Lecture Notes in Mobility

Michael Nikowitz *Editor*

# Advanced Hybrid and Electric Vehicles

## System Optimization and Vehicle Integration

bmvit Austrian Ministry for Transport, Innovation and Technology

A3PS

iea International Energy Agency

IEA International Energy Agency Hybrid & Electric Vehicle Implementing Agreement

Springer

# Lecture Notes in Mobility

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Michael Nikowitz
Editor

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## System Optimization and Vehicle Integration

Springer

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A3PS—Austrian Association for Advanced
Propulsion Systems
Vienna
Austria

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# Preface of the Operating Agent

## System Optimization—The Key to Success

Current trends in energy supply and use are unsustainable, in terms of environment, economy, and society. We have to change the path that we are now on—we have to reduce greenhouse gas emissions (GHG) and we have to improve energy efficiency. Therefore, low-carbon energy technologies/environmentally friendly mobility will play a crucial role and is one of today's major challenges for the global automotive industry on par with the growing trend towards urbanization, the increasing scarcity of natural resources, the steady rise in the world's population, and global climate change. Especially the transport sector—one of today's fastest growing sectors—is a contributor to many environmental problems due to its dependency on fossil fuels.

In the search for a sustainable solution to these challenges, electrical energy is the key to success, particularly when it comes to mobility. Vehicles driven by an electrified powertrain, including pure battery electric vehicles, hybrid electric vehicles, fuel cell electric vehicles, etc. (also known as xEVs) can significantly contribute to the protection of the environment by reducing the consumption of petroleum and other high $CO_2$-emitting transportation fuels.

However, penetration rates of electric vehicles are still low, mainly because of the high battery cost, range anxiety, and the still low level of existing charging infrastructure. Research and development plays a crucial role in the process of developing alternative power technologies, especially when it comes to the optimization of electrified vehicles.

This publication was prepared under the umbrella of the International Energy Agency's Implementing Agreement for Hybrid and Electric Vehicles (IEA-IA-HEV), which tries to analyze the potentials of these vehicles, by working on different Tasks.

One of them—Task 17—"System Optimization and Vehicle Integration"—analyzed technology options for the optimization of electric and hybrid vehicle components and drive train configurations which will enhance vehicle energy efficiency performance. Furthermore, it was the only Task within the IEA-IA-HEV, which analyzed the possibilities for the overall vehicle integration of different components, needed for an electric vehicle, like the integration of the drive train into lightweight vehicles.

After 5 years of effective networking among the various industries involved in system optimization, Task 17 successfully demonstrated the benefits, potentials, technical challenges but also chances of the overall vehicle performance.

This report highlights the final Task results, by compiling an up-to-date, neutral, and comprehensive assessment of current trends in technical as well as technological policy aspects for hybrid and electric vehicles.

Michael Nikowitz

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# Abbreviations and Nomenclature

| | |
|---|---|
| A3PS | Austrian Association for Advanced Propulsion Systems |
| AC | Alternating Current |
| ADAS | Advanced Driver Assistance Systems |
| AlNiCo | Aluminum–Nickel–Cobalt |
| AIT | Austrian Institute of Technology |
| ASICs | Application Specific Integrated Circuit |
| BAS | Belt–Alternator–Starter |
| BatPaC | Bottom-up Battery Performance and Cost Model |
| BCU | Battery Control Unit |
| BEV(s) | Battery Electric Vehicle(s) |
| BEVx | Range-Extended Battery Electric Vehicle |
| BFH | Bern University of Applied Sciences |
| BMS | Battery Management System |
| bmvit | Austrian Federal Ministry for Transport, Innovation and Technology |
| BYD | Build Your Dream (Chinese OEM) |
| CAN | Controller Area Network |
| CD | Charge Depleting |
| CFD | Computational Fluid Dynamics |
| CFRP | Carbon Fiber Reinforced Plastic |
| CULT | Cars' Ultra-Light Technologies vehicle (Car concept by manufacturer MAGNA) |
| CV | Conventional Vehicles |
| DLR | Deutsches Luft- und Raumfahrtzentrum (German Aerospace Center) |
| DoD | Depth of Discharge |
| ECU | Electronic Control Unit |
| EGVI | European Green Vehicles Initiative |
| EPA | U.S. Environmental Protection Agency |
| EPoSS | European Technology Platform on Smart Systems Integration |
| E-REV(s) | Extended-Range Electric Vehicle(s) |
| ERTRAC | European Road Transport Research Advisory Council |
| ESKAM | Elektrisch Skalierbares Achs-Modul |

| | |
|---|---|
| EUR | Euro (currency) − 1 EUR ≙ 1.091 USD in June 2015 |
| EVSE | Electric Vehicle Supply Equipment |
| EV(s) | Electric Vehicle(s) |
| FCEV(s) | Fuel Cell Electric Vehicle(s) |
| GHG | Greenhouse Gas |
| GM | General Motors |
| GnP | Graphite Nano-Platelets |
| HEV(s) | Hybrid and Electric Vehicle(s) |
| HiL | Hardware in the Loop |
| hp | Horse Power |
| HSS | High Strength Steel |
| HWFET | Highway Fuel Economy Test by U.S. EPA |
| HWY | Highway Fuel Economy Test |
| IA-HEV | Implementing Agreement for Hybrid and Electric Vehicle |
| ICCT | International Council on Clean Transport |
| ICE | Internal Combustion Engine |
| IEA | International Energy Agency |
| In. | Inches (unit of length) – 0.0254m ≙ 1 in |
| IT | Industrial Technology |
| km | Km (unit of length in the metric system) |
| kWh | Kilowatt Hour (unit of energy) |
| lb | Pound (unit of mass) – 1 kg ≙ 2.205 lb |
| Li-ion | Lithium-Ion (batteries) |
| Li-Po | Lithium Polymer (battery) |
| MCU | Module Control Unit |
| mi | Mile (English unit of length) − 1 km ≙ 1.609 mi |
| MiL | Model in the Loop |
| MPG | Miles per gallon |
| NdFeB | Neodymium–Iron–Boron |
| NEFZ | New European Driving Cycle |
| NiMH | Nickel Metal Hydride (batteries) |
| OEM | Original Equipment Manufacturer |
| PEMFC | Proton Exchange Membrane Fuel Cell |
| PHEV(s) | Plugin Hybrid and Electric Vehicle(s) |
| PTC | Positive Temperature Coefficient Element |
| PM | Permanent Magnet |
| PMSM | Permanent Magnet Synchronous Motors |
| R&D | Research and Development |
| RE | Rare Earth |
| RMB | Renminbi (Chinese currency) |
| RPM | Revolutions per Minute (measure of the frequency of rotation) |
| RTOS | Real-Time Operating System |
| SiL | Software in the Loop |
| SoC | State of Charge |
| SoH | State of Health |

| | |
|---|---|
| SR | Switched Reluctance (motors) |
| STS | Surface-to-Surface |
| SUV(s) | Sport Utility Vehicle(s) |
| TMS | Thermal Management Systems |
| UDDS | Urban Dynamometer Driving Schedule |
| UN | United Nations |
| U.S. | United States |
| US DoE | US Department of Energy |
| USD | United States Dollar (currency) − 1 EUR ≙ 1.091 USD in June 2015 |
| VCU | Vehicle Control Unit |
| VW | Volkswagen |
| xEV(s) | Common shortcut for all vehicles, driven by an electrified powertrain like EV, HEV, FCEV, etc |

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# Introduction

**Michael Nikowitz**

**Abstract** For more than a century, our society has been dependent upon oil. Today, worldwide industry and government are forced to consider alternative and sustainable solutions for transportation. Vehicles, driven by alternative drivetrain offer an unique advantage concerning energy efficiency, emissions reduction and reduced petroleum use. Thus, they have become a research focus around the world. Electric driven vehicles are seen as one way of reducing oil use and GHG emissions but the challenges for their market introduction often focus on the performance and cost of batteries as well as the corresponding charging infrastructure. Other essential aspects are often not taken into account. Therefore, a special Task of the Implementing Agreement Hybrid and Electric Vehicles under the umbrella of the International Energy Agency (IEA)—Task 17—analyzed technology options for the optimization of electric and hybrid vehicle components and drivetrain configurations that will enhance vehicle energy efficiency performance. This chapter highlights the milestones in history of electrified vehicles and explains the objectives, as well as working methods of Task 17—"System Optimization and Vehicle Integration for Enhanced Overall Vehicle Performance".

