A REVIEW OF BATTERY TECHNOLOGIES FOR AUTOMOTIVE APPLICATIONS

EUROBAT ACEA JAMA KAMA ila International Lead Association

A joint industry analysis of the technological suitability of different battery technologies for use across various automotive applications in the foreseeable future

From a technology-neutral standpoint, this report evaluates in detail the suitability of all different battery technologies for use in various automotive applications, and argues that each will continue to have a well-established and irreplaceable role in Europe's automotive sector for the foreseeable future.

The report concludes that the various battery technologies have specific performance profiles, which serve a well-defined purpose in automotive applications and continue to have an irreplaceable role in reducing CO_2 emissions from transport. Therefore it is not possible to replace one technology by another without an impact on overall performance and vehicle cost.

EUROBAT, the Association of European Automotive and Industrial Battery Manufacturers, acts as a unified voice in promoting the interests of the European automotive, industrial and special battery industries of all battery chemistries. With over 40 members comprising over 90% of the automotive and industrial battery industry in Europe, EUROBAT also works with stakeholders to help develop a vision of future battery solutions to issues of public interest in areas including e-Mobility and renewable energy storage.

The European Automobile Manufacturers Association (**ACEA**), founded in 1991, represents the interests of the fifteen European car, truck and bus manufacturers at EU level. Its membership consists of the major international automobile companies, working together in an active association to ensure effective communication and negotiation with legislative, commercial, technical, consumer, environmental and other interests.

Japan Automobile Manufacturers Association (**JAMA**) is a non-profit industry association which comprises Japan's fourteen manufacturers of passenger cars, trucks, buses and motorcycles. JAMA works to support the sound development of Japan's automobile industry and to contribute to social and economic welfare.

Korea Automobile Manufacturers Asssociation (**KAMA**) is a non-profit organization, representing the interests of automakers in Korea. KAMA is also dedicated to the sound growth of the automobile industry and the development of the national economy.

International Lead Association (ILA) is a membership body that supports companies involved in the mining, smelting, refining and recycling of lead. The ILA represents the producers of about 3 million tons of lead. ILA's work has a broad focus, covering all aspects of the industry's safe production, use and recycling of lead.

Disclaimer

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Introduction

From start-stop and basic micro-hybrid vehicles using advanced lead-based batteries, up to plug-in hybrid and full electric vehicles mostly powered by high voltage lithium-ion battery systems and a smaller auxiliary battery, several battery technologies are used to improve the fuel efficiency of Europe's vehicles.

Batteries of several technologies are employed in different automotive applications, helping vehicle manufacturers meet EU targets for reduced CO_2 emissions from transport.

Advanced lead-based batteries now provide start-stop functionality and other micro-hybrid features in a significant proportion of the new vehicles created in Europe, directly lowering their fuel consumption by 5-10%. The various grades of hybrid powertrain also require different battery combinations to provide a level of vehicle propulsion, while high-voltage lithium-ion and sodium-nickel chloride batteries have been employed to deliver zero emission driving in Europe's first generation of electric vehicles.

This report provides a joint industry analysis of how different types of batteries are used in these automotive applications, with the intention to increase the level of information publicly available on the topic. It looks to answer the following questions:

- Which battery technologies are available for different automotive applications, and where are they used?

- What technical requirements are they expected to fulfill in each application?

- How will the performance of each battery technology be improved in the foreseeable future?

Answers are provided using combined industry expertise from members of EUROBAT, ACEA, JAMA, KAMA and ILA. This group comprises Europe's combined battery and vehicle manufacturers, along with Japanese and Korean vehicle manufacturers and the international lead industry.

It is intended that the information contained in this report will be inputted into regulatory discussions on the feasibility of substituting certain battery technologies. The report emphasises that for future developments of vehicle powertrains, a fair co-existence of battery technologies on the market is essential, so that vehicle manufacturers can select the most effective option for improving fuel efficiency and reducing CO_2 emissions at each level of hybridisation and electrification.

VEHICLE TYPES

A range of different vehicle types are now available on the European market, featuring increasing degrees of hybridisation and electrification:

1. **Conventional (ICE) vehicles -** No electrification. The battery is used only for starting the internal combustion engine, lighting and ignition (commonly referred to as SLI functions).
2. **Start-stop vehicles** – Low degree of electrification. The internal combustion engine is automatically shut down under braking and rest.
3. **Micro-hybrid and mild-hybrid vehicles** – Low to medium degree of electrification. Start-stop systems combined with regenerative braking, where stored energy is then used to boost the vehicle's acceleration.
4. **Full-hybrid electric vehicles (HEVs)** – Medium degree of electrification. Equivalent characteristics to mild-hybrid vehicles, but the stored energy within the battery is also used for a certain range of electric driving.
5. **Plug-in hybrid electric vehicles (PHEVs)** – High degree of electrification. The battery is used as the main energy source for daily trips (i.e. 20-50km), but if necessary PHEVs can also run in hybrid mode using a combustion engine. Batteries may be charged with off-board electric energy.
6. **Electric vehicles (EVs)** – Full electrification . The battery is used as the vehicle's only energy source, with no internal combustion engine. Batteries are charged with off-board electric energy.

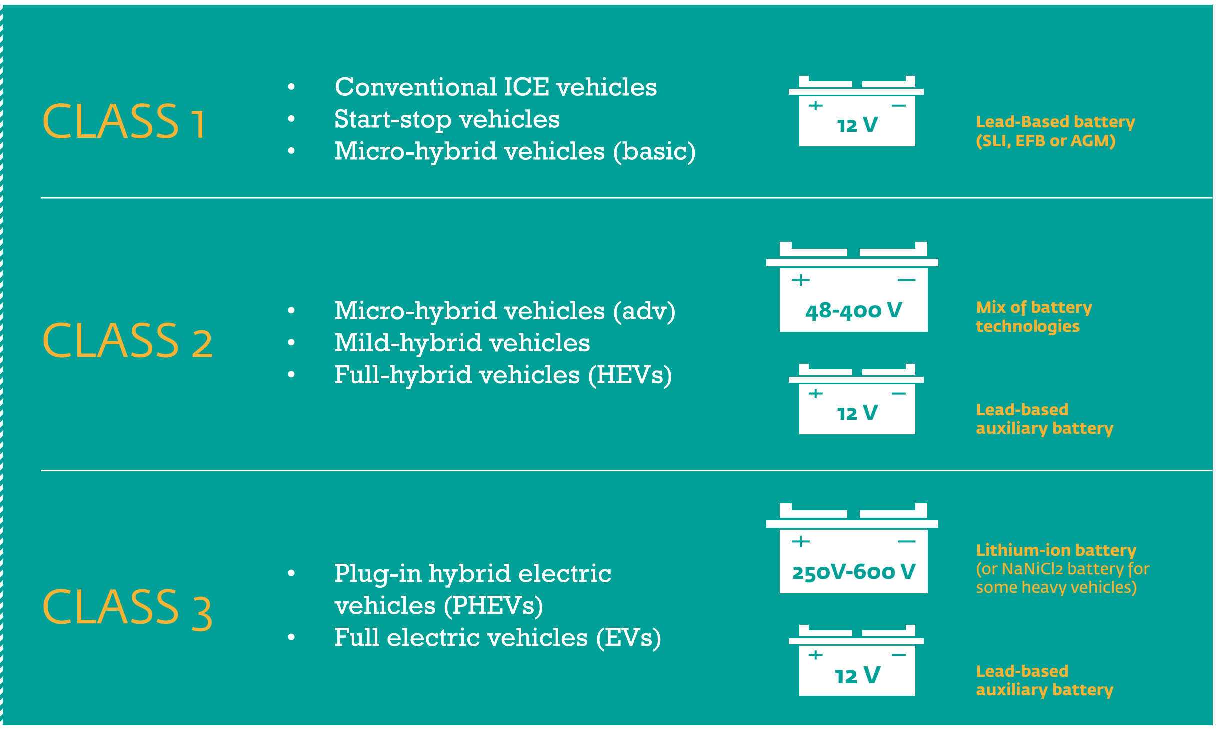
Each of these vehicle types place different requirements on the installed batteries, in terms of performance, lifetime, safety and cost.

CURRENT MARKET SITUATION

This report groups the vehicle types listed above into three classes, which can be differentiated according to the varying demands placed on the installed batteries:

CLASS 1 • Conventional vehicles (including vehicles with start-stop and basic micro-hybrid systems)

For conventional (ICE) vehicles - including start-stop and basic micro-hybrid vehicles - the 12V lead-based battery will continue to be the only viable mass market battery system for the foreseeable future. Its excellent cold-cranking ability, low combined cost and compatability with the vehicle's 12V electrical system set it apart from other battery technologies in conventional vehicles.



Overview of the three vehicle classes identified in this report, and their corresponding battery technologies

Advanced lead-based batteries (AGM and EFB technologies) are installed to meet extra requirements in start-stop and basic-micro-hybrd vehicles, due to their increased charge recoverability and higher deep-cycle resistance. In these applications, they again remain the only technology available for the mass-market.

Vehicles in this class will continue to comprise the majority of Europe's car parc for the foreseeable future.

CLASS 2 • Hybrid electric vehicles (including advanced micro-hybrid, mild-hybrid and full-hybrid vehicles)

In the different grades of hybrid vehicle, the battery is require to play a more active role, with energy stored from braking used to boost the vehicle's acceleration. In full-hybrid vehicles, the battery system is additionally employed for a certain range of electric driving.

Several battery technologies are able to provide these functions in different combinations, with nickel-metal hydride and lithium-ion batteries preferred at higher voltages due to their fast recharge capability, good discharge performance and lifetime endurance.

Although nickel-metal hydride batteries have been the predominant battery technology for full-hybrid vehicles, the decreasing costs of lithium-ion systems continue to improve their competitiveness.

These vehicles also utilise a second electrical system on a 12V level for comfort features, redundancy and safety features. This electrical system is supplied by a 12V lead-based battery.

CLASS 3 • Plug-in hybrid electric vehicles (PHEVs) and full electric vehicles (EVs)

In plug-in hybrid vehicles and full electric vehicles, high voltage systems of at least 15kWh are installed to provide significant levels of vehicle propulsion, either for daily trips (20-50km) in plug-in hybrid vehicles, or as the only energy source in full electric vehicles (100km+). In plug-in hybrid vehicles, the battery must also perform hybrid functions (i.e. regenerative braking) when its capability for electric drive is depleted.

Plug-in hybrid and electric passenger cars are propelled by lithium-ion battery systems. Due to their high energy density, fast recharge capability and high discharge power, lithium-ion batteries are the only available technology capable of meeting OEM requriements for vehicle driving range and chargeing time. For commercial applications, harsh environments and heavy duty vehicles, sodium-nickel chloride batteries are a competitive option. Nickel-metal hydride batteries and lead-based batteries cannot meet these requirements at a competitive weight.

Similar to hybrid vehicles, an auxiliary 12V lead-based battery is installed in all plug-in hybrid and electric vehicles to supply their electrical components, including the safety relevant features.

FUTURE TRENDS

The report also outlines how this market situation is expected to change in the foreseeable future (from now until 2025), and how individual battery technologies will continue to develop.

Lead-based batteries

For technical and socioeconomic reasons, 12V lead-based batteries will continue to be the essential mass-market system in Class 1 vehicles for the foreseeable future (and as auxiliary batteries in Class 2 and 3 vehicles).

By 2025, they will be expected to provide extra services in micro-hybrid vehicles to increase the internal combustion engine's fuel efficiency (i.e. stop-in-motion, voltage stabilisation). Therefore their cycle life, power density and charge acceptance will be further improved.

Lead-carbon batteries are expected to be commercialised in the near future, and will provide high performance in terms of charge acceptance and their ability to operate at partial states of charge in start-stop and micro-hybrid vehicles.

Dual batteries using lead-based batteries and other technologies at different voltages will also see accelerated commercialisation in the next decade.

Nickel-metal hydride batteries

Although nickel-metal hydride batteries have been an important technical resource in the rise of hybrid and electric vehicles, their potential for further market penetration is limited by the increased performance and reduced cost of lithium-ion batteries.

Because they have already reached a high degree of technological maturity, limited improvements are expected between now and 2025.

Lithium-ion batteries

Significant resources will continue to be spent on improving the performance, cost, systems integration, production processes, safety and recycability of high-voltage lithium-ion battery systems for hybrid and electric applications.

Large performance and cost improvements will be made through developments in cell materials and components (i.e. anode, cathode, separator and electrolyte). Lower cost cell design is expected by 2025, along with improvements in materials properties and the gradual scaling up in production of large cell formats.

These improvements will increase the competitiveness of lithium-ion batteries in other applications. It is expected that by 2025, lithium-ion batteries will be implemented in some 48V dual-battery systems together with a 12V lead-based battery to further increase fuel-efficiency in advanced micro-hybrid and mild-hybrid vehicles.

Sodium-nickel chloride batteries

In the coming years, sodium-nickel chloride batteries will be increasingly used in the automotive market for traction purposes in heavy duty plug-in hybrid and electric vehicles.

Manufacturers will work to improve the performance, cost, systems integration, production processes and safety parameters for sodium-nickel chloride batteries. Power density, cycle life, energy density and reliability are all expected to be improved by 2025, with overall cost to decrease significantly.

The study concludes that lead-based batteries will by necessity remain the most wide-spread energy storage system in automotive applications for the foreseeable future. Their low cost and unparalleled ability to start the engine at cold temperatures sets them apart in conventional and basic micro-hybrid vehicles, and as auxiliary batteries in all other automotive applications.

With regard to overall storage capacity and potential for further fuel efficiency improvements, reductions, the demand for larger battery systems based on lithium, nickel and sodium will continue to grow through the increased penetration of vehicles with higher levels of hybridsation and electrification.

2

Overview of battery technologies

for Automotive Applications

This report covers all types of automotive and industrial batteries that are used in vehicles on public roads, including lead-based batteries, nickel-metal hydride batteries, lithium-ion batteries and sodium nickel chloride batteries.

Under the EU Batteries Directive (2006/66/EC), automotive batteries are defined as "any battery or accumulator used for automotive starter, lighting or ignition power". Industrial batteries are defined as "any battery or accumulator designed for exclusively industrial or professional uses or used in any type of electric vehicle".

Different vehicle concepts require automotive and industrial batteries with different performance profiles and characteristics. For example, low temperature discharge power is a key requirement for cranking the ICE in conventional vehicles, but is not as important for batteries in electric vehicles. For these high voltage batteries, energy density and cycle life are of primary importance. The relevant characteristics for each application are outlined in this report.

Currently, several battery technologies are installed in European vehicles, from automotive batteries for internal combustion engine cranking (SLI) and start-stop functionalities, to industrial traction batteries for hybrid, plug-in hybrid and electric vehicles.

Where a single battery system cannot cope with all requirements at the same time, different combinations of several battery types are installed to operate at different voltage levels. For example, all hybrid, plug-in hybrid and electric vehicles are currently equipped with both an industrial traction battery and an auxiliary lead-based automotive battery, which is used to support the on-board electronics and safety features.

All large format battery technologies used in automotive applications are covered by the report. This includes:

LEAD-BASED BATTERIES

- For conventional vehicles, start-stop and basic micro-hybrid vehicles
- As auxiliary 12V batteries in all hybrid and electric vehicles

NICKEL METAL HYDRIDE BATTERIES

- For the propulsion of hybrid vehicles only

LITHIUM-ION BATTERIES

- For the propulsion of hybrid, plug-in hybrid, and full electric vehicles

SODIUM-NICKEL CHLORIDE BATTERIES

- For the propulsion of plug-in hybrid and full electric vehicles (primarily heavy commercial vehicles and public transport)

Other existing large-format battery technologies are not used in automotive applications, and so are not evaluated:

- Nickel-cadmium batteries
- Nickel-iron batteries
- Nickel-zinc batteries
- Sodium-sulphur batterie

To contextualise the report's forthcoming market analysis, this chapter provides a general overview of all existing automotive and industrial battery technologies, and explains why only certain types are used in automotive applications.

2.2

LEAD-BASED BATTERY TECHNOLOGY

OVERVIEW

Lead-based batteries (including lead-acid batteries) are the most widely used electrochemical system in Europe and worldwide, due to their proven safety, performance and low cost. In Europe, over 25,000 people are employed in the manufacture of automotive and industrial lead-based batteries.[1] All automotive SLI batteries are currently lead-based, as well as over 90% (by storage capacity) of industrial stationary and motive applications.

At end of life, within the EU the vast majority (>95%) of lead-based batteries are taken back and recycled by the battery industry and smelters in a closed-loop system, generating new batteries from secondary lead.[2] This is a rate higher than any other consumer product[3]. Because the lead in waste batteries does not enter into free circulation, there is no direct impact on the environment or human health.

