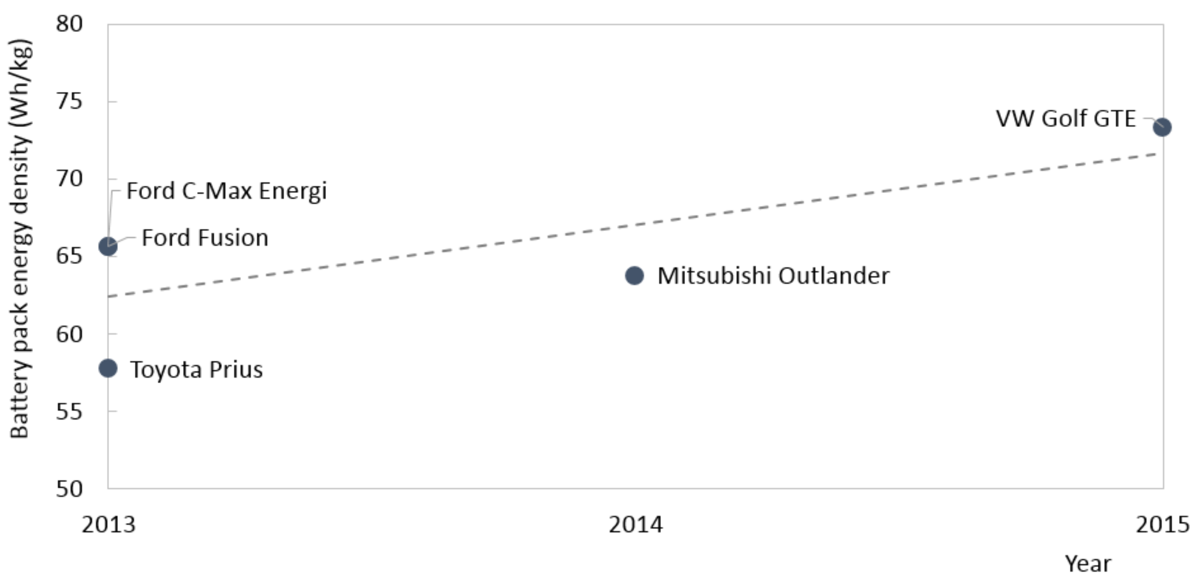

Figure 13 Observed annual pack density improvements for PHEVs[27]

[27] Based on public data aggregated by Element Energy; refer to the accompanying battery cost and performance database for details and sources.

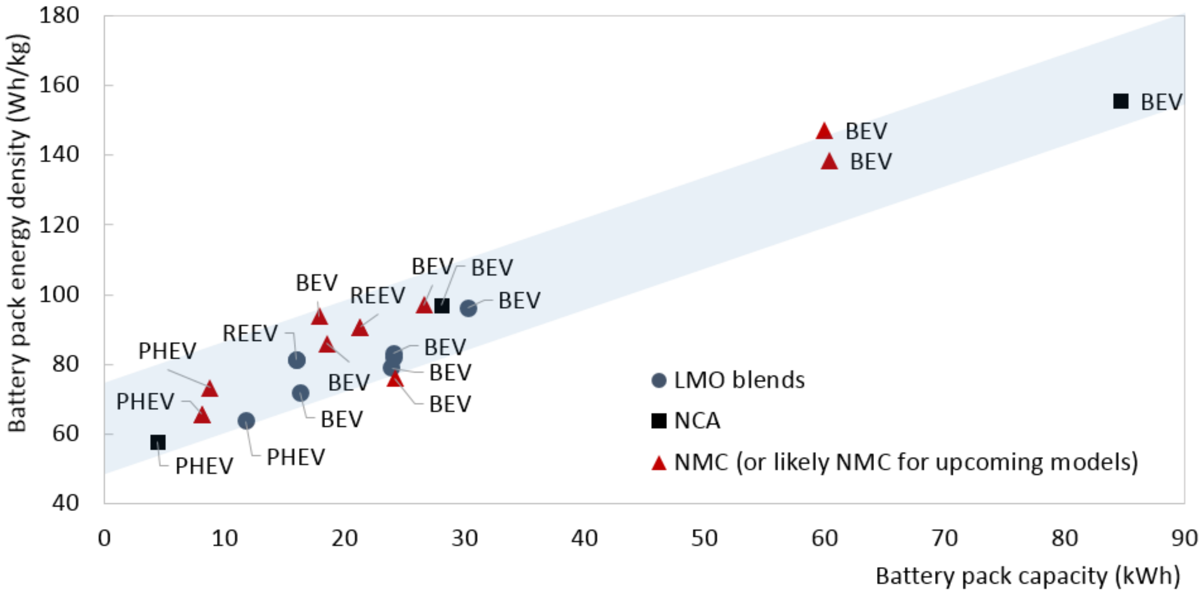

Figure 14 Relationship between battery pack energy density and the battery pack capacity for BEVs, REEVs and PHEVs [27]

Comparison of trends with the model results

Figure 15 presents a modified Figure 12 where the modelled values from Element Energy's model for three different cathode active materials (polyanion, spinel and NMC) in 2011 and 2015 have been included on top of the energy densities observed in the different EV models. **It can be seen that 2015 modelled projections are consistent with the reported market values**.

The comparison of the Nissan Leaf's pack energy density announced to enter the market by 2018 (150 Wh/kg) differs ca. 15% from the model projected values for 2018 (not shown).[28] However, it might be that this value is not based on the same bill of materials used to define a battery pack in the Element Energy model e.g. some of the housing weight is not accounted for (because it is partly integrated with the chassis)[29].

[28] Model forecasts 155Wh/kg for the packs above 60 kWh in 2020. Refer to Table 37 in the Appendix
[29] The details of Nissan Leaf 2018 model have not been disclosed yet so the exact level of integration in the chassis (and impact on overall chassis mass) cannot be commented on at this stage. This cannot be fully assessed until the 2018 model details are disclosed.

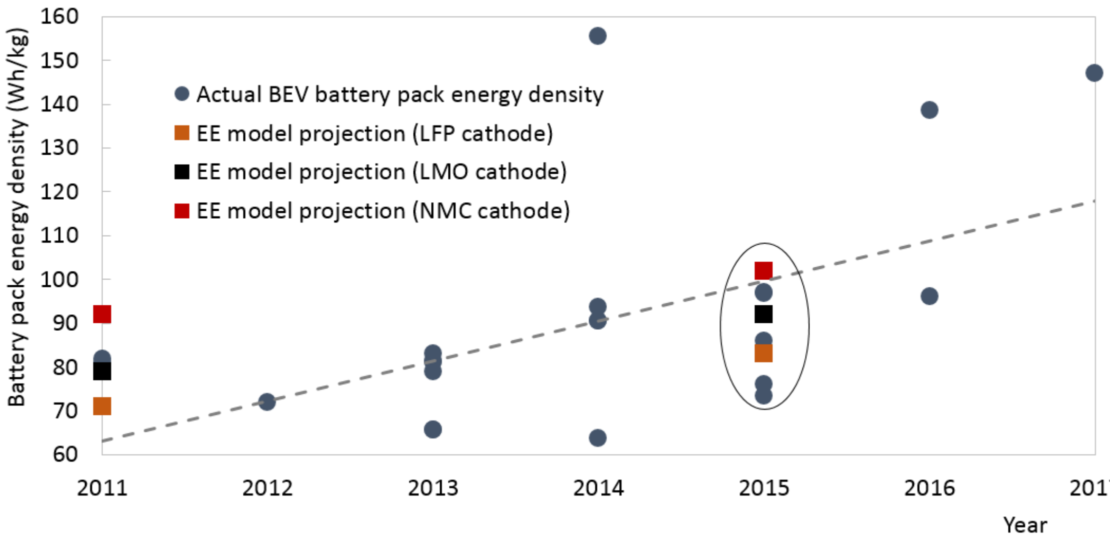

Figure 15. Comparison of market and modelled pack densities, modelled values are for a medium size car, 25 kWh BEV, baseline scenario

4.3 Drivers for improvements

The incremental changes in pack density and cost in recent years are driven by a combination of cell and pack level improvements.

The improvements at the *cell level* are explained by **improvements in the cathode chemistry, increases in the battery Depth of Discharge (DoD) window and increases in cell capacity (Ah)**. Firstly, over the last 5 years it has been observed that manufacturers have started a transition towards the use of higher density chemistries in the cathode (i.e. from LMO to NMC), while advances in NMC chemistry are being realised. Secondly, the DoD window of batteries is increasing, reducing the overdesign that is needed for performance and safety reasons. As an example, the Chevrolet Volt increased its DoD from 65 to 75% from 2013 to 2016 after changing its chemistry from G/LMO to G/NMC-LMO. Finally, large cell manufacturers such as LG Chem are pushing to increase cell capacities, as it reduces overhead at the pack level. This trend is shown in Figure 16, in which the increase of cell capacity in more recent electric car models for different manufacturers is demonstrated. There are exceptions from this trend, mainly Tesla (Daimler sourced the cells for its B-Class BEV from Tesla). Refer to Section 2.3 for the discussion on the use of small cells in the automotive industry. For comparison, the cell capacities assumed in the Element Energy model are 22 Ah in 2011, 44 Ah in 2015 and up to 87 Ah in 2020-2030.

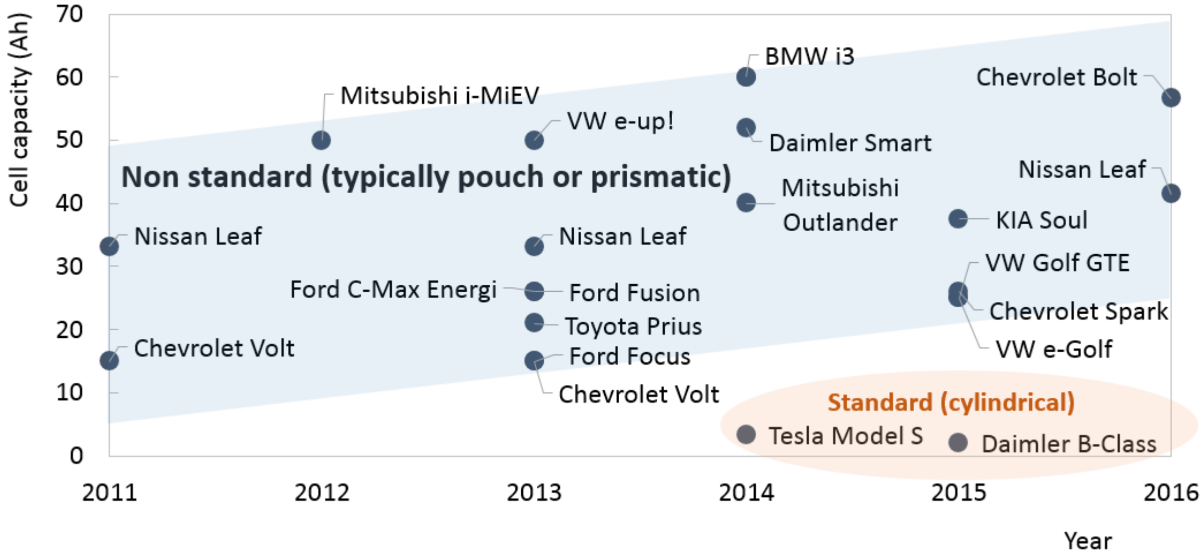

Figure 16. Observed cell capacities among different car manufacturers

At the *pack level,* improvements have been realised through the reduction in weight through advances in electronic components, changes in the way cells are assembled and streamlining of case pack structure.

5 Cost and performance modelling

This section presents three proposed scenarios for the modelling of battery performance and costs as well as an update of key model inputs, specifically: materials cost, manufacturing costs and updates on cost and mass of packing components. Lastly, the influence of battery pack size on cost is discussed.

5.1 Scenarios

For the modelling of lithium-ion battery cost and performance to 2050, three scenarios based on lithium-ion batteries are proposed – each representing a combination of a Research and Development path and an Electric Vehicle uptake path – and a 'New battery technologies' scenario in which post-lithium–ion batteries are assumed from 2025 (Table 7).

Table 7. Summary of scenarios and approach for battery costs and performance projections

Battery type	Approach to projections	Chemistries considered	Used in WP1	Scenarios
Li-ion chemistries	2015-2030 – bottom up model 2030-2050 – top down approach	Three cathode families: LMO, NMC, LFP	Yes – based on NMC cathode	3 (Base, Niche EV, EV Push)
Post Li-ion chemistries	2025-2050 – literature findings and component cost estimate based on comparison with Li-ion case	Li-S, Li-air, Na-ion	No (but tested in ECCo)	Only one case developed

As laid out in Table 8, for the case of lithium-ion batteries, the R&D path determines the introduction of improved electrode chemistries with time and their capacities (mAh/g) and voltages. This applies to both BEV and PHEV packs, i.e. both types of pack have access to the same lithium-ion chemistries and their corresponding R&D path (as currently observed and in line with other models e.g. [5]). The electric vehicle uptake path impacts the cell material and pack component costs, the plant capacity and its capex. This applies to both BEV and PHEV packs, i.e. it is assumed that packing components benefit from the learning rate of overall EV sales, without differentiating BEV and PHEV sales[30], as per [1]. Both paths are described next (from page 46) in more detail; they are used in the bottom-up model up to 2030. Post-2030, simpler 'top-down' assumptions are used:

- Annual pack cost reduction: 0.5%, 1.5% or 2% for the 'niche EV', baseline and 'EV push' cases respectively.
- Annual pack energy density increase: 0.5% in the 'niche EV' case, 1% in other cases.

These values are based on the premises that costs have to go down year on year for the product to be competitive and the fact that some efficiencies can always be made. This was discussed with a battery pack expert at Johnson Matthey who strongly agreed with the concept of continuous improvement but thought the chosen values were conservative (i.e. could be higher). They were however kept at this possibly conservative level on the basis that 1) no suitable proxies could be found to justify higher improvement rates (for a product getting close to the theoretical limits in terms of energy density) and 2) future raw material costs are highly uncertain. Strong energy density improvements are instead captured in the 'New battery technologies' scenario.

The baseline projections are used in all the narratives (Business as Usual, H_2 Push, Transport on Demand, OEM Innovation, City Led, ULEV Enabled) in the analysis conducted in WP1. The Niche EV and EV Push are used in the 'Low ULEV' and 'High ULEV' sensitivity tests, also conducted under WP1.

[30] The same learning rate applies across PHEV and BEV component costs but not all component costs are the identical, e.g. internal cell support and thermal management are most expensive for PHEVs, see Section 5.5 for more detail.

The 'New battery technologies' scenario has not been formally used in WP1 but could be tested in Stage 2, as part of the more systematic sensitivity testing[31].

Table 8. Scenarios for the modelling of lithium ion battery performance and costs

Scenario	R&D path	EV uptake	Post 2030 assumptions	Used in WP1
Niche EV	**Slow R&D** Slow material improvements	**Low uptake** EVs stay niche or localised markets	Pack cost reduction: 0.5% p.a. Pack energy density increase: 0.5% p.a.	In 'Low ULEV' sensitivity runs
Baseline case	**Baseline R&D** Improvement of existing and development of new materials	**Baseline uptake** EV uptake, supported by policy, increases steadily	Pack cost reduction: 1.5% p.a. Pack energy density increase: 1% p.a.	In all core narratives (Business as Usual, H2 Push, Transport on Demand, OEM Innovation, City Led, ULEV Enabled)
EV push	**Baseline R&D** Improvement of existing and development of new materials	**Stretch uptake** Strong global policy push for EV uptake	Pack cost reduction: 2% p.a. Pack energy density increase: 1% p.a.	In 'High ULEV' sensitivity runs
Comments:	• Each R&D scenario corresponds to a technology roadmap (mAh/g and voltage of active materials) • It dictates the cell energy density	• EV uptake scenarios affect: — Production costs (plant capacity and CAPEX) — Cost of cell materials — Costs of packing components	Top down approach; fixed rate of improvement assumed	Impact of electric vehicles cost (which include battery cost) on EV uptake are reported in D1.3 (sensitivities in D1.3 Section 5.3)

R&D paths

Table 9 and Figure 17 present the scenario definitions and the resulting cell densities up to 2030. In the bottom-up model, the cell densities are calculated from the capacity (mAh/g) and voltage of cathodes and anodes. These input values were updated and validated through industry consultation.

Table 9. Assumptions behind R&D paths

Baseline R&D	Slow R&D
Improvements of existing materials and development of new ones. Cathode reversible capacity comes close to realise its theoretical potential and anodes with blends of 8.5% of silicon start to be used by 2020	Conservative scenario. Slow development of existing materials, where anodes with blends of 1% of silicon are starting to be used by 2020

Figure 17 shows the incremental improvements of cell energy density for spinel, NMC and polyanion cathode chemistries, with spinel and polyanion reaching a plateau by 2025 and NMC showing improvements until 2030, reaching the 300 Wh/kg figure. The assumptions on the cathode and anode chemistries, capacities and voltage are detailed in the Appendix.

[31] The New battery technologies scenario has however been tested in ECCo (vehicle uptake model) and shows little impact on the number of plug-in vehicles on the road by 2050 (+2%point maximum) compared to the case where the baseline cost and energy density projections are used. This is due to the late entry of changes (from 2030) and modest cost differential (-7% on £/kWh basis).

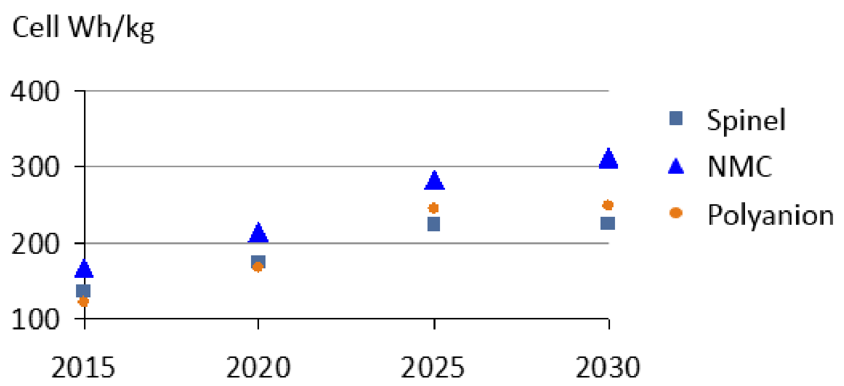

Figure 17. Cell energy densities (Wh/kg) up to 2030 for different cathode chemistries

Electric Vehicle uptake paths

Table 10 and Figure 18 present the assumptions behind the Electric Vehicle uptake paths. The values presented take into account cars and vans.

Table 10. Assumptions behind EV uptake paths (includes cars and vans)

	Low uptake	**Baseline uptake**	**Stretch uptake**
Assumption	No policy push, and EVs remain niche	Policy support in developed countries brings the uptake of plug-in vehicles to follow the same trajectory as HEVs (i.e. global EV uptake in 2016 onwards assumed equal to observed historical HEV uptake, 2005 onwards)	Strong global push at global level
Global annual EV uptake (% sales) in 2020	0.6%	1.1%	5.4%
Global annual EV uptake (% sales) in 2030	2%	4%	13.8%
Global EV sales in 2020 (million)	0.6	1.1	5.4
Global EV sales in 2030 (million)	2.4	4.7	16.3
Cumulative EV sales by 2020 (million)	2.2	4	15
Cumulative EV sales by 2030 (million)	17.8	35	123

Figure 18 presents the annual sales of PH/BEV cars and vans up to 2030 for the three modelled scenarios, together with some data points from the literature. The 'Baseline' scenario is within Avicenne's predictions [79], where the scenario 2 (S2), is based on a world in which China's uptake of electric vehicles takes off. As a reference, if North America and Europe achieved a 100% uptake (sales) of electric vehicles in 2040, with a linear increase of the uptake from today up to 2040 (i.e. ca. 50%

uptake by 2030), by 2030 ca. 20million sales of EVs (121million cumulative) would be achieved in those regions (values very similar to the proposed 'Stretch' scenario).

While the 'Stretch uptake' case, at over 5 million annual EV sales in 2020 might seem high in comparison to the baseline, this level of production is plausible. Previous analysis found that this EV annual production capacity is credible as OEMs have the capability to scale up production (existing factories do not run at full capacity and some EV models are based on existing non-EV models). Even at this level, EV production capacity in 2020 would represent less than 7% of the current total light-duty vehicle production [80].

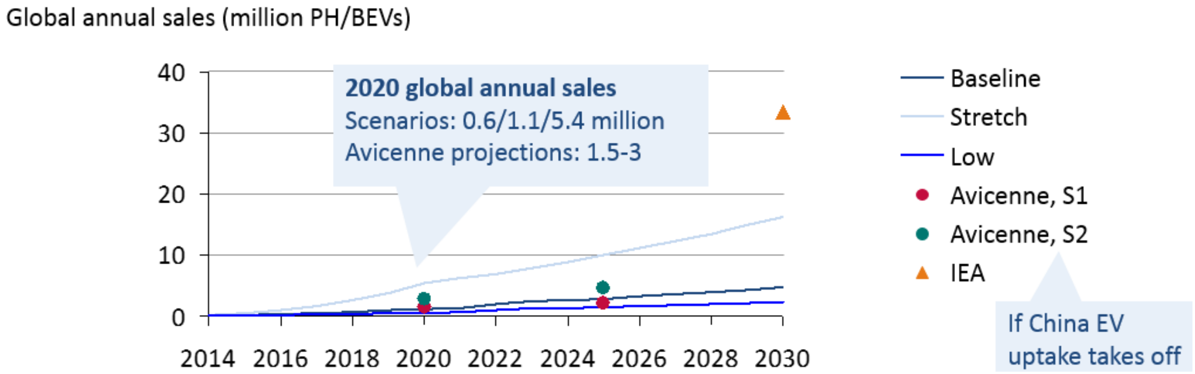

Figure 18. Global million PH/BEV sales for the three scenarios and comparison with other sources

5.2 Materials cost updates

The costs of the following components were updated, following the trends in the industry over the last years, informed by the last version of ANL's BatPac model (May 2015), a literature review process and industry validation[32] of results:

- Separator
- Positive current collector
- Negative current collector
- Electrolyte
- Active material costs

The reduction in the costs of the separator, the collectors or the electrolyte is related to a combination of factors such as higher levels of standardisation, economies of scale and higher supply chain maturity. Current and future costs (£/kg) of cathode and anode active materials were also updated downwards, informed by the consultation with industry stakeholders. However, it has to be noted that the volatility in the costs of nickel or cobalt makes future active material cost projections uncertain. The cost of the electrolyte is accounted for (see Table 30 in Appendix) but slight variations in the exact composition of the electrolyte of lithium-ion cells are not accounted for, as per assumptions used in the Argonne Bat Pack model. The details on the cost updates are provided in the Appendix (Table 30).

5.3 Cell manufacturing costs

As presented in section 2.2 the **cell production module** projects the plant capex and labour costs using the methodology developed by the Argonne National Laboratory. ANL calculations for manufacturing have been calibrated with real world plant cost research. Figure 19 presents the relationship between plant capex and plant volume production used for the calibration.

[32] Based on consultation with industry stakeholders who wanted to stay anonymous

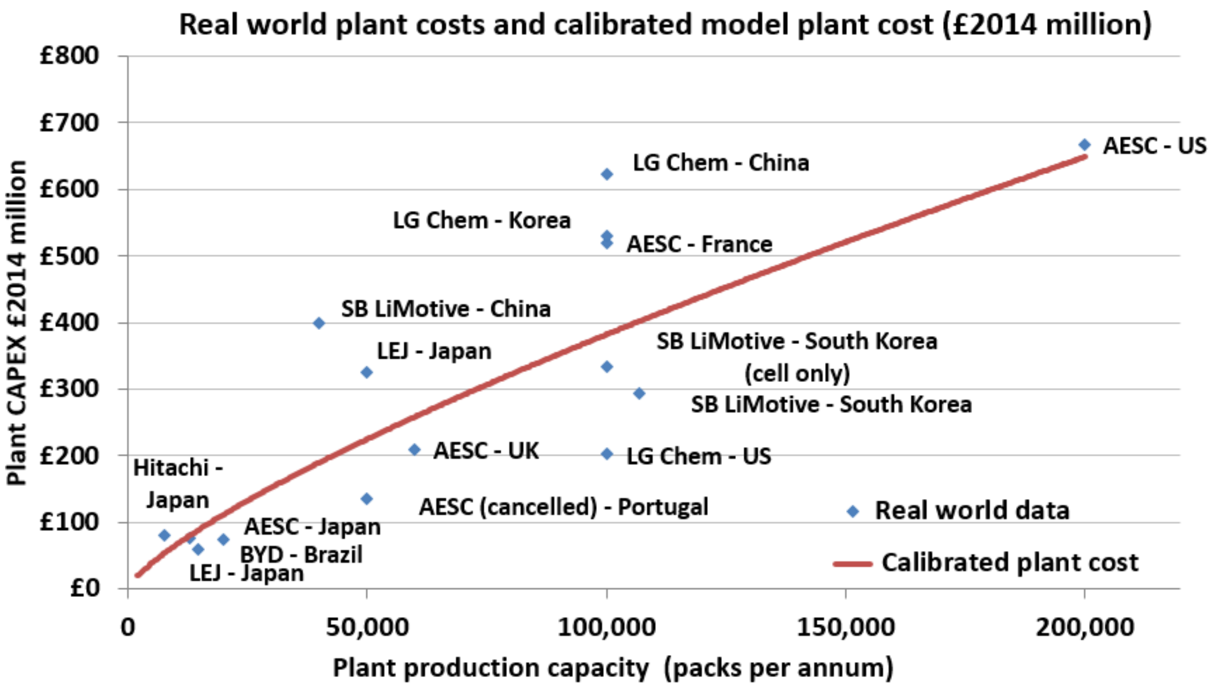

Figure 19. Investment costs (£2014, million) vs plant production capacity (packs per annum) of existing and announced automotive battery production plants. The exact pack capacity varies by +/- 20% between the plants and is 20 kWh on average

ANL's BatPac plant costs assumptions are used as the lower bound for Element Energy's capex plant costs, as that model assumes an optimised plant in operation by 2020. In the Element Energy model, the rate at which this cost is reached is dependent on the uptake scenario 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'). The production volumes assumed for each scenario are presented in Table 11.