## 1 The Need for Sustainable Mobility

**Today, there are around 1 billion automobiles in use worldwide.** This large number of vehicles has caused and continues to cause a series of major issues in our society, like GHG emissions; air pollution; oil depletion; energy security and population growth (see Fig. 1).

Regarding world population and urbanization there will be a strong shift towards urban population till the year 2050, as it can be seen from reports of the United Nations (UN) in Fig. 2.

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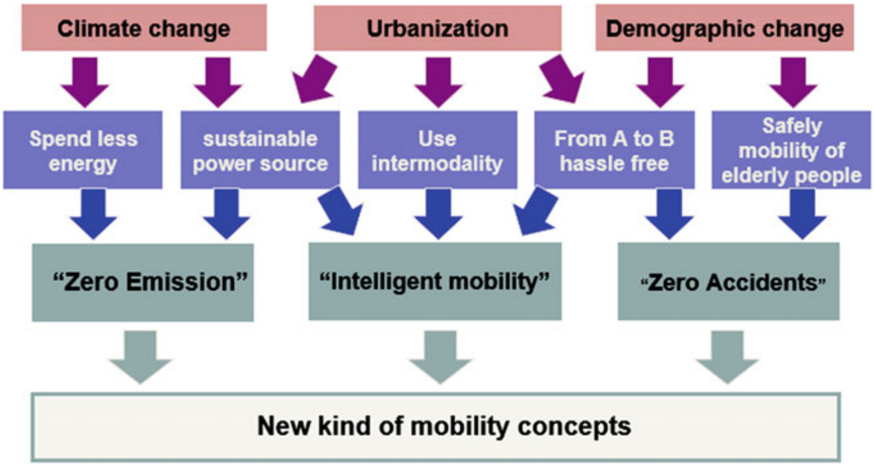


**Fig. 1** Global megatrends strongly influence the future of mobility

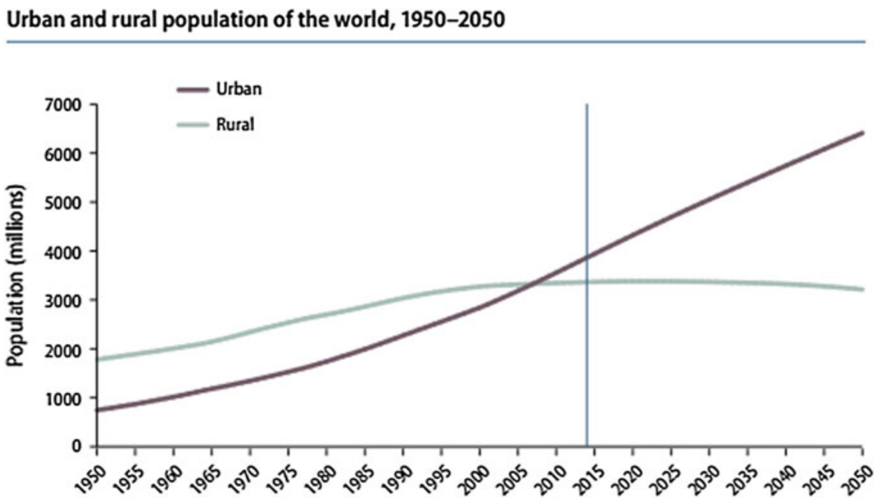


**Fig. 2** Development of urban and rural population worldwide [1]

While in 1800, around 3 % of the world's population has lived in urban areas, today nearly 54 % of the world's population is located in urban areas. By 2025, there will be 29 megacities and by 2050, over 70 % of the world population will live in big cities.

**Therefore, efficient and zero-impact transportation will be one of the key challenges of our society. Major trends like connectivity, shared mobility, automated driving, light weight vehicles, digital experience and alternative**

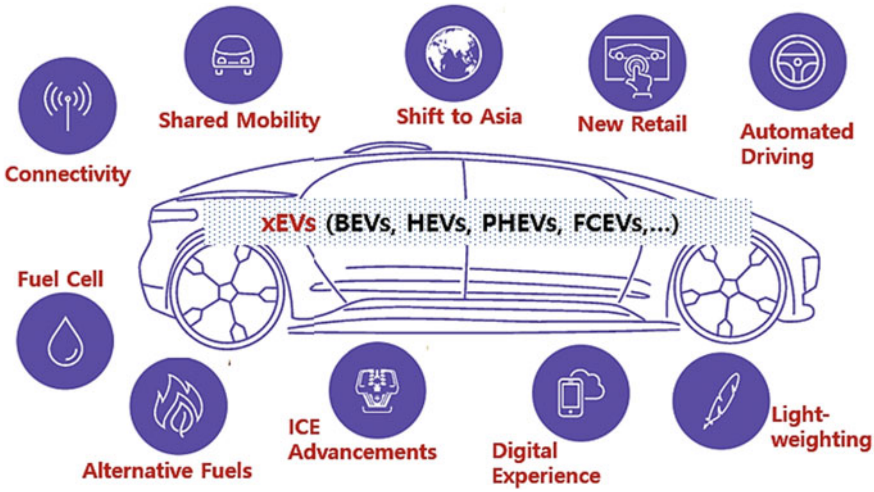


**Fig. 3** Major trends will impact the future of the automobile

**fuels will have a massive impact of the future of the automotive industry**, as it is illustrated in Fig. 3.

The automotive industry is dealing with two major trends:

- *electrification of the drive train and*
- *autonomous driving*

Worldwide industry and government are forced to consider alternative and sustainable solutions for transportation. Vehicles, driven by alternative drive train offer a unique advantage concerning energy efficiency, emissions reduction, reduced petroleum use and have thus become a research focus around the world. Therefore decarbonizing transport is providing to be one of the largest Research and Development (R&D) projects of the early 21st century. Low-carbon technologies are therefore rapidly advancing, including petrol and diesel hybrids, battery electric, and hydrogen fuel cell being developed by nearly every major manufacturer.

*A battery electric vehicle (BEV) is an electrical vehicle (EV) that utilizes chemical energy stored in rechargeable battery packs. Electric vehicles use electric motors instead of, or in addition to, internal combustion engines (ICEs). Vehicles using both electric motors and ICEs are called hybrid vehicles (HEVs) and are usually not considered pure BEVs. Hybrid vehicles with batteries that can be charged and used without their ICE are called plug-in hybrid electric vehicles (PHEVs) and are pure BEVs while they are not burning fuel [2].*

## 1.1 Timeline—History of EVs

The idea of driving electrically is not brand-new. Who invented the very first EV is uncertain and several inventors have been given credit. In fact, the EV has been around for over 100 years, and it has an interesting history of development that continues to the present.