LEAD-BASED BATTERIES FOR AUTOMOTIVE APPLICATIONS

Lead-based batteries are currently the only available mass-market technology for SLI applications in conventional vehicles, including those with start-stop and basic micro-hybrid systems, due to their excellent cold cranking performance, reliability and low cost. Starter batteries of 12V are standardised globally. The handling and behaviour of these batteries is well understood in all EU countries.

Advanced lead-based batteries (absorbent glass mat or enhanced flooded batteries) provide start-stop functionality to improve fuel efficiency in all micro- hybrid vehicles currently on the market. In start-stop systems, the internal combustion engine is automatically shut down under braking and rest, reducing fuel consumption by up to 5-10%.[3] In addition, some start-stop systems provide for regenerative braking, in which the vehicle's kinetic energy is converted to electricity and stored within the lead-based battery. Start-stop systems are already commercialised in several mass-market car models, with Pike Research estimating 37 million units for the global micro-hybrid car market by 2020.[4]

In comparison with other battery technologies, lead-based traction batteries are not competitive for use in full hybrid electric vehicles or electric vehicles because of their lower specific energy and higher weight. However, for all electrified powertrains (from micro-hybrid to full electric vehicles), the 12V board-net and electronic component supply are currently provided by auxiliary 12V lead-based batteries (in addition to the larger traction battery). The 12V lead-based battery is also used to maintain the safety management of the larger traction battery. This is expected to continue for the foreseeable future.

All lead-based batteries use the same basic chemistry. In vehicles, three lead-based sub-technologies are currently available:

- Flooded SLI batteries
- Enhanced flooded batteries (EFB)
- Absorbent glass mat (AGM) batteries

Flooded SLI batteries

Because of their lower cost, flooded lead-based batteries are used in the vast majority of conventional ICE vehicles to provide starter, lighting and ignition (SLI) functions. Flooded lead-based batteries are characterised by a vented design and an excess of free-flowing electrolyte between and above the electrode stack.

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[1] EUROBAT survey, 2012

[2] *Nachhaltihe Rohstoffnahe Produktion*, Fraunhofer Institut Chemical Technology (2007)

[3] Advanced Lead-acid battery consortium, 2012

[4] The driving force behind stop-start, innovative start-stop batteries from VARTA, Johnson Controls UK

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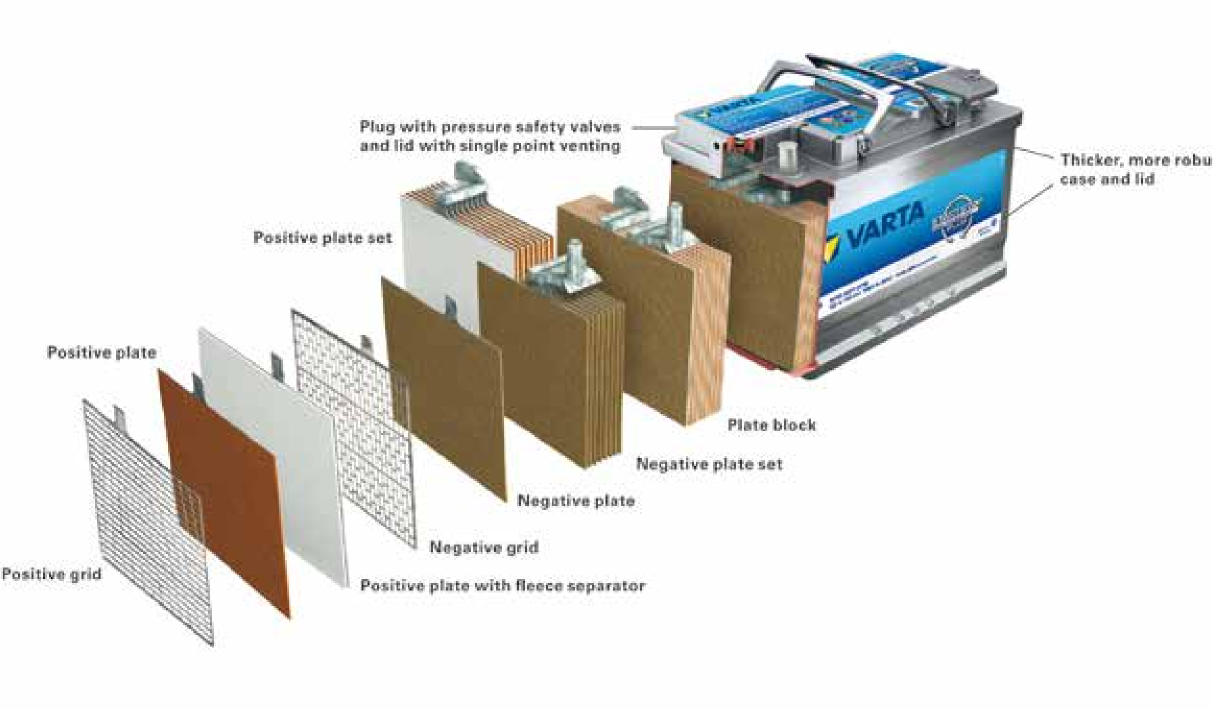
[5] *Stop-Start Vehicles - Global Market Analysis and Forecasts* - Pike Research, 2012



Example of an AGM Starter battery, Johnson Controls (2013)

Advanced lead-based batteries: AGM & EFB

Absorbent glass mat (AGM) and enhanced flooded (EFB) battery technologies have more recently been introduced for use in start-stop and basic micro-hybrid vehciles. These batteries have higher deep-cycle resistance and charge recoverability compared with flooded SLI batteries, in order to handle the more frequent stops and starts, and to provide a continued supply of electrical consumer units during the stop phase. The cranking performance of SLI batteries is carried over.

EFBs feature an improved flooded battery design with increased cyclic durability and increased ability to accept charge current, due to various changes in battery construction.

AGM batteries are valve-regulated lead-based batteries characterised by closed cells and an immobilised electrolyte held permanently in a glass fleece separator. This again allows for increased cyclic durability and improved charge recoverability.

Both EFB and AGM batteries are suitable for use in start-stop and micro-hybrid systems installed to improve fuel efficiency in conventional ICE vehicles. The deep cycling performance of AGM batteries makes them the technology of choice for vehicles with deeper cycling duty.

CHEMISTRY

Lead-based batteries all use the same basic chemistry. The active material of the positive plate mainly consists of lead dioxide, and the active material of the negative plate is finely dispersed metallic lead. These active materials react with the sulphuric acid electrolyte to form lead sulphate on discharge and the reactions are reversed on recharge. Batteries are constructed with lead grids to support the active materials. Individual cells are connected in series within a single plastic case. The nominal voltage of a cell is 2.0V.

Components of lead-based batteries [5]

- Lead and lead dioxide: average 60% of the total weight
- Electrolyte: diluted sulphuric acid: average 30% of the total weight
- Others, like alloying components and polymers (separators PE, battery case PP): average 10% of the total weight

Weight/lifecycle of lead-based batteries

The average total weight of a lead-based battery (flooded and EFB/AGM) for a compact passenger car is 18-20kg. The lifetime of an SLI battery heavily depends on usage patterns

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[5] *Derived from survey for EUROBAT members*

and the climate in the area of use. It can be estimated to be 5 – 7 years.

Successful efforts have been made to increase the efficiency of the lead-based battery by reducing the amount of lead needed to achieve the required performance. However, the increasing number of electrical components in cars and the additional functions that the battery is required to cover (e.g. start-stop functionality for improving fuel efficiency) has imposed extra requirements on the automotive battery (i.e. deeper and more frequent discharge), meaning there has not been a corresponding reduction in battery weight for EFB and AGM technologies.

EU Regulations

EU legislation governing the End-of-Life of automotive lead-based batteries includes the Batteries Directive (2006/66/EC) and the End-of-Life Vehicles Directive (2000/53/EC), with waste streams tracked through European Waste Codes.

2.3

NICKEL-BASED BATTERY TECHNOLOGY

OVERVIEW

Nickel-metal hydride batteries

NiMH batteries are primarily used in mild-hybrid and full-hybrid vehicles, where they have been the technology of choice over lithium-ion batteries because of their durability and lower cost.

At end of life, and in compliance with the Batteries and ELV Directives, all NiMH batteries from automotive applications are collected and recycled. The metals are used predominantly in the steel industry.

Nickel-cadmium batteries

NiCd batteries are used in specific industrial applications in which particular performance characteristics are required, including an excellent ability to take mechanical and electrical abuse, an ability to operate at extreme temperatures, and a lower loss of capacity when ageing. Industrial applications include air transportation, train, tram and metro rolling stock, and stand-by uses in extreme weather conditions.

NiCd batteries are no longer used in vehicles, and are only available as spare parts for vehicles put on the market before 2008.

Nickel-zinc and nickel-iron batteries

This report does not analyse nickel-zinc (NiZn) and nickel-iron (NiFe) batteries in detail, as currently these are not widely used in any automotive application, and this is expected to be the case for the foreseeable future. Both use nickel hydroxide based cathodes and work with a concentrated alkaline electrolyte, while the anode consists of either metallic zinc or iron.

NiZn batteries have been the subject of intensive research over several decades, with manufacturers still targeting the automotive segment. However, two main technical challenges still need to be solved under volume production and operating conditions: the negative Zn electrode's lack of stability under cycling conditions and the risk of dendrite growth leading to early internal short circuiting. At present, this prevents NiZn batteries from being used in applications where high reliability over a long period of life is requested, including the applications covered in this report.

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[6] Directive 2000/53/EC Article 4


HYBRID

NiMH battery used in Toyota Prius

Although NiFe batteries were used as an early rechargeable battery technology, they are unsuitable for use in automotive applications due to their low cycling stability, high self-discharge rate, and permanent hydrogen gassing.

NICKEL-BASED BATTERIES FOR AUTOMOTIVE APPLICATIONS

Nickel-metal hydride batteries

NiMH batteries have been the technology of choice in the HEV market over the last decade, due to their design flexibility, good energy density, high power performance and better environmental compatibility. This was the technology selected by Toyota when the Prius HEV was introduced in 1997. NiMH batteries are still significantly more expensive than lead-based batteries, and have not been considered for use in SLI functions because of their inferior cold-cranking performance and other limitations.

For plug-in HEVs and EVs, NiMH batteries have been an important technology while lithium-ion batteries develop to reach a sufficient maturity. However, their heavier weight, lower energy density and lower deep-cycling capability mean that they will not be able to compete with lithium-ion batteries for the next generation of plug-in HEVs and full EVs. This is apparent in Toyota's decision to use lithium-ion batteries for their plug-in hybrid Prius model.

Nickel-cadmium batteries

The use of cadmium in automotive batteries is restricted under the ELV Directive,[6] and so NiCd batteries cannot be considered to be an alternative for lead-based batteries or other batteries in vehicles. Therefore, only NiMH batteries will be considered in this report.

CHEMISTRIES

Nickel-metal hydride batteries

NiMH batteries comprise nickel hydroxide and hydrogen-absorbing alloys as basic components of the positive and negative active materials. These alloys operate in a concentrated alkaline electrolyte, usually with potassium hydroxide as the main constituent. The nominal voltage of a cell is 1.2V. Under charging, the hydrogen storing alloy (M) in the negative electrode absorbs hydrogen from the electrolyte, thus forming a metal hydride (MH). The most common hydrogen-absorbing materials are based on AB5 type alloys, where A is a rare earth mixture and B a metal composition consisting of nickel, cobalt, manganese and aluminium.

NiMH batteries have a very good power performance. However, their low temperature performance and electrochemical stability at elevated temperatures are reduced when compared with NiCd batteries.

Components of nickel-metal hydride batteries

- Nickel metal in substrate materials and hydrogen storing alloy: 55% weight
- Nickel oxide in cathode materials: 10% weight
- Cobalt additive in cathode & anode: 5% weight
- Rare Earths in NiMH batteries 15% weight
- Others (separator, electrolyte, binders): 10% weight

Weight/lifecycle of nickel-metal hydride batteries

NiMH batteries have excellent life endurance in terms of capacity turnover. When only a low depth of discharge is required (i.e. 5%), as in hybrid vehicles, 20,000 cycles are possible over battery lifetime.

The high nickel content and the significant amount of cobalt makes the product of interest for recycling and reuse. Nickel is among the most highly recycled metals in the world today, with most nickel from batteries ending up in the manufacture of stainless steel.

2.4 LITHIUM-BASED BATTERY TECHNOLOGY

OVERVIEW

Lithium-ion rechargeable battery systems entered the mass market of small-sized consumer applications in the early 1990s. Their up-front cost is at present significantly higher than corresponding battery technologies based on other chemistries. Therefore, larger-sized lithium-ion batteries are currently found in segments such as military and space applications, where their high energy and power density as well as their superior cycling ability create value. The high capacity of the active materials and a single cell voltage of up to 4.2V (depending on active material used) give lithium-ion the highest energy density of all rechargeable systems operating at room temperature.

In automotive applications, they are the product of choice for plug-in HEVs and full EVs, in which both these criteria are important. For hybrid vehicles, lithium-ion systems have started to compete with NiMH batteries and are now used at an industrial level in several hybrid cars on the market. For use in SLI, start-stop and micro-hybrid applications, lithium-ion batteries still require improvements in cold-cranking ability and economic packaging (including cost level) to be considered a viable mass-market alternative to lead-based batteries. Their strengths and limitations in these applications are under continual evaluation from European OEMs.

Research is also ongoing on the possible use of lithium-ion batteries in new segments of micro-hybrid application such as dual-battery systems (together with a 12V lead-based battery). In such combinations they provide benefits including good cycling ability and high energy yield. High levels of research and development are ongoing to raise their performance for electric vehicle applications, improve safety, and reduce costs, with strong developments projected in the next 10 years and beyond.

Lithium-ion Electric Vehicle Battery, courtesy of Nissan

At end-of-life, all lithium-ion batteries from vehicles are collected. Industrial zero-waste recycling processes at present mainly target the recovery of nickel, cobalt and copper. The recycling of lithium is technically and industrially feasible, but as only a small quantity is used in each battery (between 1 to 2% of their total weight), and because only a small number of large-format lithium-ion batteries have reached end of life, this has not yet become economically viable.

LITHIUM-BASED BATTERIES FOR AUTOMOTIVE APPLICATIONS

Lithium-ion batteries are used in hybrid and electric vehicles due to their high energy density and because their relatively greater expense is less of a barrier in these higher-end vehicles. Lithium-ion batteries are also being investigated for use in dual battery applications alongside a lead-based battery.

12V lithium-ion batteries are not expected to become a viable mass-market substitute for lead-based starter batteries in the next decade, due to limitations in their cold cranking ability and a higher cost. Early approaches are being undertaken by certain car manufacturers (with research continuing), but have so far been limited to niche applications in which weight savings are the primary driving factor and climatic conditions are not a concern.

CHEMISTRIES

There are several active materials used in lithium-ion rechargeable batteries. Systems using metallic lithium as a negative active material are called lithium-metal batteries, while systems based on carbon or lithium titanate as the negative active material are called lithium-ion. The positive active material is a lithiated metal oxide or a mixture of those components. The electrolyte is composed of fluorine-based lithium salts (such as LiPF6) dissolved in organic carbonate liquid mixtures. Non-aqueous solutions have to be used, as lithium reacts to water. A moisture-proof casing is essential to avoid moisture ingress and evaporation of the organic solvent.

While the battery is being charged, the lithium atoms from the positive electrode migrate as ions through the electrolyte toward the negative electrode, where they are deposited between carbon layers. This process is reversed during discharge. Lithium-based batteries are also available as lithium polymer batteries, which can, for example, use a lithium-metal alloy electrode in conjunction with a solid or gel-type electrolyte.

Different lithiated metal oxides are used by battery manufacturers in the battery's cathode or anode, each with unique performance characteristics.

For cells with cathode materials listed below and for graphite based anodes, the nominal voltages are in the range of 3.3V to 3.8V. When changing from graphite to lithium-titanate based anodes, the cell voltages are reduced by about 1V.

LITHIUM-ION CATHODE MATERIALS		
MATERIAL		ABBREVIATION
Lithium Cobalt Oxide	LiCoO2 (60% Co)	**LCO**
Lithium Manganese Oxide	LiMn2O4	**LMO**
Lithium Iron Phosphate	LiFePO4	**LFP**
Lithium Nickel Manganese Cobalt Oxide	LiNi0.33Mn 0.33Co0.330$_2$	**NMC**

Lithium-ion battery cathode (positive electrode) materials

LITHIUM-ION ANODE MATERIALS		
MATERIAL		ABBREVIATION
Graphite	Carbon (natural or synthetic graphite)	**C**
Lithium Titanate	Li4Ti5O12	**LTO**

Lithium-ion battery anode (negative electrode) materials

Components of lithium-ion batteries

- Various metal oxide-based materials for cathode
- Carbon based materials for anode
- Lithium salts
- Copper for negative substrate and collectors
- Aluminium or steel for positive substrate and cell case
- Others (separator, electrolyte, binders)

Weight / life cycle of lithium-ion batteries

Most available lithium-ion battery systems provide excellent calendar life and life cycle endurance, with performance depending on the specific operational mode and temperature. Recharge at low temperatures is restricted in order to avoid lithium-metal plating and early deterioration. With low depth of discharge (DoD), e.g. 2% to 5%, turnover figures of more than 20,000 nominal capacity throughput can be achieved. Under high DoD (e.g. 80%) more than 3000 cycles are feasible.