Table 11. Modelled plant production volumes in each scenario

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

A key underlying assumption in the bottom up model is that manufacturing improvements will make standardised high quality[33] large format cells achievable at high production yields (95% assumed) by 2015. Industry stakeholders contacted for this study report that yields vary across countries/organisations, with numbers as high as 98-99% in Japan and Korea[34]. A 95% figure is considered a good approximation for today's industry average. However, based on these discussions, the production yields are assumed to increase to 98% in 2020 and 99% by 2025 (whereas the yield was kept constant in the previous model version).

5.4 Packing costs and weight

Packing costs refer to the cost of components other than the cells and production costs linked to the packaging of the cells into a pack. Learning rates are applied to the cost of packing components, unchanged since Element Energy's 2012 work (in Appendix, Table 29).

[33] High quality refers to the high standards of consistency, safety and life required in the automotive industry
[34] Based on input from Johnson Matthey and one other industry stakeholder who wanted to stay anonymous

Based on input from Johnson Matthey, the following updates were implemented to the **cost of packing components**:

- **BMS**: technical advances and standardisation have the potential to reduce by a factor of three the BMS costs per cell attributed to this component by 2020 compared with the previous model assumptions. Management at the cell rather than at the pack level is currently being explored and could trigger these improvements.
- **Power electronics**: possess a low potential for cost reduction as this component is mainly made of copper, and this constitutes most of its costs. Aluminium is sometimes used instead of copper, e.g. in sports car batteries, however this is driven by weight reduction and not by cost considerations. The changes in costs compared to the previous model are due to the variations in the EV uptake scenarios (i.e. in the learning rate cost reduction approach, the opportunities for cost reduction are dependent on the cumulative EV uptake).
- **Wiring harnesses, cell interconnectors and outside world connectors**: the main cost reduction opportunities is in wiring harnesses (ca. 25% lower than in previous model in 2020-30) due to their reduction in number in the future. Interconnectors and connectors, mainly made of copper, offer a limited scope for cost reduction. Additional changes in costs compared to the previous model are due to the variations in the EV uptake scenarios.
- **Internal cell support:** cost reductions per cell of 15% and 30% in 2025 and 2030, with economies of scale and standardisation being the main triggers for cost reduction.
- **Housing:** standardisation (e.g. through the share of the housing designs among OEMs) has the potential to reduce the fixed costs of housing by 15-20% by 2025 and 2030. The integration of the housing in the chassis could offer cost and weight reduction opportunities. This is already done to some extent by some car OEMs, e.g. Tesla [81] .
- **Thermal control:** reductions per kWh of 10% in 2020-30 have been implemented as the next generation of thermal controls will be improved and smarter.

Updates in packing weight have been implemented in the housing (ca. 25% weight reduction compared with the previous model) and in other pack components (ca. 15% weight reduction).

The assumptions on the Depth of Discharge of BEVs and PHEVs have been updated to reflect the potential for increase, these are detailed in Table 12. The 2012 model assumed a constant 80% and 70% for BEV and PHEV packs respectively.

Table 12 Depth of discharge window assumptions

Pack type	2015-2025	From 2030
BEV	85%	90%
PHEV	70%	80%

5.5 Influence of battery pack size on cost

There is a substantial decrease in battery pack cost as size increases. In the C segment (i.e. medium sized car), both BEV and PHEV packs power a 70/80 kW peak power motor. The BEV pack is 26 kWh and 40 kWh in 2015 and 2030, respectively (160 km range in 2015 and 300 km in 2030), whereas the PHEV pack is 10 kWh and 8 kWh in 2015 and 2030 respectively (50 km range). This higher power to energy ratio make PHEV packs more expensive, mainly due to the higher costs of the packing components. In particular, internal cell support is four times more expensive for PHEVs on a £/kWh basis, BMS three times more expensive, and other components (e.g. wiring and power electronics) twice as high (at the £/kWh level), as the management of a PHEV pack is more complex than a BEV one and because of fixed cost effects[35] [1]. The main difference between the BEV and PHEV pack costs are [1]:

- 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; often they are liquid cooled whereas BEV packs are typically air cooled. 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 engine can also be accommodated in the PHEV. Liquid cooling offers 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 required by PHEV packs. The lower C-rate 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 the higher C-rate, requires the pack to be actively balanced throughout charging and discharging, which requires faster and more accurate sensors. This means that the balance leads (required for each of the cells in series) will need to be rated higher and therefore be more expensive in a PHEV pack.

To capture this impact, the model produces results for six size bands (see Table 13). The selected bands cover all the EVs in the market. The largest pack modelled is 69kWh, as a representative of the “>60kWh” band, as the size effect effectively tapers off at this level. The lowest size modelled is 12kWh, for the “<15kWh” band which effectively applies to PHEVs. For comparison, medium sized PHEVs on the market achieving at least 50 km electric range on official test cycles have 9kWh to 12kWh packs (V60 11kWh, Golf GTE 9kWh, Mitsubishi Outlander 12kWh).

Figure 20 presents the effect of pack size on their costs for 2015. It also shows to what extent the higher packing component costs for PHEVs contribute to PHEV packs being more expensive than larger BEV packs. The pack capacity for each car and van segment is based on the assumed electric driving range, depth of discharge and powertrain energy consumption. Values for these are presented in the Appendix. These costs by band input into the cost and performance model that sits within ECCo, informing EV uptake.

Table 13. Six bands within the model to capture the size effect on costs

Band (kWh)	**≤15**	**15-≤20**	**20-≤25**	**25-≤35**	**35-≤60**	**>60**
kWh modelled	12	17.5	22.5	30	50	69

[35] The fixed cost effect refers to the fact that a comparable amount of material/equipment is needed for some components, in particular the cell support and BMS, but for a lower kWh. In the case of the internal cell support, the ratio is based on actual cost data provided by a battery assembler for [1] and is in line with the ratio observed in the BatPack model [5]. In the case of the BMS, the BatPack model actually assumes the same fixed cost for BEV and PHEV packs (i.e. does not capture the differences in balancing approaches), making the £/kWh 2.6 times and 5 times more expensive for the PHEV pack in 2025 and 2030 respectively in the example taken here (26 and 40 kWh for BEV, 8 and 10 kWh for PHEV). Regarding power electronics, the evidence so far points to cost twice higher on a £/kWh basis (between a 12kWh PHEV pack and 30kWh BEV pack), but this is power demand dependent. It is assumed that PHEV packs must provide the same power output than a BEV pack, for a car of comparable size, i.e. that a PHEV must be able to run in pure EV mode. Thus, the power electronics are composed of a fixed cost which is the same for BEV and PHEV packs (£460 in 2015) and a £/kWh element, which is higher for PHEV packs (higher rated connectors and cables, £8/kWh and £15/kWh in 2015 for BEV and PHEV packs respectively, based on industry input [1]). Therefore, again, the final £/kWh difference between the BEV and PHEV packs is mostly down to the fixed cost effect (e.g. in 2015 the power electronics cost for a 12kWh pack is £612 (£51/kWh), 75% of which is down to the fixed cost component). The power electronic costs are therefore quite sensitive to the power demand assumption. However, the power electronics cost for a 12kWh pack represents around 10% of the total pack cost so the overall pack cost is only moderately sensitive to the fixed cost assumption.

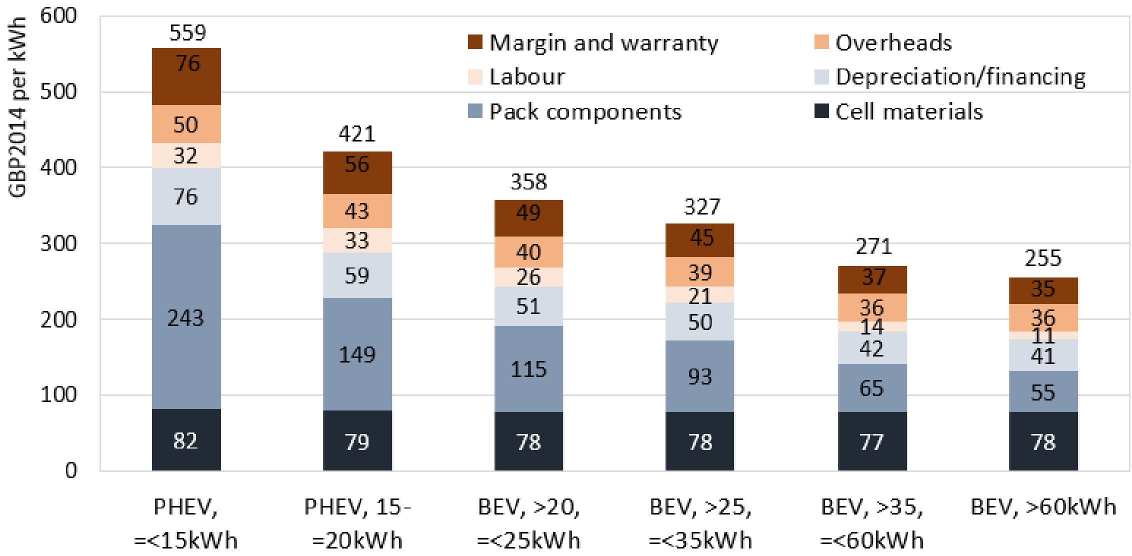

Figure 20. Modelled battery pack costs for different pack sizes in 2015 (GBP2014/kWh, Spinel)

6 Results and future trends in energy densities and costs

This section presents the cost and energy density projections for automotive batteries for the different scenarios set out in the previous chapter. Results are reported for two pack sizes only (one BEV case and one PHEV case), while results for all modelled pack sizes are reported in table format in the Appendix. In the accompanying battery cost and performance database, results are further detailed in terms of cathode chemistries and cost breakdown.

The **lithium-ion results presented are based on a NMC cathode**, as the cost and energy density results show that although NMC packs come at a slight premium, they bring ca. 15% improvement on energy density over LMO packs for BEVs (Figure 21) and ca. 10% improvement for PHEVs (Figure 22). Note that LFP energy density is lower than that offered by a NMC cathode, whilst the cost is higher at the moment and expected to remain so in the near future. Figure 22 also shows the reduction in battery pack cost and the increase in energy density for a typical PHEV battery pack.

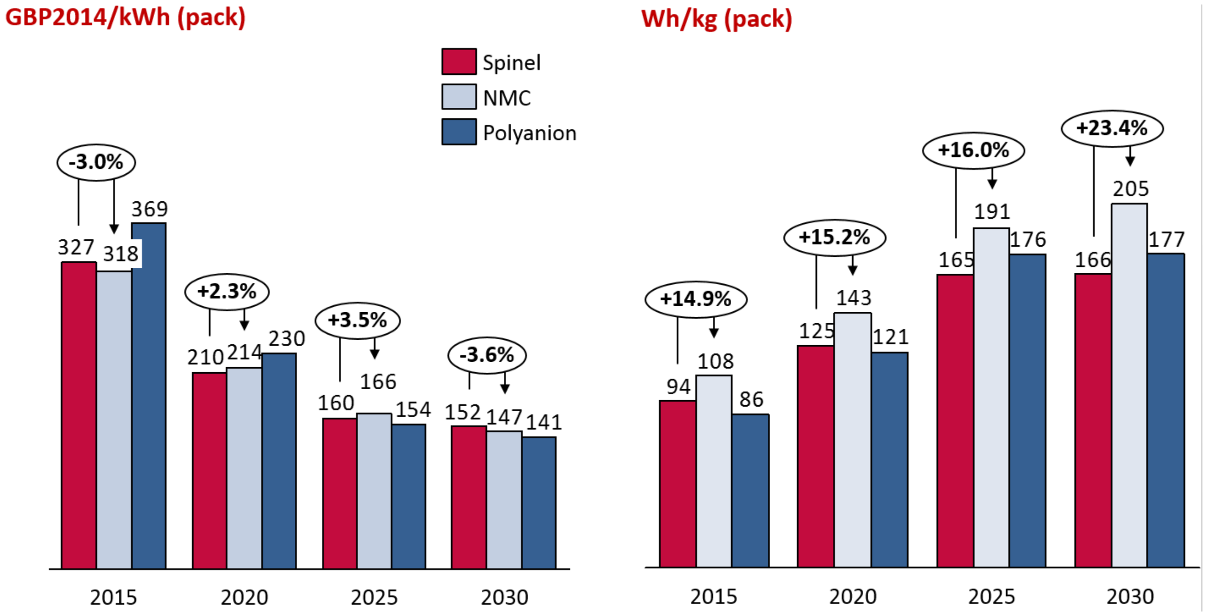

Figure 21. Comparison of a 30 kWh BEV pack costs and energy densities for spinel and NMC cathode chemistries (baseline scenario)

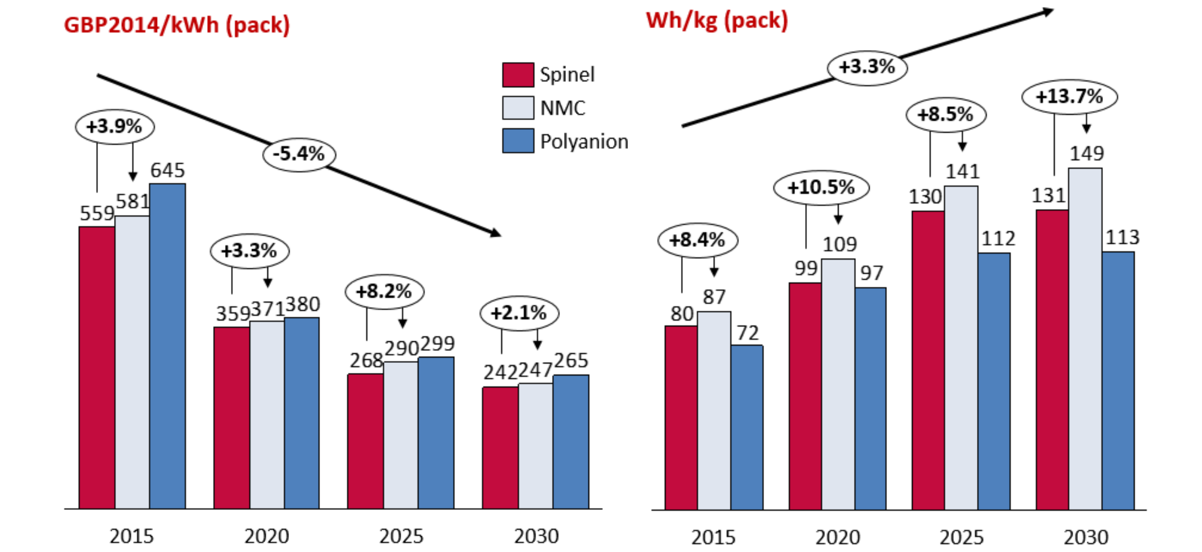

Figure 22 Cost and energy density projections for a 12 kWh PHEV battery pack (baseline scenario)

At the anode level, **results are based on a graphite anode in 2015 which incrementally accommodates an increasing level of silicon blending** (from <10% in 2020 towards ca. 40% in 2030 in the baseline R&D scenario).

Results for the 'New battery technologies' case are also provided here. They should be treated with caution and as an alternative case for sensitivity purposes only, given the remaining challenges faced by post-lithium technologies and uncertainty over their fitness for automotive applications.

6.1 Future pack densities

6.1.1 Energy density of lithium-ion battery packs to 2050

Figure 23 shows the energy density (Wh/kg) results at pack level, for a 30 kWh (solid lines) and a 12 kWh (dashed lines) lithium-ion pack, from 2015 to 2050. There are only two scenarios as the 'Baseline' and 'EV push' use the same underlying technology roadmap. In the baseline, the density of a 30 kWh BEV pack is projected to increase from ca. 110 Wh/kg today to ca. 145 Wh/kg in 2020, 205 Wh/kg in 2030 and up to 250 Wh/kg in 2050. Post-2030 values are based on a 1% annual pack energy density increase, in agreement with the most conservative industry input.

This means that for an electric vehicle using 0.137 kWh/km a 30 kWh pack with 85% DoD in 2015 would provide a ca. 190 km driving range with a 280 kg pack. In 2020, at equal capacity and DoD, and taking into account the lower electricity consumption due to efficiency improvements, the range would increase to 200 km and the pack weight reduces to 210 kg. In 2030, with a wider DoD window of 90%, 230 km of range and a 150 kg pack would be achieved[36].

In the case of a 12 kWh PHEV pack, the energy density is projected to increase from ca. 90 Wh/kg in 2015 to ca. 140 Wh/kg in 2025, 150 Wh/kg in 2030 and up to 180 Wh/kg in 2050 in the baseline scenario.

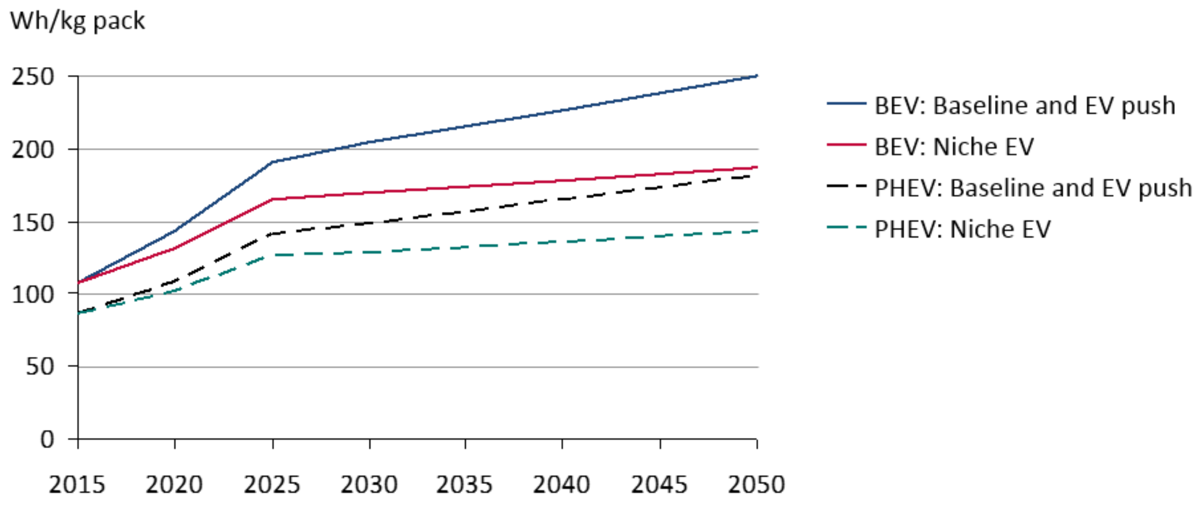

Figure 23. Total pack energy density (Wh/kg) for three different scenarios for a 30 kWh BEV lithium-ion pack (solid lines) and a 12 kWh PHEV (dashed lines). Cathode chemistry = NMC

Figure 24 shows the model results for the total pack mass and the distribution of mass between the cells and the rest of the battery pack components for a 30 kWh BEV pack. Cells constitute ca. 65% of the total battery mass and this proportion remains constant up to 2050. At the same time the overall pack mass is expected to be reduced by 2050 as illustrated in Figure 24. Equivalent relative weight reductions are expected at the cell (mainly due to chemistry improvements up to 2030 and due to improved cell design and packaging after 2030) and pack level. An annual weight reduction of 3% and

[36] Equivalent to NEDC figures, based on Element Energy vehicle performance modelling. Accounting for energy consumption improvements, the energy use would decrease to 0.132 and 0.119 kWh/km respectively in 2020/30.

1% is projected for 2020-2030 and 2030-2050 timeframes respectively. These projections are in line with industry consultation.

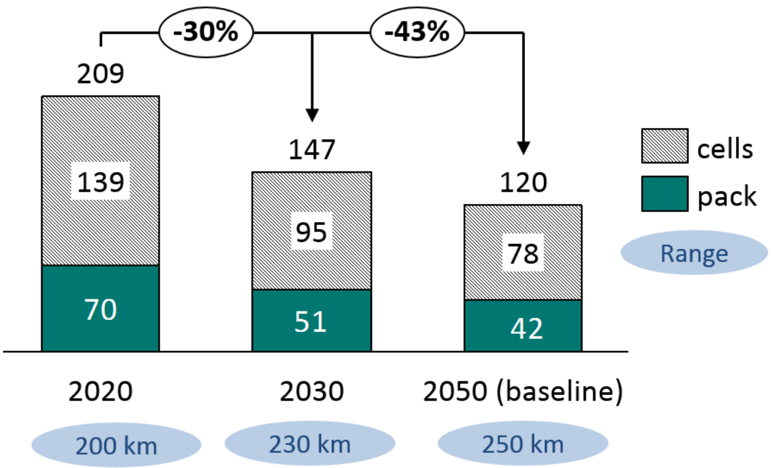

Figure 24. Total future pack mass split (kg) between cell and pack components (30kWh pack, NMC cathode, baseline scenario)[37]

6.1.2 New battery technologies scenario

This scenario is formed by the pack cost and densities of the EV push scenario up to 2020, and by the values achievable by a post-lithium ion technology from 2025 to 2050. Both the cases of lithium-sulphur and lithium-air technologies were examined. The case of sodium-ion was not considered as this chemistry does not provide an energy density benefit over lithium-ion, only a cost benefit, detailed in section 6.2.2.

Lithium sulphur

Figure 25 presents the pack energy densities of the 'New battery technologies' scenario. It is an aggressive scenario that assumes that lithium sulphur batteries start to be deployed in the automotive sector by 2025, achieving a pack energy density of 240 Wh/kg (ca. 25% higher than lithium ion batteries in that year). In 2050, lithium sulphur pack density increases to 360 Wh/kg at the pack level, ca. 50% higher than lithium ion technologies.

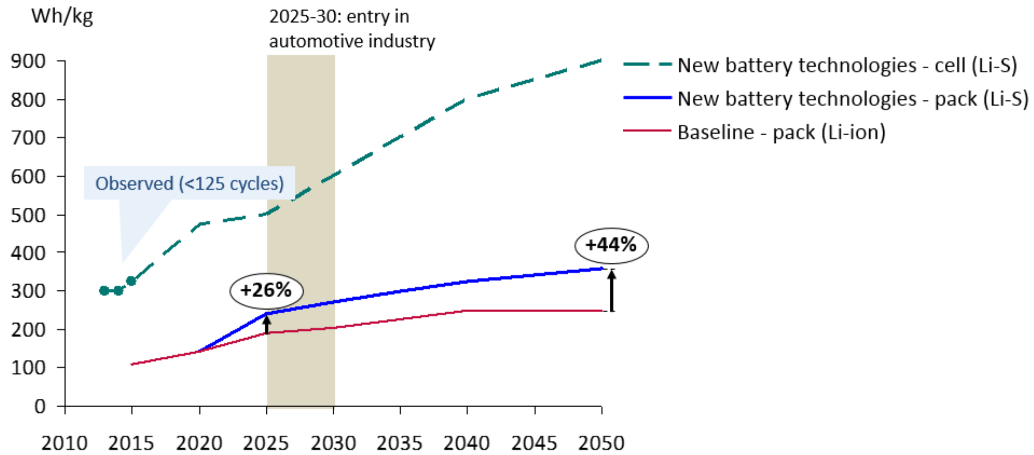

Figure 25. Comparison of pack energy densities of 'New battery technologies' and 'Baseline' scenario (30 kWh pack)

[37] Assumes: 0.132, 0.119 and 0.110 kWh/km of electricity consumption for 2020, 2030 and 2050, respectively and 85% DoD in 2020 and 90% in 2030-2050

The observed cell energy densities correspond to Oxis Energy's achievements, and the 2050 value is capped at 900 Wh/kg which is what Oxis Energy's scientists estimate for the maximum achievable. For the estimation of pack energy density, cell weight was calculated with the total pack size and the assumed cell density, and packing weight was assumed to be higher than that for lithium ion as a ratio of the volumetric energy density for both chemistries.

Lithium air

Figure 26 presents the projected lithium air pack energy densities, of 290 Wh/kg and 375 Wh/kg in 2030 and 2050 respectively, which is equivalent to 40-50% higher values than for the 'Baseline' lithium-ion scenario. Despite the high cell energy densities achievable (700 Wh/kg in 2030 and 1,000 Wh/kg in 2050), the assumed penalty in the pack weight of 30% compared to a lithium ion battery (due to the need to introduce an extra air management system) limits the energy density that can be achieved in lithium air packs in practice. This is justified by the analysis reported in academic literature that utilised BatPaC model framework for a lithium air system [82]. Specifically, a lithium air system that utilises atmospheric oxygen requires a compressor, pressure swing adsorption for CO_2 and H_2O removal and a solvent management system to prevent emissions that could occur from volatile electrolyte components leaving with the effluent. The additional weight of these gas utilisation components was estimated as ca. 30% of the total system weight [82].