In ***1898***, more than three decades before founding his namesake company, 22-year-old Ferdinand Porsche designed his first-ever automobile: an electric-powered car officially known as the Egger-Lohner EV. Porsche's prototype car boasted a low-friction drive train, due to the hub-mounted electric motors directly driving the wheels, as it can be seen in Fig. 4. In case of saving weight and creating room for a petrol engine, Porsche swapped the original 74-cell accumulator in his electro-mobile for a smaller battery with 44 cells. In the middle of the vehicle he installed two water-cooled 3.5 horsepower (hp) (2.6 kW) DeDion Bouton (a former car manufacturer from France) petrol engines—driving two generators to create electricity—each producing 2.5 hp (1.84 kW). Both engines operated independently, each delivering 20 A with a voltage of 90 V.

By the turn of the ***20th Century***, EVs were outselling gasoline cars. In major cities like New York or London, electric taxis had appeared. People liked them because they didn't smell, vibrate or make noise and they were easy to drive.

During the ***1920s*** the EV ceases to be a viable commercial product as a number of factors caused its downfall, like the desire for longer distance vehicles, their lack of horsepower, and the ready availability of gasoline.

With skipping some years of automotive history, we end up at World War II, where fuel shortages increased interest again in EVs, but those efforts were short-lived. It wasn't until the ***1970s*** that another shortage fueled interest in EVs.

In ***1977***, Volkswagen (VW) built a "City-Taxi" for an exhibition in the New Yorker Museum of Modern Art under the motto "The transport and environment-friendly vehicle for urban agglomerations and thus a considerable improvement in

**Fig. 4** Ferdinand Porsche's 1901 'Semper Vivus,' the world's first hybrid automobile [3]

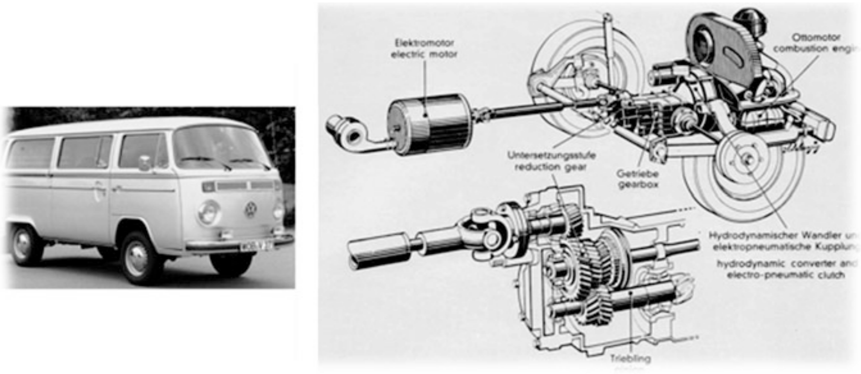


**Fig. 5** VW Hybrid Bus T2, bus (*left*) and build-up (*right*) [4]

the quality of life in the city" (see Fig. 5). In this year already the still partly valid problem of today's EVs was formulated by a VW spokesman: *"Electric vehicles are independent of liquid and gaseous fuels—on the other hand, however, limited in payload and range." But also a possibly solution was considered: "With hybrid drive it is possible to compensate the range and power deficit of your e-mobile with a gasoline engine"*. [Source: unknown]

Finally, in the ***1990s*** major auto manufacturers began to offer mainstream electric and hybrid options. In the late 1980s and 1990s, General Motors worked to put an EV on the market. Announced by Chairman Roger Smith in 1990 as the "Impact," the car that hit the streets in Arizona and California was called the EV1 (see Fig. 6). The EV1 was made available through limited lease-only agreements. By 2002, 1,117 EV1 s had been produced, though production had ended in 1999, when GM shut down the EV1 assembly line. The car's 3-phase AC induction electric motor produced 137 brake horsepower (102 kW) at 7000 RPM. The drag coefficient of 0.19 was the lowest of any production automobile in history, while typical production cars have drag coefficients in the 0.3 to 0.4 range. At 4,310 mm (169.7 inches (in)) in length, and 1,765 mm (69.5 in) in width, the EV1 was a subcompact car, with a 2-door coupé body style.

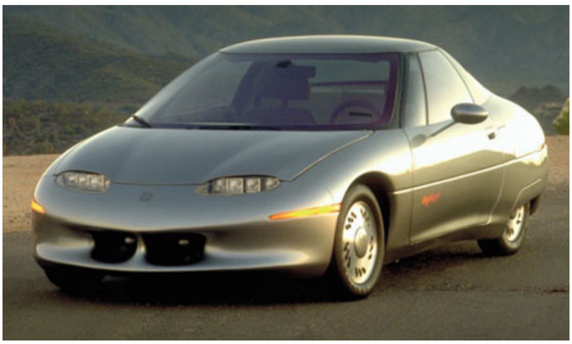

**Fig. 6** General Motors—EV1—the first mainstream EV [5]


**Fig. 7** Mitsubishi i MiEV [6]

**Fig. 8** EVs of the 20th century; Tesla S (*left*) [7] and Renault Twizzy (*right*) [8]

In ***2011***, the Mitsubishi i MiEV was the first EV to sell more than 10,000 units. Only a few months later, the Nissan Leaf overtook the i MiEV as the best-selling all-EV ever (see Fig. 7).

The success of the Leaf ended up being the catalyst for other auto manufacturers to start producing their own EV models like the Ford Focus Electric, Smart electric drive, Volvo C30, Chevy Volt, Tesla Model S (see Fig. 8), Renault Twizzy Z.E., BMW ActiveE and several others.

***Today*** there is a much more aggressive attempt to normalize the EV.

Right now, range; infrastructure and public awareness are the hurdles to overcome. Regardless of these challenges, lithium ion battery technology continues to improve, and it seems inevitable that the EV will continue to rise in popularity, as the sales of EV increase throughout the world.

Certainly, this section doesn't show all steps and events from the past, as it can be seen in the drawing [9] in Fig. 9. It just highlighted some of the most important ones to visualize, that the movement to EVs has been a slow process. It has always been dictated by consumer desires, price, and practicality.

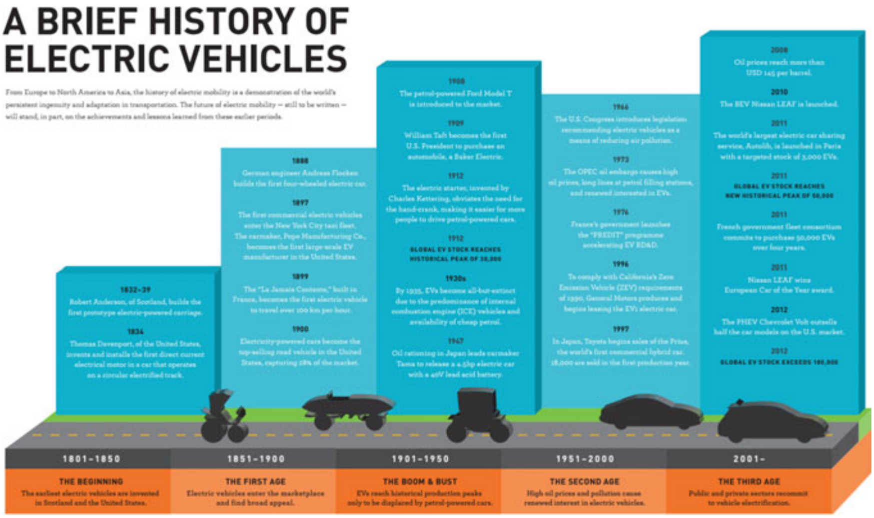


**Fig. 9** Development of EVs from 1801−2001+ —(image courtesy of IEA)

> *There are predictions that the EV market will reach 8 % of total car sales by 2020. Studies conducted by the IEA pointed out, that there are approximately 700,000 BEVs and PHEVs on the streets (as per May 1st 2015). It's expected to reach the 1 million (Mio.) mark till the end of 2015.*

According to the "European Roadmap Electrification of Road Transport" of the European Union, a mass production of dedicated BEVs and PHEVs is feasible by 2020 if fundamental progress is made in six technology fields:

- **energy storage systems,**
- **drive train technologies,**
- **vehicle integration,**
- **safety,**
- **road integration and**
- **grid integration**.