Various novel chemistries for the electrodes and the electrolyte are the subject of projects currently in the laboratory stage, with targets for first industrial applications to be established beyond 2025 (for example lithium-suphur or lithium-air batteries). More information on this is provided in Section 4 of the document.

When recycling lithium-ion batteries, a high recovery rate of materials is challenging in comparison with lead-based and nickel-based batteries. This is primarily due to the wide varieties of chemical components and system complexity. Several industrial recycling processes have begun to be established, and research projects are ongoing to recover a wider range of components, with nickel, cobalt and copper the most interesting constituents.[13]

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[7] http://www.epa.gov/dfe/pubs/projects/lbnp/about.htm

[8] http://www.hybridcars.com/hybrid-car-battery/

[9] http://www.epa.gov/dfe/pubs/projects/lbnp/about.htm

[11] No automotive application existing for Lithium Cobalt batteries

[12] LTO is an anode material. Other chemicals in the table are used as cathode materials. 13

[13] See for example the FP7 SOMABAT project, which focussed on the development of novel Solid Materials for high power Li polymer Batteries, including recyclability of components

2.5

SODIUM-BASED BATTERY TECHNOLOGY

OVERVIEW

Two types of sodium-based batteries are currently available: sodium-sulphur (NaS) batteries and sodium-nickel chloride ($NaNiCl_2$) batteries. Both operate at internal temperatures above 250°C.

Sodium-sulplur batteries were developed in the early 1980s, and are used exclusively in industrial applications such as electricity storage for grid support and space applications. Results from testing of sodium-sulphur batteries for electric vehicles during the early 1990s revealed that this technology was not suitable for automotive applications.

Sodium-nickel chlroide ($NaNiCl_2$) batteries have been commercialised since the 1990s and originally found application in heavy-duty hybrid and electric vehicles such as buses, trucks and vans. Today their use has been broadened to industrial applications, including telecom and back-up markets, and in on/off grid stationary energy storage systems used as large renewable energy power stations and for supply of ancillary services to the electrical grid.

Sodium-based batteries have a high energy density, long cycle life and can operate in harsh environments of temperatures from -40°C to +60°C due to their thermal insulation against the environment. They are fully recyclable within existing industries for the production of stainless steel and road paving.

SODIUM-BASED BATTERIES FOR AUTOMOTIVE APPLICATIONS

There are no manufacturers of sodium-sulphur batteries for automotive applications. Sodium-nickel chlroride batteries are found especially in electric vehicles and hybrid electric vehicles, including fleets of buses in Bologna, Rome, Lyon, Barcelona and Madrid.[14]

CHEMISTRY

Sodium-based batteries have a high energy density, long cycle life, and can operate in harsh environments (i.e. temperatures from -40°C to +60°C). Unlike many batteries, sodium-based batteries are based on a solid ceramic electrolyte with liquid sodium metal acting as the negative electrode. They operate at an internal temperature of between 250°C to 350°C to keep components in a molten state, which requires thermal insulation against the environment to avoid thermal losses. External heating is required in periods without electrical use to keep the battery ready to operate.

Sodium-nickel chlroride technology

The cathode in these batteries is based on nickel (Ni) and common salt (NaCl), while the anode consists of molten sodium (Na). The electrolyte is made up of tetrachloraluminate of sodium (such as $NaAlCl_4$), which is a liquid at the operating temperature of the cells. and by a ceramic separator that is conductive only for sodium ions. While the battery is being charged, nickel (Ni) and common salt (NaCl) will form the sodium ions and nickel chloride ($NiCl_2$). The sodium ions will move through the ceramic and fill up the anodic compartment. The reaction is reversed in discharge and there are no chemical side reactions. When the battery is operated, the heat produced by charging and discharging cycles compensates for the heat loss, and typically no external source is required.

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[14] For example Iveco's EcoDaily Electric van

3

Current Market Situation

While their excellent low-temperature performance and low combined cost makes lead-based batteries the only technologically feasible option for mass-market conventional vehicles, other battery technologies provide the required performance profile in vehicles with higher levels of hybridisation/electrification.

INTRODUCTION

This section evaluates the technological suitability of all battery technologies commercially available on the market in 2014 for different automotive applications. Chapter 4 will evaluate expected technological developments for all battery technologies up to 2025.

This analysis has been approached from a technology-neutral standpoint, with the report's authors supporting the coexistence of all battery technologies. Their selection in automotive applications depends on requirements regarding performance, life, safety and cost for a given application as well as the availability of resources to manufacture the batteries.

For the sake of simplification and to assure the comparability of battery technologies, three

	VEHICLE TYPE	PRIMARY BATTERY	REQUIREMENTS: PRIMARY BATTERY	SECONDARY BATTERY	REQUIREMENTS: SECONDARY BATTERY
Class 1	• Conventional vehicles • Start-stop vehicles • Micro-hybrid vehicles (basic)	• Lead-based battery (12V)	• Cold cranking performance • Capacity to bridge periods of engine shut-down; supply safety devices • 12V compatability		
Class 2	• Micro-hybrid vehicles (advanced) • Mild-hybrid vehicles • Full-hybrid vehicles (HEVs)	• Lithium-ion, nickel metal hydride or lead-based battery (48-400V)	• Cold cranking performance • Discharge power • Recharge power (recuperation) • High energy throughput	• *Lead-based battery (12V)*	• *Capacity to bridge key-off periods; supply safety devices* • *12V compatability*
Class 3	• Plug-in hybrid electric vehicles (PHEVs) • Full electric vehicles (EVs)	• Lithium-ion battery (or sodium nickel chloride battery) (250-500V)	• Energy density • Recharge power (external) • Discharge power • High energy throughput	• *Lead-based battery (12V)*	• *Capacity to bridge key-off periods; supply safety devices* • *12V compatability*

Summary of battery requirements in each vehicle class

groups of application and corresponding battery performance characteristics will be referred to, which can be differentiated according to the varying demands placed on the installed batteries.

For each class, the report provides a detailed evaluation of the different requirements placed on the battery system, and makes conclusions on which battery technology can meet those requirements.

Class 1: Conventional vehicles (including start-stop and micro-hybrid vehicles)

This vehicle class requires 12V automotive batteries to crank the engine of conventional ICE vehicles and to supply the 12V electrical system in all vehicle types (SLI functionality). These batteries can also be expected to provide start-stop functionality and entry-level braking recuperation.

Class 2: Hybrid vehicles (micro-hybrid, mild-hybrid and full-hybrid vehicles)

Vehicles with a level of hybridisation require industrial traction batteries ranging from 48 to 400V. These batteries provide several advanced functions to improve fuel efficiency in hybrid vehicles. The energy stored from braking is used to boost the vehicle's acceleration, and in full-hybrid vehicles, it is additionally employed for a certain range of electric driving.

Class 3: Plug-in hybrid vehicles and electric vehicles

In plug-in hybrid and full-electric vehicles, high voltage battery systems of at least 15kWh are installed to provide significant levels of electric propulsion, either for daily trips (20-50km) in plug-in hybrid vehicles, or as the only energy source in full electric vehicles (100km+). In plug-in hybrid vehicles, the battery must also perform hybrid functions (i.e. regenerative braking) when its capability for electric drive is depleted.

3.1

CLASS 1

CONVENTIONAL VEHICLES (INCLUDING START-STOP AND BASIC MICRO-HYBRID VEHICLES)

OVERVIEW

Automotive SLI batteries are required to power a vehicle's starter motor, lights, and ignition system, as well as providing power to the vehicle's on-board electronics. In start-stop and basic micro-hybrid vehicles the installed battery must also provide start-stop functionality and entry-level braking recuperation. This demands progressively higher deep-cycle resistance and charge recoverability, in order to deal with the vehicle's frequent stops and starts, and to provide a continued electricity supply during the stop phase.

Lead-based batteries are currently the only available mass-market technology for these applications.

BATTERY PERFORMANCE PROFILES FOR CLASS 1 APPLICATIONS

	Lead-based	NiMH	Lithium-ion	$NaNiCl_2$
Power density , (@-18°C, 10sec)	350 W/kg 800 W/l	270 W/kg 380 W/l	360 W/kg 430 W/l	N/A
Energy density (@25°C, 20h)	35-50 Wh/kg 80-120 Wh/l	35 Wh/kg 50 Wh/l	70 Wh/kg 85 Wh/l	
Self-discharge rate (@ 20°C)	~3% per month	~15-20% per month	~5% per month	
Optimal ambient T/°C range	-20 to +50°C	-10 to +45°C	-10 to +45°C	
Operating ambient T/°C range	-30 to +75 °C	-10 to +45°C	-25 to +55°C	
Operational lifetime	5-7 years (engine compartment, w/o cooling; does not need additional control units & sensors)	No experience in SLI application (in HEV applications with active cooling system 8 to 10 years)	No experience in SLI application (prognosis in HEV applications with active cooling system 10 years). Separate cooling would be necessary, as well as control electronics to prevent overheating. Packaging restrictions apply.	
Cost (€/kWh) / (€/kW) [15]	50-150 €/kWh 6-18 €/kW	700- 1400 €/kWh 90 - 180 €/kW	600-1200 €/kWh 118 -236 €/kW	

Detailed Analysis of battery technologies for conventional vehicles (including start-stop and micro-hybrid vehicles)

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[15] All cost ranges given in this reports are general estimations made by the ELV WG according to publically available market data

There are several essential requirements that automotive SLI batteries are required to fulfil:

1. Cold Cranking Performance
The battery's ability to effectively start an engine at low temperatures (down to -30°C). The vehicle's electric cranking motor requires high currents to convert electrical energy into sufficient mechanical energy. The battery's ability to provide high currents with stable voltage decreases with low temperatures, and consequently higher cold-cranking amperes (500 to 1000 CCA) are requested as part of OEMs' vehicle specification, to assure cranking function can be provided in very cold weather conditions.
In order to recharge the battery, charge acceptance at very low temperatures is also required (i.e. -10°C to -30°C).

2. Calendar Life
The elapsed time before a battery becomes unusable, whether it is in active use or is inactive. Current SLI batteries can be expected to have a calendar life of 5-7 years before replacement becomes necessary.

3. Safety
At present, SLI batteries are often placed in the engine compartment (to minimise cable resistance) and may operate at high temperatures. Services and cell stability must be maintained in all reasonable conditions.

4. On-board electronic (board-net) voltage
In all cases, a vehicle's on-board electronics operate at 12V. This includes the lighting for the car as well as control electronics, entertainment, navigation, and safety devices such as airbags or door lock systems . The operating voltage of electrical/electronic components have been globally standardised at this level, and installed batteries must be compatible with these 12V systems.

5. Cost
SLI batteries are a mass-market technology essential in all ICE-powered vehicles currently on the global market. Cost-efficiency is a primary differential for OEMs and consumers, in order to optimise overall vehicle costs and maintain competitiveness.

6. Manufacturing Base and Resource Availability
Automotive batteries are required in all 250 million vehicles of this class in Europe. Smaller 12V batteries are also currently required in all HEVs, PHEVs and EVs. A well-established and strong battery manufacturing base is required to fulfil this demand. The availability of resources used in each battery technology should be taken into account.

LEAD-BASED BATTERIES

Cold Cranking Performance

The recommended temperature range to operate a lead-based battery is between -30 and +75°C.[16] Lead-based batteries have a volumetric power of approximately 800 W/l at temperatures below -18°C, for a period of more than 10 seconds. At the end of its service life, the battery's power performance in cold temperatures will still be above 450W/l.

Consequently, lead-based batteries are able to reliably start a vehicle's combustion engine at low temperatures, something that has traditionally set them apart from other technologies. Their cranking capability is ensured even at lower temperatures down to -30°C, as required in regions of Northern and Eastern Europe and as specified by vehicle manufacturers. Reliable cold cranking performance is also secured in start-stop applications when advanced EFB and AGM designs are used.

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[16] EN 50 272-1

Calendar life

Lead-based batteries are highly durable, with their calendar life not significantly affected by high/low temperatures (although self-discharge and water evaporation from the electrolyte does increase). Lead-based batteries can be placed under the hood of the vehicle (close to the starter motor) without need for a heat-shield or a cooling system. The average calendar life of a lead-based SLI battery is 5-7 years.

An equivalent operational life is also demonstrated by advaced AGM/EFB batteries in start-stop and basic-micro-hybrid applications, after years of operation in partial states of charge (PSoC). Although such duty profiles typically generate electrolyte stratification for flooded battery designs, lowering capacity and accelerating aging, this effect is immobilised when the electrolyte is immobilised, as in AGM battery designs.

Safety

Lead-based batteries are regarded as intrinsically safe systems, both in production and operation, and can be operated within a wide temperature range. This is confirmed by a long history and by practical experience. Most lead-based batteries are sealed and the evaporation rate of the electrolyte is relatively low. Gas evolution is futher reduced with immobilised electrolyte designs such as AGM, and there is no spillage when the container is cracked, e.g. during an accident. Specific cooling is not required.

On-board electronic voltage

The vehicle's electrical system is globally standardised for all vehicles – from ICE up to EV – to be compatible with 12V lead-based batteries. A solution without a 12V battery would require either the use of a DC/DC converter (with significant additional costs) or the redesign of the board-net architecture and voltage level, which is not expected on a global basis. In start-stop and basic micro-hybrid vehicles, advanced EFB and AGM batteries in are also compatible with the 12V electrical system.

Cost

At present, lead-based batteries remain by far the most cost-effective and durable battery technology for SLI applications in conventional powertrains (in the region of 50-150 €/kWh). On top of their lower cell-level cost, they do not require heat shielding, active cooling, nor a battery management system. This is an important consideration for consumers and the automotive industry, due to the higher financial burdens that a more expensive alternative battery system would place on them.

Manufacturing base and resource availability

The European lead-based battery industry is well-developed, with over 25,000 workers. At present, the European battery industry is equipped to manufacture only lead-based SLI batteries at the mass market scale of 70 million units, which is required annually to fulfill European demand.[17] To serve the swiftly increasing market for start-stop applications, the manufacturing capability for AGM-type batteries is approaching 10 million per year in Europe. On a socioeconomic level, using alternative technologies would require major investment and restructuring as well as a long lead-in time.

Lead is without doubt the most recycled metal of all those commonly used. In 2007, Fraunhofer-Institut für Chemische Technologie confirmed that at end-of-life, the vast majority (>95%) of lead-based batteries in Europe are collected and recycled by the battery industry and other smelters in a closed-loop system. This is a rate higher than any other consumer product sold on the European market.[18]

In 2012, 10.6 million tonnes of lead were produced globally, and 1.3 million tonnes in Europe. In 2012, 75% of lead produced in Europe originated from secondary sources, the majority of which was comprised of spent lead-based batteries. Currently, 85% of refined lead produced is used to manufacture batteries, and as such most recycled lead is reused in the manufacture of new batteries. Recently, the International Lead Association assessed the resource availability of lead-based batteries and concluded that there are no long-term concerns about their availability.[19]

NICKEL-BASED BATTERIES

Cold Cranking Performance

NiMH batteries would need to be considerably oversized if they were to provide the necessary cold-cranking amperage to start an engine, in comparison with a

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[17] *European Starter Battery Market 2012-2016*, EUROBAT (2013)

[18] Nachhaltihe Rohstoffnahe Produktion, Fraunhofer-Institut für Chemische Technologi (2007)

[19] All data from *"Resource Availability of Materials used in automotive battery technologies"*. – International Lead Association (2014)

lead-based battery for the same type of vehicle. In 2010, Roland Berger estimated the oversizing factor to be approximately 30% at temperatures down to -18°C; corresponding with a weight increase of 10% for the NiMH battery, and increased overall costs.[20] Power capability at lower temperatures down to -30°C is not ensured.

Calendar Life

The calendar life of NiMH traction batteries used in full-hybrid vehicles is approximately 8-10 years. There is no experience from using them as a starter battery, but it can be assumed their calendar life would be reduced significantly due to the high temperatures in the engine compartment.[21] Even the use of a thermal management system (with a further cost for the overall system) cannot overcome this issue, as the heat after engine stop continues to warm up the battery even as the cooling is deactivated.

