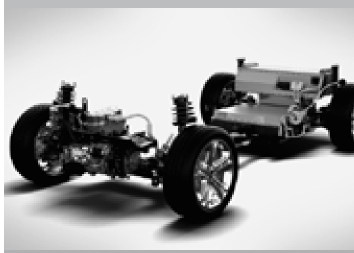

A REVIEW OF BATTERY TECHNOLOGIES FOR AUTOMOTIVE APPLICATIONS

EXECUTIVE SUMMARY

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 for 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.

Japanese 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.

Korean 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 and almost two thirds of lead production in the western world. ILA's work has a broad focus, covering all aspects of the industry's safe production, use and recycling of lead.

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01. Introduction

Batteries of several technologies are employed in different automotive applications, helping vehicle manufacturers to 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 introduced 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 (eg. nickel-metal hydride or lithium-ion batteries), while high-voltage lithium-ion and and sodium-nickel chloride batteries have been employed to deliver zero-emission driving in Europe's first generation of electric vehicles (EV).

This report provides a joint industry analysis of how different types of batteries are used in these automotive applications, with the intention of increasing 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 input into regulatory discussions on the feasibility of substituting certain battery technologies. The report emphasises that for future development of powertrains, a co-existence of existing battery technologies on the market is essential, in order to select the most effective solution for improved fuel efficiency and reduced CO_2 emissions at each level of hybridisation and electrification. The selection of a battery technology for different automotive applications is dependent on specific requirements related to performance, lifetime, safety and cost. Socioeconomic factors must also be taken into account.

02. Current Market Situation

The report's cornerstone is an overview of the current market situation for batteries in automotive applications. It outlines the different requirements placed on the battery system in three classes of vehicle, and explains how this affects battery selection. At present, lead-based, lithium-based, nickel-based and sodium-based batteries all have a well-established position across these three classes of vehicles, with each technology equipped to fulfill a different set of demands.

Class 1 CONVENTIONAL VEHICLES (INCLUDING START-STOP AND BASIC MICRO-HYBRID VEHICLES)

KEY BATTERY REQUIREMENTS FOR CLASS 1 PASSENGER CARS	
Voltage range	12 V required for compatibility with on-board electronics
Energy content	0.5-1.2 kWh
Recharge power	1 kW
Calendar life	5 years requested by OEMs
Cold Cranking	500-1000 CCA to reliably start an engine in cold temperatures, depending on type and engine displacement
Safety	Must be resistant to hot temperatures due to proximity of battery to engine
Low cost	Cost-efficiency paramount for mass-market applications

In conventional vehicles, the battery is required to start the engine and supply the vehicle's complete electrical system. In start-stop and basic micro-hybrid vehicles, the battery can also be expected to provide start-stop functionality and a level of braking recuperation.

- For technical reasons, the 12V lead-based battery will continue to be the only viable mass market battery system in Class 1 vehicles for the foreseeable future. Its excellent cold-cranking ability, 12V compatibility, and low overall economic package set it apart from other battery technologies in conventional vehicles. Advanced lead-based batteries are also best able to meet requirements in start-stop and basic-micro-hybrid vehicles.

- Alternative technologies, specifically lithium-ion batteries, still require improvement in cold-cranking ability and cost level to be considered as a viable mass-market alternative in this class. Research into improvement of these parameters through real-life testing is ongoing by OEMs.

- There are over 250 million vehicles of this class in Europe. Accordingly, there are significant economic and practical ramifications to be considered in battery selection. Automotive lead-based batteries benefit from an established manufacturing base equipped for mass-market demand, high resource availability and an excellent recycling efficiency. In addition, almost 100% of automotive lead-based batteries are taken back and recycled at their end-of-life.

Class 2 HYBRID VEHICLES (ADVANCED MICRO-HYBRID, MILD-HYBRID AND FULL-HYBRID VEHICLES)

BATTERY REQUIREMENTS FOR A CLASS 2 PASSENGER CAR	
Voltage range	48-400 V
Energy content	0.2-1.5 kWh
Discharge power	10-80 kW
Recharge power	10-50 kW
Cold cranking	5-7 kW pulses for up to 10 seconds
Capacity turnover	10,000 micro-cycles for full HEVs (e.g. <5% depth of discharge)
Calendar life	Greater than 10 years is generally requested by OEMs
Safety	Battery Management System required to manage high voltages
Weight and volume	As light and small as possible
Low cost	Needs to be competitive vs other options to reduce CO_2 emissions

In different types of 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 employed for a certain range of electric driving.

- Several battery technologies are able to provide these functions in different combinations, with nickel-metal hydride or 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 competiveness. In terms of performance, nickel-metal hydride batteries are comparatively limited by their heavier weight, lower energy density, and lower deep-cycling capability.