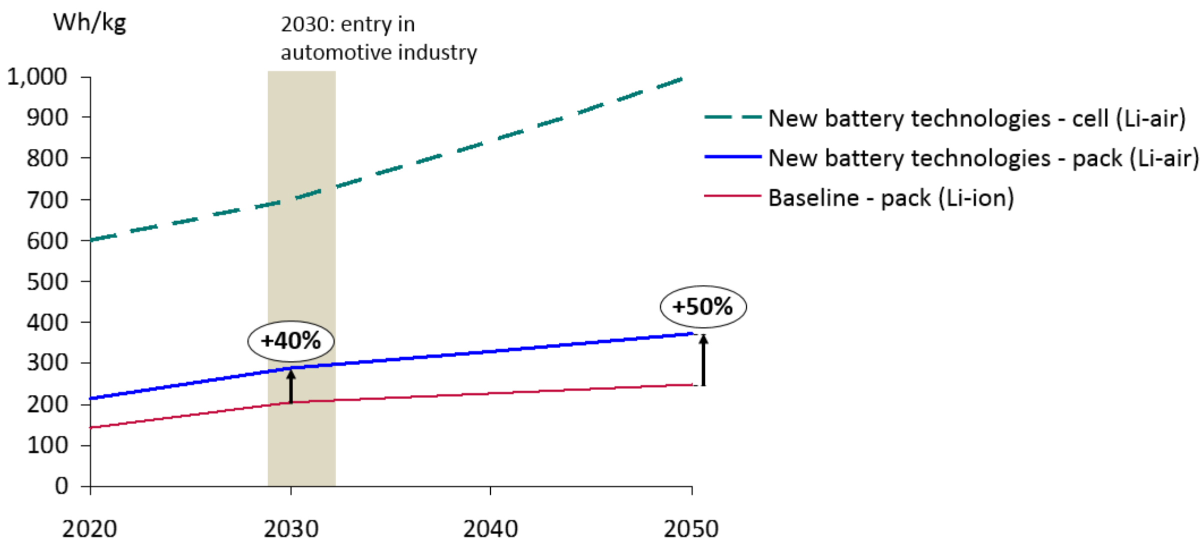

Figure 26. Comparison of pack energy densities of lithium-air and 'Baseline' scenario, 30 kWh pack

Summary

Comparing the estimates for lithium-sulphur and lithium-air batteries shows that, despite a higher theoretical cell density, the energy density of lithium-air battery packs is not expected to be significantly different from lithium-sulphur. The challenges faced by Li-air cells are significant, as described in Section 3 However, as this technology has the potential to offer the highest energy density, the projections based on Li-Air have been chosen as the values underpinning the post lithium ion scenario. Table 14 presents the assumed pack energy densities for the three scenarios.

Table 14. Pack energy densities (Wh/kg) for the three scenarios (25-35kWh band)

	2015	2020	2025	2030	2040	2050
Baseline and EV push (Li-ion)	108	143	191	205	226	250
Niche EV (Li-ion)	108	131	165	169	178	187
New batteries technologies (Li-Air)	108	143	191	288	329	374

6.2 Future pack costs

The costs presented in this section include a profit margin, which is assumed to be constant over time (and set at 10%). The model does not attempt to reproduce the current pricing strategy mentioned by industry experts we consulted with, who report that the current battery production overcapacity is leading to some strategic low deals between cell/pack manufacturers and car OEMs to secure market share and future opportunities for growth.

6.2.1 Cost of lithium-ion battery packs to 2050

Figure 27 shows the total pack cost (GBP2014/kWh) results at pack level, for a 30 kWh BEV and a 12 kWh PHEV lithium-ion pack, from 2015 to 2050 for three scenarios. In the baseline, the BEV pack cost is projected to decrease from ca. £320/kWh today to ca. £215/kWh in 2020, £150/kWh in 2030 and down to £110/kWh in 2050. Values up to 2030 are modelled and projections up to 2050 are based on a 1.5% annual cost decrease. Both for the BEV and PHEV packs the highest relative reduction in costs between 2015 and 2030 is projected for cell materials at 53%, with pack component cost reductions at 46%. The Drivers behind these cost reductions are detailed in section 5

The difference between the three scenarios is down to several factors. Part of the difference originates from the fact that each scenario assumes different costs trajectories for the cathode active material (detailed in the accompanying battery cost and performance database). Furthermore, whilst baseline and EV push scenarios use the same R&D path, Niche EV scenario assumes a lower R&D path. Both the cell voltage and the cathode capacity increase more slowly with time in the Niche EV scenario, leading to higher costs per kWh.

For a >60kWh BEV pack (not shown on the graph) the model projects lower costs as the required power to energy ratio is lower, as detailed in Section 5.5. Thus, a baseline pack cost is projected to be £170/kWh (£150-190/kWh for the other scenarios) by 2020. This contrasts with the target for the Tesla Gigafactory of £170/kWh by 2017, indicating that if that were to be achieved then 18650 cells[38] bring the equivalent of a three year advantage over larger cells.

[38] Small format cells used by Tesla

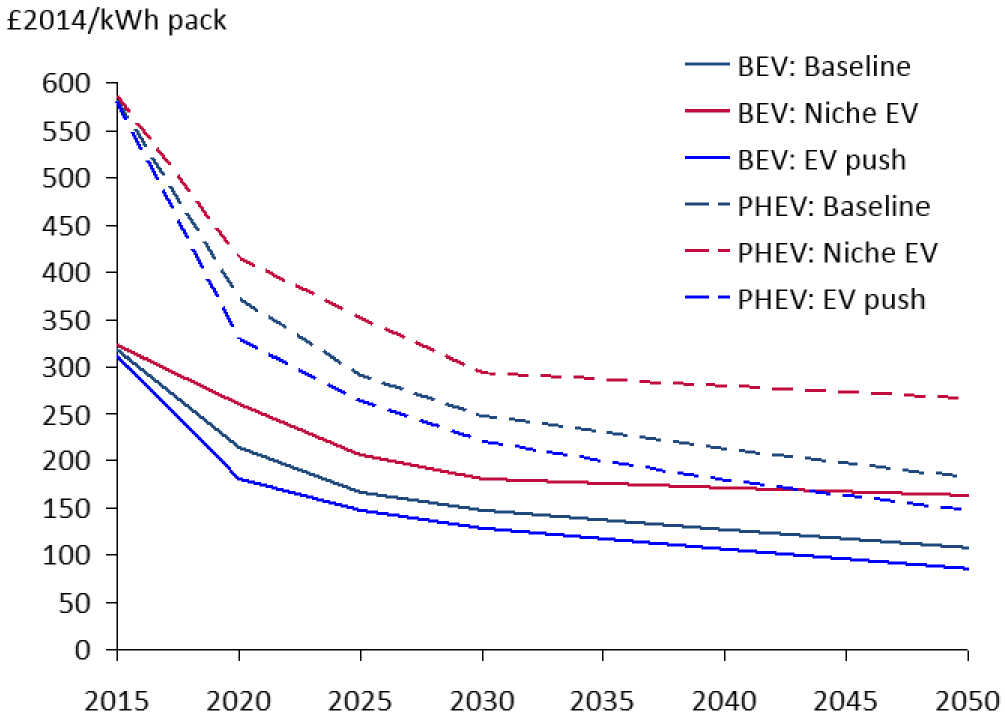

Figure 27. Total pack costs (GBP2014/kWh pack) for three different scenarios for the case of a 30 kWh BEV lithium-ion pack (solid) and a 12 kWh PHEV lithium-ion pack (dashed) - NMC cathode

Figure 28 shows the cost breakdown in terms of cell materials (25-30%), pack components (ca 27%), depreciation (ca. 15%), labour (ca. 5%), overheads (13%), and margin and warranty (14%). It also shows the impact of R&D developments and learning rates bring an equivalent of ca. 5% p.a. cost reduction over 2015-2030. This highlights the assumption of a post-2030 rate of 1.5% p.a. cost decrease, representing a relative slowdown in progress, reflecting that it will become harder to find efficiency gains. Among cell materials, the cathode active material costs (the most volatile costs) represent ca. 40-50% of the cell material costs 2020 onwards, meaning a doubling in their cost (which is an extreme example) would create a ca. 15% increase in the total pack cost (£/kWh level). Equivalent results are shown for the case of a 12 kWh PHEV pack in Figure 29. The cost reduction rate between 2015 and 2030 is even higher than for the BEV case because the reduction in pack component costs is the major contributor to the overall cost reduction, and the relative pack components contribution to costs is higher for a smaller pack.

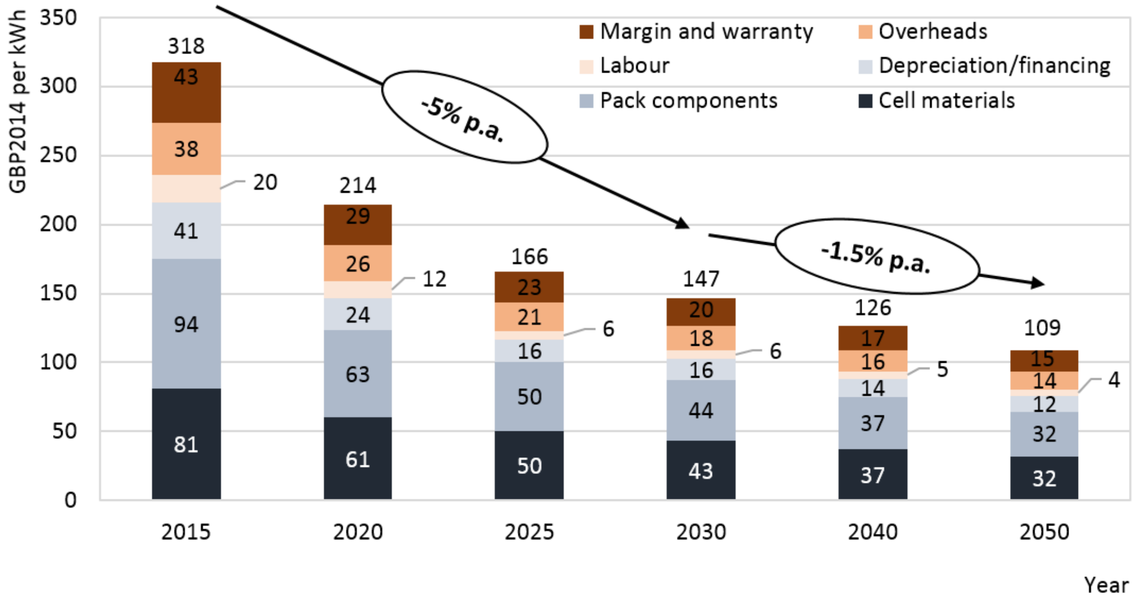

Figure 28. Modelled total pack costs (GBP2014/kWh) for a 30 kWh BEV lithium-ion pack, in baseline scenario (NMC cathode)

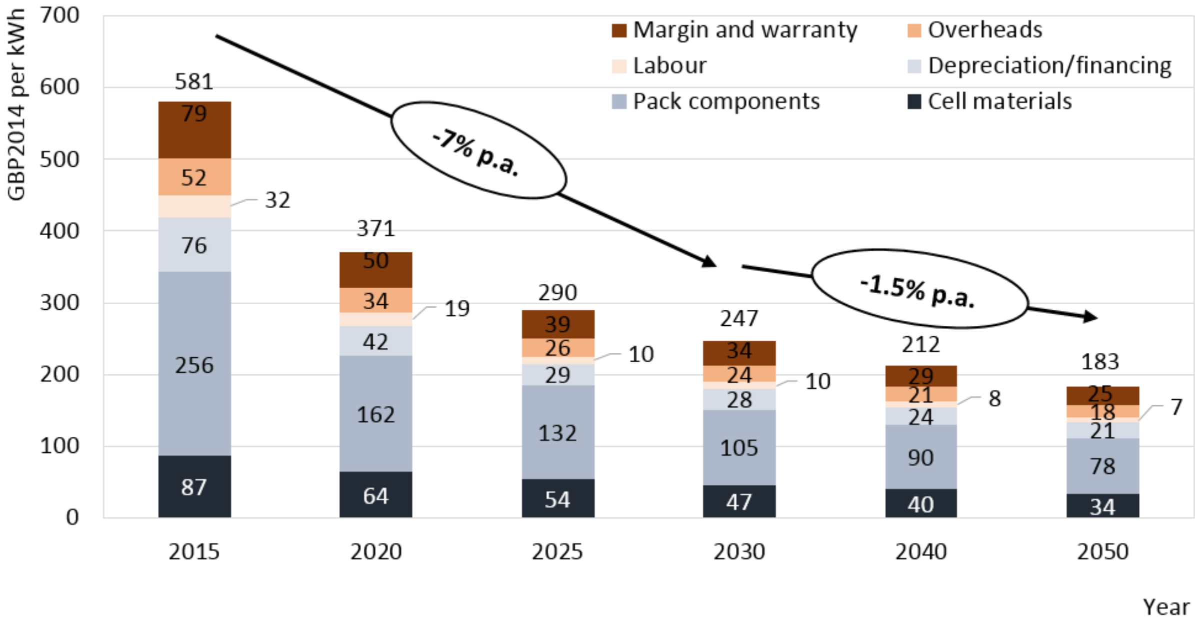

Figure 29 Modelled total pack costs (GBP2014/kWh) for a 12 kWh PHEV lithium-ion pack, in baseline scenario (NMC cathode)

6.2.2 New battery technologies scenario

For this scenario, the potential cost savings or cost premiums over an advanced 2030 lithium-ion battery brought by post-lithium ion technologies have been estimated for each battery component. This was done for the cases of lithium-sulphur, lithium-air and sodium-ion technologies.

Lithium sulphur

Table 15 shows the top-down approach for the estimation of the pack cost per kWh of a lithium sulphur battery in 2030, and its comparison with the incumbent battery at that point (i.e. a NMC cathode, blended silicon anode lithium ion battery). Results show that by that time, *if production costs (capex and labour)*

were equal, lithium sulphur could be produced at a slight reduced cost (ca. 7%) offering a pack gravimetric energy density ca. 35% higher than lithium ion technologies.
Despite the fact that lithium sulphur offers higher potential energy density and reduced materials cost compared to lithium ion, one of the challenges for lithium sulphur batteries is to develop a cost-efficient production process (as it is partly different from the lithium ion production process). Hence, although lithium sulphur batteries have the potential to be cheaper than the lithium ion ones once at volume, lithium ion manufacturing by 2030 will have more than a decade of experience ahead of lithium sulphur[39]. Lithium sulphur batteries count on the advantage of the use of sulphur, a lower cost, more abundant active material with a lower cost volatility compared to lithium ion active materials (cobalt in particular, as commented on in Section 3.3), however they possess a lower volumetric energy density.

Lithium sulphur cells can be used over the full DoD range without the aging and safety issues that lithium-ion cells suffer from. However, in practice, due to fluctuations in performance and battery life protection, lithium sulphur packs would very likely be designed to work on a DoD window close to 90%. This value is the same as assumed for lithium ion chemistry to achieve by 2025, the year in which lithium sulphur is assumed to enter the automotive market. For this reason, this parameter has not been considered in the top-down approach presented in Table 15.

Lithium air

Table 16 presents the top-down approach for lithium-air, presenting a small cost reduction by 2030. Again, as discussed for lithium sulphur, these figures are potential, if economies of scale were realised, and in particular in the case of lithium air, if the remaining challenges were addressed. At the moment, there is no prototype that achieves the high number of cycles required by the automotive industry.

[39] More than a decade for large cells manufacturing, and over 20 years if considering all cell formats

Table 15. Lithium sulphur cost estimation top-down approach (2030, £2014, compared to NMC)

Component	2030 Adv. NMC	2030 Li-S estimate	Comment
Cathode and anode (£/kWh)	£ 27	£ 11	Sulphur cathode ca. x3 cheaper than NMC (£/kWh) as sulphur active material is cheaper and is needed in a lower quantity. Sulphur anode 25% cheaper, as manufacturing is easier (i.e. no need to coat Li-S anode) **-£16/kWh at the pack level**
Electrolyte (£/kWh)	£ 4.5	£ 4.5	Costs similar for Li-S and Li-ion. Li-S will develop new and more complex electrolytes, but Li-ion will also do, making their costs comparable
Other cell components (e.g. foils, separator)	£ 12	£ 12	Assumed to be equal for both chemistries
Cell voltage (V)	3.8	2.2	Sulphur chemistries support low voltages, and hence will require a higher number of cells
Packing – BMS, wiring, interconnectors, internal cell support (depend on number of cells, £/kWh)	£ 14	£ 16	10-20% higher costs for Li-S packs as a result of a larger number of cells (due to their lower voltages) **+£2/kWh at the pack level**
Packing – power electronics (£/kWh)	£ 12	£ 12	Assumed to be equal, as their costs are dependent on kWh, not in #cells
Packing – housing (dependent on volume, £/kWh)	£ 9	£ 12	35% litres needed per Wh (cell level) for Li-S, assumed to translate in 35% additional housing costs for Li-S **+£3/kWh at the pack level**
Packing – Temperature control (£/kWh)	£ 9	£ 9	Assumed to be equal for both chemistries
Other costs (depreciation, labour, overheads, margin and warranty)	£ 60	£ 60	Assumed to be equal for both chemistries
Total (GBP2014/kWh)	£ 147 (30kWh)	£ 136 (30kWh)	**Li-S has 7% lower costs**

Table 16. Lithium air cost estimation top-down approach (2030, £2014, compared to NMC)

Component	2030 Adv. NMC	2030 Li-air estimate	Comment
Cathode and anode (£/kWh)	£ 27	£ 11	Li-air cathode x3 times cheaper, as there is no need of active material (i.e. it is air taken for the exterior), anode assumed 25% cheaper, as manufacturing is easier (i.e. no need to coat) **-£16/kWh at pack level**
Electrolyte (£/kWh)	£ 4.5	£ 5.5	Cambridge Li-air battery uses anhydrous electrolyte and an additive (lithium iodide, LiI). Assumed premium of 20% **+£1/kWh at pack level**
Other cell components (e.g. foils, separator)	£ 12	£ 12	Assumed to be equal for both chemistries
Cell voltage (V)	3.8	3	3V for non-aqueous electrolyte
Packing – BMS, wiring, interconnectors, internal cell support (dependent on number of cells, £/kWh)	£ 13	£ 18	30% increase in costs as the number of cells increases with lower cell operational voltages **+£4.1/kWh at the pack level**
Packing – power electronics (dependent on kWh, £/kWh)	£ 12	£ 12	Assumed to be the same, as their costs are dependent on kWh and not in #cells
Packing – housing (dependent on volume, £/kWh)	£ 9	£ 9	Similar volumetric densities (1,000Wh/L for NMC and 700-1000Wh/L for Li-air at cell level)
Packing – Temperature control (£/kWh)	£ 9	£ 9	No changes
Other costs (depreciation, labour, overheads, margin and warranty, £/kWh)	£ 60	£ 60	Assumed to be equal for both chemistries
Total (GBP2014/kWh)	£ 147 (30kWh)	£ 136 (30kWh)	**Li-air has 7% lower costs**

Sodium ion

Faradion, the UK sodium ion battery manufacturer, claims that *the total cost of the battery would be around 30-35% cheaper than for a comparable lithium ion battery*[40]. The main advantage of this chemistry over lithium ion is its abundance and cheaper costs (with sodium salts being ca. 90% cheaper than those of lithium) [39], [83], [84]. Additionally, it would benefit from a manufacturing process very similar to those of lithium ion, hence being able to capture economies of scale with the same equipment used for lithium ion batteries [83]. The lower cost, however, would come at the expense of pack energy density, which together with the early stage of development of the technology poses the question whether sodium ion will find a place in the automotive industry, or if instead it will be targeted towards other applications (such as, for example, grid energy storage, where battery size and weight is a lower constraint than for vehicles).

[40] Quote by Faradion's chief technical officer Jerry Barker [83]

6.3 Summary of results

Table 17 summarises the modelling projections presented in this section, along with the literature review findings presented in Section 3 . This aims to provide a snapshot of battery projections by showing the results for the 30kWh BEV pack in the baseline scenario for lithium-ion and post-lithium-ion technologies. Results for further pack sizes, years, scenarios and cost breakdowns are provided in the accompanying battery cost and performance database.

For lithium-ion technologies, the comparison shows that, whilst the packs based on polyanion cathodes appear to have a slight cost advantage, the packs based on NMC cathodes have the greatest energy density. For this reason, and in line with observed industry trends, the results taken forward in the wider modelling framework of the CVEI project are based on the NMC cathodes.

For post-lithium-ion technologies, it has been previously noted that the remaining challenges in reaching automotive performance and durability requirements means it is still uncertain if they will indeed become practical for automotive batteries. Achieving a high power to energy ratio as needed in PHEVs is an additional challenge, so the assumption that these technologies will be adequate for PHEV battery pack is also uncertain. For these reasons, the cost and energy density projections made are used in the 'New battery technologies' scenario, which is used for sensitivity testing only. The projections taken forward for modelling are based on lithium-air, as it achieves the highest energy density. Comparing the theoretical advantages with projected cost and energy density shows that:

- Sodium-ion technologies are limited in terms of energy density and cannot bring improvement over lithium-ion in this area, although they could have a cost advantage. It is anticipated that this technology will be more suited to stationary than automotive applications.
- Lithium-sulphur and lithium-air could indeed bring significant gravimetric energy density advantages over lithium-ion (estimated at up to 50% at pack level), although the volumetric density of lithium-sulphur would remain lower than lithium-ion.
- On the other hand, the theoretical lower cost of lithium-air and lithium-sulphur do not appear to materialise when compared with lithium-ion packs that will have decreased in cost by c.-30% between 2020 and 2030. The modest cost advantage of lithium-sulphur and lithium-air over lithium-ion NMC is based on cost component estimates, i.e. it assumes the same manufacturing costs. This assumption could be seem as optimistic (given that the manufacturing process is likely to be different and thus might not directly benefit from the cumulative learning that lithium-ion packs would have accumulated over several decades), reinforcing the conclusion that post-lithium-ion technologies might bring significant energy density benefits, but not significant (if any) cost benefits.

Table 17 Summary of literature review and modelling results/projections (base case, 30kWh pack, rounded numbers) for comparison

Property		LI-ion (graphite anode, increasing blend of silicon). Cathode type:			Li-sulphur	Li-air	Sodium ion
		NMC	Polyanion	Spinel			
Energy density Wh/kg (pack level)+	2020	145	120	125	N/A – not ready for automotive market		
	2030	205	175	165	270	290	Lower than li-ion
	2050	250	215	200	355	375	Lower than li-ion
Pack cost £/kWh+	2020	215	230	210	N/A – not ready for automotive market		
	2030	150	140	150	140	140	Lower than li-ion
	2050	110	105	115	100	100	Lower than li-ion
Safety/ abuse tolerance		Good	Best of li-ion	Worst of li-ion	Dendrite growth leading to short circuit and H_2S formation if ruptured	Anode dendrite formation issue, electrolyte decomposition	Good. Can be transported totally discharged
Cell voltage (V) [future]		3.6 [3.7]	3.2 [4.4]	3.8 [4.6]	2.1	2.9	3.2
Maturity – tech. BTRL		6			5-6	2-4	5-6
Maturity – manufacturing		Large production (over 300,000 li-ion based light duty EVs sold)			Pre-production cells (1000s cells made in 2015)	Development of proof-of-concept	Very similar to Li-ion. Incremental CAPEX (<1000 cells made so far)
Theoretical advantages over lithium-ion					Cost, higher Wh/kg, cheaper, more abundant and less volatile sulphur	Cost, higher Wh/kg	Cost, safety
Inherent disadvantages over lithium-ion					Low voltage, poor rate capacity, low cycling capability, relatively low volumetric energy density, high self-discharge	High capacity fading, poor rate capability, need of air control, challenging optimisation of cathode design	Lower energy density may restrict their usage to electricity grid applications

+ Projections, as reported in the previous sections, based on a 30kWh pack (rounded numbers)

7 Battery Management System in the context of EVs integration in the electricity system

7.1 Introduction

This section assesses the state of the art for vehicle Battery Management Systems (BMS), and identifies the gaps in the capabilities required to implement the strategies, policy and regulatory frameworks, and commercial arrangements identified in WP1a for the integration of EVs in the electricity system.

In addition to the identification of areas of improvement and new capabilities in the BMS itself, this section also comments on other components and capability gaps for the integration of electric vehicles in the electricity system (defined below). To this effect, communication flows between the car, the electricity system and the user, or standardisation of communications, are explored.

7.1.1 EV system integration

To understand the future capability requirements of Battery Management Systems and broader vehicle communications and data flows, it is important to define the types of interactions that plug-in vehicles are likely to have with the electricity system. Table 18 presents the different EV system integration levels that will be considered in this section, their basic characteristics and parameters in terms of how often the response is required/provided, what type of incentive or price signal is provided (i.e. Time of Use tariffs or direct payments), what reliability of response is expected and whether they do or do not change with time. It also differentiates between integration through:

- User managed charging realised through time of use (ToU) tariffs (typically through the electricity supplier) – summarised on the left side of the table.
- Supplier managed charging (provision of grid services) – summarised on the right side of the table. These are referred to as 'Grid to Vehicle' (G2V) when the power flow is from the grid to the vehicle only, and 'Vehicle to Grid' (V2G) when the power flow is bi-directional. Although V2G services are not the primary focus of analysis in WP1, they have been considered here as they potentially affect the capability requirements for managed charging.

In practice, grid services are a form of managed charging for EVs, the difference being in the contractual route and the level of response of automation in the integration. Grid services refer to balancing mechanism National Grid contracts to generators or large users (generally through aggregators in the case of users), such as frequency control, Short Term Operating Reserve etc. Services have different response times and minimum capacity requirements as described in Table 41 in the Appendix. EV integration into the electricity grid is expected to proceed through contracts with aggregators to meet the minimum capacity requirements. However, the time of response needs to be ensured by the use of appropriate hardware and protocols, i.e. both the EV on-board charger and the charging point communication controller should comply with the standardised protocol. Software that is compatible with such a protocol should be installed in the EV, at the charging point and on the grid side (e.g. in the hardware allowing power back into the grid).