Mass deployment of the technology will however require significant increases of energy efficiency and reductions of cost which may be provided as of 2025 by a fully revised EV concept. Figure 10 shows the Milestones of the Roadmap mentioned above. The lower black curve symbolizes the evolutionary development of accumulated number of EV/PHEV. The upper black curve shows the expected development under assumption of reaching the major technological breakthroughs.

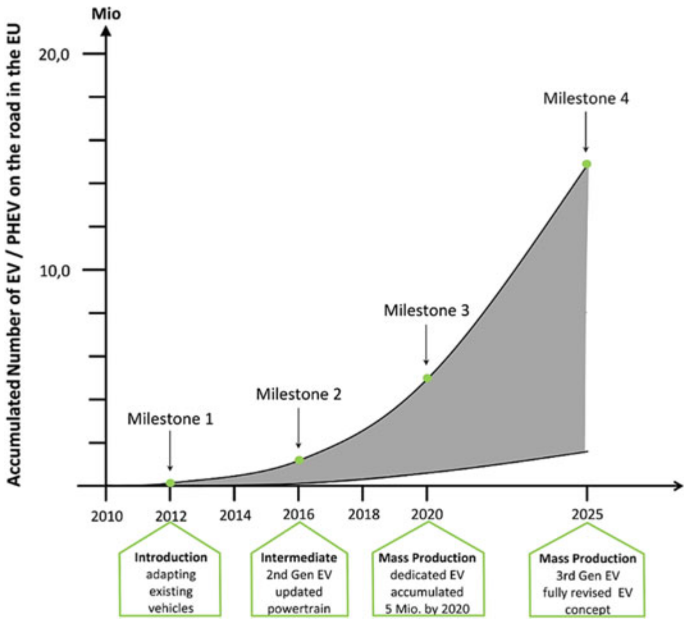


**Fig. 10** Milestones of the European Roadmap Electrification of Road Transport [10]

The future of EVs, relies on how good the car batteries can become: how much power they can hold, and for how long.

## *1.2 Task 17—System Optimization and Vehicle Integration*

**Electric driven vehicles (BEVs, HEVs, PHEVs, FCEV, …)—further referred as xEVs in this report**—are seen as one way of reducing oil use and GHG emissions and to improve local air quality. In recent years, sales of those vehicles have risen steadily but sales figures are far behind the expectations of car manufacturers.

The discussion of the difficulties facing electro-mobility (e-mobility) is often focused on battery performance, charging aspects like missing infrastructure and time and costs. Other aspects like the integration and optimized configuration of components including the optimization of the interfaces e.g. system management and monitoring should also be brought to the discussion since they could provide a significant contribution to the feasibility of this transport alternative.

Therefore Task 17 within the Implementing Agreement (IA) “Hybrid and Electric Vehicles” (HEV) of the International Energy Agency (IEA) was started in 2010.

*Member Countries contributing to Task 17 were Austria, Germany, Switzerland, and the United States. Assignment of this Task was to analyze technology options for the optimization of EVs, PHEVs and HEVs as well as components and drive train configurations that will enhance vehicle energy efficiency and performance.*

Electronic systems, used to operate and monitor all types of vehicle have benefited from substantial improvements during the past few years. Additionally these systems have also improved the prospects for xEVs. Improved power electronics have resulted in new opportunities to control and steer the increasingly complex-component configurations. In addition, new integration options for components have undergone rapid improvements during the past few years. Further optimization of these components is necessary—like new concepts for integrating them in the overall system and tuning them—to meet the specific requirements of different vehicle applications.

These developments and the opportunities they provide have been analyzed in Task 17.

### 1.2.1 Scope of Task 17

The **scope** of this Task was the monitoring and analysis of progress in design and configuration as well as trends and strategies for vehicles with high degree of electrification.

Thus, Task 17 was focusing on:

- overview and analysis of **present vehicle components** on the market available and further analysis of their development potential,
- overview and comparison of **selected current configurations of components** in vehicles on the market in terms of an advanced vehicle performance assessment,
- analysis of existing **component technologies** and their development potential,
- **Original Equipment Manufacturer** (OEM)s-review of different strategies and technologies for EVs and follow-up of new prototypes,
- analysis of theoretical **possible operation and configuration concepts** and assessment of their advantages and disadvantages,
- **workshops** with Task members and additional external experts' from industry and research institutions,
- overview and analysis of different **simulation tools** and
- considerations of design depending on different applications for EVs.

### 1.2.2 Impacts of Task 17

The following **impacts** on the following aspects of system performance have been analyzed:

- **integration and control of software solutions** (by software architecture strategies for real-time minimization of losses),
- **improvements in energy efficiency** (by optimizing thermal and electric energy management), operational safety and durability through better monitoring of component operation,
- **reductions in the cost of components** (through increased efficiency in operation and production, alternative materials, etc.),
- **reductions in weight/volume** through the optimized assembly of the drive train,
- **Range Extender modules** (internal combustion engine, fuel cell), electronic control concepts for Range Extenders,
- **configurations for energy storage systems** and/or Range Extenders and
- **drive train configurations** (fixed and variable gearing, single and multiple motor drive, in-wheel drive).

### 1.2.3 Working Methods of Task 17

Task activities predominantly consisted of preparing this technology assessment report on trends and providing opportunities for member countries to exchange information. The scope of work has focused on the participant's capabilities and fields of expertise and basically covered the monitoring and analysis of component development and vehicle architecture relative to trends and strategies for EVs progress. Thus, working methods included:

- **questionnaires, personal interviews and several workshops** with industry (in- and outside automotive companies, academia, user organizations, technology and innovation policy experts),
- **foresight analyses** of future options and opportunities,
- **simulation** of different component configurations,
- **International networking** using momentum and achievements of external partners (EU-FP7, FCH-JU, ERTRAC, etc.),
- **information exchange** and close coordination with other running Tasks of the Implementing Agreement using their results for vehicle integration investigations,
- **cooperation with other Agreements** like the Implementing Agreement for Advanced Motor Fuels or Advanced Fuel Cells and
- **dissemination of results** of participating countries in giving support to their policy and industrial decision makers and leading R&D representatives in their responsibility for setting of research priorities.

**Fig. 11** Impressions from Task 17 workshops

**The most common method of work was represented by workshops** (see Fig. 11), which enabled the dissemination of information about relevant activities within an international context.

Since 2010, nine workshops took place, including experts from industry as well as R&D and policy makers.

In numbers:

- **nine workshops** took place on **seven locations** (worldwide):
- 2010: Vienna (Austria)—“***Kick Off Meeting*** *and* ***First Steps*** *for System Optimization and Vehicle Integration of EVs*”

- 2011: Geneva (Switzerland)—"***Current Status of R&D for EV Components - Focus on Energy Efficiency Improvements***"
- 2011: Chicago (United States)—"***Battery Management Systems***"
- 2012: Santa Monica (United States)—"***E/E-Architecture and Evaluation of Electric Vehicle Performance***"
- 2012: Vienna (Austria)—"***System Integration and Mass Impact***"
- 2013: Chicago (United States)—"***Innovative Thermal Management for Hybrid and Electric Vehicles***"
- 2013: Vienna (Austria)— "***Thermal Management Concepts for Hybrid and Electric Vehicles***"
- 2014: Schaffhausen (Switzerland)— "***Functional and Innovative Lightweight Structures and Materials in xEVs***"
- 2015: Berlin (Germany)—"***Power Electronics and Drive Train Technologies for future xEVs***",
- in total, **84 speakers** from 42 companies, institutes and policy makers participated in these workshops (compare Table 1), additionally about **131 participants** from **eight countries** have been participated in these **workshops** and on several **technical visits**, e.g. Vienna Climatic Wind Tunnel, Iron Library, Lightweight Center of Georg Fischer, etc.
- the **Operating Agent** was represented through the **Austrian Association for Advanced Propulsion Systems** (A3PS)—a strategic public private partnership which was initiated by the Austrian Federal Ministry for Transport, Innovation and Technology (bmvit) in order to support the development and market introduction of alternative propulsion systems and their energy carriers. This association enables a close cooperation between its stakeholders, the ministry as well as R&D and industry and **three Operating Agents** (Ms. Gabriela Telias (2010−2012), Mr. Mark-Michael Weltzl (2012−2013) and Mr. Michael Nikowitz (2013−2015) and one Vice-Operating Agent (Mr. Andreas Dorda (2010−2015) have been involved.