Safety

NiMH batteries are intrinsically safe battery systems. This is confirmed by practical experiences in hybrid vehicles. As with other aqueous systems, there may be natural gas production under abuse conditions (overcharging). This requires additional care when employing these systems in vehicles and for other applications. An electronic battery management system must be installed to maintain correct operating parameters.

On-board electronic voltage

About 10 cells in series are necessary for compatibility with a vehicle's standardised 12V architecture. The voltage characteristics of nickel-based systems are rather flat and for that reason are generally aligned with what is used in vehicles today.

Cost

NiMH batteries for SLI applications would cost approximately 4-5 times more than their lead-based equivalents, due to higher cell costs and the additional costs for their battery management system, shielding and housing. This cost differential is too high for NiMH SLI batteries to be considered as a viable alternative technology for use in mass-market conventional vehicles.

Manufacturing base and resource availability

Nickel is mined throughout the world, including in Europe. The metal is used in a variety of applications, particularly as an alloy. Reserves of nickel are sufficient to satisfy demands for the metal for decades, and exploration is finding additional deposits for possible future deployment.[22]

Nickel is also easily recycled from many of its applications. Due to its high recyclability, only about 1.4 million tonnes of primary nickel is produced annually.[23]

LITHIUM-BASED BATTERIES

Cold cranking performance

Specially designed lithium-ion batteries are technically capable of satisfying a conventional vehicle's cold-cranking requirements down to the reference temperature of -18°C.

At lower temperatures down to -30°C, lithium-ion batteries still have significantly inferior discharge characteristics and need to be oversized in order to meet the individual vehicle's cold cranking power demand. Furthermore, a limited recharge rate at low temperatures must be taken into account.

Calendar life

The calendar life of lithium-ion traction batteries used in hybrid vehicles (and PHEVs/EVs) is approximately 10 years. If used as a starter battery, its calendar life would be reduced to two to four years because of the high temperatures caused by close proximity to the engine (which is needed to avoid high cable resistance). Even the use of a thermal management system (with a further cost for the overall system) cannot overcome this issue, as the heat after engine stop continues to warm up the battery while the cooling is already deactivated in key-off periods.

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[20] *Impact of the end date for the exemption of lead in automotive batteries* – Roland Berger, 2010

[21] *Ibid.*

[22] Critical Metals in Strategic Energy Technologies – European Commission Joint Research Centre, 2011

[23] Information from "Resource Availability of Materials used in automotive battery technologies". – International Lead Association (2014)

Safety

Operations of lithium-ion batteries are restricted to a specific temperature and voltage range. If operated at temperatures or cell voltages outside of the operational window, the battery no longer provides services, with ptential risk to its surroundings.

(N.B.: In single battery architectures including ICE vehicles with start-stop and micro-hybrid features, it is not permitted to disconnect the battery at any time, in order to ensure the operation of essential features such as the hazard warning lights).

The management system incorporated in the battery monitors and restricts temperature and voltage parameters at cell, module and battery level. This increase in technological complexity results in additional costs.

Costs

On a cell level, the upfront costs of lithium-ion batteries remain significantly higher than for equivalent lead-based batteries. System level cost is further increased by the required battery management system, shielding and housing (with total upfront system cost ranging from 600-1200 €/kWh).

Although some of these high upfront costs could eventually be distributed over the Total Cost of Ownership (TCO), they remain another barrier against lithium-ion batteries being considered as a viable alternative to lead-based batteries for use in mass-market conventional vehicles with a single 12V battery with SLI function.

Manufacturing base and resource availability

There is already a strong lithium-ion battery industry for portable applications, primarily in Asian countries (China, Japan and South Korea). This has allowed Asian industry to develop a strong market presence in production of large-format lithium-ion batteries, taking advantage of what has been technically achieved and implemented since the lithium-ion chemistry first appeared on the market two decades ago. Additionally, a strong industry for machinery and material supply has been established in that period.

The manufacturing base for lithium-ion batteries in Europe is well developed for the needs of existing industrial and military applications, with several plants and R&D facilities installed across the continent. In recent years, this industrial base has begun adapting to the additional demand for serial lithium-ion battery production for hybrid and electric vehicles. If lithium-ion batteries are to be required to fulfil SLI functions in all European commercialised vehicles, major and prolonged investment and restructuring of this manufacturing base would be required to meet extra demand.

The majority of primary lithium originates from salt lakes in Bolivia, Chile and Argentina, where it is obtained by evaporation of the water from the salt lakes.Current estimates suggest that resources are sufficient for the EU to fulfil rising demand for Hybrid Electric and Electric vehicles until at least 2030. However, were lithium-ion batteries required to replace all lead-based batteries with an SLI function, there would be a significant difference between lithium demand and current production. This deficit would have to be met by significantly increasing the primary production of lithium, and should be taken into account.[24]

Information on the recycling of lithium-ion batteries is available on pages 20-22.

SODIUM-BASED BATTERIES

Being mostly an energy battery type, the classic SLI is not today a realistic application for sodium-based batteries: the technology has not been developed nor considered for this purpose.

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[24] From *"Resource Availability of Materials used in automotive battery technologies"*. – International Lead Association (2014)

CONCLUSION

From the above analysis, it is clear that lead-based batteries remain the only technologically viable mass-market option for conventional vehicles, as well as for start-stop and micro-hybrid vehicles. Their excellent performance in cold and hot conditions and their low combined cost sets them apart from other battery technologies. This, combined with their low self-discharge rate, unmatched reliability, safety and the well-established European manufacturing and recycling industry, establish them as the most practical option for the foreseeable future.

The further advancement and development of lithium-ion batteries could permit an opportunity for their use in limited SLI applications, albeit primarily as a performance option when weight saving is a sufficient driving factor to accept increased cost and their lower performance in cold conditions.

European OEMs are continuing R&D efforts to evaluate the limitations and benefits of lithium-ion technologies in real applications, in order to develop further insights on this topic.

3.2 CLASS 2

HYBRID ELECTRIC VEHICLES (INCLUDING ADVANCED MICRO-HYBRID, MILD-HYBRID AND FULL-HYBRID VEHICLES)

Overview

In hybrid vehicles, extra requirements are placed on the battery system. The energy stored from braking is used to boost the vehicle's acceleration, and in full-hybrid vehicles, it is additionally used for a certain range of electric driving.

Hybrid vehicle batteries are only required to store a small amount of energy, as they are recharged frequently during driving. They operate at a low depth-of-discharge (<5%), and do not fully charge. Due to the large number of micro-cycles they must carry out, hybrid batteries require more power than energy, in contrast to electric vehicle batteries.

The hybrid functions listed above require a battery technology with low internal resistance and high power performance. Its energy storage capability is also important, allowing the vehicle to operate independently of the internal combustion engine.

In contrast, batteries for advanced micro-hybrid and mild hybrid vehicles are characterised by lower demands for power performance. High energy efficiency and charge acceptance is still essential, although the required energy content is smaller.

Typical requirements for Class 2 batteries:

1. **Voltage range** - The voltage range for all hybrid vehicles is higher than for SLI applications. It ranges from 48V for Micro -hybrids to more than 400V for full HEVs.

2. **Discharge power** - For micro-hybrids, a small boost power of about 10 kW may be adequate. Full HEVs require a power performance of up to 80 kW for a mid-size vehicle.

3. **Recharge power** - A battery's recharge power reflects its ability to reabsorb energy from braking and deceleration. This may range from less than 10 kW for micro-hybrids to more than 50kW pulses for full-hybrid vehicles.

4. **Cold cranking** - Similar to SLI battery requirements, a certain power performance is needed to crank the internal combustion engine (ICE) of the vehicle even at very low temperatures (-18°C). Depending on the individual combustion engines, 5kW to 7kW pulses of approximately five seconds in length are normally required by vehicle manufacturers.

5. **Energy content** - For micro-hybrid applications, an energy storage capability of approximately 0.2 to 1 kWh is sufficient. Full hybrid vehicles require batteries of more than 1.5 kWh to provide all functions, including electric drive.

6. **Capacity and calendar life** - Hybrid vehicle batteries generally experience much higher capacity turnover than conventional SLI batteries. This is due to their direct involvement in the vehicle's part-electric drive train system. In comparison with electric vehicles, the depth of discharge remains

BATTERY PERFORMANCE PROFILES FOR CLASS 2 APPLICATIONS

	Lead-Based	NiMH	Lithium-Ion	NaNiCl2
Power density (@20°C, 10sec)	500 W/kg 1.100 W/l	1200 W/kg 3000 W/l	1500 W/kg 3000 W/l	Sodium technologies are not suitable for use in hybrid passenger cars. They are used in heavy duty vehicles with required energy over 20kWh
Energy density (@25°C, 20h)	30-45 Wh/kg 80-110 Wh/l	40 Wh/kg 100 Wh/l	70 Wh/kg 130 Wh/l	
Self-discharge rate (@ 20°C)	~3% per month	~15-20% per month	~2-5% per month	
Optimal ambient T/°C	0 to +40° °C	-10 to +45°C	-10 to +45°C	
Operating ambient T/°C range	-30 to +75 °C	-10 to +45°C	-10 to +55°C	
Operational lifetime	No market experience in series hybrid application	In applications with active cooling system 8 to 10 years	Product on the road since 2009, industrial production qualified by several European car manufacturers for 10 year duration	
Cost	100-200 €/kWh 10-20 €/kW	800-1400 €/kWh 27 - 47 €/kW	800-1200 €/kWh 30-75 €/kW	

Detailed Analysis of Technologies for Hybrid Applications (48-400V / 2kWh)

low (<5%), but there may be many of these micro-cycles in a short time period. Over the battery's lifetime, more than 10,000 nominal capacity turnovers will be required.

Besides cycle life endurance, calendar life is a critical feature. More than 10 years of service life are expected from vehicle manufacturers.

7. Safety - The system is expected to behave safely under all operational and non-operational conditions.

8. Cost - Vehicle manufacturers place cost limitations on the battery system, that vary depending on their specific vehicle concept.

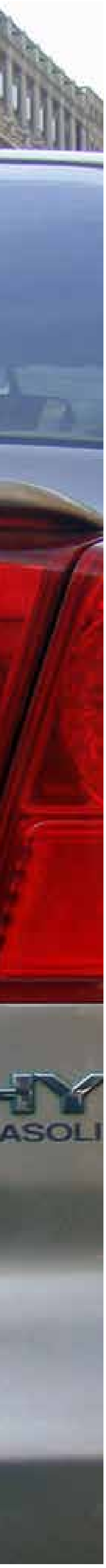
9. Manufacturing base and resource availability - As hybrid vehicle technology achieves greater market penetration, the availability of manufacturing sites has become increasingly important. As hybrid batteries are significantly larger than those used for SLI applications, new manufacturing capability will eventually be needed to meet demand.

10. Weight & volume – Vehicle manufacturers require hybrid batteries to be as small and light as possible.

LEAD-BASED BATTERIES

Voltage range

In general, it is not a problem to produce lead-based batteries up to hundreds of volts, as demonstrated in stationary applications. However, such batteries have to be carefully monitored to avoid overcharge and over-



discharge, especially under fast cycling conditions.

Discharge power

Meeting higher power demands, especially under continuous discharge, affects the battery's life endurance as a thinner electrode configuration must be used. Batteries with reliable life endurance allow a continuous power-to-energy ratio of 3 kW/kWh. This makes it difficult to serve longer acceleration periods in vehicles with small batteries.

Recharge power

Lead-based batteries are limited in their recharge power capability. The typical recharge power for a 1 kWh system is sufficient for a micro-hybrid vehicle, but will not meet full HEV requirements.

Cold cranking

Lead-based batteries with more than 800Wh are able to meet cold cranking requirements (-18°C), which consist of a 10 second pulse with a power in the range from 5kW to 7kW.

Energy content

The energy-to-weight content of a lead-based power-optimised system is in the range of 30-45Wh/kg.

Capacity and calendar life

Even at low depth of discharge (DoD), lead-bsaed batteries have a modest maximum capacity turnover, which is unable to meet the requirements of full HEVs. Lithium-ion and NiMH systems provide figures more than 15 times higher.

It should also be noted that the lead-based battery's lower energy density would inhibit the vehicle's electric-only range.Expected calendar life is more than seven years.

Safety

Due to the use of an aqueous electrolyte, the system is very safe from a chemical perspective. Management of high voltages is a separate issue affecting all battery systems. A fire is unlikely even in the event of a short circuit.

Cost

The cost on a kWh basis is the lowest among all currently available battery systems.

However, when sizing the battery to deliver the required power capability and capacity turnover, lithium-ion and NiMH batteries become more cost-competitive.

Manufacturing base + resource availability

Lead-based batteries are the most widely available system for automotive and industrial applications, with a strong existing manufacturing base in Europe. As highlighted in Section 3.1, the vast majority of lead-based batteries are taken back and recycled at end-of-life in a closed loop system,[25] and there are no long-term concerns associated with their resource availability.[25]

NICKEL -BASED BATTERIES

Voltage range

NiMH cells can be combined into batteries to reach high voltages. As the single cell voltage is relatively low (1.2V), many cells must be connected in series to reach the required voltage. Usually, these cells are connected to sub-modules that serve as the basic element of larger battery systems. The voltage and temperature of these modules are controlled by electronic devices.

Discharge power

The availability of relatively thin electrodes gives NiMH batteries a high continuous power performance. Values of up to 1200 W/kg are achievable on a system level.

Recharge power

Due to its excellent charge absorption, the NiMH system also provides superior recharge performance. Here, the only limitation is the battery's upper voltage, state-of-charge, and temperature. Under normal ambient conditions, a specific recharge power capability of up to 1000 W/kg is possible.

Cold cranking

Continuous discharge capability strongly decreases for NiMH batteries at lower temperatures. Nonetheless, short pulses (5kW for 5 seconds) can be delivered by a 1 kWh NiMH hybrid battery system. This is sufficient to meet cold cranking requirements.

Energy content

NiMH hybrid batteries have a modest energy content, comparable to lead-based batteries in SLI applications. Values of 35-40 Wh/kg (on a gravimetric base) are usual.

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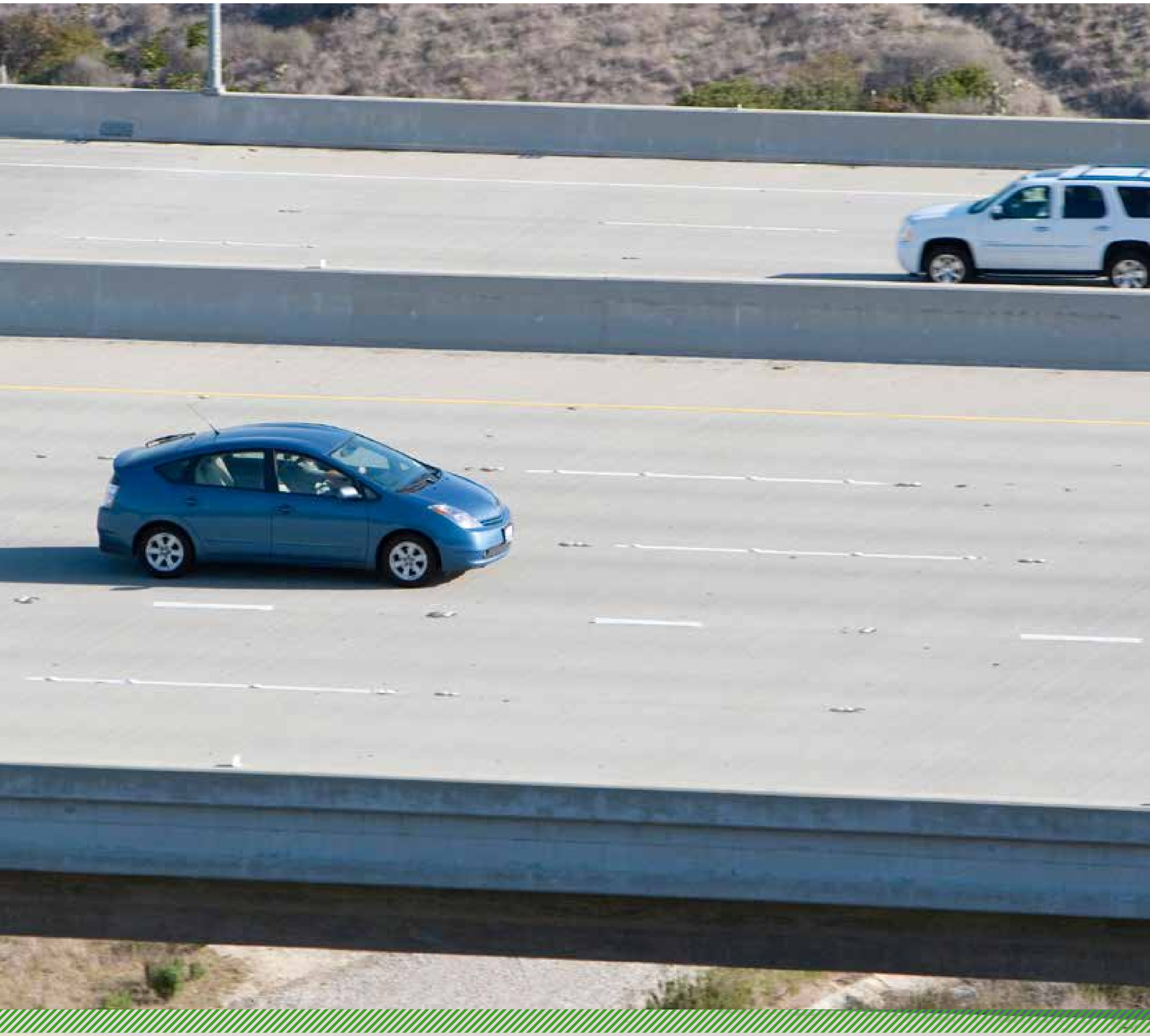
[25] Nachhaltihe Rohstoffnahe Produktion, Fraunhofer Institut Chemical Technology (2007)

[26] *Initial Battery Materials Survey* – International Lead Association (2013)


HYBRID
GASOLINE-ELECTRIC



Capacity and calendar life

The cycling stability of NiMH high power batteries strongly depends on the required depth of discharge Under 100% discharge conditions, 3,000 cycles can typically be achieved. Reducing the DoD to less than 5%, as required by most hybrid vehicles, increases the battery's nominal capacity turnover to more than 15,000 cycles.