- These vehicles also utilise a second electrical system on a 12V level for controls, 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)

BATTERY REQUIREMENTS FOR A CLASS 3 PASSENGER CAR	
Voltage range	250-500 V (up to 800V for commercial vehicles)
Energy content	14 kWh for 100km driving range
Discharge power	Up to 100 kW
Recharge power	Up to 50 kW
Cold cranking (PHEV only)	5-7 kW pulses for up to 10 seconds
Capacity turnover	2,000-3,000 cycles at high depth of discharge (e.g. 80%)
Calendar life	Greater than 10 years is generally requested by OEMs
Safety	Battery Management System required to manage high voltages
Weight and volume	As light and small as possible
Low Cost	Needs to be competitive vs other strategies to reduce CO_2 emissions

In plug-in hybrid vehicles 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 perform hybrid functions (e.g. regenerative braking, engine boosting) when its capability for electric drive is depleted.

- Class 3 passenger cars are propelled by lithium-ion battery systems, due to their high energy density, fast recharge capability, and high discharge power.
- In passenger cars, lithium-ion batteries remain the only available battery technology capable of meeting OEM requirements for vehicle driving range and charging time. Nickel-metal hydride and lead-based batteries cannot meet these requirements at a competitive weight.
- For commercial applications, harsh environments, and heavy duty vehicles, high-temperature sodium nickel chloride batteries are a competitive option.
- All PHEVs and EVs also utilise a second electrical system on a 12V level for controls, comfort features, redundancy, and safety features. This electrical system is supplied by a 12V lead-based battery.

03. Future Trends

The report also outlines how the battery market is expected to change in the foreseeable future (i.e. until 2025), and how the individual battery technologies will continue to develop. At all levels of e-Mobility, vehicle manufacturers are demanding increased battery performance to meet short-term and long-term EU carbon emission targets.

Significant research efforts are therefore directed towards the 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.

This report identifies the following priority areas for improvement between now and 2025:

ADVANCED LEAD-BASED BATTERIES

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

By 2025, they will be required to provide extra services in micro-hybrid vehicles to increase the internal combustion engine's fuel efficiency (e.g. 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 higher performance both in terms of charge acceptance and in their ability to operate partial state of charge applications.

Dual battery systems 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 has been reduced as a consequence of the increased performance and reduced cost of lithium-ion batteries.

Because nickel-metal hydride batteries 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.

LITHIUM-ION BATTERIES

Significant resources will continue to be spent on improving the performance, cost, systems integration, production processes, safety, and recyclability of high voltage lithium-ion battery systems for HEV, PHEV and EV applications. This is required to improve the market-competiveness of such vehicles.

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 also expected by 2025, along with improvements in materials properties and the gradual scaling up in production of large cell formats. Other areas of improvement are outlined in the report.

These improvements can expect to spill over into other automotive applications, given the upgraded performance and lower cost of lithium-ion technologies at a cell level. It is expected that lithium-ion batteries will be implemented in selected 48V dual-battery systems along with a 12V lead-based battery to further increase fuel-efficiency in the advanced micro-hybrid and mild-hybrid segment.

SODIUM NICKEL CHLORIDE BATTERIES

In the coming years, sodium nickel chloride batteries will be increasingly used in the automotive market for traction purposes in PHEVs and EVs. They will be used primarily in heavy duty vehicles (buses, trucks) or in applications with very harsh environmental requirements.

Manufacturers will work to improve the performance, cost, systems integration, production process, 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 expected to decrease significantly.

NOVEL BATTERY TECHNOLOGIES

In the long-term future, other novel battery technologies (zinc-air, lithium-sulphur, 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 cannot be considered for the foreseeable future.

04. Conclusions

From this analysis of technical requirements and market trends for battery technologies 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 by another 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 technical requirements of conventional vehicles (including start-stop and basic micro-hybrid vehicles). 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, various 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 providing the most competitive performance as requirements increase.

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

DEVELOPMENT TIME

Using alternative battery technologies would also likely result in **additional development costs to adapt the vehicle to that new technology**. Changes such as installing a battery management system and 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.

SOCIOECONOMIC 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 250m conventional ICE vehicles (plus start-stop and basic micro-hybrid vehicles) in Europe, and therefore any corresponding 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 manufacturers of applications, so they can choose the most suitable batteries for their products. **The EU's legislative and regulatory framework should guarantee a fair and technology-neutral competition between battery technologies.**

05. Acknowledgements

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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.

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.

This document provides a joint industry analysis of the current and future availabilities of resources and materials used in a range of battery technologies. The document focuses on automotive batteries, and does not cover other battery technologies that are not currently used for this application. The report aims to answer the following questions:

- *Are there any current resource availability issues associated with the manufacture of automotive battery technologies?*
- *Are the any future issues that could affect the resource availability associated with the manufacture of automotive battery technologies?*

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RESOURCE AVAILABILITY OF METALS USED IN BATTERIES
FOR AUTOMOTIVE APPLICATIONS

EXECUTIVE SUMMARY

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