*The desired output of Task 17 is this task report on its activities in order to give an up-to-date, neutral and comprehensive overview on current trends in xEVs worldwide.*

Therefore the final report was split in the following subtopics:

- OEM and Industry—Review
- International Deployment
- Advanced Vehicle Performance Assessment—Testing
- System Optimization and Vehicle Integration:
    - E-Motors
    - Battery Management
    - Thermal Management

**Table 1** List of workshop-participants (2010–2015)

| | | | |
|---|---|---|---|
| 3A Composites | 4a manufacturing GmbH | Austrian Association for Advanced Propulsion Systems | Austrian Institute of Technology |
| Argonne National Laboratory | Alfred Wegener Institute | AVL List GmbH | Bern University of Applied Sciences |
| Bitter GmbH | Federal Ministry for Transport, Innovation and Technology | Robert Bosch GmbH | Federal Ministry of Education and Research |
| French Alternative Energies and Atomic Energy Commission | Connova AG | Delphi Thermal Systems | DLR - German Aerospace Center |
| Technical University of Denmark | eNOVA | Swiss Federal Institute of Technology in Zurich | European Commission |
| Fraunhofer Institute | Georg Fischer AG | Groschopp AG | Hella KGaA Hueck & Co. |
| Idaho National Laboratory | Inspire AG | Magna Steyr Fahrzeugtechnik AG & Co KG | University of Leoben |
| University of Applied Sciences and Arts Northwestern Switzerland | Porsche AG | Punch Powertrain | Qpunkt GmbH |
| Quadrant Plastic Composites | Rail Tec Arsenal | Rhine-Westphalia Institute of Technology Aachen | Siemens |
| Swiss Federal Office of Energy SFOE | Technical University of Vienna | U.S. Department of Energy | Valeo Climate Control |
| Virtual Vehicle | VDI/VDE-IT | | |

- Simulation Tools
- Lightweight
- Power Electronic and Drive Train Technologies for future xEVs

- Summary

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# OEM and Industry Review—Markets, Strategies and Current Technologies

**Michael Nikowitz**

**Abstract** This chapter focus on the current status of battery, hybrid and fuel cell electric vehicles, from an electrochemical and market point of view in order to give a common understanding. It also provides an overview about the advantages and disadvantages between the different technologies, as well as a comparison towards conventional vehicles. Besides that an overview of famous OEMs of electrified vehicles with their respective markets but also their penetration strategies is shown. A comparison of all countries demonstrates that the United States leads in number of total registered electric vehicles, while Norway leads in the market share of such vehicles. The demand for electrified vehicles has grown so rapidly within the last year, that the market for the batteries going into these cars is expected to grow more than sevenfold by 2020.

> The global number of vehicles—driven by an electrified drive train—has exploded since 2011. At the end of 2014, the global sales number of BEVs and PHEVs increased to around 700,000 vehicles worldwide. But the 320,000 electric cars bought worldwide in 2014 made up less than half of a percent of the 85 million new vehicles sold in 2014. The demand has grown so rapidly that the market for the batteries going into these cars is expected to grow more than sevenfold by 2020.

In this section the most important vehicle technologies currently used in today's vehicles are briefly introduced to give a common understanding. Furthermore a short overview of famous OEMs of xEVs with their respective markets and their penetration strategies is shown.

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# 1 OEM Markets

**By region, the United States and Japan are currently the world's largest markets for HEVs, representing a combined 80 % of global sales.** Based on the degree of government support and OEM sales targets, the countries are expected to take a similar lead in EVs sales. But China and Europe will likely become the biggest EV markets as the decade progresses and initial government incentives are phased out. Figure 1 shows how the global EV market has grown from less than 10,000 (2009), to about 710,000 units (2014). Thus, overall global sales approximately doubled in each of the past four years.

## *1.1 China*

In 2009, strong growth was expected during 2013 and 2015 as local and foreign vehicle makers aggressively roll out EVs and Extended-Range Electric Vehicles (E-REVs), supported by growth in the charging infrastructure and declining Lithium- Ion (Li-ion) battery prices—supported by various governmental incentives programs. These trends made the Chinese EV market a highly interesting destination for many vehicle manufacturers. In 2010, the Chinese government intended to make China the leading EV market by 2015 and therefore offers several incentives and subsidies for the development and purchase of EVs. The Ministry of Industry and Information Technology in China provided a 20 billion RMB [2] (around 2.9 billion EUR or 3.2 billion USD) package from 2010 to 2012, offering tax breaks and R&D support to OEMs developing new energy cars, including EVs. The Ministry of Science and Technology offered a 10 billion RMB (around 1.4 billion EUR or 1.6 billion USD) subsidy package to sponsor the R&D activities of

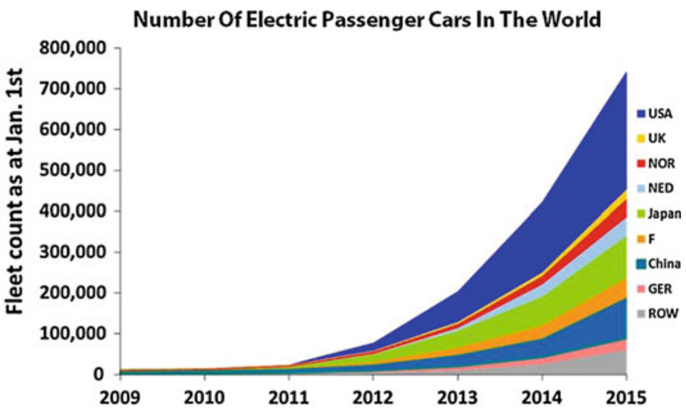


**Fig. 1** Number of electric passenger cars worldwide [1]

local OEMs in designing and manufacturing new energy cars. The Chinese Government offers cash incentives of up to 8,095 EUR (8,824 USD) per EV and between 6,017 EUR (6,618 USD) and 6,745 EUR (7,353 USD) per EREV in 13 selected cities.

Many potential Chinese customers still don't clearly understand that the running cost of EVs is much lower than that of conventional cars. Moreover, the ability of EVs to reduce pollutant emissions is not fully acknowledged. In addition to high cost, prospective customers are also concerned about the high voltage system and worry about safety issues of Li-ion battery packs. These negative consumer perceptions are some major challenges that will need to be overcome in the Chinese EV market.

Nevertheless, subsidies and incentives offered by the Chinese Government, along with the aggressive re-charging infrastructure plan they have rolled out, will ensure the mass adoption of EVs in China where there is already a huge market for electric two-wheelers. Additionally, as domestic OEMs like BYD, Chana and SAIC are also eyeing the E-REV market, this will boost consumer confidence in the driving range and performance of an EV. In the future, the massive government backing, aggressive infrastructure plans for restructuring and focus on all types of EVs will constitute key reasons for growth of the overall EV market in China.