Safety

The aqueous-based electrolyte and the relatively modest energy content make NiMH a safe system.

Weight and Volume

NiMH batteries offer a compromise between weight and volume which, combined with other characteristics (particularly their technological maturity at the time hybrid vehicles started to be manufactured), have enabled strong penetration in hybrid vehicles.

Cost

The use of nickel as a material covering more than half of the battery's weight share, combined with the use of rare earth materials, make NiMH batteries significantly more expensive than lead-based battery systems. On a system level, the cost of high-power systems for hybrids is expected to vary between 800-1400 €/kWh (27-47 €/kW in terms of power).

Manufacturing base and resource availability

As NiMH batteries have been displaced from portable markets, there are only a few mass manufacturing sites available, most of them in Asia. At present, the biggest manufacturer of NiMH HEV batteries remains Toyota/PEVE.

LITHIUM-BASED BATTERIES

Voltage range

Because of their higher cell voltage, it is possible to build high voltage lithium-ion batteries with a lower number of cells, compared with other technologies. As long as normal safety measures are taken, there is no maximium voltage limitation.

Discharge power

Hybrid vehicle applications require high discharge performance and low internal resistance. Through special design, lithium-ion batteires can provide continuous discharge rates of up to 30C. This translates into a typical specific power performance of up to 2700W/kg on system level.

Recharge power

Recharge power depends strongly on the temperature of the battery system. Charging at low temperatures may lead to lithium plating, which causes a degradation of the battery system. At 25°C, the charge performance of lithium-ion battery systems can be as high as 30 kW/kWh.

Cold cranking

HEV battery systems based on lithium-ion technology, with an energy content significantly above 1kWh, are capable of 6-8 kW pulses (10 seconds) at -18°C. This allows lithium-ion batteries to narrowly meet the engine cranking requirements for this class of vehicles.

Energy content

The maximum specific energy content of lithium-ion systems for hybrid applications is in the range of 70 Wh/kg, with volumetric values at about 130 Wh/l. This is impacted by the battery's size and employed auxiliary devices. Different battery designs allow for larger sizing to meet higher energy requirements.

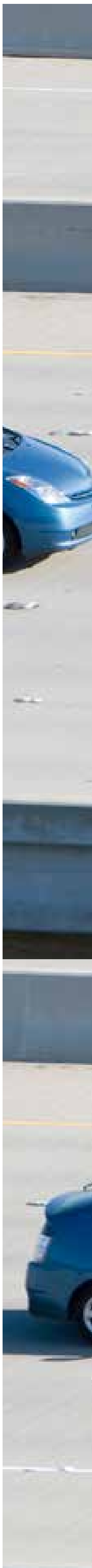
Capacity and calendar life

Under typical HEV conditions with smaller micro-cycles at low depth of discharge, lithium-ion batteries supply excellent capacity turnover. Under a high depth of discharge, a large number of cycles can also be achieved. Calendar life at normal ambient temperatures is expected to exceed 10 years and may reach more than 20 years.[27]

Safety

Mainly due to their organic electrolyte and relatively high energy content, lithium-ion battery systems presents more safety challenges than nickel and lead-based batteries. It is particularly important the the individual cell voltage ranges are adequately controlled. Overcharging caused by exceeding specified thermal limits may cause critical thermal events.

Lithium-ion batteries are equipped with sophisticated control electronics (battery management systems, cooling systems etc.),



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[27] However, field experience for 10 years under real use conditions is still missing, so this will need to be validated.

which offer precise management and state-of-charge control, ensuring safe operation in line with these parameters.

Weight and volume

Lithium-ion batteries offer optimum performance from this point of view.

Cost

More technically demanding manufacturing technology (thin and long electrodes, high sealing quality) and the use of more sophisticated materials make the lithium-ion system relatively expensive in comparison with other battery technologies. Depending on the specific technology and battery design, costs on an energy basis are in the range of 800-1200 €/kWh. Based on given power capability, this translates to 30-75 €/kW.

Manufacturing base and resource availability

Please refer to Section 3.1 for an overview of the manufacturing base and resources for lithium-ion batteries. Current estimates suggest that resources are sufficient for the EU to fulfil rising demand for hybrid and electric vehicles, assuming no significant changes in demand in other applications.

SODIUM-BASED BATTERIES

Because of their relatively low power-to-energy ratio, sodium nickel-chloride batteries are not available at small enough sizes for use in hybrid passenger cars. However, sodium-nickel chloride batteries are appropriate for use in heavy duty hybrid vehicles such as buses or trucks, where the energy required exceeds 20kWh.

CONCLUSION

In ICE vehicles with higher degrees of electrification, including intensive recuperation of kinetic energy during deceleration/braking and other advanced micro-hybrid features, such as providing active boosting, the battery is required to fulfil a more active role. This is especially true for full hybrid vehicles, where the stored energy is also used for vehicle propulsion.

Nickel-metal hydride and lithium-Ion batteries cope best with this additional load due to their excellent performance characteristics in terms of fast recharging, discharging performance, and lifetime endurance. Such batteries will operate at elevated voltages, in many cases significantly higher than 60V, which requires special safety precautions (i.e. battery management systems). Lead-based batteries are limited by their lower recharge/discharge power and insufficient capacity turnover.

Although NiMH batteries have until now been the technology of choice in full hybrid vehicles, the decreasing costs of lithium-ion systems are improving their competitiveness in this respect. The heavier weight, lower energy density and lower deep-cycling capability of the mature NiMH technology puts them at a disadvantage to lithium-ion batteries, even though the overall system cost is similar.

However, at this stage no single technology dominates this segment, and car manufacturers continue to offer a range of vehicle concepts with different degrees of hybridisation. In the foreseeable future, different combinations of several battery types, operating at different voltage levels, will enter into service.

It should also be noted that a second electrical system on a 12V level is required to supply the electrical components including the safety features in all hybrid vehicles. The 12V Lead-based battery provides voltage stabilisation and active redundancy. It can also deliver the power for engine cranking in the low temperature range.

3.3

CLASS 3

PLUG-IN-HYBRID ELECTRIC VEHICLES (PHEVs) AND ELECTRIC VEHICLES (EVs)

Overview

In plug-in hybrid and full electric vehicles, high voltage battery systems of at least 15kWh are installed to provide significant levels of vehicle propulsion, either for daily trips (20-50km) in plug-in hybrid vehicles, or as the only energy source in full electric vehicles (100km+). In plug-in hybrid vehicles, the battery must also provide hybrid functions (e.g. regenerative braking) when its capability for electric drive is completed.

As a consequence of these requirements, batteries for plug-in hybrid vehicles must provide both energy and power performance (or in other words, both shallow cycle durability and deep cycle durability). Comparatively, batteries for electric vehicles require a higher energy density because of their longer electric driving ranges.

Although batteries for plug-in hybrid and electric vehicles have significant differences, they have been grouped together in this document because they both must respond to higher demands for energy content in contrast to those for HEV batteries, in order to provide sufficient levels of electric propulsion.

Therefore, the battery's energy density is a primary focus in this class. Fast recharge capability is also required to limit the period of time needed for recharge, with quick recharge to 80% important to extend the operating range of the vehicle. Batteries for both types of vehicle must also be highly efficient, with low internal electrical resistance and sufficient calendar life. Manufacturers look to provide a battery system covering the whole vehicle lifetime.

Requirements for plug-in hybrid vehicle and electric vehicle batteries:

1. **Voltage range** - The voltage range for Class 3 vehicles ranges from 250V to more than 500V for full electric vehicles, and up to 800V for electric buses.

2. **Energy Content** – The energy content of batteries in this class needs to be high, in order to provide sufficient energy for extended driving on electric power. The required electric energy is dependent on the overall vehicle mass. For a vehicle with a weight of 1 metric ton, the minimum required battery storage capability would typically be 14kWh for a 100km electric range.

   Plug-in hybrid vehicles at the same weight, which aim for electric autonomy of about 50 to 60km, will require a battery with an energy storage of typically 10kWh. According to their considerably higher weight, heavy vehicles, buses and trucks will require a significantly higher energy storage capability.

3. **Discharge power** – Full EVs and PHEVs require a power performance of up to 100 kW for a mid-size vehicle.

4. **Recharge power** - Recharge power capability depends on the individual requirement to reabsorb energy from braking and deceleration, which can reach up to 50 kW pulses for full electric vehicles.

5. **Cold cranking** – This requirement is only relevant for plug-in hybrids where an internal combustion engine is installed. Similar to SLI battery requirements, a certain power

BATTERY PEFORMANCE PROFILES FOR CLASS 3 VEHICLES

	Lead-based	NiMH	Lithium-ion	NaNiCl2
Power density (@25°C, 10sec)	300 W/kg 1.000 W/l	150 W/kg 440 W/l	300 W/kg 750 W/l	180 W/kg 270 W/l
Energy density (@25°C, 5h)	30-35 Wh/kg 70-110 Wh/l	66 Wh/kg 180 Wh/l	110 Wh/kg 275 Wh/l	120Wh/kg 185 Wh/l
Self-discharge rate(@ 20°C)	~3% per month	~15-20% per month	~5% per month	No self-discharge at cell level. Dependent on the application as it is necessary to keep the battery in temperature; ~1%/ day
Optimal ambient T/°C	0 to +40°C	-10 to +45°C	-10 to +25°C	-40 to +60°C at battery level
Operating ambient T/°C range	-30 to +75 °C	-10 to +45°C	-25 to +50°C	270 °C to 350°C at cell level
Operational lifetime	3-8 years without active cooling	In HEV applications with active cooling system 8 to 10 years	Product on the road since 2009, industrial production qualified by several European car manufacturers for 10 year duration	
Cost EV	100-250 €/kWh 10-25 €/kW	400 – 500 €/kWh 910 - 1140 €/kW	300 - 450 €/kWh 100 - 200 €/kW	500 – 700 €/kWh 750 - 1050 €/kW
Cost PHEV			800 – 1200 €/kWh 30 - 75 €/kW	

Detailed Analysis of Technologies for EV and PHEV Applications (250-500V / 5-25kWh)

performance is required to crank the vehicle's internal combustion engine even at very low temperatures (-18°C). 5kW to 7 kW pulses of approximately 10 seconds in length are normally required by vehicle manufacturers.

6. Capacity turnover and calendar life - Batteries for plug-in hybrids and for electric vehicles experience higher capacity turnover than other applications, because of their direct involvement in the electric drive train system of the vehicle. Normally, the DoD is relatively high. In addition to cycle life endurance, calendar life is a critical feature. More than 10 years of service life is expected by the car industry.

7. Safety - The battery system is expected to behave safely under all operational and non-operational conditions..

8. Cost - Cost expectations from vehicle manufacturers vary depending on individual vehicle concepts, particularly in respect to economic/environmental scenarios.

9. Manufacturing base and resource availability - The availability of manufacturing sites is an essential point to meet European targets on the number of electric vehicles on European roads. As the batteries are significantly larger than those used for SLI applications, new manufacturing capability will be needed to meet demand.

LEAD-BASED BATTERIES

Voltage range

As already outlined in Section 3.2, there is no concern with combining lead-based cells / batteries into high voltage systems, provided it is ensured that the single cells are working in the relevant voltage and state-of-charge (SOC) window. Exceeding these limits affects battery life endurance and reliability.

Energy content

The gravimetric energy density of lead-based traction batteries is relatively low, ranging from 30 to 35 Wh/kg. The 10 kWh energy storage system needed for 50-60 km of electric autonomy for a plug-in hybrid vehicle would corresponds to an approximate weight of 300 kg. A full electric vehicle with 150 km electric range would require a battery with a mass of more than 900 kg. This high weight burden is the most significant obstacle to using lead-based systems for PHEVs and EVs, and is not expected to be overcome in the future.

Discharge power

As long as the battery is large enough, there are no concerns with respect to discharge performance. With a 10 kWh system needed for a plug-in hybrid vehicle, up to 30 kW discharge pulses for acceleration are possible with lead-based batteries. The same is valid for full electric vehicles, as a 30 kWh system should deliver 90 kW pulses.

Recharge power

Batteries sufficiently sized in capacity and power performance are capable of absorbing short power pulses from regenerative braking. Electric power absorbance of up to 3 kW/kWh of energy is possible. More critical is the requirement for the battery's continuous recharge at an external plug, where charging periods below three hours are requested. The recharge power-to-energy ratio must accordingly be in the range of 0.35 kW/kWh, which is not feasible without losing service life.

Cold cranking

Cold cranking is only a concern for plug-in hybrids if the batteries supplying the electric drive train fall into a low state-of-charge. Typical lead-based batteries with approximately 10 kWh, however, will still have enough power to crank the vehicle, even at a low state-of-charge.

Capacity turnover and calendar life

Under a typical 80% depth of discharge, 600 to 800 cycles are achievable until capacity decreases to 80% of the initial value. In terms of calendar life, 5 to 7 years is realistic.

Safety

There are no safety concerns with lead-based systems in general.

Cost

Depending on the specific battery type and extra requirements, system costs range from 100 to 250 €/kWh.

Manufacturing base + resource availability

Please refer to Section 3.1. for further details on the existing manufacturing base. To meet a larger plug-in hybrid and electric vehicle market, these capabilities would have to be extended. Since the basic technology is available, this would be possible with low risk.

NICKEL-BASED BATTERIES

NiMH batteries have been used for plug-in hybrid vehicles, but are now utilised only in full-hybrid configurations due to their modest specific energy content.

Voltage range

NiMH systems are disadvantaged by their relatively low cell voltage. To reach the high voltages required for plug-in vehicles and electric vehicles, a large number of single cells must be connected in series. A 400V system, for example, would required more than 330 individual cells. For practical reasons, sub-sections comprising up to 12 single cells in a module are typical.

Energy content

The maximum specific energy content of a high energy NiMH battery system is approximately 65 Wh/kg.

Discharge power

High energy NiMH systems provide a continuous power performance of 150 W/kg. A plug-in hybrid with a 10 kWh battery on board would provide about 30 kW, which may be insufficient for a typical mid-size car. A full electric vehicle with a 30 kWh battery will have a typical power performance of greater than 90kW, which will not affect its acceleration ability.

Recharge power

High energy NiMH batteries can be recharged to almost 100% state of charge within one


electric drive

hour. The charge must be managed by an adequate electronic and electric control system, and an active cooling system is also required.

Cold cranking

This feature is a problem only for plug-in hybrid vehicles, in which the installed battery must also crank the vehicle's engine. A typical 10kWh battery system will have sufficient power performance to start the engine even in a relatively low state-of-charge. For a 10 kWh plug-in hybrid battery, a power-to-energy ratio of 1 kW/kWh (at -18°C) translates into 10 kW (for a 10-second pulse).

Capacity turnover and calendar life

At a typical 80% depth-of-discharge, NiMH capacity turnover is more than 2,500 cycles. Calendar life is above eight years and may even exceed 10 years under moderate temperature conditions.[28]

Safety

The aqueous electrolyte in nickel-based batteries makes the system intrinsically safe. In the event of overcharge and overheating, there is a danger of smouldering and hydrogen emission. A battery management system ensures safe operation under these parameters.