Table 18. EV system integration levels in scope for this report

Category	User managed charging		Supplier managed charging - grid services	
	Static	Dynamic	Grid to Vehicle (G2V)	Vehicle to Grid (V2G)
Frequency	daily/always		on demand, generally with requested minimum availability windows	
Payment	reduced electricity bill		direct payments or reduced electricity bill	
New contract in place?	No, usual relationship with electricity supplier (and/or via OEM app)		Contract with aggregator that in turn has a contract with National Grid (or a DNO) or no contract seen by end user e.g. interface with car OEM or electricity supplier only	
Implementation options	Static Time of Use tariffs	Dynamic Time of Use tariffs	Dynamic Direct Control, with EV owners having control over windows of time offered[41]	
	Indirect management (i.e. user free to respond or not to price signals)		Control time, duration and/or charge rate	As Grid to Vehicle plus power from battery is fed back to the grid

7.1.2 Structure of the section

Sub-section 7.2 focuses on current capabilities: it provides a review of current BMS capabilities and current options available for the integration of EVs in the electricity system.

Sub-section 7.3 reviews the capabilities needed for the realisation of an integrated demand management system, focusing in turn on the BMS and data flow requirements (between EVs and the different actors of the electricity system).

In sub-section 7.4, related on-going demonstration projects are summarised to show to what extent the identified needs are in place, in development or not studied yet. This section also maps other R&D projects relevant to the identified gaps, and provides a list of funding opportunities for new work.

Sub-section 7.5 lays out recommendations for new research projects to address the identified gaps related to BMS and the integration of EVs into the energy system.

7.2 Review of current BMS capabilities and current EV integration in the electricity system

The battery management system is the set of electronic components that monitors and controls the battery. It monitors the state of health and state of charge of the battery, measuring and controlling key parameters to ensure a safe battery operation and implements a cell balancing strategy. The main functions of the battery management system are to protect the battery and cells from damage, to

[41] Although National Grid controls the window of time for grid services, it is expected EV users will be given the option by aggregators to opt out on certain day/times. It will be for the aggregators to manage their ability to respond to National Grid demands, e.g. through enrolment of a large number of EVs and incentives for EV owners to participate in managed charging.

prolong the battery lifetime, to ensure that battery state is fit for the application purpose and to interface with the host application.

Figure 1 (page 13) presents the main BMS components as part of the battery pack, and a more detailed overview of its components and functions is shown in Figure 30. The temperature and voltage sensors in the slaves located in each cell module are connected through wiring harnesses to the master electronics. The Master centralises the monitoring of different parameters and, through communication ports, interacts with the end application, i.e. the vehicle's energy management system, the motor controller etc. The boxes "Customer Interface" and "Diagnostics" in Figure 30 refer to this part of the BMS functionality. A simple set of data (SOC, temperature) is passed on through the customer interface, while more advanced cell level data is communicated through the diagnostic port.

The BMS architecture, as in how cell modules, slave and master controls are laid out, can vary but does not influence the vehicle's demand management capabilities. The general trend is to improve reliability and reduce wiring by transitioning to the "daisy chain" BMS structure, where each of the slave units are connected in series to the master or offer wireless communication to the master.[42] Some companies like Dukosi are working on a BMS which is embedded in every cell to monitor temperature, voltage and current, make SoC and SoH calculations and provide protection to the cell. The system is also wireless; the cells communicate to each other and to an interface board which in turn communicates with the host vehicle. This system would remove a large proportion of the wiring, reducing BoM cost and assembly time. It also gives the cells a known history or provenance which is useful for second life applications and improved security against non-original equipment.[43] These trends are driven by cost reduction and reliability, not by grid integration requirements.[42,43]

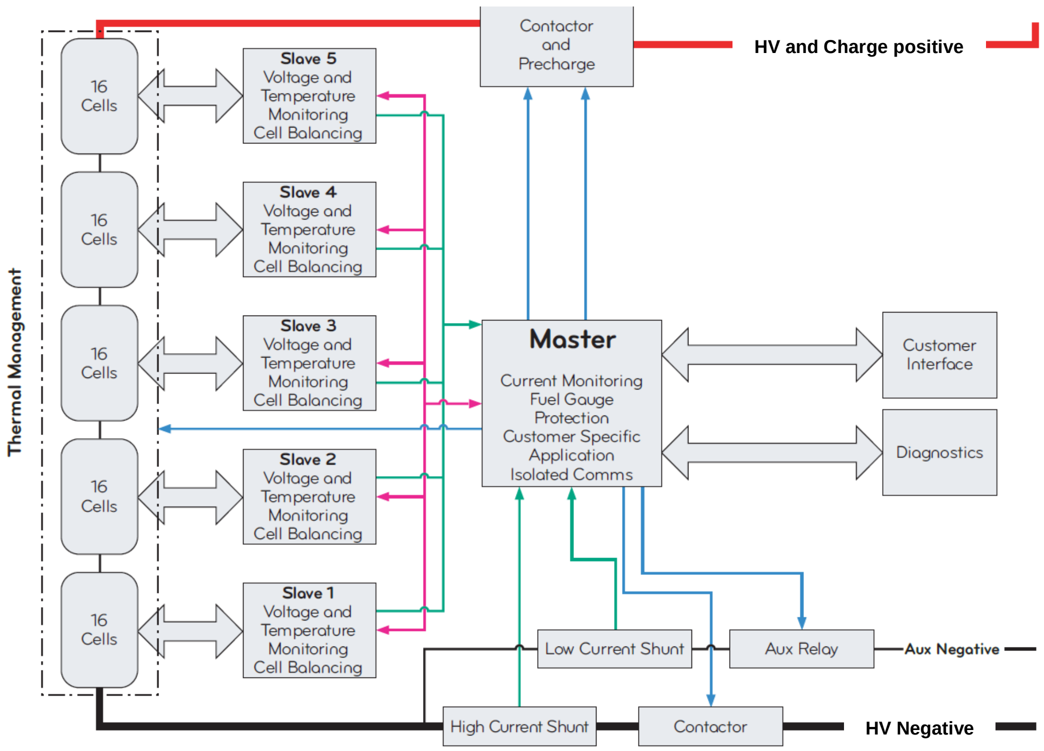

Figure 30. Schematics of a typical BMS. The figure originally provided by and reproduced with the permission of Johnson Matthey / Axeon, it is the copyright of Johnson Matthey Battery Systems [2][44]

[42] Based on the discussion with Johnson Matthey
[43] Based on the discussion with Dukosi
[44] Notes: fuel gauge = state of charge; wiring colours are used for better visibility only. HV stands for high voltage

7.2.1 BMS capabilities

Figure 31 presents the capabilities of a battery management system. The monitoring and evaluation of certain parameters guarantees safe operation of the battery, while the capability of cell balancing ensures an optimal cell performance. Communications between the BMS, the vehicle and the rest of the battery pack are also enabled. These capabilities are commented on next.

Monitor

- Cell temperature
- Cell voltage
- Load current
- Serial number (for cell localisation)

Retrieve & evaluate

- Cell and pack performance
- State of charge, state of health
- Internal impedance
- Dis/-charging cycles
- Log and retrieve history, including history before connection to the BMS

Cell balancing

- Dynamically re-balance the pack (in terms of cells state of charge) according to a specific algorithm

Safety assurance

- BMS monitors key indicators linked to control actions (e.g. cooling or power disconnect)

Additional safety through:

- *Cell level safety devices*
- *External circuit devices*

Communications

- Between:
  - BMS and the vehicle (the vehicle's energy management system, the motor controller)
  - BMS and the rest of the battery pack

Figure 31. Overview of BMS capabilities

Monitor and Retrieve & evaluate

Monitoring of the cell parameters (temperature, voltage and current throughput) is realised by the sensors installed in each cell. This information is passed from the sensors to the monitoring unit that evaluates the required data.

Typically, the number of cycles is determined by integrating the current flow over time. Parameters such as number of cycles, maximum and minimum voltages, temperatures and maximum charging and discharging currents are recorded and stored in the "Log Book Chip" for subsequent evaluation [85].

An essential function of the BMS is to calculate the SOC and the SOH of the battery. While SOC normally is estimated in real time, SOH sampling intervals may be as low as once per day depending on the evaluation method [85]. The BMS also contains a memory block for holding all the reference data and for accumulating the historical data used for evaluating the battery SOH and other parameters. Storing the information on SOC enables calculation of the number of full equivalent cycles at any point in time. The SOH and SOC of the battery calculated by the BMS provides the reference points for triggering control actions, e.g. dumping excessive regenerative braking charges when the battery is fully charged.

Recording the cell history (from conditions experienced before being connected to the BMS, such as temperature, SOC profiles and manufacturing test results to history while in use in the vehicle) would be useful to inform both the cell management strategy and maintenance/replacement strategy, as well as supporting a second life (by providing evidence of state of health and thus value of the cell)[45]. This

[45] Logging the battery history can also be useful for the continuous improvement process. Most automotive companies use "birth history" results logged against serial numbers to trace components and facilitate configuration management. This is useful for condition based monitoring and post-manufacture investigations like recalls. The in-process test waveforms (for example, leak detection tests, voltage, current etc.) are stored against serial number.

is an area cell OEMs are working on, based on conversations with Dukosi, a UK-based developer of cell level technology allowing recording of the complete cell history.

Safety assurance

It is through the measurement of a reduced number of key parameters (i.e. temperature, voltage and current) that the State of Health and State of Charge of the battery can be evaluated, and that the BMS can trigger control actions implemented by the Energy Management System (EMS), such as cooling, reduction in/termination of power demand or termination of charging to ensure the safety of the system. The development of these control systems is carried out by each BMS OEM (i.e. there is no standardisation), as different cells with different sensitivities require different approaches. However, the fundamental underlying principles are the same for the different solutions. The only case where the BMS exerts direct control over the battery output (as opposed to only pass on the monitoring data to the EMS) is in case of a severe safety situation that requires a power disconnect to protect the battery from irreversible damage (and/or thermal runaway). Warning messages would typically be sent out to the driver through the EMS so action can be taken (e.g. pulling to the side of the road). The level of control given to the user versus protecting the battery varies across car OEMs, and there are no regulations or protocols to dictate how the trade-off should be made.

The BMS also enables safe charging. **Lithium-ion batteries** charge at constant current then constant voltage once the maximum voltage has been achieved, with the current falling towards zero[46]. Charge algorithms use data monitored by the BMS (the SoC, temperature and SoH of the battery) to determine the best profile: i.e. if the battery is cold it may charge more slowly until the cells heat up, then increase the charge rate. It can also reduce the charging current near the top of charge to protect the cells. Although **Na-ion batteries** are still at relatively early stages of development, the operation principle of these batteries is very similar to Li-ion batteries and therefore the same charging strategies should be applicable.

The information on particular charging strategies for the **post Li-ion battery chemistries**, such as Li-air and Li-S, is limited by the early stages of development of these technologies. However, on a fundamental level, there are a few considerations that may affect the relevant BMS functionality in these systems. Specifically, a decreased rate of charging at low temperatures is implemented in Li-ion batteries to prevent Li plating on the carbon anode [85]. This is not relevant for Li-air and Li-S batteries, as Li metal is used on the anode.

Cell overcharging is a major safety hazard in Li-ion cells as it can lead to dendrite growth leading to cell short-circuiting and thermal runaway, or equally it can cause the formation of unstable oxides on the cathode that also lead to thermal runaway [78], [86]. Both of these issues are not relevant for Li-air and Li-S because of the self-passivation reactions upon overcharge [87], [88]. From that point of view, the charging algorithms for Li-air and Li-S may be simplified compared to Li-ion cells. On the other hand, controlling the rate of charging/discharging and the depth of discharge is still relevant for Li-air and Li-S batteries for safety reasons. Li-metal electrodes are known to be prone to dendrite formation due to uneven current distribution, particularly at high charge/discharge rates [89]. Equally, operating at low depth of discharge was shown to increase the cycle life of a Li-air battery [45]. Monitoring the temperature is also important to keep the electrolyte and Li metal at safe operating temperatures.

[46] The charge algorithm for Nickel-based chemistries is different from Li-ion. Typically, these are fast charged initially (at ca. 1C). When reaching a certain voltage threshold, a rest of a few minutes is added, allowing the battery to cool down. The charge continues at a lower current and then applies further current reductions as the charge progresses. This scheme continues until the battery is fully charged [150]. The lead acid battery on the other hand should be charged in three stages, which are: constant-current charge, topping charge and float charge. During the constant-current charge, the battery charges to about 70 percent. The remaining 30 percent is filled with the slower topping charge. The float charge in the third stage that maintains the battery at full charge [151].

Besides the controls triggered by the BMS evaluation of state of health, there are other safety mechanisms that would be triggered if the BMS failed to act or if a sudden event happened (i.e. vehicle accident). These are hardware based, at cell level or external circuit devices. Cell level devices consist of current interrupt devices (that electrically disconnect the cell in case of excessive internal pressure), shut down separators (they might be able to shut their pores in the case of a thermal runaway and are designed to prevent short circuits), pressure vents and flame retardant covers. External circuit devices are resistor-based devices and switches that protect against over-current, fuses and cell isolation to prevent event propagation[47].

Safety is also introduced by vehicle design, the pack being located outside the passenger compartment (e.g. under the floor) and behind the vehicle forward bulkhead (i.e. not in the engine compartment which is part of the crumple zones of the car) [2].[48] Figure 32 presents a summary of battery safety design.

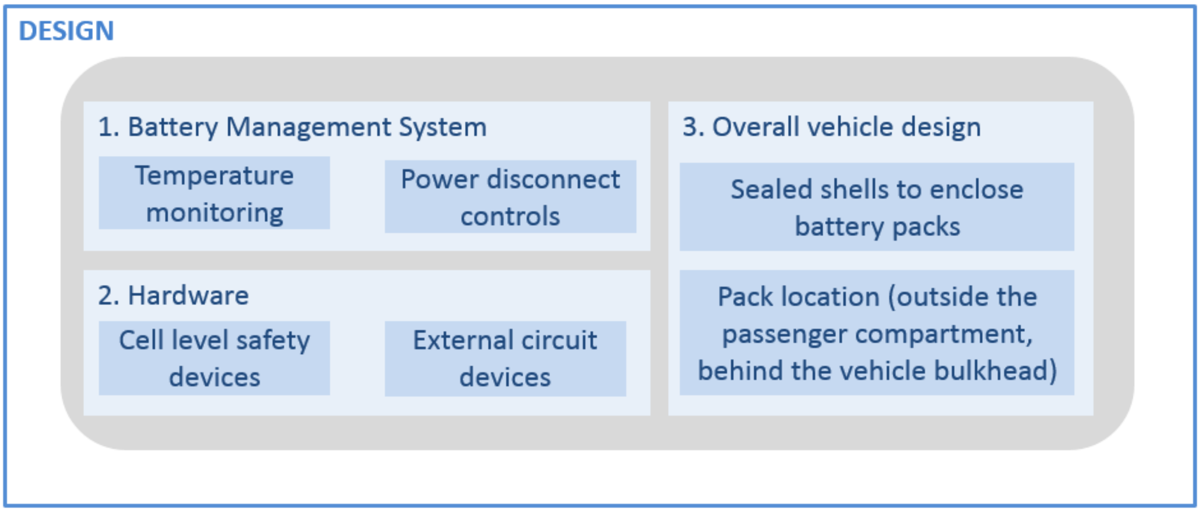

Figure 32. Battery safety design

Cell balancing

Ideally, all the cells in a pack would have the same electrochemical behaviour (i.e. the same internal resistance). However, in practice there are slight variations between cells arising from the manufacturing process, which are also dependent on other parameters such as temperature or age. The implication of unbalanced cells is that they might reach the full state of charge or discharge sooner than others in a given string causing premature termination of the charging process, subsequently reducing the usable capacity of other cells below their real practical limit. For this reason, cells are managed by balancing their SOC operational window to maintain optimum pack performance. Cell balancing is dictated by algorithms that, for example, might trigger the dissipation of small amounts of energy in particular cells in order to balance the cell potentials across the entire pack (passive balancing), and hence optimise pack capacity. In active balancing, energy from overcharged cells is transferred to undercharged cells.

Communications

The BMS communicates with the vehicle through a vehicle interface, where the information is typically transferred by CAN-BUS, an automotive standard communications protocol [2].

[47] Note regarding transients (momentary fluctuations in voltage): these would not affect the BMS nor the cells, which work on DC only. Transients are filtered out outside of the battery pack, by an inverter circuit in the vehicle charger or between the battery and the grid.

[48] Part of the bodywork that is located below the windshield and separates the driver from the engine compartment

Communications between the BMS and the rest of the battery pack are typically through RS232 and RS485 protocols that can also be used for engineers to communicate with the battery externally [85], [86]. Additionally, OEMs and Tier 1 suppliers are developing proprietary protocols.

As discussed previously, BMS developers are working on wireless designs. These might use proprietary communication protocols (this is the case of Dukosi, who has a patent for this[43]), wireless local area network ('wifi'), less energy consuming protocols such as Near Field Communication protocols, or other short distance communication protocol e.g. Zigbee.[42]

Communication flows for EV integration in the grid are discussed in Section 7.2.3.

7.2.2 EV system integration: market overview

A summary of the charging control capabilities that are currently being offered by car OEMs to EV owners through apps is presented in Table 19. Some of the features are enablers of a good integration of EVs in the electricity system, such as the ability to set the charging time, to charge remotely, to turn on climate control remotely or to view the battery charging status – although EV drivers might use these to set charging to a time convenient for them, without consideration of grid impact, e.g. if no advantageous tariffs are in place. These features are offered by all the main EV OEMs.

On the other hand, more advanced features that further automate the integration of EVs in the electricity grid are currently offered by only a limited number of OEMs. These include the optimisation of charging based on household consumption and/or on the maximisation of the use of in-home produced renewable electricity. In this case, the charging point in combination with a smart home system are the key components that enable those capabilities. A detailed description of the capabilities offered by some of the OEMs is presented after Table 19.

Table 19. Summary of current EV system integration and 'smart' capabilities

Function / Product	Set charging time	Start/stop charging remotely	Turn on climate control remotely	View battery charging status	Optimised charge based on household consumption	Optimised charge to use home renewables	Control charge times based on electricity cost
Allows EV integration in energy system?	Indirectly, by giving user control over charging time and information needed to take decision on this (state of charge)				Yes, these functions optimise the integration of EVs either for local system to automatically answer price signals		
BMW i Wallbox Remote App	No	Yes	Yes	Yes	Yes	Yes	No
Nissan Connect EV	Yes	Yes	Yes	Yes	No	No	No
Tesla Motors beta App	Yes	Yes	Yes	Yes	No	No	No
VW CarNet App	Yes	Yes	Yes	Yes	No	No	No
Renault Z.E. Services App	Yes	Yes	Yes	Yes	No	No	Yes (new App; on trial)*
Chevrolet MyVolt / OnStar RemoteLink	Yes	Yes	Yes	Yes	No	No	Yes

*New app will be available for Dutch users in the first half of 2016

BMW i Wallbox Remote App

The display shown on the App is also presented on the Wallbox charging point. The overview window shows:

- *Smart Home*: if active, it controls domestic energy and load management so that energy can be used more efficiently. It requires the installation of an energy meter in the charging point and of a smart home controller that centrally controls several loads (such as 'Mygekko').
- *Load management*: when there is a threat of overload at the household level, the charging current to the vehicle is reduced and the required power output is made available to the household so that the triggering of the fuse is avoided. An energy meter must be installed in the charging point.
- *Domestic energy:* on-site generation sources (e.g. solar panels) must be connected to the energy meter. Two charging preferences can be set:
    - Charging with maximum charging current, where charging is set under that condition, even when there is not enough domestic energy available: the charging starts as soon as the vehicle is connected to the charging point.
    - Charging with maximum domestic energy, which enables prioritisation of the use of on-site production in a pre-set time window.

Figure 33 presents the schematics of the information and electricity flows in the services offered by BMW i Wall remote Application.

The most evolved capabilities (i.e. the optimisation of charging based on household consumption or on the maximisation of the domestic energy consumption) are enabled through the charging point, in which an energy meter has been embedded, and a smart home controller, centralising the control of the different household loads and generation sources.

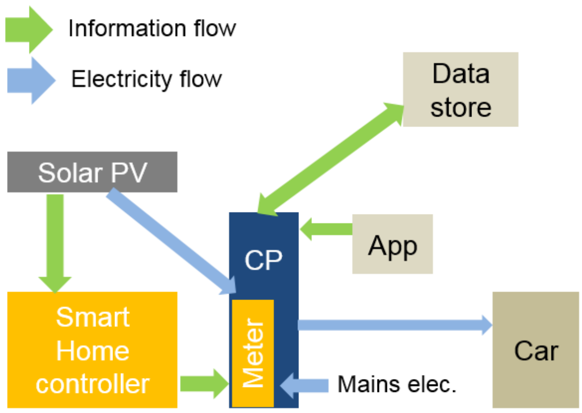

Figure 33 Schematic of BMW i Wall Remote App. Com flow when charging is scheduled to maximise consumption of self-generated electricity and to avoid overloads

Renault Z.E. Services App

A new application allowing charging when electricity is cheapest is being developed by Renault in collaboration with a Dutch utility, and it is currently being trialled in Germany by 11 ZOE users [87]. **Figure 34** presents the component and communication flows underpinning the service. The car communicates its charging status via a Renault Global Data Center to The Mobility House (TMH, a smart charging point provider) management platform, which schedules the vehicle charging in order to minimise the electricity costs. TMH provides dynamic electricity tariffs through the acquisition of electricity 24 hours per day through a power exchange partner. The charging point then receives the charging schedule and implements the orders accordingly.

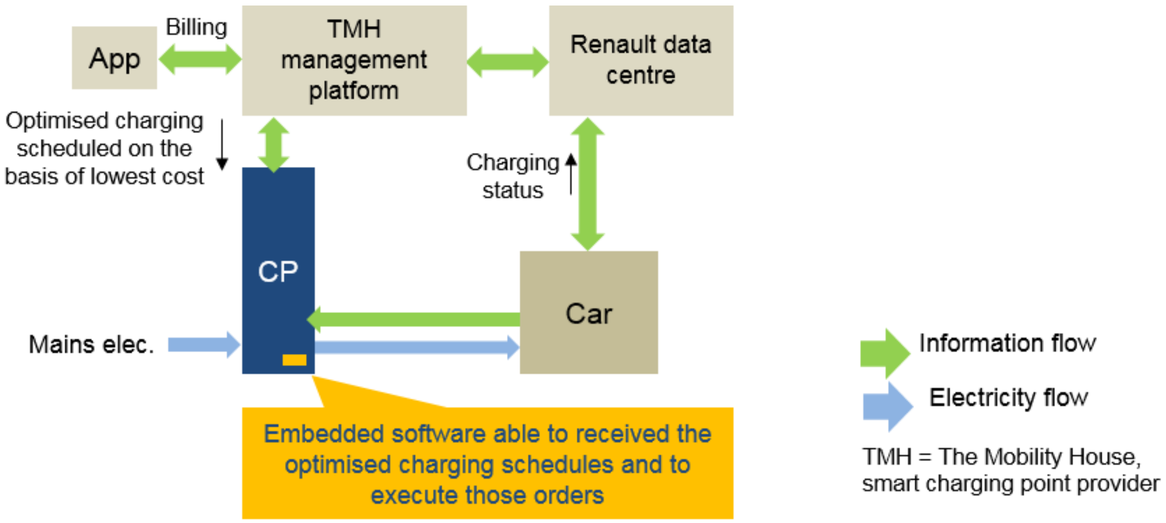

Figure 34. Schematics of Renault Z.E. services new App: charging scheduled to coincide with the periods of lower electricity costs

7.2.3 Communication flows

For the integration of electric vehicles in the electricity system communications between the different components of the system have to be enabled.

Between car and electricity system

Figure 35 presents the communication flows between the car and the electricity system[49]. The charging point acts as the main interface between both, thus becoming critical for the system integration of EVs, while the BMS guarantees the battery safety and optimum performance, and does not have a role as a linking point between the car and the electricity system.

The detail of the schematic shows that the BMS communicates to the charging point through the Energy Management System (EMS), which subsequently communicates with the on-board charger, the final connection to the charging point. At the moment, the frontend communication (i.e. between the EV and the charging point) proceeds through signalling defined by the **IEC 61851 standard**.

A bidirectional IP-based communication protocol defined by the **ISO/IEC 15118** standard is designed to allow for an active load management through EV feedback [88]. However protocol development based on the ISO/IEC 15118 standard started in 2009 consists of five stages, two of which (network and application protocol conformance test, and physical layer and data link layer conformance test) are still under development [89]. The backend communication (i.e. between the EV and the electricity system) is not in the scope of ISO/IEC 15118. There is no standard communication protocol to allow the charging point to read the EV battery parameters either, and different hardware and communication types can be observed across the industry.

The **IEC 61850** standard focuses on grid automation and was proposed as a core standard for the backend communication. However, basic functionality for charge point operators, like authenticating a user who wants to charge at a charge point is missing, because it was considered out of scope of IEC 61850 from the beginning. Thus another standard is required to address the business domain of charge point operators and fulfil the requirements such as authentication and authorisation, transaction handling and reservation of a charge point [88].

[49] Extra hardware that might be needed for EV integration e.g. smart meter is not shown on this schematic that focuses on communication flows between the car and the electricity system

To address this issue, the Open Charge Alliance announced in November 2015 that it had chosen to standardise the **Open Charge Point Protocol (OCPP)** and to align it with IEC 61850 for the backend communication. This will also be harmonised with ISO/IEC 15118 used for the frontend communication [90].