Auto maker Volkswagen, known for trend setting innovations and technologies, sees the largest future market for EVs in China. To ensure that carbon emissions in the future are reduced, the automobile company planned to make sure its production of EVs starts off in a big way by 2014. In 2011, it was planned that production of EVs will begin in 2013/2014 in China under FAW Volkswagen and Shanghai Volkswagen, both joint ventures of Volkswagen in China. At that time, Volkswagen wanted to make sure that production of EVs reaches 100,000 units globally by 2018. Due a lack of buyers and charging infrastructure, Volkswagen started the production of EVs later than expected, in the middle of 2014 (although the EV "Carely"—was still developed). In 2014, Volkswagen announced to double the production capacity of EVs in China by 2018—to more than four million vehicles.

In 2014, sales of EVs have failed to gain traction, though this may be changing. Through the first nine months of 2014, an estimated 42,493 EVs were sold, accounting for just 0.33 % of the total market. However, China has rolled out a set of measures, including tax exemptions, subsidies for car purchases, parking spaces for cars with alternative drive only and requirements for government purchasing policies to promote the use of new energy vehicles. In addition, more charging stations will be built As a result, EV sales in October were 11,991 units and accounted for 28 % of the total for the year. On an annualized basis, September's sales would indicate a yearly rate that is well above the sales rates in the United States and Europe.

China is going as far as subsidizing the domestic manufacture of electric cars. This is part of China's two-prong strategy: to encourage Chinese consumers to buy Chinese-brand cars and to encourage wider adoption of electric cars. Finally, Chinese consumers bought 54,000 electric cars in 2014, a 120 % jump but a blip compared to the more than 20 million new cars bought in China in 2014.

By the year 2016, at least 30 % of new vehicles purchased by public authorities have to be BEVs, PHEVs or HEVs.

Nevertheless, due to the weak sales of EVs in China, the Chinese government has revised its forecast in 2014. Thus, the Chinese government plans to have about 5 million EVs on Chinese roads in 2020.

Local car companies are leading the way in China. Kandi Technolgies Group, Inc. (“NASDAQ GS: KNDI”), an industry newcomer, is the clear leader with 37 % of the market (2014), while BYD (China’s EV pioneer), Chevy and Zoe follow and account for a combined 46 %.

Tesla, which has made a point of its objectives for the country, rounds out the top five with an estimated 2,849 cars sold through September 2014.

The EV sector is growing globally and majority of the demand for EVs is expected to come from China in the future, with Beijing, Shanghai, Shenzhen and Hangzhou leading the way.

Of all the auto markets in the world, China may represent the single best potential opportunity for EVs due to the increasing demand for energy, as well as high levels of air pollution.

However, the development of EVs in China may require a different business model than that used in more developed markets. As indicated by the recent success of Kandi, which sold almost 7,000 units or 56 % of the total, in September, 2014 the China EV market appears to be developing differently than the other major auto markets in the world.

## *1.2 United States*

The United States is the largest electric car market in the world. The latest research predicts that with sales of 1.8 million vehicles a year by the end of the decade, North America will account for almost 50 % of the global electric car market. The latest, courtesy of Pike Research, suggests that PHEVs will continue to grow in popularity in U.S. cities as the decade continues, leading to sales of 1.8 million in the largest 102 U.S. cities by 2020. “More than a quarter of all annual U.S. PHEV sales will be in the top five metropolitan areas for PHEV sales—New York, Los Angeles, San Francisco, Seattle, and Portland,” says senior research analyst Dave Hurst. “But thanks to a combination of positive attitudes towards green driving, high fuel prices, and state government support, California metropolitan statistical areas will account for more than one in five PHEVs sold.” The latest forecasts regarding global sales of EVs estimate that worldwide sales will hit 3.8 million a year by 2020, which means that with 47 % of predicted sales, the US will be the largest single market for PHEVs by the end of the decade.

The U.S. federal government currently offers tax credits of up to 6,880 EUR (7,500 USD) for zero- or low-emission vehicle purchases while more than half of U.S. states offer their own incentives.

As of June 2014, the United States had the largest fleet of PHEVs in the world, with over 226,000 highway-capable plug-in electric cars sold since the market launch of the Tesla Roadster in 2008. U.S. consumers bought 117,000 all-EVs in 2014, led by the Nissan Leaf, Tesla Model S and BMW i3, putting the total number of EVs at about 290,000. While the U.S. leads in total number of electric cars, the market share remains well under 1 %. While this represents a 26 % increase over the number sold during the same period in 2013, it is a small percentage of the total U.S. market, and the impact of gasoline at 2.06 EUR (2.25 USD [3]) per gallon is yet to be determined. Moreover, 55 % of the electric cars sold in the U.S. are PHEVs, suggesting that consumers still do not trust the range of cars powered solely with electric.

Evidence of this change in mindset and focus, away from horsepower, Sport Utility Vehicles (SUVs) and straight-line speed, was clear to see at the 2014 North American International Auto Show which featured a number of electric, electric-hybrid and super-energy efficient gas engine vehicles from a host of major manufacturers, including Ford and General Motors, as well as committed U.S. EV manufacturers such as Tesla.

Against initial expectations, sales of series production BEVs during its first years in the U.S. market have been lower. According to the U.S. Department of Energy (U.S. DOE), combined sales of PHEVs and BEVs cars are climbing more rapidly and outselling by more than double sales of HEVs over their respective 24 month introductory periods.

In terms of winners in the U.S. market, the all-electric Nissan Leaf and range-extended Chevy Volt (operated by a gasoline engine back-up), have been the top sellers in 2014, accounting for almost 50 % of electric car sales, followed by Tesla Model S and BMW i3. The Toyota Prius, Ford Fusion and Ford C-Max Energi, round out the top five with another one-third of the market.

## *1.3 Japan and Korea*

Japanese and Korean companies, producing cells for consumer electronics, are the market leaders in the automotive industry. But competition is increasing with Chinese and North American companies entering the market. Presently, the Li-ion automotive market is entering a phase in which smaller companies could fail or be acquired due to an inability to reach volume production. Asia is attributed with strong expertise in battery technology.

Japan's early move to HEV market through the Toyota Prius led to extensive knowledge in integrating the entire energy system in vehicles. Sony and Sanyo (taken over by Panasonic) belong to the largest cell producers based in Japan. This shows that nearly all of Japan's main technology companies concentrate on the production of batteries. A high share of their development force is focused on battery technology. It can be expected that the Japanese battery manufacturers will continue to play an important role in the market due to their very strong investment. Although Korean firms occupy a leading market position in battery technologies, several important battery components are imported from Japan. Know-how related to capacitor technology and other components such as the motor and inverter is relatively low except for its application to battery knowledge. Most Korean companies active in this field are small and medium enterprises which lack in innovation but work hard in development.

*"Japanese OEMs have greatly reduced the price of EVs on their domestic market compared to other countries," says Thomas Schlick, Partner at Roland Berger Strategy Consultants. "Japanese customers are now paying up to 40 % less than their European counterparts for a new EV. This better value for money leads to a situation in which 80 % of EVs in Japan are now being used privately." In addition, Japan is continuously expanding the charging infrastructure for EVs—a key driver for e mobility* [4].

## 1.4 European Union

China and Europe—not the United States, as many may have thought—will be the largest markets for EVs in 2020, driven by strong government support. EVs will account for approximately 8 % of new car sales in Europe by 2020, supported by consumer's higher willingness to pay for green technologies, the region's high emissions standards, and high gasoline and diesel fuel taxes.

Targets for reducing the $CO_2$ emission vary by country and regions. The European Union's target for $CO_2$ emissions in 2020 (95 g $CO_2$/km for the new-vehicle fleet average), for example, is far more aggressive than the targets of the United States, Japan, and China.