Cost

On a large production scale, overall battery system cost ranges from approximately 400 to 500 €/kWh. However, these costs are susceptible to change because of the high amount of nickel and rare earth materials in the electrodes of the cells.

Manufacturing Base and Resources

As NiMH systems are produced on a significantly smaller scale than lead-based systems, currently-available production capabilities are limited. Supplying a larger electric vehicle fleet would require significant investment.

LITHIUM-BASED BATTERIES

Voltage range

A comparably low number of lithium-ion cells are required to assemble a high voltage battery system. For safe operation, a battery management system supervising the voltage of each single cell is required.

Energy content

In particular, lithium-ion batteries have a superior energy content in terms of weight and volume. Their high energy density sets them apart from other technologies for plug-in hybrid and electric vehicles. On a system level, the high energy battery systems currently available on the market provide more than 110Wh/kg.

Discharge power

Lithium-ion batteries designed for high energy applications in electric vehicles normally provide a peak discharge power performance from 3-10 kW/kWh, which corresponds to approximately 300-1000 W/kg. Even for a small 10 kWh battery system, this results in sufficient power for use in electric vehicles.

Recharge power

Under normal ambient temperatures, charging can be undertaken with currents up to a 0.5C rate. This normally translates into a ratio of charging power to battery energy storage capability of 0.5 kW/kWh. Even faster charging up to a 2C rate (2kW/kWh) is generally possible, ashas been demonstrated by the ChaDemo-initiative in Japan. However, fast charging may require an active cooling system, in order to avoid a reduction of battery lifetime.

Cold cranking

This is a concern only for plug-in hybrids in case the battery has been depleted. With a relatively large battery system on board (approximately 10kWh), however, there is normally enough power performance even at low temperatures and low state-of-charge to serve a short high power pulse, required for cranking the combustion engine.

Capacity turnover and calendar life

Lithium-ion batteries used under normal charging and discharging conditions can provide more than 3000 full cycles before exceeding the threshold of 80% residual storage capability. Ageing experiments with lithium-ion electric vehicle batteries indicate that calendar life may exceed 10 years under normal ambient conditions.

Safety

The high energy content and use of an organic electrolyte mean that extra precautions are required to guarantee lithium-ion

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[28] However, Field experience for 10 years under real use conditions is still missing, so this will need to be validated

battery safety. A highly reliable battery management system is required to protect against overcharge and maintain safe operating conditions. High-quality cells are also required during battery construction, as internal mechanical defects can lead to the spontaneous release of high amounts of energy.

Cost

The current cost for high energy lithium-ion plug-in hybrid or electric vehicle systems ranges from 400-800 €/kWh. This cost is projected to decrease to 300-450 €/kWh over the next decade[29]. As the share of strategic metals (e.g. nickel, cobalt) is relatively low, there are no concerns about sensitivities to raw material cost fluctuations.

Manufacturing base & resource availability

The manufacturing base and resource availability of lithium-ion batteries has already been outlined in Section 3.1.

Current estimates suggest that international resources would be sufficient for the EU to fulfil demand for hybrid electric and full electric vehicles for the foreseeable future.[30]

SODIUM-BASED BATTERIES

Sodium-nickel chloride batteries have been tested in several plug-in hybrid and electric vehicle applications, with light commercial vehicles (LCVs) and buses remaining a primary focus. Cumulatively, more than 200 million km have been driven by vehicles equipped with this technology. Their existing applications include electric and hybrid bus fleets in Bologna and Rome (Italy), Lyon (France), Barcelona and Madrid (Spain).

Voltage range

Sodium-nickel chloride batteries for automotive application typically operate at 20 to 30 kWh in both 300 and 600 V ranges. Packs can be connected in parallel.

Energy content

Due to the high energy density of sodium-nickel chloride batteries and a very efficient and compact thermal insulation technology, the maximum specific energy of a complete battery is 120 Wh/kg or 185 Wh/l.

Discharge power

Power density achievable by sodium nickel chloride batteries is 180 W/kg and 270 W/l at battery pack level. Battery performance is not affected by the ambient temperature.

Recharge power

Recharge power is independent of the ambient temperature of the battery system. Charge currents up to 0.8C are achievable for limited periods of time.

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[29] For example, Element Energy - "Cost and Performance of EV Batteries", 2012

[30] Second Life and Recycling of EV batteries – Frost and Sullivan (presentation at Batteries 2011)

Cold cranking

Being a high-temperature battery, the performance of sodium-nickel chloride batteries is not affected by ambient temperature.

Depending on the specific configuration of the vehicle, the high voltage battery can provide enough power performance to start an ICE.

Capacity and Calendar Life

Under 80% discharge conditions, typically 3,000 cycles can be achieved.

Safety

Sodium-nickel chloride batteries are based on strings of cells enclosed in a stainless steel case that includes thermal insulation, and a battery management system provides thermal management and maintains optimal usage conditions, preventing the risk of electrical abuse.

The chemical reaction in sodium-nickel chloride batteries is intrinsically safe, which results in the removal of the most hazardous materials (sodium recombining into common salt, NaCl) in case of a failure resulting in ceramic rupture. Cells in these batteries are held within a hermetically sealed container, preventing the release of hazardous materials. The battery is additionally sealed in a double container, preventing cell damage from external hazards. Finally, electronic control and safety interlock exists, protecting cells against unwanted physical or electrochemical deviations that could otherwise lead to hazardous conditions.

Cost

Depending on battery design, the cost at battery level ranges from 500 to 700 €/kWh.

Manufacturing base and Resources

The production capacity for sodium-nickel chloride batteries in Europe currently stands at 100 MWh/ year, with a potential installed capacity of 300 MWh/year.

The basic materials of a sodium-nickel chloride battery are nickel, iron, common salt and ceramic. The thermal insulation is a silica based material. All of these materials are readily available and recyclable, without major risk of resource shortages in the future.

CONCLUSION

Electric vehicles operate with an electrical storage system of at least 15kWh. Due to the need for high energy density, this segment is currently dominated by high-voltage lithium-ion battery systems, due to their superior energy density, fast recharge capability and high discharge power.

For commercial applications, harsh environments and heavy applications, sodium- nickel chloride batteries are a competitive option. Nickel-metal hydride batteries have been used in certain PHEVs in the past, but are gradually being superceded by lithium-ion batteries across this segment, which continue to decrease in cost. The high weight and lower capacity turnover of lead-based batteries limits their use in both PHEVs and EVs, with their corresponding energy density too low to match the requirements of vehicle manufacturers.

This situation is not expected to change, with research and innovation efforts focussing on improving the competitiveness of lithium-ion and sodium nickel chloride technology, or on developing entirely new battery concepts.

As in the case of hybrid vehicles, an auxiliary 12V lead-based battery is additionally required in PHEVs and EVs to supply all electrical components including the safety relevant features on a 12V level.

4

Future Trends in Battery Technology

for Automotive Applications

Increasing oil costs and a desire for greater decarbonisation of transport will encourage further technological and economic improvements in all battery technologies for their use in each level of vehicle hybridisation and electrification.

This chapter will look at the future expected trends in the automotive market as well as expected developments in batteries and their potential to fulfil OEM requirements. A horizon of 2025 has been used to ensure an accurate prediction of expected developments in the coming years. Insight has again been drawn from the collected membership of EUROBAT, ACEA, JAMA, KAMA and the ILA.

Due to the increasing cost of oil and a desire for greater decarbonisation of transport, the global and European markets for start-stop and micro-hybrid vehicles is expected to increase significantly over the next decade. This, in turn, will drive an increased demand for advanced lead-based batteries.

Greater demand will also develop for hybrid, plug-in hybrid and full electric vehicles/ Power demand is likely to increase for all applications (including ICE vehicles), requiring an increase in the performance of all batteries, and therefore the resources used in their manufacture.

	CLASS 1: CONVENTIONAL VEHICLES (INCLUDING START-STOP AND BASIC MICRO-HYBRID VEHICLES)	CLASS 2: HYBRID ELECTRIC VEHICLES (INCLUDING ADVANCED MICRO-HYBRID, MILD-HYBRID AND FULL HYBRID VEHICLES)	CLASS 3: PLUG-IN HYBRID ELECTRIC VEHICLES AND FULL ELECTRIC VEHICLES
Lead-Based Batteries	Expected to continue to dominate the market as a reliable, cost effective, efficient and proven technology. Expected developments in cycle life, efficiency and power delivery.	**Primarily expected to be used as auxiliary battery to support the board-net. Increased industrial potential of advanced lead-based batteries in micro-hyrbid and mild-hybrid applications.**	Expected to be used only as auxiliary battery to support the board-net and for supply of active redundancy safety mechanism.
Nickel-Based Batteries	Nickel-based batteries are a mature technology but are not expected to be present in the SLI application due to limitations such as the need to oversize to meet requirements for cold cranking requirements, calendar life, and cost compared to lead-based batteries.	**Nickel-based batteries are expected to continue in this application although with greater competition from emerging lead and lithium-based technologies.**	Nickel-based batteries are a mature technology and are not expected to develop in this application because of their characteristics such as low cell voltage and their significantly higher weight compared to lithium-ion technology.
Lithium-Based Batteries	Energy density and power ability will continue to increase, even at low temperatures. Increased industrial potential and improved techniques for recycling. Increased interest of manufacturers for future developments in this segment (especially as a performance option when weight is the driving factor).	**Technology of choice for hybrid applications where significant power is expected from the battery. Increased industrial potential and improved techniques for recycling. Continuous reduction of product cost.**	Only viable solution where high power and energy are expected. Increased industrial potential and improved techniques for recycling.
Sodium-Based Batteries	Being mostly a high voltage energy technology, sodium nickel chloride batteries are not expected to be used in the classic SLI application, as they were not developed for this purpose.	**Hybrid cars are not today a realistic application of sodium nickel chloride batteries, because the relatively low power to energy ratio is not compatible with the small size of batteries used in hybrid cars. However, they are already used in heavy duty hybrid vehicles such as buses or trucks, where the required energy exceeds 20 kWh or in harsh environmental conditions.**	Sodium-based batteries are expected to continue improving in this application, especially for heavy duty vehicles and public transport (buses, trams, etc.). In the future, improved performance, better integration into vehicles, and more sophisticated energy management is expected.

Summary Forecast of Battery Technologies for select applications to 2020

4.1 EXPECTED EVOLUTION OF THE AUTOMOTIVE MARKET

As Europe moves towards a low-carbon transport sector, advanced 12V automotive batteries will continue to play a significant role in optimised ICE vehicles, while the market penetration[31] of industrial traction batteries of various technologies in hybrid and electric vehicles will progressively increase.[32]

This section provides a broad overview of the expected evolution of the automotive market for the foreseeable future (until 2025), with an analysis of priority research areas for the battery technologies focussed on in this report: lead-based, lithium-ion, nickel-metal hydride and sodium-nickel chloride batteries.

This overview leads to the conclusion that a balanced portfolio of different battery technologies and powertrains will continue to be necessary in the short to long-term. This includes the use of 12V lead-based batteries for mass market applications worldwide and their production in Europe, as well as the continued development of advanced traction batteries (lithium-ion, nickel-metal hydride, sodium-nickel chloride, etc.) for hybridised and electrified powertrains.

EXPECTED DEVELOPMENTS IN THE FORESEEABLE FUTURE (UNTIL 2020)

Mass market rollout of start-stop and micro-hybrid vehicles.

In the period from now until 2025, a significant development for the European and global battery industry will be the projected mass-market roll-out of start-stop and micro-hybrid vehicles. This has been confirmed by a 2013 survey of car manufacturers. Already in 2013, a major portion of new vehicles being placed onto the European market by OEMs contain start-stop systems powered by advanced lead-based batteries,[33] with Pike Research, for example, estimating 37 million units for the global micro-hybrid car market by 2020.[34]

Start-stop and micro-hybrid vehicles are an important bridge between conventional ICE vehicles and higher-priced hybrid and electric vehicles. This allows OEMs to improve fuel efficiency in line with EU targets, without significant extra prices being imposed onto consumers. The growth of these segments will create an increased demand for advanced lead-based batteries (EFB and AGM designs), as the only feasible commercialised option for use in start-stop and basic micro-hybrid systems.

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[31] *A Portfolio of Powertrains for Europe, a fact-based analysis*, pg.11 – McKinsey & Company, 2010

[32] OECD International Transport Forum Transport Outlook 2011

[33] Marklines 2013 statement that "70% of new cars in Europe are equipped with start-stop systems"

[34] *Stop-Start Vehicles - Global Market Analysis and Forecasts* - Pike Research, 2012

A second micro-hybrid generation of vehicles is also currently under development, placing further requirements on the battery:

- Increased charge acceptance, including at low temperatures
- Improved cycling ability at partial state-of-charge (due to new and more demanding charge & discharge profiles).
- Increased energy demand

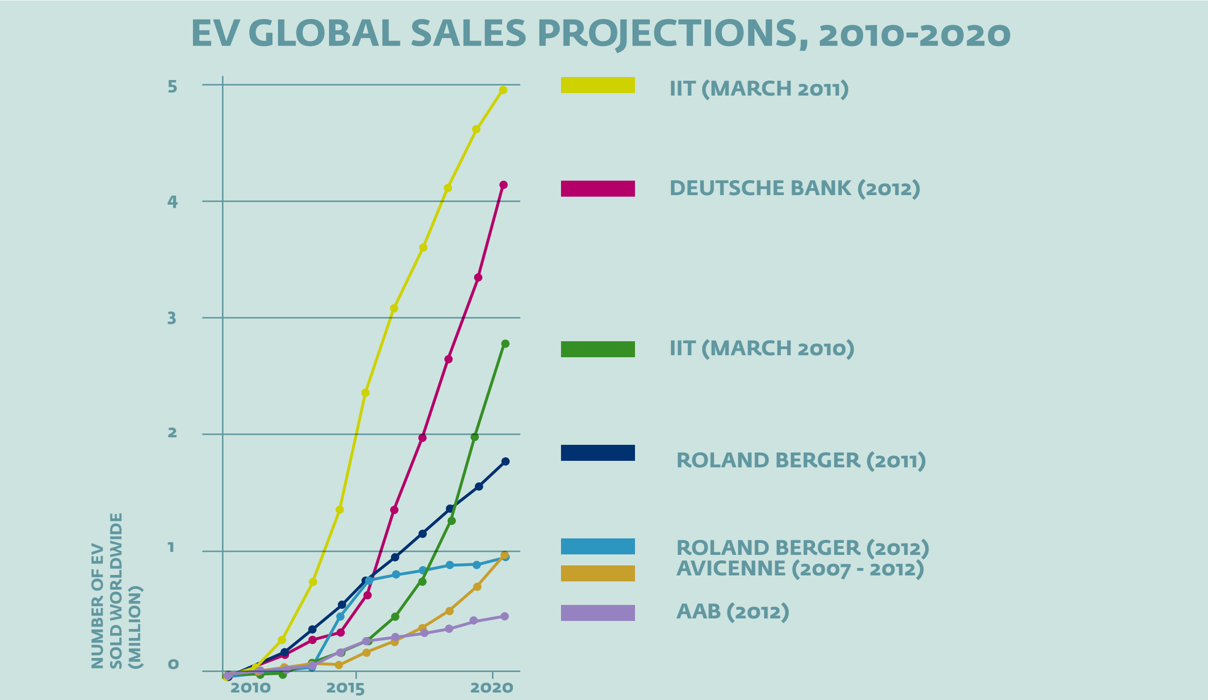
These extra demands will require bigger or more efficient batteries in terms of energy and power. A range of battery technologies can be implemented to fulfil such requirements, including for example dual battery systems.

Gradual increase in market penetration of HEVs, PHEVs and EVs

The market penetration of hybrid, plug-in hybrid, and electric vehicles is expected to steadily increase from now until 2025. As the below table demonstrates, forecasts for this development vary widely, with anywhere between 0.5 and 5m electric vehicles to be sold globally by 2020. Therefore, this document does not exclusively reference any single source.