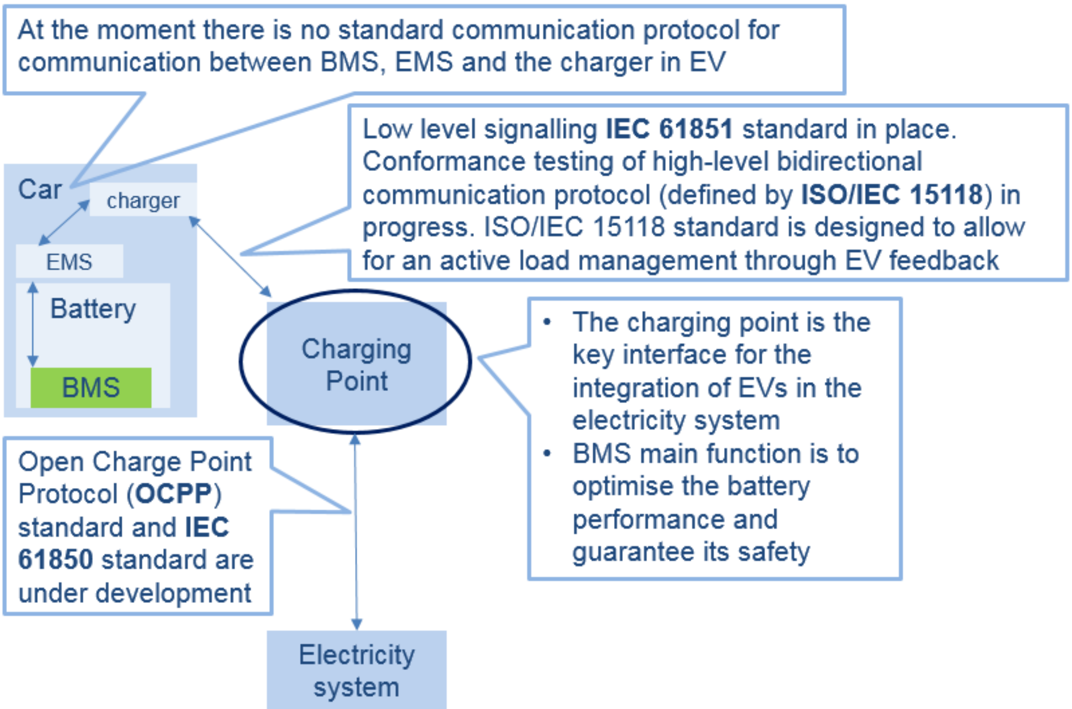

Figure 35. Communication flows between the car and the electricity system

Between car and user

Figure 36 presents the communication flows between the car and the user. At the moment, there is some standardisation in these communications, but it seems likely that the communications for advanced features will differ among OEMs. Nissan uses a SIM card to establish the communication between the mobile phone application and the car, and there will be a transition from 2G to 3G in the next Leaf generation. In addition to SIM cards and 2G, other OEMs are using additional paths (e.g. Renault Zoe uses GPRS). There are no special commands or protocols between the cars and the applications, just an API window through the server.

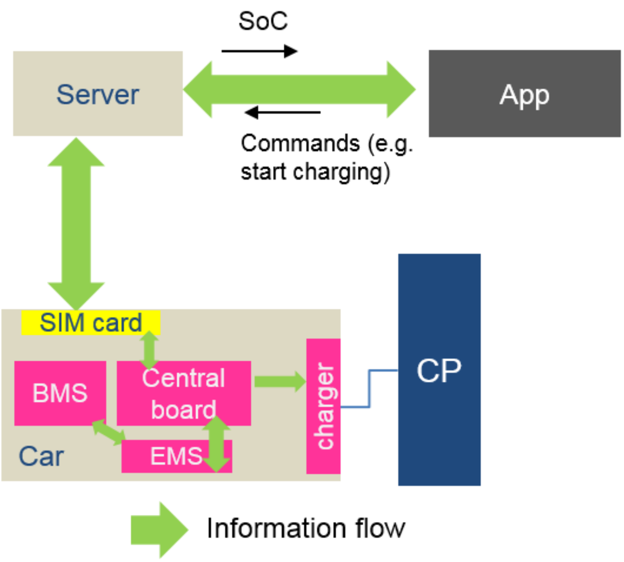

Figure 36. Typical communication flows between the car and the EV owner

7.3 New capabilities needed in an integrated Demand Management System

The previous section presented the BMS role and capabilities, the current products/interfaces in place to help EV owners control the charging of their vehicle, and the corresponding communication flows.

In this section, the capabilities needed for the integration of electric vehicles into the electricity system are explored. Figure 37 presents a high-level schematic of the communication flows between the different actors of an integrated EV world. For completeness, the diagram shows the 'customer engagement' and 'connected car' topics, but these are not explored in this study.

The BMS role in this integrated system is highlighted in red, namely it monitors/calculates the State of Health and State of Charge (and ensures safe use of the battery). As such, the BMS will influence the rate of charge/discharge and the decision to start/stop charging, and a reliable and accurate BMS is therefore required for efficient integration of electric vehicles into the electricity system.[50]

The figure also shows that the BMS is not the only interface for the integration of EVs in a central system. For this reason, future BMS capabilities and future requirements for broader vehicle communications are considered jointly in this section.

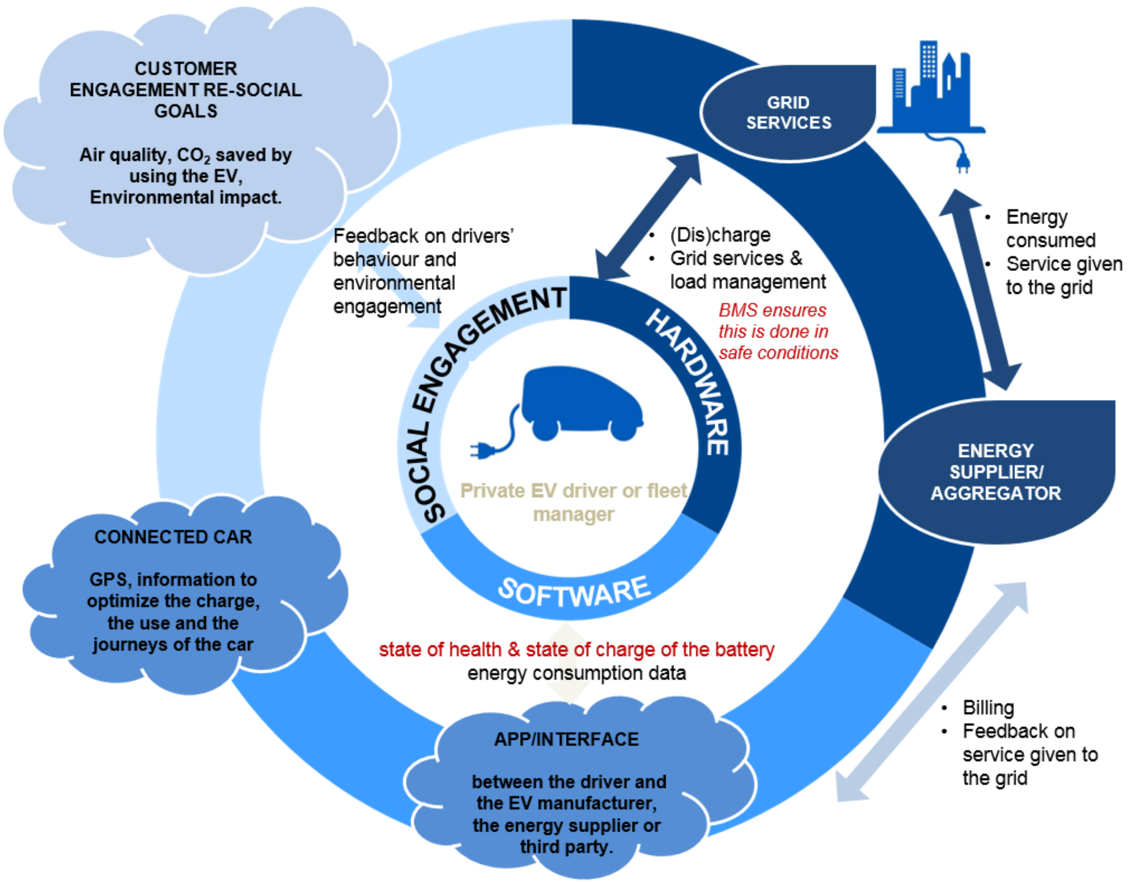

Figure 37. A high-level schematic of the communication flows between the different actors in an integrated EV system

[50] Note on reactive power: as reactive power is on the AC circuit side while the battery and BMS work on DC, providing reactive power would never be done off an automotive battery/BMS. The on-board charger or charging point could include a voltage converter circuit. Such circuits can adjust injection of reactive power to the grid by controlling the magnitude and phase angle of the voltage generated by the inverter [152]. In the case of DC charging (typical of 50kW+ charging rates), the injection of reactive power into the grid would need to be done by an inverter circuit within the charging point.

7.3.1 New capabilities and improvements in the BMS to enable an integrated demand management system

Figure 38 presents the new BMS capabilities and improvements identified for the integration of EVs into the energy system and to improve the battery safety, performance and cost [91], [92].[51] The three main BMS capabilities required in order to enable EV system integration are: (a) real-time State of Health (SOH) monitoring, (b) the ability to predict capacity loss and (c) to identify abnormal performance trends.

If V2G services are deployed, the BMS would additionally need to recognise specific V2G discharge profiles and trigger the appropriate controls through the EMS, e.g. to prevent overheating during continuous discharge at constant current[52]. As visibility of the state of development across EV OEMs is limited, it is not clear to what extent these capabilities are already implemented/in development. Although this information may not be publicly available, the progress in ISO/IEC standardization of the interface for grid services may be a proxy for up to date information on BMS functionality development. For example, the functionality for capacity reservation supported by the ISO 18115 standard for vehicle to grid communication assumes that the BMS in the EV should be able to accurately determine current SOC and the maximum capacity based on the vehicle SOH. Other technical developments that have been identified are the creation of techniques and models to improve the estimation of state of health and state of charge in cells and packs, and improved thermal management.

If participation in managed charging and grid services has a negative impact on battery SOH, then the car/EMS (based on data provided by the BMS) needs to accurately assess the effect of any managed charging scenario on the battery, potentially making a decision not to participate if the economic benefit did not exceed the increased battery degradation.

This additional decision making capability may not be required if car OEMs pre-decide on the option to participate in managed charging. This is already the case to some extent, with car OEMs offering customers ways to automatize the charging decision (as presented in 7.2.2). Nissan is also ready to rollout vehicle to grid services without an impact on the warranty they offer on the battery (discussed in more detail later).

However, particular managed charging strategies can impact ageing of the battery as discussed in detail in Deliverable D3.2 – Battery State of Health Model report, section 2.6.1 [93]. For example, E.ON has previously conducted research that analysed the sensitivity of PHEV batteries to the SOC in the context of controlled and uncontrolled charging, and concluded that uncontrolled charging leads to a higher average SOC and therefore an increase in the degradation rate [94].

The managed charging trial to be conducted in Stage 2 of the CVEI project will provide real world battery usage profiles under managed charging and will allow a better assessment of the possible impact on SOH and battery degradation cost. This will inform the decision whether or not to embed an 'economic decision making algorithm' in the car, as opposed to e.g. an ability to enter or not into different managed charging configurations pre-programmed by the car OEM.

[51] Partly based on discussions with Johnson Matthey and the review of on-going EU projects
[52] This is also true for the case of 'vehicle to home' where the energy from the battery is used to power up a house and/or take power from the local micro generation.

New BMS capabilities

Objective: enable EV system integration

- live state of health reporting for real-time optimisation of charging
- advanced reporting of state of health to allow prediction of availability for demand management services
- BMS algorithms (e.g. that allow the BMS to distinguish the normal aging and performance trends from those that are unusual)

Objective: safety, performance and cost optimisation

- transition from BMS at the pack level to the cell level, allowing cost and weight reduction (e.g. SMART-LIC project)
- Transition from passive to active battery balancing (to improve safety features and capacity available)
- Security against fake cells (e.g. as the brand recognition in printer cartridges)

BMS technical developments

- Techniques for improved state of charge, state of health, fault and temperature estimation in cells and packs
- Models for improved estimation of state of charge
- Improved thermal management
- Battery history (i.e. keep log of how cells have been used)

Figure 38. New BMS capabilities and technical improvements for the integration of EVs in the energy system

About the State of Health calculation

Even though the accurate estimation of the SOH is crucial for battery safety and charging/discharging routine optimisation, there is no current consensus in the industry on how it should be determined. In general, the SOH can be estimated either by [92], [95]:

A. Predicting variations in capacity on the basis of previous measurement and simulation of the physical processes responsible for degradation, i.e. employing a battery lifetime model.
B. Measuring current battery parameters and linking them to the SOH.

In terms of on-board operation, the disadvantage of the lifetime model approach (approach A) is high complexity. High accuracy models require high processing power and data storage capacity currently offered only by supercomputers. Therefore, these are unlikely to be deployed for on-board diagnostics in the foreseeable future. For applications where a first order estimate of SOH is required (e.g. to make a financial decision), a semi-empirical approach that also fits in the lifetime model category but does not require high computation power may be sufficient. Although this approach is not suitable for on-board usage due to several limitations (refer to Deliverable D3.2, State of Health report for details), it offers a high degree of flexibility in terms of modelled parameters and is therefore suitable for investigating the feasibility of the ways of integrating EVs into the wider electricity network. A semi-empirical Excel-based model relying on the calculation of cycle damage and calendar damage for SOH estimation has been delivered as part of the ETI CVEI project (Deliverable D3.2).

Approach B does not rely on complex simulations and is more suitable for on-board diagnostics. The research gaps in SOH determination suggest two principal directions for BMS development:

1. The first option, pursued by some companies and academic groups, is to focus on installing advanced rapid-test equipment, e.g. for EIS analysis on-board or to employ advanced diagnostic techniques [96], [97].
2. The second option is to develop new methods of estimating SOH from basic measurements of temperature, voltage and current already performed by BMS.

A widely used advanced diagnostic technique (option 1) to monitor degradation processes in batteries is Electrochemical Impedance Spectroscopy (EIS), which allows measurement of the internal resistance of the battery and assignment of different components to individual physical processes [98]. However, the EIS equipment requires expensive high precision components and therefore is not part of a typical BMS. As a minimum, EIS capability requires a printed circuit board with operational amplifiers and a microcontroller connected to data logging channels (for each cell) capable of sampling at up to 10 kHz. Even assuming high volume manufacturing, this could substantially increase the cost of BMS. Therefore, the alternative approach (option 2) of relying on simple measurement techniques is often pursued.

A novel diagnostic technique, termed differential thermal voltammetry, is capable of monitoring the state of the battery using voltage and temperature measurements alone (option 2) and does not require information on the battery history [99]. The technique relies on the fact that battery electrodes undergo phase transitions at certain potentials. These phase transitions cause changes in the entropic heat and can be monitored with simple thermocouples. As the battery ages, Li inventory loss causes the phase transitions to occur at slightly different voltages. Therefore, simultaneous monitoring of temperature and voltage allows tracking of battery SOH in real time and is suitable for on-board use.

Diagnostic techniques capable of SOH estimation that rely on the measurements already performed by state-of-art BMS are most attractive from an economic standpoint and therefore are likely to dominate in the near future. This approach is assumed for battery pack projection costs submitted with this report, in line with the assumptions used by ANL in their modelling the performance and cost of Li-ion batteries for EVs [4].

7.3.2 Data requirements for integration of EVs in the electricity system

Table 20 presents the data that aggregators (or utilities, or vehicle OEM smart phone apps in the case of managed charging) require from the electric vehicle in order to provide grid services. It is also worth noting that aggregators are allowed to refuse to respond to a demand of service a limited number of times per year, without breaching their contract with National Grid. That number might prove impractical in the case of EVs and National Grid might need to become more flexible for EVs in order to provide these services. This contractual limit might also mean that aggregators will have to develop ways to communicate with EV owners, e.g. to nudge or incentive further EV owners that are not opting in managed charging events often enough (and are thus putting the aggregators at risk of breaching their contract with National Grid).

The need for data on the length of time the EV is plugged-in (4th row in Table 20) is related to the contractual terms of the services provided to the grid. Some services must be provided for a minimum amount of time, therefore aggregators will need to be able to predict charging duration with a good level of accuracy. Contracts between public CP network operators and aggregators to detail availability windows might be needed if charging times prove too unpredictable/variable. Such contracts between EV owners and aggregators are not expected to be acceptable for the EV owners, and hence ‘softer’ measures such as price signals tied to leaving cars plugged in for longer may be needed to encourage the desired charging behaviour.

Table 20. Electric vehicle data requirements for contractual integration of EVs in electricity system

Data	Comment	Status of development
Battery SOC when connecting	• Calculated by the BMS	• Work in progress to increase the accuracy of the outputs
Charge rate available	• Linked to car charger limits as well as SOH • SOH calculated by BMS	• Work in progress to increase the accuracy of the outputs
Duration of the period when EV is plugged-in	• Contracts between EV owner (or public CP network operator) and aggregator needed (e.g. detailing availability windows)	• Not available at the moment but time spent at home is regular and predictable. On this basis Nissan is to offer V2G capabilities for frequency regulation to UK Leaf owners from 2017 from home charge points (see section 7.4.1) • Enabling technical solutions under development for public CP (e.g. analysis through satellite navigators)
Time the car needs to be fully charged by	• EV owners can already interface with their car through provided apps.	• Links between OEM apps and aggregators to be established or new apps to link EV owner and aggregator to be developed

Table 21 presents the data that aggregators (or utilities in the case of managed charging) require from the charging point to provide grid services, as well as the data needed by the charging point.

In the next section, recent and current EV integration demonstration projects are reviewed, to show to what extent solutions to communicate the identified data requirements have been developed.

Table 21 Charging point data requirements for contractual integration of EVs in electricity system

Data	Data from - to	Comment	Status of development
Degree of charging point intelligence	From charging point to aggregator	• 'Dumb' vs 'smart' charging points: charging modes 3 & 4[53] allow 2-way data communication and hence smart charging • The OCPP is the most widely used 2-way communication protocol	• Virtually all newly installed public and home charge points are mode 3 or 4 • At depots, some users might choose simpler/dumber hardware (mode 2) • Current OCCP is v1.5, OCPP 1.6 under development • Open Charge Alliance has chosen to standardise OCPP
Rate of battery (dis)charge and ability to communicate	From charging point to aggregator	• Slow (3kW), fast (7-22kW) or rapid (40kW+) rate – not all EVs capable of all rates	• Not all charging points are able to communicate what is the maximum combined (dis)charge rate of CP and car
Grid frequency - for frequency response (FR) only[54]	At the charging point	Electricity grid frequency needs to be locally measured at the charging point[55]	• At the moment the hardware to measure grid frequency is not embedded in charging points and only provided by specific suppliers (e.g. Ecosynergy)
Availability of the capacity on the local grid to (dis)charge the battery	From DNO/ aggregator to charging point	Grid to Vehicle and Vehicle to Grid services require two-way communication of system needs/ customer ability to respond in real time	• No technical barriers. Several commercial aggregators exist with the relevant communications in place • The challenge is on the alignment of the interests of industry actors and on the creation of market frameworks that allow it • The UK Energy Networks Association (ENA) is developing a shared services framework for a coordinated industry approach to access DM resources

7.4 Identification of R&D projects, actors and funding opportunities for new capability development

In this section, recent and current EV integration R&D and demonstration projects are presented, along with a literature review of the BMS-related research. This is followed by a review of funding opportunities for the development of the required new capabilities in battery management systems.

[53] For details on charge point terminology refer to

Table 42 in the Appendix
[54] Other grid demand reduction services only need to respond to on/off commands
[55] Frequency response is an automatic change in power output or demand in response to a frequency change, provided as a service to National Grid, to help maintain the system frequency at 50Hz, see Appendix 10.4 for details on the service parameters.

7.4.1 Identification of R&D projects and actors

EV integration demonstration projects and actors

Table 22 and Table 23 (pages 88 and 89) present trials of different types of managed charging in which technical and commercial EV system integration is being demonstrated (in Europe and outside Europe respectively). This shows to what extent the identified needs are in place, in development or not studied yet.

The findings emerging from this review are:

- There is no focus on the BMS per se, although some projects focused on studying the possible impact of grid services on the battery (and concluded there was little or no negative impact). The majority of projects used standard EVs/PHEVs on sale today with no modifications to their BMS. Instead the innovation was in the communication between the vehicle/charging point and wider electricity system to allow optimised charging strategies to be used.
- Most projects are led by utilities, i.e. focus on managing the demand to optimise the utility price offer. Utilities could however become aggregators for grid services.
- Until 2015, all managed charging projects were conducted on home or work charging points (i.e. private), but a frequency regulation service is being piloted in the Netherlands in 2016, with over 25,000 public charging points.
- Various communication pathways have been demonstrated (between grid/utility and charging point, between grid/utility and user through apps, etc.), and for various focuses (e.g. response to tariffs, response to local generation, respect to drivers rules regarding time the vehicle must be charged by, etc.).
- Projects generally focus on BEVs, with PHEVs included in only two studies, both of which are focused on battery pack testing combined with grid system modelling, as opposed to trials:
    - The Germany–based E.ON study included battery ageing testing in laboratory conditions and the development of a simulation model for PHEVs in a distribution grid segment.
    - The Danish EDISON project was also mostly model-based and a few (5) BEVs were used to test the technology (communication vehicle – grid), but no consumer research was conducted.

  This lack of large scale managed charging trials involving PHEVs (and mass market consumers) will be addressed in the Stage 2 of the CVEI project.

The projects are also mapped (in the 5th row of Table 22 and Table 23) to the three main areas of development identified in Figure 37: (a) hardware, (b) software, and (c) social engagement. Table 22 and Table 23 demonstrate that the majority of the projects are focused on the development of software solutions, e.g. the development and testing of smart charging algorithms. Social engagement is inherently part of the trials, however the companies seem to be focusing on functionality testing at this stage[56].

Besides these demonstration projects that typically involve vehicle OEMs, utilities and/or charging point providers, it is worth noting other actors are entering the EV integration sphere. Nest, a US based company that started in 2010 with smart house thermostats (and was acquired by Google in 2014) has now developed a strategy to interact with solar PV, EV and battery providers. Nest are already in talks with Solar City, Tesla and un-named inverter companies. The plan is for Nest to control add-ons such as solar PV systems and EVs to optimise customers' energy generation/consumption to deliver best value against ToU tariffs. In the USA, Nest offer "Rush Hour Rewards" for DM for cooling and "Seasonal

[56] Note that participants in these trials are likely to be pioneers/early adopters (as opposed to “mainstream” customers), therefore the results regarding behaviour cannot necessarily extrapolated. However the focus in this report is on the technical feasibility, which is not influenced by customer profiles per se.

Savings" to optimise winter heating control. Nest has an established API to interface with energy utilities. Nest has 80 energy partners spanning 7 countries (including the UK) and 100 million homes [100]–[102].

Demonstration projects involving EV integration are briefly described below.

Renault Zoe smart charging [87]

Figure 34 in Section 2.2 presents the schematics of this pilot. The project started in November 2015 and involves Zoe-owning Renault employees in Germany that tested the system at their homes. The system schedules vehicle charging on the basis of energy cost data.

IBM and EKZ [103]

A data recording device installed in the vehicle transmits data (SOC, car location, power in/out of battery) to IBM's cloud via the cellular network. The user can programme the app to start charging at a certain time, or can delegate charging to the utility provider, which can schedule charges to coincide with production from renewables (real-time production data sent from solar panels to IBM's cloud service).

EDISON [104]

International research project partly publicly funded through the Danish transmission system operator (TSO) Energinet.dk's research programme FORSKEL, and carried out between 2009 and 2012. The main goals of the project were to:

- develop system solutions and technologies for PH/BEVs where EV storage capacity is used in a power system with a large amount of intermittent renewable generation;
- prepare and provide a technical platform for Danish demonstrations of EVs, focusing on power system integration;
- develop standard system solutions for EVs.

Five charging scenarios were studied (from 'dumb' charging to timer-based and grid services), including testing the potential for aggregating EVs to provide demand management. EV Virtual Power Plants were tested successfully during the project.

Knowledge was gained on the impact of the different charging schemes on battery lifetime through tests and mathematical modelling, concluding that intelligent charging schemes can be performed without any negative influence. The project was therefore mostly based on modelling, as opposed to trial data.

Five BEVs (Mitusbishi iMiEVs) were used to gain driving and charging data in order to verify some of the assumptions regarding driving patterns for electric vehicles. However, no PHEV trial was conducted during the project.

My Electric Avenue [105]

This Ofgem-supported project analysed how local electricity networks can cope with increasing numbers of BEVs. 100 Nissan Leafs participated in the trial for 18 months. The aim was to test a technology ('Esprit') that monitors and controls the electricity flow when a car is being charged. The Esprit system is designed to avoid any potential power outages and damage to network infrastructure. The technical aims of the project were:

- to learn customer driving and EV charging habits
- to trial equipment to mitigate the impact of EV charging
- to explore the network benefits of such technology

The results of the project's modelling have shown that across Britain 32% of low voltage (LV) feeders (312,000 circuits) will require intervention when 40% – 70% of customers have EVs, based on 3.5 kW (16 amp) charging. The project showed that the Esprit system was successful in curtailing charging when necessary, and therefore Esprit has the potential as a solution for DNOs to prevent the replacement of existing electricity cables.

Nissan and ENEL partnership [106]

Nissan has developed a Vehicle to Grid (V2G) system in partnership with the Italian utility ENEL, where vehicles will be able to act as energy hubs, drawing in or giving back electricity to/from the grid as required.

It uses a novel two-way home charging point and an energy management system; the communication flows are presented in Figure 39. Trials are taking place in Denmark, and the service will be launched there commercially before the end of 2016. It is expected the service will come to the UK in the short term too, as there are no regulatory barriers to EVs providing grid services (unlike some other European countries)[57].

For this service, Nissan and their local partners (Nissan will partner with local stakeholders in each country where they deploy V2G) have developed:

- An algorithm that will decide whether or not to provide the service based on an economic optimisation.
- New hardware to be fitted in the home charge point, with a reaction time of milliseconds (which current communication protocols are not capable of).