To make EVs for buyer much more attractive some European Union countries offer tax reductions or exemptions like free parking spaces, e-car sharing models, reduced taxes or free charging stations.

In terms of technology, Germany has relinquished its leading position and now lags slightly behind South Korea. The change in Germany's position is mainly due to a slight drop in the number of affordable German models, where the mix is gradually moving in the direction of higher-priced vehicles.

As per end of 2014, around 95,000 electric cars were sold in Europe. The Mitsubishi Outlander, a PHEV, leads the way with a 23 % market share, and the Nissan Leaf and BMW i3 follow with another 28 % of the market.

While the U.S. leads in number; Norway leads in share—Norwegians more than doubled their EV fleet last year, to 43,400, leading the world with a 1.6 % market share. Thanks to high vehicle taxes, Norway's tax breaks on electric car purchases are so generous that the Tesla Model S costs less than comparable gas-burning luxury cars made by Porsche and BMW, which is why Tesla Motors made Norway a key export market from the start.

> While the U.S. leads in number; Norway leads in market share of EVs.

***Combined, EVs and HEVs could reach 15 % of aggregate new-car sales in the four major markets—Europe, North America, China, and Japan—in 2020*** [5].

## 2 OEM Strategies

This subchapter emphasis the various strategies of some of the most important OEMs of xEVs. The selection of the OEMs was made randomly.

### *2.1 Build Your Dream*

With its headquarter in Shenzen, Build Your Dream (BYD) Company Ltd. (founded in 1995) started as a rechargeable-battery factory, competing in the Chinese market against Japanese imports. After its foundation, the company, developed rapidly and enlarged its field of activity and entered into the market for new-energy, where BYD especially focuses on the solar segment. Two years later, BYD acquired Xi'an Tsinchuan Auto Co., Ltd., which is today known as BYD Auto Company Ltd. Thus, BYD is mainly operating in three completely different markets nowadays: Batteries, new-energy and automobiles. As the largest supplier of rechargeable batteries in the world, BYD has the largest market share for nickel-cadmium batteries, handset Li-ion batteries, cell-phone chargers and keypads worldwide. Furthermore, its automotive division is amongst the 10th biggest car manufacturers in China and plays a leading role in the e-mobility segment.

The aim is to become China's top automobile manufacturer by 2018 and a major global player by the end of 2025. In its automobile division BYD cooperates with the German Daimler AG. This joint venture was mainly established to develop an e-car, which was introduced in the Chinese market in 2014. Currently, BYD is mostly known for their electric busses which are still in operation in several parts in Europe like Amsterdam, Barcelona, Copenhagen, London, Milan, etc.

In March 2015, BYD unveiled the first long-range battery-electric bus—the BYD C9—at the United Motorcoach Association Expo in New Orleans. The +305 km (+190 mi.) range of the C9 puts BYD's new offering in a category all its own as far as electric buses go—extending the potential uses of such buses far beyond immediate urban environments. It possesses a single-charge range of over 190 miles, and a top speed of 100 km/h (62.5 mph) when on the highway.

The company also plans to start taking orders for electric trucks from overseas buyers in the second half of the year 2015 and begin deliveries in 2016, with the U.S. one of the likely first destinations. The plan is to manufacture the trucks in U.S. after exporting them from China [6].

## 2.2 General Motors

General Motors (GM) will focus its vehicle electrification efforts on three main technologies: light electrification, E-REVS and BEVs, such as the Spark EV. In a vehicle electrification symposium for the media, GM Senior Vice President, Global Product Development Mary Barra noted that until recently, GM's strategy had essentially been to "cover the waterfront" in terms of pursuing as many technologies as possible. "That's not how GM is doing business today," she said. "We need to refine our strategy and do focused work. We need to make educated bets on which technologies hold the most potential for creating value for our customers and our company." GM is tracking to sell more than 50,000 vehicles a year with some form of electrification, the majority of which will be eAssist systems. With selling the Volt, GM is market leader of the Plug-in vehicle segment in the US. GM is looking at new ways to provide E-REV technology to provide more options for customers but the new focus doesn't mean that GM will entirely ignore the full hybrid segment, but those efforts will be relegated to point solutions for specific customer need. The two-mode hybrid system for light trucks, for example. Moreover GM is well-positioned with respect to hydrogen fuel cell vehicles, but for the success of that technology a lot depends on the infrastructure.

*Electrified vehicle attributes will continue to be shaped by demanding customer expectations and regulatory requirements. An increasing shift of the global population to cities creates both opportunities for innovation in electrified transportation and yet challenges in infrastructure to support Plug-in Vehicles. While niche markets have emerged proven customer excitement can be won with electrified vehicles, the balance of price, total range and operating cost drive OEMs development activities to meet these customer expectations. Creating e-Motional Electrified Vehicles that customers not only choose to purchase, but love to own, is at the heart of what we are doing at General Motors* [7].

## 2.3 Hyundai and Kia

The Kia Motors Corporation, based in South Korea, has 12 manufacturing and assembly plants and subsidiaries in 165 countries around the world. Globally the Hyundai Kia Group is now the fourth largest car company in the world.

HEVs are competing with clean diesel vehicles in the Korean domestic market. As Korean consumers prefer large models of HEVs, the production of these vehicles is increasing continuously. Hyundai dominated the hybrid market in Korea and increased exports. Still in 2011, Kia produced almost 72,678 hybrid vehicles. Recently, Kia produces hybrid models in the foreign market. In 2014, KIA produced 15,020 HEVs, while Hyundai produced 26,111 units. Thus, sales of HEVs have increased continuously but slowed in 2013. Reasons for this are the competition between HEVs and clean diesel vehicles in the Korean market. Further, Toyota is introducing various hybrid models to compete with European diesel in the Korean market.

Additionally, EV prices are falling and government subsidies are increasing. Thus, Kia has set their focus on EVs.

Between 2010 and 2014, Kia increased sales of EVs by nearly two thirds, giving it higher totals than Dodge or Subaru can muster in the U.S. With an electrified concept unveiled and the Soul EV outperforming expectations, the Korean brand has begun wielding electric vehicles as a weapon to expand U.S. market share.

In 2014, Kia sold 580,234 units of vehicles, a record for the automaker and 63 % better than its performance in 2010. Over half of those sales belonged to Optima, the brand's best seller (159,020 units), and Soul, which gained 23 % in 2014 over the previous year with 145,316 sales. Taken together, the brand posted 8.4 % growth on the U.S. market. Among its most conspicuous debuts was the Kia Soul EV, the first BEV from Hyundai Motor Group and the green version of the popular city car [8].

*To survive in this rapidly changing environment, automakers need to secure future competitiveness through forecasting future trends correctly and developing sustainable technology. Hyundai Motor Group has a Clean Mobility technology roadmap. We are moving forward with our HEV system which improves fuel efficiency by using a combustion engine and electric motor, with the goal of developing zero-emission vehicles including EVs and FCEVs.*

*Specifically, through a full line-up of more than 22 eco-car models by 2020, we will contribute to making a clean environment and fulfilling our social responsibility.*

*The important thing is that this will make Clean Mobility possible in a future mainstream with cooperation among related industries, such as battery component technology, and governments with supporting infrastructure policies* [9].

## 2.4 Renault

Renault is the first full-range car manufacturer to market zero-emission vehicles in use, available to the greatest number. For Renault, the EV is a real long-term solution to today's environmental and noise pollution issues in cities. For Renault and its customers, EV have to be practical, attractive and reassuring: EVs will retail at the same price as equivalent diesel models (without the battery, which is leased), running costs are roughly 20 % lower than an equivalent combustion vehicle, maintenance costs are half, e-motors offer similar levels of performance as that of gasoline and diesel cars. Renault is still working on a number of fronts to accompany the launch of its range of zero-emission vehicles in use: in R&D, an important investment has been made on EVs as part of the Renault-Nissan Alliance, cooperation with governments on infrastructure development and purchase incentives, partnerships are being formed with mobility operators worldwide.