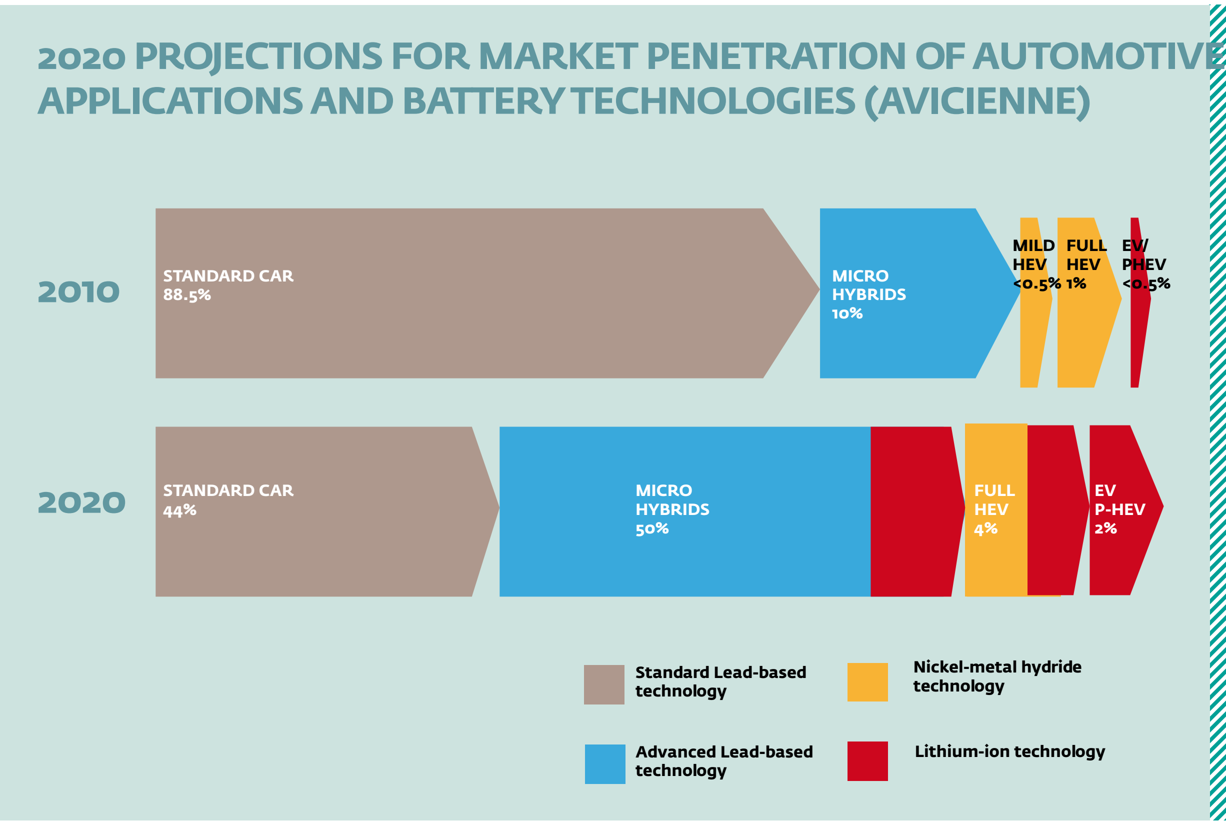
However, under all scenarios, PHEVs and EVs will still only comprise a releatively minor share of the total global vehicle market by 2020 or 2025, with significant barriers remaining to the mass-market take-up of such advanced powertrains (vehicle price, driving range, consumer acceptance etc.). These will require continued development from all stakeholders and regulators in the medium and long-term.

Regardless, the increasing market penetration, higher oil prices and a pressure for decarbonised transport will encourage significant further improvements to the price and performance of lithium-ion and sodium-nickel chloride plug-in hybrid and electric vehicle batteries; through greater economies of scale, improved production processes, and continued R&D funding.



Summary Forecast of Battery Technologies for select applications to 2020, *Avicienne (2013)*

Under these assumptions, market consultancy Avicenne have made the following projection for the impacts on the battery market (for automotive applications) by 2020, giving a general overall vision of how the overall vehicle and battery mix could develop. All battery technologies continue to have an



Avicienne's 2020 projections for market development of automotive applications and their corresponding battery technologies (2013)

important role, with particular advances in market share for advanced lead-based and lithium-ion technologies. The table above is provided as a general indication only.

Long-term projections

Looking further ahead is an even more difficult exercise, and so detailed post-2020 projections are not given in this document. However, for the purposes of its focus, it is worth making a general note that in the long-term, a mix of different battery technologies will still be required for the European vehicle fleet. Conventional diesel and petrol ICE vehicles (featuring lead-based SLI batteries) are projected to continue to make up a major percentage of the EU's new passenger vehicle fleet from now until at least 2030.

As an example, McKinsey and Company's 2010 *A portfolio of powertrains in Europe: a Fact-based analysis* has projected that electric vehicles, fuel-cell electric vehicles and plug-in hybrid electric vehicles will only be cost-competitive with ICEs in relevant segments by 2030. At this point, their three credible scenarios still predict a 65-80% market share for ICE-powered vehicles in Europe's vehicle mix. Even by 2050, it is estimated that Europe will "likely move from a single powertrain (ICE) to a portfolio of powertrains in which battery electric vehicles and fuel cell electric vehicles play a complementary role" with ICE vehicles.

HEVs, PHEVs and EVs will continue gaining market share from 2025 onwards, due to their improving cost-competitiveness and continuing regulatory pressure, and therefore demand for high-voltage traction batteries (especially lithium-ion batteries) providing electric propulsion is expected to increase significantly. Unless further developments are made, it can also be expected that a smaller 12V battery (usually lead-based) will be required in these vehicles to meet the power requriements of the board-net and battery safety features.

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[35] *A portfolio of powertrains in Europe: a fact-based analysis* – McKinsey and Company, 2010. Report available at *http://ec.europa.eu/research/fch/pdf/a_portfolio_of_power_trains_for_europe_a_fact_based__analysis.pdf*

4.2 EXPECTED DEVELOPMENTS OF BATTERY TECHNOLOGIES FOR AUTOMOTIVE APPLICATIONS

Significant levels of global R&D have been directed towards improving the competitiveness of lithium-ion and other batteries for hybrid and electric vehicles, while the continued pressure to improve fuel efficiency in conventional ICE vehicles is also stimulating improvements in advanced lead-based technologies.

This section outlines priority areas for further improving the competitiveness of the existing battery technologies focussed upon in this report, from now until 2025. Insights have been gained predominantly from a survey of EUROBAT's membership.

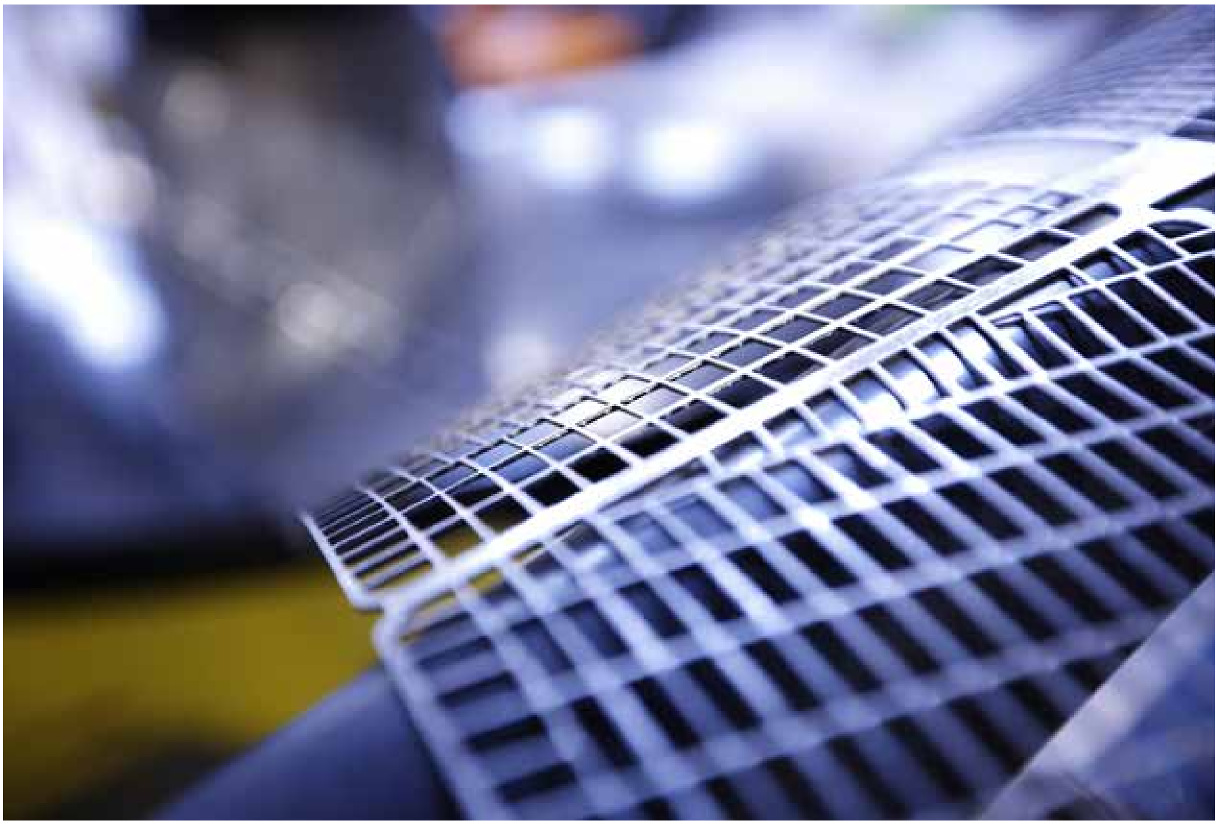
Significant research efforts are directed towards the further development of electric vehicle battery systems, which must meet consumer demands for lower costs and longer vehicle driving ranges. European industry is also continuing to improve the performance of 12V automotive batteries in order to meet the power requirements of new micro-hybrid systems.

In the far future, other novel battery technologies (e.g. zinc-air, lithium-suplhur, lithium-air) may become competitive for use in electric vehicles, and can theoretically deliver higher energy densities than lithium-ion chemistries are capable of. However, these technologies are still in early phases of development, and so are not focussed upon in this report.

ROADMAP FOR LEAD-BASED BATTERIES

Research and development is ongoing to increase the performance of automotive lead-based batteries, while lowering the quantities of lead used in their manufacture. EUROBAT members spent a cumulative total of €50 million on R&I into lead-based batteries in 2011.[37]

In order to cope with increasing power requirements and expand the capabilities of micro-hybrid vehicles, European manufacturers are refining battery design to optimise deep-cycle resistance and charge



recoverability. Research projects from the Advanced Lead Acid Battery Consortium (ALABAC) have also demonstrated the successful use of advanced lead-based battery systems in mild-hybrid vehicles, either individually or in 48V/12V dual battery systems [36].

Priority areas for improving performance

European lead-based battery manufacturers have identified several priority areas for increasing the competitiveness of their products in micro-hybrid applications:

- Higher cycle life
- Higher power density
- Better charge acceptance
- Lower battery weight

To reach these targets, several improvements are been made in the chemistry and design of lead-based batteries. European battery manufacturers are currently working to implement the following general improvements:

- Carbon nanotechnologies – *developing new types of additives to improve the conductivity of active materials*
- High surface area doping materials – *increasing charge acceptance while avoiding hydrogen evolution (gassing)*
- Low-cost catalyst – *recombining hydrogen and oxygen produced at regenerative brake events*
- Light-weighting solutions – *developing new designs and materials*

By 2025, these developments will enable lead-based batteries in micro-hybrid vehicles to provide several additional functions to improve fuel efficiency, including:

- Start-stop with voltage stabilisation system, potentially including lead-based AGM battery with supercapacitors
- Engine off while approaching a stop, but at vehicle speed <20 km/h (not only after complete vehicle standstill as today)
- "Stop-in-motion": Engine off at higher speeds whenever acceleration is not needed.

For full hybrid, plug-in hybrid, and electric applications, lead-based batteries are not expected to develop the required energy density that would off-set the considerable weight of the required battery. This will

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[36] See, for example, the Advanced Lead Acid Battery Consortium's (ALABAC) 48V LC Super Hybrid concept

[37] Figure derived from 2012 EUROBAT survey


CPT
Valeo
LC
48V
LC59 ABC

continue to limit the use of lead-based traction batteries in vehicles with higher levels of hybridisation and electrification.

Key new technology developments

In addition to these design and chemistry improvements, the following key technology developments are expected to be introduced to the European market in the period from now until 2025:

EFB and AGM batteries with enhanced carbon in the negative plate (lead-carbon batteries)

Where increased electrical functionality is required, lead-carbon designs have been introduced to inhibit the negative plate sulphatation frequently observed in the battery's partial state-of-charge operation.

Various lead-carbon batteries have been introduced to the market in recent years including the PbC® battery and Ultrabattery® , as well as those with carbon blended into the negative active material. The three main approaches comprise:

1. Blending carbon with the standard negative lead paste that is used in negative electrodes;
2. Developing split-electrodes in which half of the negative electrode is lead and the other half is carbon;
3. Completely replacing the lead-based negative electrode with a carbon capacitor electrode assembly.[38] Therefore, this setup has a sloping capacitor voltage characteristic, not the typical stable battery voltage characteristic.

Through these developments, lead-based batteries can provide higher performance both in terms of charge recoverability and by their capability to operate at partial states-of-charge. These improvements will increase their competitiveness in micro-hybrid and mild-hybrid vehicles.

Dual Battery Systems

Dual battery systems have been on the market for the last decade. Several luxury vehicles use two 12V lead-based batteries to secure cranking capability under stress operational conditions. Furthermore, several vehicles with start-stop functionality use a second lead-based battery to stabilise the system voltage upon automatic engine restart, for comfort and security reasons.

A dual board-net allows for batteries of different voltages to be integrated in vehicles, without having to change the voltage of on-board electronics. 48V/12V systems are beginning to be considered for increasing fuel efficiency in micro- and mild-hybrid vehicles.[39] Such a configuration involves a conventional 12V network using a lead-based battery, but adds an additional 48V network powered by a 48V battery (lithium-ion, lead-based etc.). It should be noted that the maximalcharge voltage (of the legal limit of 60V) is still being defined by OEMs.

In this setup, the 12V network continues to handle traditional SLI loads (lighting, ignition, entertainment, audio systems, electronic modules), while the 48V system supports the vehicle's active chassis systems, air conditioning compressors, and regenerative braking. This has the potential to further increase fuel efficiency in mild-hybrid vehicles.

ROADMAP FOR NICKEL-BASED BATTERIES

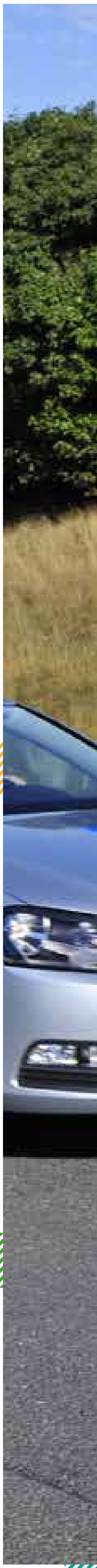
Although nickel-metal hydride batteries have been an important technical resource in the rise of hybrid and electric vehicles, their potential for further market penetration has been reduced as a consequence of the increased performance and reduced cost of lithium-ion batteries.

Because they have already reached a relatively high degree of technological maturity, it is expected there will be only limited performance and cost improvements between now and 2025.

ROADMAP FOR LITHIUM-BASED BATTERIES

PLUG-IN HYBRID AND ELECTRIC VEHICLES

To 2025 and beyond, the global battery industry will work to improve the performance, cost, systems integration, production process, safety and recyclability of lithium-ion batteries. All of these areas need further development to improve their market competitive integration into electric vehicles,



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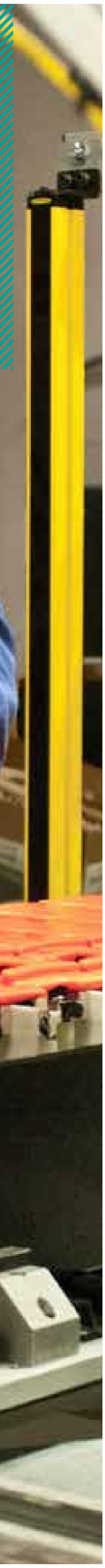
[38] http://www.altenergymag.com/emagazine.php?issue_number=09.02.01&article=leadcarbon

[39] 48V battery systems are now being offered by several EUROBAT members



and this process will likely stretch further than 2025.[40]

Performance and cost

Primarily, battery and vehicle manufacturers will focus on improving the performance of lithium-ion PHEV/EV batteries and reducing their cost. These factors are paramount to the speed with which these vehicles will gain market share. Current engineering efforts are aimed at the improvement of cell materials to optimise their functionality in electric vehicles. Competitiveness is expected to increase in the following areas:

- Reduced cost at battery pack level
- Increased energy and power density
- Improved battery lifetime
- Increased charge acceptance

Significant performance and cost improvements will be made through the improvement of cell materials and components (i.e. anode, cathode, separator, electrolyte). Cost reductions are expected through lower cost cell mechanical design, the improvement of materials properties, and gradual scaling up in production of large cell formats.