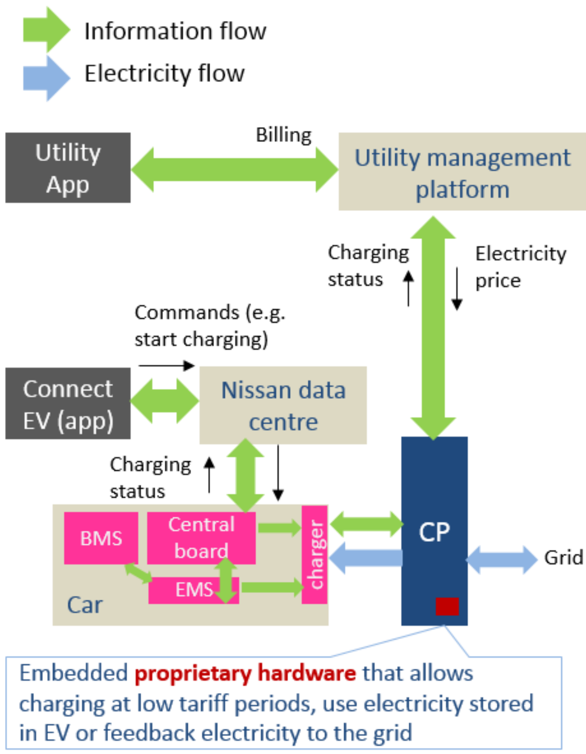

Figure 39. Vehicle to Grid service schematics developed by Nissan and Enel

The New Motion and TenneT project [107], [108]

The New Motion operates an expanding network of 25,000 "intelligent" public charge points across the Netherlands. By measuring the frequency of the grid, the charge points can translate the deviation from the standard electricity grid frequency of 50 Hz into a request to decrease the EV charging rate. The New Motion partnered with the electricity transmission system operator TenneT to trial the automatic adjustment of charging speed based on network demand. The primary objectives of the trial are:

- To prepare the energy system for the increased use of intermittent renewable energy generation
- To demonstrate the value of the contribution to the electricity grid from an aggregated pool of EVs

The first stage of the project involves the automatic reduction of EV charging speed when the electricity network load is high. This functionality is available to all clients of The New Motion who voluntarily

[57] Source: telephone interview with Nissan UK. Since the first version of this report, the UK V2G trial has been announced, see [115].

enrolled into this programme through the company website. There is no financial incentive for the clients for participating in this project, however the reduction in charging speed is relatively small – up to 6%. Upon successful completion of this stage of the project, The New Motion is considering the deployment of V2G technology enabling discharge of the battery for balancing the grid. To achieve this, The New Motion is collaborating with the company called Nuvve, who has already successfully demonstrated the V2G concept in the US.

E.ON Active storage systems for the grid [94], [109]

The study was primarily focused on the German market of PHEVs with batteries in the range of 4-20 kWh. Note that this is a modelling study and no PHEV brand/model have been assumed for the model in particular. The aim of the study was to identify what effect the integration of PHEVs into the grid might have on costs and emissions. It was assumed that relatively small batteries will not benefit from using high-power charging systems, and therefore in order to avoid extra costs the scope of the study included only the existing private-access charging, e.g. standard power outlet in a user's garage.

The project considered the use of the following charging patterns:

- Uncontrolled charging (the entire 0-100% SOC range is used)
- Cost-optimised charging (the PHEVs are charged during low-level demand times when the electricity price is lowest. The price data is grouped in 15 minutes intervals and the algorithm searches for the cheapest charging intervals in the next 24 hours to reach 100% SOC)
- SOC-optimised charging (SOC is kept below 90% for more than 70% of the standstill time to extend the battery lifetime)
- Charging to deliver grid balancing services (bidirectional charging[58] through a trading algorithm that has been implemented to calculate the ideal charging and discharging program to ensure a full battery charge at departure and optimise selling and buying based on electricity prices)

The grid simulation was carried out by using the program PowerFactory from DIgSILENT with a co-simulation of Powerfactory and MatLab. Battery parametrisation was performed based on the cycling tests of NCA cells. The weekly driving patterns of 1,221 different vehicles were used for the simulation. The information about the time of each departure and arrival of the vehicle in addition to its destination and driving distance were sourced from German Mobility Panel survey [110].

It was found that the uncontrolled charging of PHEVs will lead to (a) overloading of local grid elements and (b) a decrease in battery lifetime. On the other hand, if intelligent charging strategies are implemented, the PHEV integration into the grid has the potential of reducing TCO and providing the balancing services without any negative impacts on the battery lifetime. Bidirectional cost-optimized charging[58] showed ca. 37% lower electricity costs compared to uncontrolled charging. The highest reduction in annualised battery costs due to prolonged battery lifetime was found to be achieved with SOC-optimised bidirectional charging.

BMW i ChargeForward [111]

This 18-month managed charge pilot started in August 2015, includes ca. 100 drivers, and is led by BMW Group Technology Office, together with Pacific Gas and Electric Company (PG&E) in California. The aim is to provide the utility with up to 100kW of capacity at any given time, through a voluntary load-reduction program. The charging of an individual car is delayed by up to an hour to offset peaks in demand, while e-mobility needs of users are prioritised (i.e. they provide the time at which vehicles should be fully charged). The user is notified of delays by text message, and can opt out via the

[58] Bidirectional charging refers to the EV management strategy when V2G services are provided in addition to managed charging, i.e. energy is able to flow into and out of the battery.

ChargeForward Application. Users are paid $1,000 (£670) to take part, with up to $540 (£360) more at the end of the pilot depending on the levels of participation.

EVCS Pilot [112]

The Electric Vehicle Charging Station (EVCS) Pilot was carried out in 2013 and 2014 in the US (Colorado), where 20 customers took part. The aim of the project was to gain an understanding of how technically and operationally feasible it is to interrupt vehicle charging through demand management. Half of the customers had a charge point installed, which sent data to the energy company, but not the customer. The other half had control devices fitted into their existing charging stations, and both the energy company and the customer were able to access the load data collected. The energy company could interrupt charging up to 12 times per year for up to 4 hours in each case.

The results showed that:

- controlling EV charging is technically feasible;
- customers showed interest in an off-peak EV rate;
- most customers were either not inconvenienced, or mildly inconvenienced, by the control events and felt that the yearly incentive of $100 (£67) was sufficient.

Victoria project [113]

An end-to-end system was established in ten Australian households using a home charging point (Figure 40), in which a set of four different management scenarios was tested:

- Predictable peak electricity demand events (e.g. extreme weather conditions);
- Scheduled maintenance of network infrastructure (e.g. planned outage of a transformer or power line);
- Avoidance of system overloads (e.g. due to a combination of unexpected network infrastructure failure and extreme weather/high demand scenarios);
- Unplanned failures of network infrastructure (e.g. due to lightning strikes).

Users could opt out of controlled charging in each scenario, but were rewarded if they did not.

Demand Clearinghouse [114]

The US-based subsidiary of the German utility company RWE are investing in the development of a cloud-based solution for smart charging. This initiative builds on the demonstration project at UC San Diego in partnership with a clean energy firm KnGrid. The aim of the project is:

- To automate the start/stop charging of electric vehicles in California based on the current electricity price;
- To support the implementation of the ISO 15118 communication standard between the EV on-board charger and the charging point supporting time-controlled and tariff-controlled charging [89].

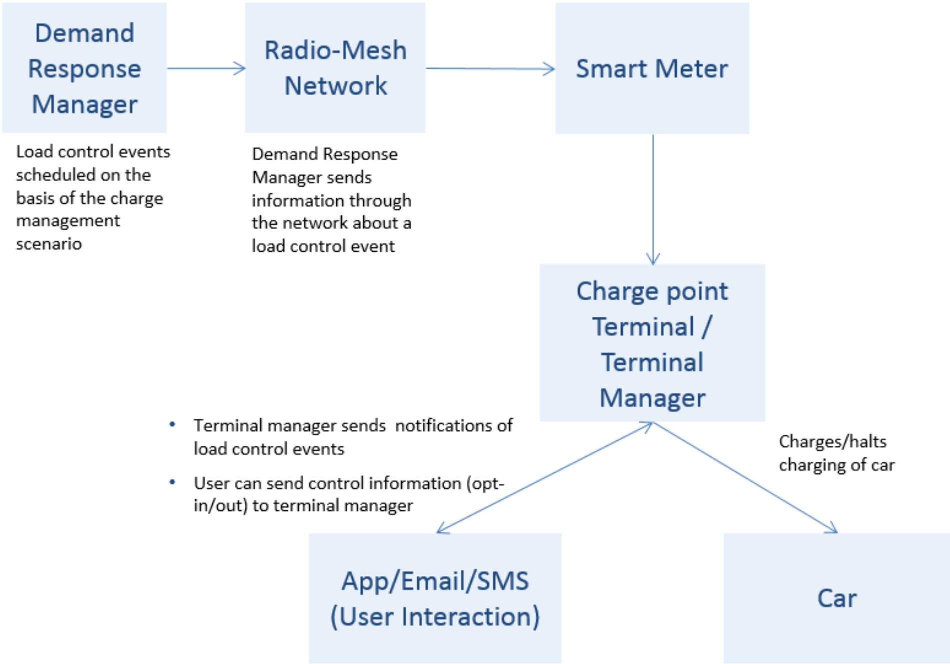

Figure 40. End-to-end charging demand management system deployed

Upcoming V2G capabilities

It was mentioned above that Nissan has developed and trialled a Vehicle to Grid (V2G) system and that a commercial rollout is expected in 2016 in Denmark, shortly followed by the UK [115].

Nissan have no concern regarding the impact on the battery, as the V2G service will target frequency regulation and be limited to 10kW (which is a low discharge rate for a pack capable of ca. 90kW). For this reason the 8 year warranty offered by Nissan on the battery will not be affected by the V2G service[59]. Note that the fact that Nissan has no concerns regarding the impact on the battery is linked to the cautious nature of the V2G services offered, i.e. limited power and frequency response (shallow discharge/charge cycles). Grid services provided at high power and/or requiring deep discharge may have a negative impact on the battery lifetime as discussed in Section 2.6 of Deliverable D3.2 – Battery State of Health Model report.

This level of development, and the fact that Nissan confirms all remaining technical glitches have been addressed, places Nissan ahead of all other OEMs and of most demonstration projects (summarised in Table 22). This also means developments in this area could be very quick, as other OEMs will follow suit in offering integrated solutions to their customers.

It is also interesting to note that Nissan has conducted focus groups to test consumers' responses. The results were positive and showed that, as users do not understand the details, it is best to keep the explanation/presentation simple. The main points to communicate to users are that battery health will not be impacted and that they can derive some revenues.

[59] Here and below: based on discussion with Nissan

Table 22. Summary of a selection of demonstration projects testing EV system integration in Europe

	R. Zoe smart charging	IBM and EKZ	EDISON	My Electric Avenue	Nissan and ENEL	The New Motion and TenneT	E.ON Active storage systems for the grid
Location	Germany	Switzerland	Denmark	UK	Denmark	Netherlands	Germany
Actors (date)	Charging point provider and car OEM (2015-16)	Utility and app developer (2011)	Utility and comms providers (2009-12)	Utility, car OEM and technical consultancy (2013-2015)	Car OEM and utility (2015)	Transmission System Operator, charging solution provider (2016)	Utility (2008 - 2011)
Scope	Automation of charging to align with low cost electricity schedules	Automation of charging to align with utility schedules based on renewable resources availability	Test of different charging scenarios including an EV Virtual Power Plan	Study of impact of 'EV clusters' and load management to mitigate impact on the local network	Trial of cost-optimised charging for Nissan Leaf	Automatically manage the charging speed based on the measurement of grid frequency. Potential increase in charging time is 6%.	Investigation of the charging pattern impact on battery lifetime and development of business models for PHEVs integration into the distribution grid
Focus area	Testing new functionality of automated charging based on low electricity prices	Testing new functionality of automated charging based on utility schedules	Influence of different charging schemes on battery lifetime	Learning about managing the strain on the grid from increased number of EVs	• Two-way charging trials (G2V, V2G) • 'Second life' for batteries	Test the potential of EVs to act as buffer storage to balance the grid with high penetration of renewables	• Potential of "smart" charging to increase the lifetime of the battery • Cost benefits of using intelligent charging
Addressed Layer	Software	Software	Hardware	Software, Social engagement	Software, Hardware, Social engagement	Software	Hardware
Grid services?	No – utility focus	No – utility focus	Yes (as well as charging at times of low prices)	No – utility and DNO focus	Yes (as well as charging at times of low prices)	Yes (frequency regulation G2V; V2G planned next)	Yes (preliminary analysis of the cost-benefits of G2V, V2G)
Charging location & EV type(s)	Home BEV	Home BEV	Home and public BEV (PHEV modelled only)	Home BEV	Home BEV	Public BEV	Home PHEV (modelled only)

Table 23. Summary of a selection of demonstration projects testing EV system integration outside Europe

	BMW i Charge Forward	EVCS (EV Charging Station)	Victoria project	Demand Clearinghouse
Location	US, Calif.	US, Colorado	Australia	US, California
Actors (date)	Utility and car OEM (2015-16)	Utility (2013-14)	DNO and charging point provider (2013-2014)	Utility and clean tech firm (2016)
Scope	Charging automatically delayed to offset demand peaks. The program also includes a “second life” for used MINI E batteries.	Load control devices in domestic charge points (20 users) and understanding customer charging patterns and behaviours.	Automation of charging based on four set scenarios End-to-end charging demand management system	Cloud-based system regulates charging of the connected vehicles based on the grid load and electricity pricing
Focus area	• Understanding flexibility in charging • Design of products beneficial for utilities and users	Technical and operational feasibility of interrupting vehicle charging through Demand Response	Test of end-to-end system Understanding of user preference in managed charging scenario	Smooth the intermittencies in electricity grid resulting from high penetration of renewables.
Addressed Layer	Software, Hardware, Social engagement	Software, Hardware, Social engagement	Social engagement	Software
Grid services?	No – utility focus	No – utility focus	Yes (grid balancing)	Yes (grid balancing)
Charging point location & EV type(s)	Home BEV	Home BEV	Home BEV	Home and public BEV

Published research

A review of scientific articles identified as relevant to the Vehicle-to-grid ecosystem previously depicted in Figure 37 was conducted as part of the CVEI project. Table 43 and Table 44 (in the Appendix) categorise the identified publications whilst the conclusions are summarised here.

Vehicle to grid applications

Among the literature, two papers in particular definitively identify two major topics for Vehicle-to-grid applications, which are: a) the hardware connection between the EV and the grid and b) the connection between the car, the driver and the cloud to efficiently deliver vehicle-to-grid services.

A UK study from 2011 showed that EV charge point power can be varied relatively rapidly compared with a typical generation plant, making participation in (currently high value) primary frequency response appear to be particularly attractive for EVs [116].

The paper by Y. Mu et al., included in Table 44, investigates how EVs might contribute to the primary frequency response [97]. Several key findings have been identified:

- EVs have significant potential to provide an effective system primary frequency response. There is negligible impact by the time delay induced by EV charger points on the provision of primary frequency response from EVs.
- The simulation results of the paper show that sometimes not all of the EVs that are connected to the grid need to provide primary frequency response, thus an important topic for future research is to determine an optimal number of EVs for the purpose of provision of the service and how participation will be allocated/partitioned between EV users.

The literature review suggests improved BMS are central in the realisation of the smart grid and the growth of the EV industry [91]. However, the currently available BMS solutions developed by car OEMs, Tier 1 suppliers in-house (e.g. Bosch, Continental, Ricardo) or sourced from the specialist companies (e.g. Johnson Matthey, Vayon Group, Dukosi, etc) are likely to be able to provide the required functionality for Vehicle-to-grid services without any or with minimal modification. The on-going research and developments efforts in this area have been identified in Section 7.3.1. These are primarily aimed at improving the accuracy of SOH estimation without dramatically increasing the complexity and the cost of BMS. EV battery pack reliability, whilst an important topic to address, has not been identified as a primary hindrance towards EV integration into electricity grids.

The Connected Car

In parallel, the connected car has been identified as a central topic to the vehicle-to-grid ecosystem. A survey by AutoScout24 gives a general overview on what could be done in this area in the coming years and which features will find useful applications in vehicle-to-grid services [117].

The key findings in this survey indicate that the "Connected Car Cloud" will drive the success of the Connected Car, but the infrastructure of this cloud has yet to be designed. An open source platform with a strategy based on use of drivers' smart phones (rather than embedding the technology in the car itself) could trigger the Connected Car market to quickly reach mass market, including the second hand car market. The study concludes that future initiatives aimed at bringing the Connected Car to the market should focus on identifying specific consumer needs (e.g. increased safety, infotainment features), ensuring uninterrupted and affordable network access (e.g. laws abandoning high mobile roaming costs in the EU), and facilitating alliances between vehicle OEMs and companies such as Apple, Google or Microsoft to set up standards for the app development.

7.4.2 Funding opportunities

Table 24 lists the funding opportunities related to the BMS and system integration of EVs, in terms of funding programme, call & topic, budget and deadline for application. Most identified calls are part of the **European Horizon2020 programme**. The most relevant call – call GV-08-2015 – actually closed in October 2015 (but the winners are not known yet). This call, titled "Electric vehicles' enhanced performance and integration into the transport system and the grid" focuses on the following aspects concerning BMS research:

- improved modelling and simulation tools for BMS;
- standardisation of the BMS components and interface protocols;
- testing methodologies for estimating battery parameters relevant for battery reliability and lifetime.

In the UK, the **Advanced Propulsion Centre** (APC) in association with Innovate UK provides funding opportunities for car technologies that have the capability to achieve significant reductions in vehicle emissions. In particular, this includes innovations in energy storage and energy management on-board systems. Technologies that primarily reside off the vehicle, such as charging infrastructure, are out of the scope of APC funding.

However these are supported by **Ofgem**, who has established a Low Carbon Networks Fund through which it supports projects led and sponsored by Distributor Network Operators (DNOs). The LCNF is now replaced by the electricity Network Innovation Competition (NIC) [118]. The aim of this fund is to facilitate the uptake of low carbon initiatives relevant for electricity networks. A relevant example of a completed project supported under this funding is the Customer-led Network Revolution, which developed a roadmap to guide the development of smart grid technology based on the electricity network customer trials.

Note that Table 24 includes schemes even if their deadlines are in the very near term, as it provides an indication of the type of R&D being funded. In some cases, the calls re-open annually so a near term deadline does not always mean the opportunity is missed.

It is worth noting that current work and demonstration projects typically do not involve DNOs. Most projects are investigating the provision of services for the grid as in the Transmission System Operator, but not services to the local grid/DNO. When DNOs have been involved in demonstration projects, it has been with the angle to understand/minimise the network upgrade cost, not with the focus of looking at how to use managed charging, in particular V2G, as a way to run the network more efficiently and possibly generate revenue for the end user. This is perceived as a barrier to complete EV system integration by Nissan, the EV OEM most advanced in the development of managed charging offers.

Outside the EU, the California Energy Commission in the US is active in funding projects for the development of smart grids. "Developing the Smart Grid of 2020: Clean, Safe, and Highly Intelligent" (call GFO-15-313) has $8million (£5.3million) allocated to it, and opened in January 2016 [119].

In addition to public R&D funding sources, private sector stakeholders may be prepared to fully or partly invest in EV integration initiatives to test new business concepts and to position themselves to secure future revenues from a large smart charging sector in the medium to long term. Given the relatively small nature of managed charging services, such investments are inherently speculative in nature, with insufficient short term returns to be justified as part of normal operations. However, many stakeholders in the electricity value chain have dedicated business units to explore these long-term opportunities, such as the National Grid's European Business Development unit which operates alongside its regulated business in the UK. Several DNOs also have non-regulated commercial arms that can invest in EV integration projects. Other private funding sources could include demand management aggregators who may be willing to invest in development projects for EV integration to grow the aggregation market. Finally, vehicle OEMs themselves are likely to continue their investments in EV integration R&D (and the continuing rollout of rapid charge points) as an enabling action to increase sales of EVs by securing financial benefits for their users.

Table 24 UK and EU funding opportunities related to BMS and EV system integration [120]–[122]

Programme / organisation	Topic	Budget	Deadline	Relevance
Horizon 2020 (GV-08-2015)	Electric vehicles' enhanced performance and integration into the transport system and the grid. A particularly important element that needs to be addressed is the battery management system.	EUR 5-10 million	Oct 2015	High
Horizon 2020 (GV-08-2017)	Electrified urban commercial vehicle integration with fast charging infrastructure. Development of a drivetrain concept for electrified medium duty trucks and buses for urban use. Negative effects on battery life and the grid, and measures to mitigate them should also be developed.	EUR 5-15 million	Feb 2017	High
Horizon 2020 (LCE-02-2016)	Demonstration of smart grid, storage and system integration technologies with increasing share of renewables: distribution system. Specific focus is smart integration of grid users from transport (e.g. electric vehicles) for charging, providing storage capacity or for their capacity to supply electricity to the grid.	EUR 12-15 million	Apr 2016	High
Horizon 2020 (LCE-04-2017)	Demonstration of smart transmission grid, storage and system integration technologies with increasing share of renewables. Includes developments of control tools for flexible generation and support of demand-response mechanism and its interface to the distribution grid.	EUR 15-20 million	Feb 2017	High
Horizon 2020 (MG-4.2-2017)	Supporting 'smart electric mobility' in cities. Testing and validating business models for electro-mobility solutions.	EUR 4-5 million	Jan 2017	High
Horizon 2020 (GV-05-2017)	Electric vehicle user-centric design for optimised energy efficiency. Integration of advanced systems and components, reducing the weight and thermal inertia, testing of the different solutions at the full vehicle level.	EUR 7-10 million	Feb 2017	Low
Innovate UK, APC, BIS	Development of low carbon, low emission automotive propulsion technologies. The competition's aim is to develop on-vehicle technologies, including energy storage and energy management.	£5-40 million	Mar 2016 (18-42 months)	Medium
Ofgem	The Network Innovation Competition supports projects that explore how networks can facilitate the take up of low carbon and energy saving initiatives such as electric vehicles, heat pumps, micro and local generation and demand side management.	Up to £500 million	April 2016 (annual calls)	Medium

7.5 Recommendations on new projects

Components that are required for EV intelligent charging (i.e. managed charging; V2G and G2V services) reside within several layers that can be broadly categorised as:

- Physical layer – hardware installed on the EV and the charging station that is compatible with managed charging.
- Communication layer – data protocols that can handle digital certificates, respect customer charging requirements and adjust charging based on price tables from energy suppliers, among other capabilities. The back-office functionality relies on this layer.
- Human interface layer – software (e.g. a phone app or in-vehicle display) that allows the user to configure settings for intelligent charging and choose to participate in the provision of certain grid services.

Progress is currently being made in all three of these areas. In principle, current state of the art BMS should be able to provide grid services if the communication protocols in line with ISO/IEC 15118 and IEC 61850 standards are in place as discussed in Section 7.2.3. Software that allows EV owners to participate in managed charging and to provide grid services is being developed and trialled by car OEMs as discussed in Section 7.2.2. However, several aspects of BMS need to be improved to take full advantage of EV integration with electricity grids.

Future BMS research should focus on a combination of the following:

- **Cell-level battery monitoring and testing methodologies** – development of sensing elements to measure voltage, current, temperature, impedance and pressure coupled with actuators for active balancing and electronics for data storage and processing at a cell level (rather than pack or module level). This should allow accurate and fast SOH estimation that facilitate efficient EV integration. This research should also focus on bringing the cost of sensors down.
- **Reliability** – introduction of improved BMS monitoring methodologies for efficient EV integration into the grid will inevitably lead to higher BMS electronic system complexity. Issues such as excessive wiring may become a failure point. Wireless communication approaches could be developed to avoid excessive wiring and simplify maintenance of the BMS.
- **Data safety** – communication with the grid (e.g. implemented through a cloud database) leads to potential data security risks. Thus, robust cryptography solutions should be implemented on all levels, including the BMS data flows.

A number of partners should be involved in future BMS research projects to achieve high impact:

- **electronics manufacturers** for new component (e.g. sensors) development;
- **battery system developers** for building a new system prototype;
- **research institutes** for verification and validation of the proposed concepts and the prototype;
- **automotive manufacturing companies** for technology integration and testing;
- **technical consultancies** for definition of concept, project requirements and coordination.

Based on the previous projects focused on the development of an improved BMS, such as SMART-LIC and ESTRELLA, the approximate budget can be expected in the region of 4-5 million pounds for a ca. 3 year project [123], [124]. These projects have been partly funded (ca. 60%) through the EU Horizon2020 initiative, which continues to support projects focused on EV integration into the grid [125]. Electronic component manufacturers, battery system developers, car OEMs and utility companies are potential stakeholders who may be prepared to invest in such projects in future.

It should be noted that experts interviewed at Nissan and Johnson Matthey as part of this Work Package highlighted the risk that multi-year, collaborative research projects on BMS designs risk falling behind the cutting edge of developments in individual OEMs and component suppliers, for example developments being prepared for the next generation of EVs/PHEVs. They suggest that the value of collaboration is highest where the focus is on standardisation of communication or interactions with the wider EV integration chain (e.g. cloud solutions, apps, data transfer to aggregators or renewable energy generators) rather than on the core BMS functionality.

This section focused on the BMS and future capabilities, but it is worth noting that some industry stakeholders consulted for this work think the topic of battery ageing/State of Health as the area needing most work, in particular to generate more data on real-world degradation in different use cases. This is not BMS research per se but would support the algorithms in place in the BMS. Not all degradation mechanisms are understood yet, and accelerated test procedures are also needed to simulate heavily used packs that are not yet available from vehicles in service given the average age of current plug-in vehicles. This is covered in more detail in D3.2 on State of Health.

Other areas mentioned as needing more research:

- High power packs for hybrid vehicles and high performance PHEVs (e.g. in terms of electrolyte and thermal management).
- Split packs that combines good energy storage modules and high power modules.

8 Conclusions

The objective of this study was to produce an updated set of cost and performance projections for automotive battery packs to 2050, for both battery EVs and plug-in hybrid EVs. This data is due to be used in ECCo – the car and van uptake model used in the Consumers, Vehicles and Energy Integration Project – and thus will affect the projected level of EV uptake and conditions required to influence uptake (e.g. higher or lower subsidies).

8.1 Approach

The study built on (and updated) the Element Energy bottom up model of lithium-ion battery pack performance and costs, developed in 2012 for the Committee on Climate Change, and benefitted from industry stakeholder inputs, notably Johnson Matthey's input regarding packing components. The bottom up model combines battery sub-components specifications and costs to 2030, while a top down approach is used for post-2030 projections.

Comparison of recent trends in automotive battery packs and the model's predictions revealed a good match. The model reproduces the cost reduction of ca.10 % p.a. and ca. 5% p.a. energy density gain observed over the last 5 years (ca. 40% cost reduction and 15% pack density improvement), resulting in today's cost and energy density of ca. £350 kWh (GBP2014) and ca. 100 Wh/kg for a 25 kWh pack.

A detailed review of both lithium-ion chemistries and post-lithium ion technologies was carried out to understand the upcoming improvements in cell energy density (mostly dependent on the active material mAh/g and voltage) and possible transition to cheaper materials. Another key cost driver in the model is the assumption on global EV sales, as these are used with learning rates to calculate the future cost of some components.

8.2 Technology review findings

The current research on cells, gathered through the literature review and discussions with industry stakeholders such as active material suppliers and cell developers, brought the following conclusions regarding lithium-ion cells and post-lithium ion cells:

- **Lithium-ion cells**
  A transition from manganese oxide cathodes (spinel) to nickel based oxides cathodes is on-going and there is still scope for improvement in the reversible mAh/g (thus energy density) of these cathodes. The development of solid electrolytes (on-going) would bring increased safety.

- **Post-lithium ion cells**
  The most advanced technologies and/or promising in terms of theoretical energy density are lithium-sulphur and metal-air batteries. As for lithium-ion cells, both would benefit from the development of solid electrolytes in terms of safety. However they all have remaining challenges to overcome to become viable automotive cells, typically in terms of cycle life, efficiency, (dis)charge rate, volumetric density and/or scalability.

  Lithium-sulphur is the only technology already at the stage where prototype cells are being trialled by car OEMs. UK based Oxis Energy is the most advanced developer of this technology and is involved in several EU funded projects aiming at delivering Li-S based automotive packs. Current cells are at 325 Wh/kg and 100-125 cycles, and Oxis Energy scientists estimate the practical limit would be 700-900 Wh/kg.

  Among metal-air technologies, lithium-air batteries get more headlines in non-academic articles due to their very high theoretical energy density (~3,500 Wh/kg). Progress over recent years has however been limited and several institutions have abandoned research on this topic. Recent work on zinc-air batteries has recently delivered the first rechargeable cells (achieving 150 Wh/kg at cell level and 100 cycles), however it is unclear if they will ever be suitable for the automotive market due to their low voltages and poor cyclability.

Sodium-ion technologies have also showed some encouraging progress in recent years, with prototypes achieving 10-100s cycles and 140 Wh/kg (cell level). These are based on cheaper materials than lithium-ion cells. However their theoretical energy density, lower than that of lithium-ion, limits their scope for automotive applications with most developers today focusing on grid/ stationary storage applications.

These findings must be placed in the context of automotive cell requirements (over 1,000 cycles, no/low self-discharge, safety, high (dis)charge rates). The development timescale, from discovery of a new electrode material or process, to prototyping and scale up to an automotive cell is 10-12 years. This applies to chemistries for which the proof of concept has already be made and even to variations of the already fully commercial lithium-ion cells.

These timescales have the following implications, taken into account in the results:

- Over the next 10 years there is no 'step change' technology in view for automotive batteries, with an improvement in lithium-ion cells expected instead. Many improved lithium-ion cells are currently at different stages of the prototype cycle and will bring incremental improvement over time.
- Breakthroughs reported today in post lithium-ion technologies might not reach the automotive market before 10-20 years' time (and requirement for further fundamental breakthroughs means is it not yet certain that post lithium-ion technologies will be successfully commercialised even in the long term).

8.3 Cost and performance projections

Several scenarios were developed, to cover a range of outcomes:

- A **baseline case**, where EVs see a high global uptake (reaching 4 and 35 million cumulative sales by 2020 and 2030, respectively), R&D delivers cell improvement to the extent that the lithium-ion limits are reached by 2030, and significant blending of silicon in the anode is achieved.
- An '**EV push**' case where the same R&D outcomes as above are coupled with a higher global uptake of EVs (15 and 123 million cumulative sales by 2020 and 2030, equivalent to 5 and 14% global EV uptake by 2020 and 2030).
- An '**EV niche**' case corresponding to a lower energy density and higher cost trajectory: R&D efforts are slower to deliver improvements in energy density, and global EV sales are also lower.

The cost and performance projections for post lithium-ion chemistries constitute an alternative scenario for post-2030 values, called 'New battery technologies'.

Results were developed for six battery pack size bands, the format compatible with ECCo. This allows the results to capture the impact of pack size on cost: because of fixed costs, the larger the capacity, the lower the cost per kWh. This also applies (to a lesser extent) to energy density.

Under the baseline case, a 30 kWh pack would decrease in cost from ca. £320/kWh in 2015 to ca. £215/kWh in 2020 and ca. £150/kWh in 2030, a 35% and 55% decrease respectively. The energy density is projected to increase by ca. 30% in 2020 and ca. 90% in 2030, compared to today's pack level density (ca. 100 Wh/kg).

Taking into account vehicle energy use efficiency improvements and future wider depth of discharge windows, a 30 kWh pack in a medium size car goes from providing a ca. 190 km driving range at a cost of £9,530 and mass of 280 kg in 2015, to providing 200 km in 2020, at a cost and mass of £6,430 and 200kg respectively. By 2030, a 30 kWh pack would have gone further down to £4,400 and 150 kg, providing 230 km of driving range.

Cost and energy density are projected to improve further post-2030 for a lithium-ion pack, through continuous efficiency gains, to reach £109/kWh and 250 Wh/kg (pack level) by 2050 (assuming a 2% p.a. decrease in pack costs 2030 onwards).

Baseline results for a 30kWh battery pack

30kWh pack	2015	2020	2030	2040	2050
Total pack cost, 2014GBP	£9,526	£6,433	£4,977	£4,407	£3,788
2014GBP/kWh	£327	£214	£147	£126	£109
Wh/kg	108	143	205	226	250
Mass, kg	277	209	147	133	120
Depth of discharge	85%	85%	90%	90%	90%

For the 'New battery technologies' scenario, hypothetical lithium-sulphur and lithium-air batteries were compared to the projected 2030 lithium-ion pack to identify potential cost differences. Although both technologies offer areas where cost reductions could be achieved (e.g. lower electrode material costs), other components would be more expensive (e.g. higher packing costs due to lower voltage). This leads to overall comparable 'bill of material' costs (<10% reduction estimated for a 30kWh pack). If remaining challenges are addressed and post-lithium ion cells achieve the automotive cell grade, they will start production at high volume at least 10 years after large lithium-ion cells and thus might not be competitive from the start.

For these reasons, under the 'New battery technologies' scenario, post-lithium ion batteries are mostly bringing energy density improvements. The energy density projections are based on theoretical cell densities, typical theoretical to practical ratios and assume new cell technologies would benefit from the streamlined manufacturing process developed for lithium-ion cells. The projected 'New battery technologies' energy densities are ca. 290 Wh/kg in 2030 and ca. 360 Wh/kg in 2050.

The gain in energy density could be used in two different ways:

- Keeping the same driving range but reducing the vehicle mass (and hence improving efficiency): the previous 30 kWh lithium-ion pack delivering 260 km range in 2030 would weigh 25% less (weight of ca. 100kg).
- Increasing the driving range: at equal mass, the pack could be 41 kWh (total, assuming a 90% DoD) and increase the range to ca. 310 km.

8.4 BMS capabilities and research gaps

Current capabilities

For the integration of electric vehicles into the electricity system, the BMS is an important component as a source of battery parameters used to inform the decisions on specific charging/discharging routines. But there are other critical components for this system integration, such as algorithms able to gather the needs of different actors and to optimise the use of the battery accordingly, which are likely to be embedded in other components than the BMS.

There are several capabilities enabling managed charging that are provided by all OEMs, such as allowing the user to set the charging time. They are enabled through the communication between a mobile application and the car. Managed charging capabilities, such as the optimisation of charging based on household consumption and/or on the maximisation of the use of in-home produced renewable electricity, are only being offered by specific OEMs. In this case, the charging point, in combination with a smart home system, are the key components that enable those capabilities, in parallel with the energy utilities (retail and DNO) and National Grid.

New BMS capabilities needed and research gaps

The three main BMS capability developments that have been identified for the integration of EVs into the energy system are:

- Reporting state of health in real-time to optimise charging and usage of EVs.
- Advanced state of health reporting to allow prediction of availability for demand management.
- New algorithms (for example, algorithms that enable the identification of unusual aging trends).

The lack of these do not prevent the integration of EVs through managed charging, as demonstrated by the numerous pilot projects already on-going, but they would improve this integration, in terms of battery protection and the state of charge window available for grid services. Further improvements in SOH estimation will help minimise the impact of additional charging cycles on the battery lifetime, and improve understanding and evaluation of second life EV battery applications (both technical and commercial/economic). It was however noted that Nissan is going to deploy V2G services to Leaf owners while maintaining the 8 year warranty on the battery pack; they confirmed (through direct discussion) that they had no concerns over battery life.

The SOH model developed as a part of Deliverable D3.2 partly addresses the point regarding the advanced SOH reporting, i.e. it uses a semi-empirical approach to predict the battery ageing based on the average temperature, C-rate, etc. The implemented approach is beneficial in terms of the flexibility around different chemistries when a relatively simple set of inputs is available. However, the advanced SOH estimation models used on-board EVs are likely to rely on more advanced algorithms such as differential thermal voltammetry or, if costs come down, the inputs based on the results of Electrochemical Impedance Spectroscopy or similar techniques enabling higher accuracy for specific battery chemistries instead [91], [126].

A review of both demonstration projects and literature reveals a low emphasis on the BMS in the context of EV grid integration. Research is on-going, however, on the development of the capabilities mentioned above.

Funding opportunities and main actors

Funding for projects looking at EV integration into the electricity system is available both on the EU and the UK level. Relevant calls for proposals have been issued by the European Commission as a part of the Horizon 2020 funding programme. Development of on-board EV technologies, such as BMS, is addressed through the “Green Vehicles” Horizon 2020 calls. Infrastructure challenges are part of “Competitive low-carbon energy” calls and “Mobility for growth” calls. The “Competitive low-carbon energy” calls are focussed on the socio-economic and behavioural research, whilst the “Mobility for growth calls” are looking at innovative technologies that would allow the transition to renewable electricity generation.

In addition to EU funding, the UK has established mechanisms for national funding to support the development of low carbon vehicles technologies and their integration into the UK electricity networks. The Advanced Propulsion Centre, in partnership with Innovate UK and the Department for Business Innovation and Skills, is seeking proposals for developing the UK’s supply chain in the field of low carbon vehicles. As the same time, charging infrastructure development is in the scope of the Network Innovation Competition available through Ofgem.

Utility companies, charging point OEMs and car manufacturers are best positioned to work on EV integration into electricity grids and are currently leading the projects in this field. However, general clean tech or data companies are tapping into this space and are likely to emerge as new actors in smart charging development.

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10 Appendix

The first sub-section provides some comparison of battery technologies; the second sub-section provides more detail on the model input updates (refer to Section 5 for approach and sources) whereas the third sub-section lays out the battery cost and performance projections to 2050. The last sub-section supports Section 7.

10.1 Comparison of different battery types

Table 25 Technical performance comparison of different battery types [2]

Property	Unit	Lead Acid	NiMH	Li-ion
Cell Voltage	Volts	2	1.2	3.2-3.6
Energy Density	Wh/Kg	30-40	50-80	100-200
Power Density	W/Kg	100-200	100-500	500-8000
Maximum Discharge	Rate	6 -10C	15C	100C
Useful Capacity	Depth of Discharge%	50	50-80	>80
Charge Efficiency	%	60-80	70-90	~100
Self-Discharge	%/Month	3- 4	30	2-3
Temperature Range	ºC	-40 +60	-30 +60	-40 +60
Cycle Life	Number of Cycles	600-900	>1000	>2000
Micro-cycle Tolerant		Deteriorates	Yes	Yes
Robust (Over/Under Voltage)		Yes	Yes	Needs BMS

Table 26 Technical performance comparison of different Li-ion battery types by cathode chemistry. Adapted from [2]

Property	Unit	NMC	LFP	LMO	NCA
Cell Voltage	Volts	3.6	3.4	3.8	3.6
Energy Density (cell level)	Wh/kg	100-200	90-150	150-240	130-240
Typical power		3-6C	5-10C	3-10C	2-3C
Temperature range	°C	-20 to 60	-30 to 60	-20 to 60	-20 to 60
Approximate safety thermal runaway onset	°C	210	270	250	150
Year of introduction to the market		2008	1996	1996	1999

10.2 Detailed model inputs

Table 27. Assumed cathode and anode chemistries, capacities and voltage – baseline and EV push R&D case

	2015	2020	2025	2030
Polyanion cathode	$LiFePO_4$ (LFP)	$LiMnPO_4$ (LMP)	$Li(M)SO_4F$	$Li(M)SO_4F$
Reversible mAh/g	145	150	150	150
Voltage, V	3.5	4	4.5	4.5
NMC cathode	NMC441	NMC441	Adv. NMC	Adv. NMC
Reversible mAh/g	160	170	205	220
Voltage, V	3.7	3.7	3.7	3.8
Spinel cathode	$LiMn_2O_4$ (LMO)	$LiMn_2O_4$ (LMO)	$LiMn_{1.5}Ni_{0.5}O_4$	$LiMn_{1.5}Ni_{0.5}O_4$
Reversible mAh/g	110	120	120	120
Voltage, V	4	4	4.7	4.7
Anode	Graphite	Si/C	Si/C	Si/C
Reversible mAh/g	330	650	1,500	1,750
Voltage, V	0.1	0.1	0.1	0.1
Level of silicon blending	n/a	8.5%	30%	37%

Table 28. Assumed cathode and anode chemistries, capacities and voltage – niche EV R&D case

	2015	2020	2025	2030
Polyanion cathode	$LiFePO_4$ (LFP)	$LiMnPO_4$ (LMP)	$Li(M)SO_4F$	$Li(M)SO_4F$
Reversible mAh/g	130	150	150	150
Voltage, V	3.5	4	4.5	4.5
NMC cathode	NMC441	NMC441	NMC441	NMC441
Reversible mAh/g	160	170	175	175
Voltage, V	3.7	3.7	3.7	3.7
Spinel cathode	$LiMn_2O_4$ (LMO)	$LiMn_2O_4$ (LMO)	$LiMn_{1.5}Ni_{0.5}O_4$	$LiMn_{1.5}Ni_{0.5}O_4$
Reversible mAh/g	110	110	120	120
Voltage, V	4	4	4.5	4.7
Anode	Graphite	Si/C	Si/C	Si/C
Reversible mAh/g	330	370	840	1,050
Voltage, V	0.1	0.1	0.1	0.1
Level of silicon blending	n/a	1%	13%	19%

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[60] and resulting component costs have been reviewed by the authors' partner, Johnson Matthey.

Table 29 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%.

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

Table 29. Learning rates applying to pack components. Source: EE for CCC, 2012

Component	Rate	Comment
BMS	90%	Repetitive electronics
Power electronics	90%	If standardisation of parts
Wiring harnesses	85%	Very manual process
Cell interconnections	85%	Very manual process
Internal cell support	97%	Cost mainly machinery and raw materials
Housing	91%	Cost mainly machinery and raw materials

Table 30. Summary of material cost updates

	Original model for CCC				Updated model			
Separator ($2010/m^2)	2				1.2			
Positive current collector ($2010/kg)	15				6			
Negative current collector ($2010/kg)	17				11			
Electrolyte ($2010/L)	21.6				17			
Spinel active material cost* ($2010/kg)	**2015** 15	**2020** 22	**2025** 21	**2030** 20	**2015** 10	**2020** 10	**2025** 15	**2030** 15
NMC active material cost*($2010/kg)	**2015** 39	**2020** 36	**2025** 34	**2030** 32	**2015** 20	**2020** 20	**2025** 25	**2030** 23
Polyanion active material cost* ($2010/kg)	**2015** 18	**2020** 15	**2025** 14	**2030** 12	**2015** 17	**2020** 15	**2025** 14	**2030** 12
Anode active material cost* ($2010/kg)	**2015** 24	**2020** 46	**2025** 34	**2030** 34	**2015** 24	**2020** 30	**2025** 34	**2030** 34

* Baseline EV uptake scenario

10.3 Model outputs for use in ECCo

Cost and energy density projections, for use in the ECCo model are given in table format next, for each scenario. These will be combined with the vehicle total pack capacity. For indication, ECCo baseline assumptions for these are given in Table 31, Table 32, Table 33 and Table 34. The pack capacity for each car and van segment is based on an assumed electric driving range target, depth of discharge (see Table 12 in section 5.5) and powertrain energy consumption (vehicle performance model developed by Element Energy in 2015 for DfT). Two scenarios for the electric driving range were developed for ECCo in 2015, shown on Figure 41, Table 35 and Table 36.

Table 31. Pack size (kWh) for each car segment (BEV)

Segment	2015	2020	2025	2030	2040	2050
A MINI	14	19	22	22	21	20
B SUPERMINI	20	23	22	22	21	20
C LOWER MEDIUM	26	37	38	40	41	39
D UPPER MEDIUM	28	41	41	43	45	43
E EXECUTIVE	45	62	61	63	66	68
H DUAL PURPOSE	44	47	48	46	44	43
I MULTI PURPOSE	34	36	37	36	34	33
F LUXURY SALOON	67	90	88	90	93	96
G SPECIALIST SPORTS	52	70	69	71	74	76

Table 32. Pack size (kWh) for each car segment (PHEV)

Segment	2015	2020	2025	2030	2040	2050
A MINI	9	8	7	7	7	6
B SUPERMINI	10	9	8	8	7	7
C LOWER MEDIUM	10	9	9	8	8	8
D UPPER MEDIUM	11	10	10	9	9	8
E EXECUTIVE	12	11	10	10	9	9
H DUAL PURPOSE	14	13	12	12	11	11
I MULTI PURPOSE	11	10	10	9	9	8
F LUXURY SALOON	16	15	14	13	12	12
G SPECIALIST SPORTS	13	12	11	11	10	10

Table 33. Pack size (kWh) for each van segment (BEV)

Segment	2015	2020	2025	2030	2040	2050
SMALL CAR DERIVED	15	23	23	22	22	21
LARGE CAR DERIVED	22	32	31	30	29	29
STANDARD PANEL	29	54	64	69	67	66
LARGE PANEL	33	60	71	77	75	73
PICK UP	33	61	72	78	75	74

Table 34. Pack size (kWh) for each van segment (PHEV)

Segment	2015	2020	2025	2030	2040	2050
SMALL CAR DERIVED	9	8	8	8	8	7
LARGE CAR DERIVED	11	10	10	10	10	9
STANDARD PANEL	15	14	13	13	13	12
LARGE PANEL	17	15	15	15	14	14
PICK UP	9	8	8	8	8	7

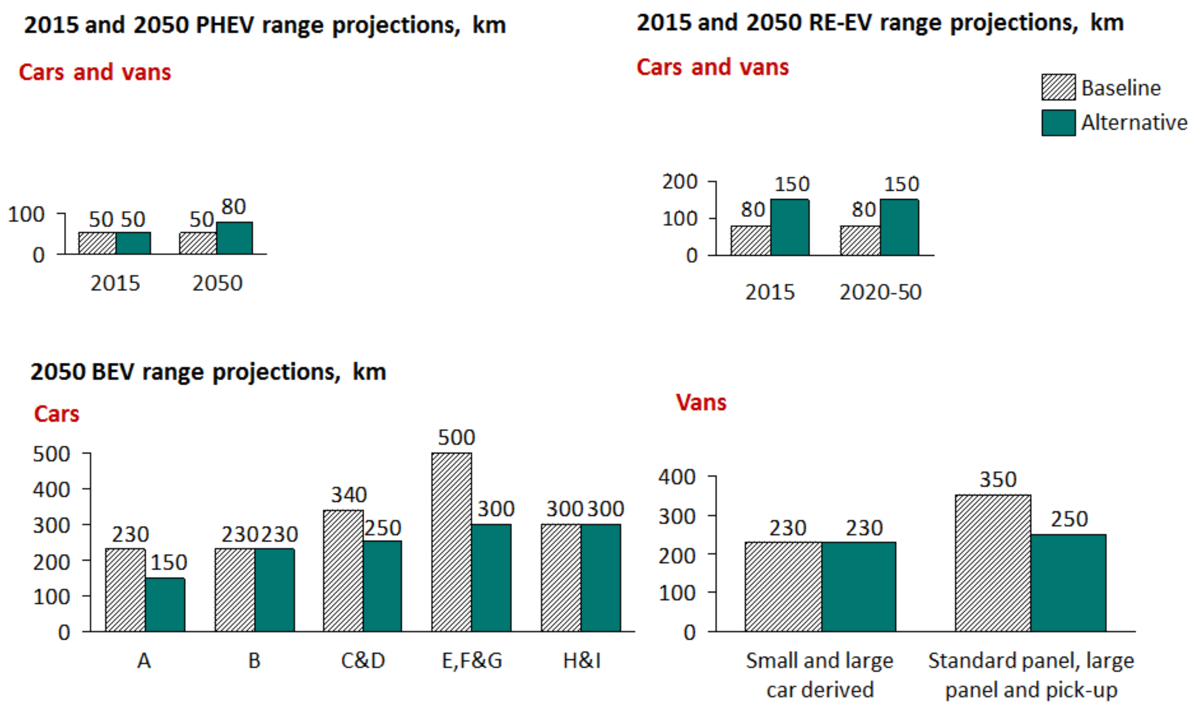

Figure 41. 2050 range assumptions for cars and vans (km)

Table 35. NEDC baseline range assumptions for cars (km)

Powertrain	Segment	2015	2020	2025	2030	2040	2050
BEV	A MINI	150	200	230	230	230	230
BEV	B SUPERMINI	200	230	230	230	230	230
BEV	C LOWER MEDIUM	200	280	300	320	340	340
BEV	D UPPER MEDIUM	200	280	300	320	340	340
BEV	E EXECUTIVE	300	400	425	450	475	500
BEV	H DUAL PURPOSE	250	280	300	300	300	300
BEV	I MULTI PURPOSE	250	280	300	300	300	300
BEV	F LUXURY SALOON	300	400	425	450	475	500
BEV	G SPECIALIST SPORTS	300	400	425	450	475	500
PHEV	All	50	50	50	50	50	50

Table 36. NEDC baseline range assumptions for vans (km)

	Segment	2015	2020	2025	2030	2040	2050
BEV	SMALL CAR DERIVED	170	230	230	230	230	230
BEV	LARGE CAR DERIVED	170	230	230	230	230	230
BEV	STANDARD PANEL	170	275	325	350	350	350
BEV	LARGE PANEL	170	275	325	350	350	350
BEV	PICK UP	170	275	325	350	350	350
PHEV	All	50	50	50	50	50	50

10.3.1 Baseline results

Table 37. Pack costs and densities for the baseline scenario (GBP2014/kWh and Wh/kg) – NMC cathode

Parameter	Band	2015	2020	2025	2030	2040	2050
Pack cost, £/kWh	=<15kWh	581	371	290	247	212	183
	15-=20kWh	434	282	215	192	165	142
	>20, =<25kWh	368	244	187	166	143	123
	>25, =<35kWh	318	214	166	147	126	109
	>35, =<60kWh	267	190	140	123	106	91
	>60kWh	255	172	135	113	97	83
Pack density, Wh/kg	=<15kWh	87	109	141	149	165	182
	15-=20kWh	97	128	168	179	198	218
	>20, =<25kWh	102	136	180	192	212	234
	>25, =<35kWh	108	143	191	205	226	250
	>35, =<60kWh	114	149	206	222	245	271
	>60kWh	114	155	207	230	254	281

10.3.2 EV push results

Table 38. Pack costs and densities for the EV push scenario (GBP2014/kWh and Wh/kg) – NMC cathode

Parameter	Band	2015	2020	2025	2030	2040	2050
Pack cost, £/kWh	=<15kWh	579	328	263	221	180	147
	15-=20kWh	432	240	190	167	136	111
	>20, =<25kWh	366	209	166	145	119	97
	>25, =<35kWh	315	187	148	129	106	86
	>35, =<60kWh	265	168	126	110	90	73
	>60kWh	253	154	122	101	83	68
Pack density, Wh/kg	=<15kWh	87	109	141	149	165	182
	15-=20kWh	97	128	168	179	198	218
	>20, =<25kWh	102	136	180	192	212	234
	>25, =<35kWh	108	143	191	205	226	250
	>35, =<60kWh	114	149	206	222	245	271
	>60kWh	114	155	207	230	254	281

10.3.3 EV niche results

Table 39. Pack costs and densities for the EV niche scenario (GBP2014/kWh and Wh/kg) – NMC cathode

Parameter	Band	2015	2020	2025	2030	2040	2050
Pack cost, £/kWh	=<15kWh	585	414	350	294	280	266
	15-=20kWh	439	317	266	228	217	207
	>20, =<25kWh	373	273	232	201	191	182
	>25, =<35kWh	322	240	207	180	172	163
	>35, =<60kWh	272	211	186	155	147	140
	>60kWh	259	191	170	151	144	136
Pack density, Wh/kg	=<15kWh	87	102	127	129	136	143
	15-=20kWh	97	118	148	151	159	167
	>20, =<25kWh	102	125	157	160	169	177
	>25, =<35kWh	108	131	165	169	178	187
	>35, =<60kWh	114	136	171	181	191	200
	>60kWh	114	141	177	182	191	201

10.3.4 Alternative energy density: 'New battery technologies' case

Table 40. Pack costs and densities for the New battery technologies scenario (GBP2014/kWh and Wh/kg)

Parameter	Band	2015	2020	2025	2030	2040	2050
Pack cost	=<15kWh	581	371	289	244	199	163
	15-=20kWh	434	282	215	190	155	127
	>20, =<25kWh	368	244	186	164	134	110
	>25, =<35kWh	318	214	165	145	119	97
	>35, =<60kWh	267	190	139	122	99	81
	>60kWh	255	172	135	112	91	75
Pack density, Wh/kg	=<15kWh	87	109	141	210	239	272
	15-=20kWh	97	128	168	252	288	327
	>20, =<25kWh	102	136	180	270	308	350
	>25, =<35kWh	108	143	191	288	329	374
	>35, =<60kWh	114	149	206	313	357	406
	>60kWh	114	155	207	324	370	421

10.4 Battery management system supporting tables

Table 41 reports on the main grid balancing services; there are others, e.g. primary frequency response that has a timescale of 10s (instead of 30s for firm frequency response).