The energy density of lithium-ion batteries is being improved by developing electrode materials with a higher specific capacity (mAh/g), or developing cells using higher voltage chemistry. The negative electrode will be evolved through a shift from carbon-based materials (such as graphite) to new materials. Engineering of the positive electrode will eventually include novel materials (such as $LiNiO_2$, $LiMn_2O_4$, $LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2$).

In addition to these components, further innovative and unique materials based on new ideas are expected over the next decade. .

Novel materials will also be developed for housing and integration of the cell, with the aim to lessen the reduction of battery performance at low temperatures. New technologies delivering higher energy density are expected to reach the market by 2025.

Systems integration

Research will also be directed at improving the systems integration of lithium-ion batteries within the vehicle. Progress is being made in optimising the mechanical shape, overall weight, and standardisation of Battery Management System (BMS) components and interfaces. More advanced thermal management systems will also be developed to enable a wider range of operating conditions with reduced system complexity. Notably, this will begin to lessen the reduction in battery performance at very low temperatures.

Safety/Recylability

On a different level, stakeholders are also working to further improve the safety of lithium-ion batteries across their lifecycle, and to increase their recyclability at end of life.

Safety precautions will be improved through the development of efficient and high fidelity state-of-function monitoring techniques and advanced state-of-charge/ state-of-health indicators, as well as cell diagnostic and supervision systems to support the understanding of ageing.

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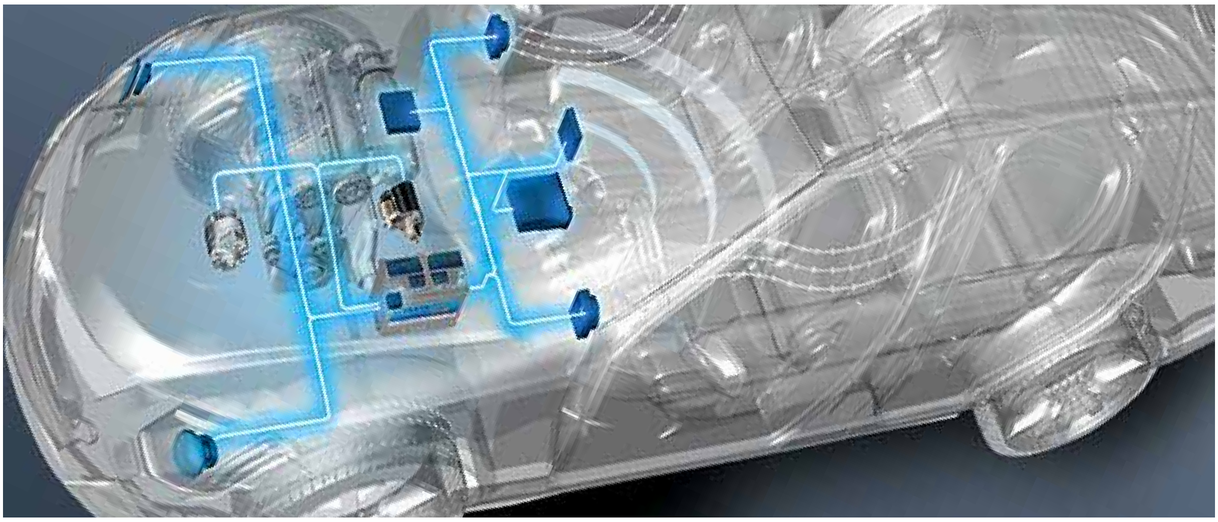
[40] This has been most recently prioritised in the EU's Horizon 2020 European Green Vehicles Initiative package, which features a specific call for the *Next generation of competitive lithium ion batteries to meet customer expectations* (GV1)



Realistic standards for abuse tolerance are also being worked on, as well as improvements to the robustness of cell design.

With the recycling industry for lithium-ion batteries still in its infancy, a variety of actors are also looking at how to optimise the separation of lithium-ion battery components at the battery's end-of-life. This can be facilitated by developing security concepts for dismantling, and by exploring potential uses of slags containing metal phosphates in cooperation with the fertiliser industry or other industries. It will also be important to establish sufficient capacity in the recycling industry to handle the expected volume from increased EV sales. These are long-term projects, expected to extend past 20205

HYBRID VEHICLES

All of the above improvements would improve the competitiveness of lithium-ion batteries in other applications. For example, lithium-ion batteries are eventually expected to replace NiMH as the technology of choice for full hybrid vehicles.

By 2025, it is expected that lithium-ion batteries will also be used in advanced micro-hybrid and mild-hybrid vehicles. For this segment, research efforts will focus on improving the battery's cost/watt ratio in charge and discharge at system level, and at lowering the cost of battery thermal management and electronics.

It is expected that lithium-ion batteries will also be implemented in 48V dual battery systems together with a 12V lead-based battery, in order to further increase fuel efficiency in the advanced micro-hybrid and mild-hybrid segment. The 48V system would support chassis systems, air conditioning compressors, and regenerative braking.

ROADMAP FOR SODIUM-BASED BATTERIES

In the future, sodium nickel chloride batteries will be increasingly used in the automotive market for traction purposes in plug-in hybrids and electric vehicles. They will continue to be used primarily in heavy duty vehicles (buses, trucks), where the energy need for the application exceeds 20kWh, or in applications with very harsh environmental requirements (high or low temperatures). Their competitiveness in this segment will be improved through the following expected developments:

Performance and cost

There are several priority areas for improving the performance of sodium nickel chloride EV batteries:

- Increased power density by further developing collector design, material composition, and cell geometry.
- Increased cycle life through optimisation of cathode composition and an advanced cooling system.
- Increased energy density through optimisation of cathode composition
- Increased reliability by a total quality programme including significant BMS improvement.

Overall battery cost will also decrease significantly, through optimisation of the production processes, and by reducing the scrap rates of ceramic components.

System integration

As with lithium-ion batteries, a primary focus will be to improve the battery's integration into the vehicle, both mechanically, and by establishing more advanced communication between the Battery Management System and on-board supervisory systems. This will improve the interface for energy management of the vehicle and traction system.

Production process

The production process for sodium nickel chloride batteries will be further optimised by reducing assembly time and introduction of automatic quality control for ceramic components. Synthesis of beta-alumina will also be improved in the period from now until 2025, while greater economies of scale will help to lower production costs.

Safety parameters

Sodium nickel chloride batteries are known for their intrinsic safety features, and further projects are in progress to improve their resistance against strong vibration and to introduce a new cooling system.

4.3 CONTINUING BARRIERS TO CHANGEOVER TO DIFFERENT TECHNOLOGIES

Despite ongoing efforts to develop new technologies and improve on existing battery types, a number of limitations nonetheless remain in the selection of a battery technology for a specific application.

This supplementary section provides an overview of some of the wider obstacles to take-up of alternative technologies for Class 1 vehicles (i.e. conventional vehicles, as well as start-stop and micro-hybrid vehicles), in order to demonstrate the difficulty of forcing substitution of an established technology.

Board-net voltage

Currently, all automotive components have been developed for 12V power supply. Changing the voltage of the system would require a total redevelopment of the electrical system and components of all cars, which would impose a significant cost onto OEMs and suppliers of automotive parts.

This cannot be enforced in Europe in isolation, as the 12V power supply is standardised throughout the world. It would only be possible to change the voltage if all global car manufacturers acted together[41]. Dual voltage battery systems could however be implemented.

On-board electric systems of vehicles currently in production are designed for an optimal use of a 12V battery, in practice a lead-based battery. Changing the battery output voltage would imply a full redesign of many of the vehicle's electrical components of a vehicle (e.g. its starter, generator, various electric powered appliances, engine controllers, security features and switches, entertainment, comfort and guidance devices). These components would have to be redesigned to make optimal use of the battery system, as is the case for currently employed lead-based battery systems.

Development time for new vehicles

A survey of European OEMs has estimated that the development time for new vehicles is between 54 and 80 months, depending on the model and its predecessor.

However, the lead-in times will be longer if new technologies or components have to be implemented into new vehicles. Specifically, when there is a need to use alternative materials, this can take many years and depends on the type and function of the component. To accommodate a completely different battery technology into new vehicle models, European OEMs estimate that the required installation and ramp up of the technology would as a worst case require an implementation time of over 10 years.

Under this worst-case timescale, if a technology were already available as a technical substitute for 12V batteries used in conventional vehicles, it would not be until at least 10 years later that it could

Although this section concentrates only on barriers to changeover in Class 1 vehicles, similar considerations should be applied for all levels of automotive application.

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[41] From 2012 survey of car manufacturers

Example of a Lead-based EFB battery, courtesy of EXIDE Technologies

be implemented into new vehicles being released onto the European market. As this document has demonstrated, no such technical alternative currently exists for the mass-market.

Manufacturing infrastructure

Currently, all batteries used in commercially available Class 1 vehicles (conventional, start-stop and basic micro-hybrid vehicles) operate on a lead-based battery. According to EUROSTAT figures, 70,313,259 automotive lead-based batteries were produced for SLI applications in the EU in 2011, with the vast majority destined for the European market.

It is highly unlikely that sufficient manufacturing capacity could be provided to replace this quantity with alternative technologies in the short and medium-term, as this would require:

1. Sufficient financial investment – something not widely available in the current financial crisis

2. Sufficient transition time – the manufacturing processes of one technology are not the same as for another, and existing plants would need to be completely replaced and existing factories re-tooled to a new purpose.

In addition, employees would have to be retrained in the new processes and new manufacturing methods.

Resource Availability

The International Lead Association has conducted a recent survey on the *Resource availability of metals used in automotive battery technologies.* This report assesses the current and future availabilities of resources for a range of battery technologies, with a particular focus on the impacts from fully replacing automotive lead-based batteries with an alternative technology.

ILA's report concludes that *"if in addition to their current applications, lithium-ion batteries were required to replace automotive lead-based batteries in an SLI function, significant future challenges would be predicted for the global supply of lithium"*.[42]

Battery selection is always dependent on a combination of technical, economic and socioeconomic considerations, and all of these must be taken into account.

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[42] "Resource Availability of metals used in automotive battery technologies". – International Lead Association (2014)

5

Conclusions

From this analysis of technical requirements and market trends for batteries in automotive applications, the report draws the following conclusions:

SUBSTITUTING TECHNOLOGIES

Battery technologies have specific performance profiles that serve a well-defined purpose in automotive applications, and because of this **it is not possible to replace one technology with another technology without impacting on overall performance and vehicle cost.**

- 12V lead-based batteries are the only battery technology tested for the mass market that satisfies the energy supply requirements of conventional ICE vehicles (including vehicles with start-stop and basic micro-hybrid systems). For the foreseeable future, as long as any residual risks to human health and the environment are properly managed, their cost-efficiency, durability and cold-cranking ability will set them apart from other technologies in this high volume segment.

- The performance profile of high voltage lithium-ion battery systems makes them the technology of choice for plug-in hybrid and electric cars (with sodium-nickel chloride batteries a competitive option for heavier vehicles). These batteries are set apart by their high energy density, low weight, good recharge capability and energy efficiency.

- In between, several combinations of battery technologies can be used for different levels of hybridised powertrain (from 48V micro-hybrid vehicles to 400V full hybrid vehicles), with nickel-metal hydride and lithium-ion batteries coping best as requirements increase.

The performance and competitiveness of battery technologies in these applications will continue to be improved between now and 2025.

DEVELOPMENT TIME

Using alternative technologies would also likely result in **additional development costs to adapt the vehicle to that new technology**. Changes such as installing a DC/DC converter, re-designing the board-net architecture in ICE vehicles, or revising packaging and weight distribution of the vehicle would have a significant lead-in time

SOCIECONOMIC FACTORS

As well as technical considerations, **socioeconomic factors must be taken into account when selecting the most appropriate battery technology for a given application.** For example, there are over 250 million conventional vehicles on the road in Europe, and so any battery technology must be available at the mass-market scale required to meet this demand.

REGULATORY FRAMEWORK

The authors of this report therefore advocate for the fair co-existence of battery technologies on the market. Where substitution between technologies is possible, this should be left to the application manufacturers, so they can choose the most suitable batteries for their products. **The EU's legislative and regulatory framework should guarantee a fair competition between battery technologies.**

6

EU Research Projects on Batteries

for Automotive Applications

Energy storage, a key technology for decentralized power, power quality and clean transport; RTD Info European Communities Luxembourg 2001; ISBN 92-894-1561-4 ; ftp://ftp.cordis.europa.eu/pub/eesd/docs/db_energy_storage_eur19978.pdf [requested 02.07.2013]

EU project NECOBAUT, *New Concept of Metal-Air Battery for Automotive Application based on Advanced Nanomaterials*; FP7 Project reference: 314159 (From 2012-10-01 to 2015-09-30)

EU project LANMR, *Unraveling the chemistry of the lithium-air battery by novel solid state NMR techniques*; FP7 Project reference: 301709 (From 2012-03-01 to 2014-02-28)

EU project SMART-LIC, *Smart and Compact Battery Management System Module for Integration into Lithium-Ion Cell for Fully Electric Vehicles*; FP7 ICT Project reference: 284879 (2011-05-01 to 2014-04-30)

EU project SUPERLIB, *Smart Battery Control System based on a Charge-equalization Circuit for an advanced Dual-Cell Battery for Electric Vehicles*; FP7 Project reference: 285224 (From 2011-05-01 to 2014-04-30) ; http://ec.europa.eu/information_society/apps/projects/logos/4/285224/080/deliverables/001_D41SuperLIBDeliverablev03942012final.pdf

POLYZION, *Fast rechargeable zinc-polymer battery based on ionic liquids*; FP7 –Energy ; Project reference: 226655 (From 2009-08-01 to 2013-01-31)

EU project ELIBAMA, *European Li-Ion Battery Advanced Manufacturing for Electric Vehicles*; FP7 Transport Project reference: 285385 (From 2011-11-01 to 2014-10-31)

MAT4BAT, *Advanced materials for batteries*; FP7 –NMP Project reference: 608931 From 2013-09-01 to 2017-02-28

MEMLAB, *Melt Spun and Sintered Metal Fibre Networks for Lead-Acid Battery Advancement*; FP7 SME Project reference: 315261 From 2012-11-01 to 2014-10-31

EU project HELIOS, *High Energy Lithium-Ion Storage Solutions*; FP7, project reference : SST – RTD 233765 from 2009-11-01 to 2013-10-31

Lead Carbon Super Hybrid project, *ALABAC*

6.1

DEFINITIONS AND ABBREVIATIONS

AGM – Absorbent Glass Mat

BMS – Battery Management System

DoD – Depth-of-Discharge

EFB – Enhanced Flooded Battery

(B)EV – (Battery) Electric Vehicle

FCEV – Fuel Cell Electric Vehicle

HEV – Hybrid-Electric Vehicle

ICE – Internal combustion engine

Li-Ion – Lithium-Ion

LCV – Light Commercial Vehicles

NaNiCl2 - Sodium-Nickel Chloride

NiCd – Nickel-Cadmium

NiMH – Nickel-Metal Hyrdride

OEM – Original Equipment Manufacturer

PHEV – Plug-in Hybrid-Electric Vehicle

PSoC – Partial-State-of Charge

SLI – Starter, Lighting, Ignition

SoC – State-of-Charge

7 Acknowledgem

This document was drafted by all battery manufacturing member companies of EUROBAT's Automotive Batteries Committee (Johnson Controls EMEA, EXIDE Technologies, FIAMM, SAFT, Moll Batterien, Banner Batterien, Dow Kokam, S.C. Rombat, and Inci Aku).

It was then extensively reviewed and endorsed by members of the International Lead Association (ILA), European Automotible Manufacturers Association (ACEA), Japanese Automobile Manufacturers Association (JAMA) and Korean Automobile Manufacturers Association (KAMA).

With thanks to all for their contributions.

nents

From a technology-neutral standpoint, this report evaluates in detail the suitability of all different battery technologies for use in various automotive applications, and argues that each will continue to have a well-established and irreplaceable role in Europe's automotive sector for the foreseeable future.

The report concludes that all battery technologies have specific performance profiles that serve a well-defined purpose in automotive applications. Therefore it is not possible to replace one technology by another without impacting on overall performance and vehicle cost.

This conclusion is reached using the combined input of Europe's automotive and battery industries, as well as contributions from the International Lead Association

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JAPAN AUTOMOBILE MANUFACTURERS ASSOCIATION, INC.

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A joint industry analysis of the technological suitability of different battery technologies for use across various automotive applications in the foreseeable future. From SLI and start-stop systems only using lead-based batteries, up to plug-in hybrid and full electric vehicles powered by high voltage lithium-ion technology and a smaller 12V lead-based accompaniment, the report demonstrates that established battery technology continues to have a well-established and irreplaceable role in Europe's developing automotive sector

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EUROBAT ACEA JAMA KAMA ila International Lead Association

A REVIEW OF BATTERY TECHNOLOGIES FOR AUTOMOTIVE APPLICATIONS

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