Beyond these services, there has been recent relevant additions:

- There is now an “FFR bridging” contract, this is an FFR contract for demand management (DM) with aggregated capacity less than 10MW. It is meant for DSM aggregators that are growing their portfolio over time: they can start on a bridging contract with less than 10MW and increase capacity over time, but payments are fixed and slightly lower than in the full FFR case. The aim is that once their portfolio is larger than 10MW they move to FFR.
  Link: http://www2.nationalgrid.com/UK/Services/Balancing-services/Frequency-response/Firm-Frequency-Response/FFR-Bridging/

- NG has opened a tender for enhanced frequency response (1s response instead of 10s) with contract durations of 4 years. This tender is primarily aimed at grid scale batteries, but also open for other providers (e.g. DM). NG aims to procure 200MW if there are sufficient economic bids (for comparison primary frequency response requirements are 1000-1400MW). There are no decisions on what happens after this one tender, but NG has stated that they expect to need more of this type of response in the future.
  Link: http://www2.nationalgrid.com/Enhanced-Frequency-Response.aspx

- Similar to FFR bridging there is a “STOR runway” contract for DSM aggregators with a portfolio of lower capacity than required for STOR proper.
  Link: http://www2.nationalgrid.com/UK/Services/Balancing-services/Reserve-services/Short-Term-Operating-Reserve/STOR-Runway/

Table 41 Main grid balancing services, the minimum quantities and timescales required [127]

	Description	Speed of Response	Minimum capacity
Firm frequency response (FFR)	Firm frequency response is an automatic change in active power output or demand in response to a frequency change.	<30 sec	10 MW
Short-term operating reserve (STOR)	The provision of extra power through standby generation and/or demand reduction, in order to be able to balance unforeseen mismatches in supply and demand. Service must be maintained for no less than two hours	Up to 4 hr (but typically 20 minutes)	3 MW
Fast reserve	Similar to STOR, but requires a faster delivery to cover predictable large changes in demand (e.g. turning kettles on in the morning)	<2 min	50 MW
Frequency Control by Demand Management	The provider must deliver a reduction in demand, for minimum 30 minutes	< 2s	3 MW

Table 42 Charge point terminology: charging modes [128], [129]

Charging modes
Mode 1: single or three-phase AC, with a maximum permitted current of 16A. The supply voltage is up to a maximum of 250V for single-phase or 480V for three-phase. As no residual current device is included in the equipment, Mode 1 is not recommended for public or commercial use.
Mode 2: single or three-phase AC supply, with a maximum permitted current of 32A. The supply voltage is up to a maximum of 250V for single-phase or 480V for three-phase supply. Mode 2 includes the use of a residual current device located within the cable.
Mode 3: single or three-phase AC supply, with a maximum permitted current of 32A. The supply voltage is up to a maximum of 250V for single-phase or 480V for three-phase supply. As Mode 3 includes data connection, Mode 3 enables full vehicle isolation and 'smart' charging capability.
Mode 4: incorporate an 'off-board' charge point and provide a DC supply at the socket. The DC supply has a maximum permitted current of 1000VDC (typically 500VDC) and current of up to 400A (usually 125A). Mode 4 includes a full 'handshake' so enabling 'smart' charging capability.

Table 43 - Web searches - selection of papers and articles related to BMS and wider energy system. Key words used: BMS, vehicle-to-grid

Platform	Article title, authors, [reference] and abstract
Google Scholar	**Primary Frequency Response From Electric Vehicles in the Great Britain Power System (June 2013)** Yunfei Mu, Jianzhong Wu, Janaka Ekanayake, Nick Jenkins, Hongjie Jia [130] With the increasing use of renewable energy in the Great Britain (GB) power system, the role of electric vehicles (EVs) contributes to primary frequency response was investigated. A tool was developed to estimate the EV charging load based on statistical analysis of EV type, battery capacity, maximum travel range and battery state of charge. A simplified GB power system model was used to investigate the contribution of EVs to primary frequency response. Two control modes were considered: disconnection of charging load (case I) and discharge of stored battery energy (case II). For case II, the characteristic of the EV charger was also considered. A case study shows results for the year 2020. Three EV charging strategies: "dumb" charging, "off-peak" charging, and "smart" charging, were compared. Simulation results show that utilizing EVs to stabilize the grid frequency in the GB system can significantly reduce frequency deviations. However the requirement to schedule frequency response from conventional generators is dynamic throughout the day.
Google Scholar	**Contribution of Plug-in Hybrid Electric Vehicles in power system uncertainty management (January 2016)** Jamshid Aghaei, Ali Esmaeel Nezhad, Abdorrezza Rabiee, Ehsan Rahimi [131]

	Electric vehicles, including both PEVs and PHEVs have been recently interested to a large extent in global markets due to their capabilities. These plug-in vehicles are able to absorb/inject power from/to the electric grid that turns them into an interesting solution for the power systems. However, large numbers of such plug-in vehicles can be a threat to power systems. In this regard, it seems necessary to investigate the problems caused by the uncertain driving nature of such electric vehicles. On the other hand, the opportunities provided by the presence of a large fleet of plug-in vehicles as mobile storage/load should be discussed. For this end, this paper reviews the challenges and the problems caused by charging/discharging of PHEV/PEVs in large numbers and investigates their capabilities as a solution to integrate the RESs and demand response programs in power systems.
Google Scholar	**Electric vehicle charging to support renewable energy integration in a capacity constrained electricity grid (February 2016)** Nathaniel S. Pearre, Lukas G. Swan [132] Digby, Nova Scotia, is a largely rural area with a wealth of renewable energy resources, principally wind and tidal. Digby's electrical load is serviced by an aging 69 kV transmission line that often operates at the export capacity limit because of a local wind energy converter (WEC) field. This study examines the potential of smart charging of electric vehicles (EVs) to achieve two objectives: (1) add load so as to increase export capacity; (2) charge EVs using renewable energy. Multiple survey instruments were used to determine transportation energy needs and travel timing. These were used to create EV charging load timeseries based on "convenience", "time-of-day", and idealized "smart" charging. These charging scenarios were evaluated in combination with high resolution data of generation at the wind field, electrical flow through the transmission system, and electricity load. With a 10% adoption rate of EVs, time-of-day charging increased local renewable energy usage by 20% and enables marginal WEC upgrading. Smart charging increases charging by local renewable energy by 73%. More significantly, it adds 3 MW of load when power exports face constraints, allowing enough additional renewable electricity generation capacity to fully power those vehicles.
Research gate	**Book: Integrated Systems: Innovations and Applications. Chapter: Integrated Battery Management System (2015)** M. Foad Samadi, Mehrdad Saif [133] Increased concerns over limited sources of energy as well as the environmental impact of petroleum based transportation infrastructure have led to an ever increasing interest in electric transportation infrastructure. Thus, electric vehicle (EV), hybrid electric vehicle (HEV), and plug-in hybrid electric vehicle (PHEV) have received a great deal of attention in recent years. Issues dealing with the battery technology and related systems remain a central challenge in vehicle electrification. The objective of this chapter is to shed light on some of the challenging issues, in regards to the battery management system design from a control theoretic perspective and highlight some open areas of research.
Research gate	**Article: An outlook of electric vehicle daily use in the framework of an energy management system (June 2015)** Hugo Neves de Melo, João P. Trovão, Carlos Henggeler Antunes, Paulo G. Pereirinha, Humberto M. Jorge [134] The purpose of this paper is to present a prospective study of sustainable mobility in the framework of supporting energy management systems (EMS). Technological

	advances are still required, namely electric vehicles (EV) endowed with improved EMS in order to increase their performance by making the most of available energy storage technologies. As EVs may be seen as a special domestic load, EMS are proposed based on demand-sensitive pricing strategies such as the Energy Box discussed in this paper. Design/methodology/approach – The study presents an overview of electric mobility and an urban EV project, with special focus on the utilization of its energy sources and their relation with the energy demand of a typical urban driving cycle. Results based on the ECE 15 standard driving cycle for different free market electricity tariffs are presented. Findings – The analysis based on present Portuguese power and energy tariffs reveals that it is highly questionable whether the resulting profit will be enough to justify the potential inconveniences to the vehicle user, as well as those resulting from the increased use of batteries. Practical implications – The conclusions indicate that more studies on the trade-offs between grid to vehicle and vehicle to grid schemes and electricity pricing mechanisms are needed in order to understand how the utilization of EVs can become more attractive in the end-users' and utilities' perspectives. Originality/value – The paper proposes an approach for future electricity tariff behavior that could be applied to EVs in order to understand whether or not their grid integration in charge and discharge situations would be beneficial for end-users and utilities, in the framework of smart energy management technologies.
Research gate	**Article: The importance of grid integration for achievable greenhouse gas emissions reductions from alternative vehicle technologies (July 2015)** Brian Tarroja, Brendan Shaffer, Scott Samuelsen [135] Alternative vehicles must appropriately interface with the electric grid and renewable generation to contribute to decarbonization. This study investigates the impact of infrastructure configurations and management strategies on the vehicle–grid interface and vehicle greenhouse gas reduction potential with regard to California's Executive Order S-21-09 goal. Considered are battery electric vehicles, gasoline-fueled plug-in hybrid electric vehicles, hydrogen-fueled fuel cell vehicles, and plug-in hybrid fuel cell vehicles. Temporally resolved models of the electric grid, electric vehicle charging, hydrogen infrastructure, and vehicle powertrain simulations are integrated. For plug-in vehicles, consumer travel patterns can limit the greenhouse gas reductions without smart charging or energy storage. For fuel cell vehicles, the fuel production mix must be optimized for minimal greenhouse gas emissions. The plug-in hybrid fuel cell vehicle has the largest potential for emissions reduction due to smaller battery and fuel cells keeping efficiencies higher and meeting 86% of miles on electric travel keeping the hydrogen demand low. Energy storage is required to meet Executive Order S-21-09 goals in all cases. Meeting the goal requires renewable capacities of 205 GW for plug-in hybrid fuel cell vehicles and battery electric vehicle 100s, 255 GW for battery electric vehicle 200s, and 325 GW for fuel cell vehicles.
Research gate	**Article: Impact of Electric Vehicle Charging on Voltage Unbalance in an Urban Distribution Network (May 2015)** Azhar Ul-Haq, Carlo Cecati, Kai Strunz, Ehsan Abbasi [136] During the last few years, assessment and evaluation of power quality index due to large-scale penetration of electric vehicles in the system have gained significant attention. Voltage unbalance in the low voltage distribution network is amongst the main power quality issues caused by electric vehicles and therefore it has been quantified and analyzed in this paper. A CIGRE benchmark model of low voltage distribution network is taken as test network and simulations are performed on a sample urban power distribution network. An electric vehicle grid integration and its

	charging model is implemented in Simulink. Results for two charging strategies including uncontrolled charging and tariff based electric vehicle charging under different electric vehicle penetration levels and uneven charging scenarios have been obtained. The presented results show that an uneven EV charging scenario can cause significant voltage unbalance that goes beyond its allowed limit of 2%.
Research gate	**Article: Electric vehicle fleet management in smart grids: A review of services, optimization and control aspects (April 2016)** Junjie Hu, Hugo Morais, Tiago Sousa, Morten Lind [137] Electric vehicles can become integral parts of a smart grid, since they are capable of providing valuable services to power systems other than just consuming power. On the transmission system level, electric vehicles are regarded as an important means of balancing the intermittent renewable energy resources such as wind power. This is because electric vehicles can be used to absorb the energy during the period of high electricity penetration and feed the electricity back into the grid when the demand is high or in situations of insufficient electricity generation. However, on the distribution system level, the extra loads created by the increasing number of electric vehicles may have adverse impacts on grid. These factors bring new challenges to the power system operators. To coordinate the interests and solve the conflicts, electric vehicle fleet operators are proposed both by academics and industries. This paper presents a review and classification of methods for smart charging (including power to vehicle and vehicle-to-grid) of electric vehicles for fleet operators. The study firstly presents service relationships between fleet operators and other four actors in smart grids; then, modeling of battery dynamics and driving patterns of electric vehicles, charging and communications standards are introduced; after that, three control strategies and their commonly used algorithms are described; finally, conclusion and recommendations are made.
Research gate	**Article: Decentralized energy management strategy based on predictive controllers for a medium voltage direct current photovoltaic electric vehicle charging station (January 2016)** Juan P. Torreglosa, Pablo Garcia-Trivino, Luis M. Fernandez-Ramirez, Francisco Jurado [138] The use of distributed charging stations based on renewable energy sources for electric vehicles has increased in recent years. Combining photovoltaic solar energy and batteries as energy storage system, directly tied into a medium voltage direct current bus, and with the grid support, results to be an interesting option for improving the operation and efficiency of electric vehicle charging stations. In this paper, an electric vehicle charging station supplied by photovoltaic solar panels, batteries and with grid connection is analysed and evaluated. A decentralized energy management system is developed for regulating the energy flow among the photovoltaic system, the battery and the grid in order to achieve the efficient charging of electric vehicles. The medium voltage direct current bus voltage is the key parameter for controlling the system. The battery is controlled by a model predictive controller in order to keep the bus voltage at its reference value. Depending on the state-of-charge of the battery and the bus voltage, the photovoltaic system can work at maximum power point tracking mode or at bus voltage sustaining mode, or even the grid support can be needed. The results demonstrate the proper operation and energy management of the electric vehicle charging station under study.
Research gate	**Article: Second Life Li-ion Batteries for Enhancing Renewable Energy Grid Integration (Under Review, February 2016)** Andoni Saez-de-Ibarra, Egoitz Martinez-Laserna, Daniel-Ioan Stroe, Maciej Swierczynski, Pedro Rodriguez [139]

	Connecting renewable power plants to the grid must comply with certain codes and requirements. One requirement is the ramp rate constraint, which must be fulfilled in order to avoid penalties. As this service becomes compulsory with an increased grid penetration of renewable, all possible solutions must be explored especially that large battery energy storage systems are still expensive solutions. Thus, in order to make battery investment economic viable, the use of second life batteries is investigated in the present work. This paper proposes a method for determining firstly, the optimal rating of a second life battery energy storage system (SLBESS) and secondly, to obtain the current demanded to the batteries and battery state of charge profiles during the operation. These will constitute the cycling patterns for testing batteries and studying the agein effect of this specific application. Real data from the Spanish electricity market for a whole year are used for validating the results.

Table 44 - Web researches selection of papers and articles related the connected car and electric cars. Key words used: Connected Car (unless indicated)

Platform	Article title, authors, [reference] and abstract
Research gate	**Survey Connected Car 2014 Connected Car Business Models – State of the Art and Practical Opportunities (July 2014)** *Robert Martignoni, AutoScout24* [117] Connecting the car to the Internet could lead to major changes in the automobile industry. It introduces the IT business to a traditional industry segment. This new field of business follows different rules and has contrasting characteristics. There are some advantages and also a number of challenges that accompany the introduction of the Connected Car. However, not only carmakers stand to benefit from the development of the Connected Car. The industry is set to undergo a great many changes and see new market entrants within the next few years. These new market participants have the opportunity to expand their businesses and enter the automobile sector. This is especially true for the telecommunications industry and the digital sector. These markets are very consumer-driven. Therefore, the main goal of this study is to identify use cases that provide greater value for the consumer. The results will then be categorized and analysed. The study begins by explaining the methodology that was applied. This chapter is followed by a description of the relevance of the Connected Car field. The study then analyses the current trends affecting the Connected Car. We asked 27 market experts to state their opinions and share their insights on this topic. The future of the connected vehicle faces numerous challenges that are described in the chapter prior to the outcome and findings of the study. The use cases will also be mentioned and categorized. Furthermore, these possible applications are evaluated and ranked according to their importance. The study then concludes by outlining the position of AutoScout24 and providing an outlook.
Google Scholar	**Strategic management of next-generation connected life: Focusing on smart key and car–home connectivity (November 2015)** *Jihoon Hong, Jungwoo Shin, Daeho Lee* [140] With the development of wireless technology, connectivity is becoming a more common feature of daily life. Connected cars and smart homes are typical examples, and the two markets are beginning to merge, as indicated by Apple's launch of “CarPlay” and “Home Kit” and iControl's partnership with Zubie. However, little research has been done on this subject because the integration of connected cars

	and smart homes has just begun. This study examines consumer preference for smart key functions (vehicle functions requested from outside the car) and car–home connectivity functions (communications between car and home), among others. Both revealed and stated preference datasets from a survey of U.S. drivers are used. The multivariate probit model and Bayesian estimation method are used to analyze consumer preferences. The results showed different preferences depending on socio-demographics and vehicle types. This paper provides marketing strategies for smart key functions and car–home connectivity functions by revealing socio-demographic characteristics and consumer preferences.
Google Scholar **Key words:** **Connected Car, Cloud,Vehicle,Driver**	**Book: A Framework on Cloud Based Connected Car Services (February 2016)** *Sumendra Yogarayan, Afizan Azman, Kirbana Jai Raman, Hesham Ali Alsayed Elbendary, Mohd Fikri Azli Abdullah, Siti Zainab Ibrahim* [141] The connected car is a loaded term describing all the technological advances happening inside automobiles with assistance of cloud technology to transfer information. The best known connected-car technology is satellite navigation, which uses the global-positioning system (GPS) simultaneously with a database of roads to provide directions and find points of interest. Following globalized technology era, many consumers are now adding internet connectivity to their cars in portable device which acts as the “smart” phone. Besides that, a two-way internet link allows for more detailed forms of navigation, and also makes it possible to gather and accumulate information from small to large numbers of vehicles. Smartphone’s is continuously changing how consumers interact with the world around them. Connected car with cloud technology can broaden this interactive dynamic to drivers on the road. In this paper, we proposed to deliver in-car experience for drivers or passengers using cloud technology.
Research gate	**Article: Automotive Processor with Integrated LTE Modem and Machine Intelligence for the Connected Car (January 2016)** *J. Knox* [142] Qualcomm snapdragon 820 automotive Family offers LTE-advanced connected platform with heterogeneous compute, machine intelligence, scalability from premium to standard tiers, and leading graphics and video capabilities
Research gate	**Article: The Connected Car in the Cloud: A Platform for Prototyping Telematics Services (November 2015)** *Tobias Haberle · Lambros Charissis · Christoph Fehling · Jens Nahm · Frank Leymann* [143] The Connected-Car Prototyping Platform provides both a back end for applications interacting with connected cars and an abstraction of such connected devices for developers. It also provides services such as identity management and data storage. Its main purposes are experimentation, prototyping, evaluation of ideas, and reduction of time-to-market for successful applications.
Research gate	**Conference Paper: Business Model Patterns for the Connected Car and the Example of Data Orchestrator (June 2015)** *Martin Mikusz · Christopher Jud* [144] Along with the connected car, previously isolated business models of traditional goods-producing industry melt together with those of software businesses. It is becoming apparent that software businesses may have to play an important role, provided that they are capable of building up competencies in engineering business models for this emerging and converged market. We identify and cluster business model patterns that we rate as being capable of transforming product innovations, enabled by abilities and characteristics of cyber-physical systems and the underlying

	technical platforms, into business model innovations. We discuss further the pattern cluster Data Orchestrator.
Research gate	**Conference Paper: Security issues and vulnerabilities in connected car systems (June 2015)** *Tamás Bécsi · Szilárd Aradi · Péter Gáspár* [145] The Connected Revolution has reached the automotive industry and the Internet penetrates into the modern vehicles. Formerly acquiring data from a vehicle was the tool of Fleet Management Systems handling commercial vehicles. In the recent years connectivity began to appear in the passenger vehicles also. The first features were infotainment and navigation, having low security needs remaining far from the vehicular networks. Then telematics and remote control, such as keyless entry appeared and created a new security threat in the vehicle. The paper shows how the connected feature changes the vehicle and also presents vulnerabilities of each element to show the importance of cautious system security design.
Research gate	**Article: Addressing Challenges in Automotive Connectivity: Mobile Devices, Technologies, and the Connected Car (May 2015)** *Patrick Shelly* [146] With the dramatic mismatch between handheld consumer devices and automobiles, both in terms of product lifespan and the speed at which new features (or versions) are released, vehicle OEMs are faced with a perplexing dilemma. If the connected car is to succeed there has to be a secure and accessible method to update the software in a vehicle's infotainment system - as well as a real or perceived way to graft in new software content. The challenge has become even more evident as the industry transitions from simple analog audio systems which have traditionally served up broadcast content to a new world in which configurable and interactive Internet-based content rules the day. This paper explores the options available for updating and extending the software capability of a vehicle's infotainment system while addressing the lifecycle mismatch between automobiles and consumer mobile devices. Implications to the design and cost of factory installed equipment will be discussed, as will expectations around the appeal of these various strategies to specific target demographics.
Research gate	**Article: Connected Car: Quantified Self becomes Quantified Car (March 2015)** *Melanie Swan* [147] The automotive industry could be facing a situation of profound change and opportunity in the coming decades. There are a number of influencing factors such as increasing urban and aging populations, self-driving cars, 3D parts printing, energy innovation, and new models of transportation service delivery (Zipcar, Uber). The connected car means that vehicles are now part of the connected world, continuously Internet-connected, generating and transmitting data, which on the one hand can be helpfully integrated into applications, like real-time traffic alerts broadcast to smartwatches, but also raises security and privacy concerns. This paper explores the automotive connected world, and describes five killer QS (Quantified Self)-auto sensor applications that link quantified-self sensors (sensors that measure the personal biometrics of individuals like heart rate) and automotive sensors (sensors that measure driver and passenger biometrics or quantitative automotive performance metrics like speed and braking activity). The applications are fatigue detection, real-time assistance for parking and accidents, anger management and stress reduction, keyless authentication and digital identity verification, and DIY diagnostics. These kinds of applications help to demonstrate the benefit of connected world data streams in the automotive industry and beyond where, more

	fundamentally for human progress, the automation of both physical and now cognitive tasks is underway.
Research gate **Key words:** **Connected electric vehicle**	**Article: Design of High Ratio DC-DC Converter Applied to PV-Grid Connected Electric Vehicle Charging Station (September 2015)** *Dimas Anto Asfani, Daniar Fahmi, Edi Wibowo, Heri Suryoatmojo · Dedet Candra Riawan · Prabowo Prabowo* [148] In this paper, we propose design of the boost converter with hybrid transformer ratio for hybrid power source charging station. This converter is addressed as DC step up converter. This converter has high ratio conversion that converter to DC bus 24 Volt to AC system 220Volt. The combination between resonance modes and pulse width modulation (PWM) is used to achieve high voltage ratio conversion. The advantage of proposed method is use only single switching device; therefore it is easy to control. Moreover, voltage stress on diode and switching device is relatively low and independent from input voltage. The experiment result show that the converter is able to operates in wide range input voltage and has good conversion efficiency up to 90%. Based on the operation and conversion characteristic, the converter can be operated in power inverter with duty ratio 0.7-0.8 to synchronizing with AC system.
Research gate **Key words:** **Connected electric vehicle**	**Article: Development of an Android OS Based Controller of a Double Motor Propulsion System for Connected Electric Vehicles and Communication Delays Analysis (March 2015)** *Pedro Daniel Urbina Coronado · Horacio Ahuett-Garza · Vishnu-Baba Sundaresan · Ruben Morales-Menendez* [149] Developments of technologies that facilitate vehicle connectivity represent a market demand. In particular, mobile device (MD) technology provides advanced user interface, customization, and upgradability characteristics that can facilitate connectivity and possibly aid in the goal of autonomous driving. This work explores the use of a MD in the control system of a conceptual electric vehicle (EV). While the use of MD for real-time control and monitoring has been reported, proper consideration has not been given to delays in data flow and their effects on system performance. The motor of a novel propulsion system for an EV was conditioned to be controlled in a wireless local area network by an ecosystem that includes a MD and an electronic board. An intended accelerator signal is predefined and sent to the motor and rotational speed values produced in the motor are sent back to the MD. Sample periods in which the communication really occurs are registered. Delays in the sample periods and produced errors in the accelerator and rotational speed signals are presented and analyzed. Maximum delays found in communications were of 0.2 s, while the maximum error produced in the accelerator signal was of 3.54%. Delays are also simulated, with a response that is similar to the behavior observed in the experiments.