Nordmand G. explained Renaults success at the Electric Vehicle Symposium (EVS) 28 in Korea: *4 years after the launch of the first EVs, EV market is still* *growing fast (+55 % in 2014). The start of EV sales is 25 times quicker than start of hybrid cars on comparable periods. The success of EV is based on the best customers' satisfaction rate ever registered by automotive company (>95 %). Every 3 min in the world, a customer switches from ICE to EV! Renault is a pioneer in the development of EVs, thus the RENAULT- NISSAN alliance is leader with 50 % market-share and accelerates its efforts to develop this market and keep its domination despite quick arrival of followers. All automotive companies in the world will offer EVs before end 2018. The leading EV market in the world, NORWAY, with already 15 % of registrations in pure EV, leads the path and confirms feasibility of an even quicker growth. All the indicators (battery technology visibility, EV car-sharing programs all over the world, satisfaction of customers, success of TESLA…) confirm the forecasts of RENAULT-NISSAN and encourage our teams to move forward* [10].

## 2.5 VW and Audi

VW and Audi have both shown plug-in hybrid diesel concept vehicles in the past. VW estimates the production cost of a PHEVs or BEVs powertrain to be about five times the cost of a conventional powertrain. Such costs can be mitigated to some extent through integration, but this is expected to take about ten more years. Given the present range limitations, VW expects BEVs to be used as second or third household vehicles or as light transport and delivery vehicles, in addition to a small early adopter market.

Volkswagen has designated 2013 the Year of the Electric Car.

"We will make 2013 the year of electric mobility," declared Chairman of the Board of Management of Volkswagen AG, Dr Martin Winterkorn, at the annual press conference on 12 March, 2012. The brochure "0 % Emissions. 100 % Emotions." describes how Europe's number one automobile manufacturer conceives the way to sustainable mobility in the future.

In 2014, VW launched the models "e-up!" and "e-Golf". The Volkswagen Group has set its sights on global market leadership in e-mobility. By electrifying all vehicle classes VW wants to become the top automaker in all respects, including e-mobility, by 2018.

In the middle of 2015, Audi started a cooperation with the Chinese search engine provider Baidu (pendant to google), in order to increase the progress on interconnectivity of Audis vehicles. CEO Rupert Stadler said at the Annual General Meeting in Neckarsulm (May 2015): "Last year, only 7 % of the global equipment had been connected. In five years, there will already be 25 % of all devices connected with each other."

In 2015, Audi started several cooperation's with Industrial Technology companies like map providers as Tom or manufacturers of mobile phones and software providers.

## 3 OEM—Key Messages

The list of OEMs mentioned above present just a small amount of all global car manufacturers. Every OEM is following a different strategy but there might be some common trends which shouldn't be disregarded.

*Key takeaways*

- *OEMs started cooperation's with software manufacturers, map providers, mobile phone manufacturers,* etc. *in order to enable Advanced Driving Assistance Systems and to be aware and ready for autonomous driving,*
- *OEMs have intensified their efforts in the field of Life Cycle Assessment and Sustainability,*
- *light weighting the car by use of sustainable, renewable materials is followed by every OEM as it can be beneficial used in any kind of vehicle,*
- *"Green Cars" like BEVs and HEVs are no longer "exotics", nearly every manufacturer deals with them. Every OEM has its own strategy but in a common view, the ICE will consist till 2030 and will be further improved by downsizing, use of alternative fuels,* etc. *Further work on xEVs strongly depends on the effort in battery technologies and infrastructure in the near future. Thus it can be said, which technology (BEV, HEV, PHEV, FCEV) will substitute the conventional vehicle in the future,*
- *the current situation—to introduce vehicles as quickly as possible on the market—leads to an accumulation of errors and recalls. Thus. OEMs are spending more money in (virtual) simulations than in the years before,*
- *countries as Brazil, Russia, India and China (BRIC) are getting more important in the near future, as well as*
- *the shift towards Asia, away from Europe and North America.*

## 4 Current Status of Low-Carbon Vehicle Technologies (2013–2015)

Many automotive manufacturers are now focusing their research activities on high energy efficiency and renewable energy vehicles due to the problems caused by conventional ones. Currently there is no clear answer as to which solution could dominate the future market.

Vehicles considered in this chapter are passenger vehicles using alternative propulsion system technology with the ability to substitute conventional drive train technology. Ranging from small segment (small EVs for cities, at least 3 wheels, one person) medium segment (4 persons) to SUVs and Vans (6 persons).

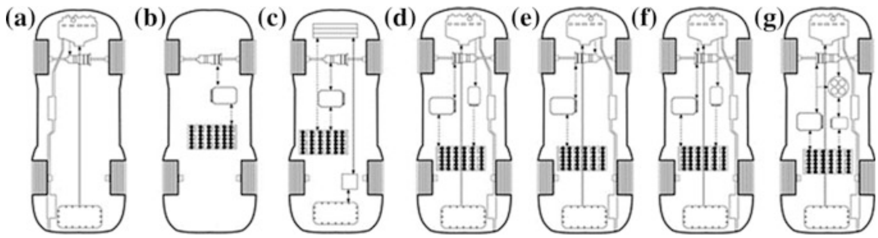


**Fig. 2** Schematic drawings of seven types of vehicle classes [11]

Commercial applications for localized distribution, forklifts or pallet trucks are exempted. 2 wheelers, trucks and buses are not considered in this chapter. There are no limitations regarding body and chassis design or used materials. Also not for the powertrain configuration which ranges from very low grade of electrification to EVs and FCEVs.

This section shows the performance data of different vehicle classes (2010–2015) which have been used for studies and workshops within this Task and enables a brief overview about current configurations on the market available. As this Task started in the year 2010, the list of mentioned vehicles also include earlier generation models.

In general vehicles can be classified according to the way in which power is supplied to the drive train (compare Fig. 2).

In this report the distinction has been made between the "extreme forms of technologies":

- Technology Extreme—Internal Combustion Engine (ICE),
- Technology Extreme—BEV,
- Hybrid Vehicle Technology (HEV) (solution between ICE and BEV), including:
  - Electric Vehicles with Range Extender (EREVs) and
  - Plug-in Hybrid Electric Vehicles (PHEVs),
- Fuel Cell Electric Vehicles (FCEVs)

## *4.1 Technology Extreme—Conventional ICE Vehicles*

*An Internal Combustion Engine is an engine which generates motive power by the burning of petrol, oil, or other fuel with air inside the engine, the hot gases produced being used to drive a piston or do other work as they expand* [12].

The design of the ICE has been perfected over 150 years. It dominated and will continue to dominate automobile technology for many years. Even in today's HEVs the ICE is still the first choice as the main power supply. Continuing to improve the

**Table 1** Data sheet of a conventional vehicle: Ford Focus 2.0

| | | |
|---|---|---|
| FORD: FORD FOCUS 2.0 (2ND GENERATION) |  | |
| Type**: Compact car** | **Drive:** Front-wheel | **Top speed**: 195 km/h (121 mph) |
| Production**: Series** | **Motor**: Otto Engine | **Tank volume**: 55 l |
| Length**: 4.342 m (170.9 in)** | **Distance** between wheels: 2.64 m (103.94 in) | **Fuel consumption**: 7.1/100 km |
| Width**: 1.834 m (72.2 in)** | **Base curb weight**: 1,227 kg (2,705 lb) | |
| Height**: 1.409 m (55.5 in)** | **Torque**: 123 Nm | |

efficiency of ICE is still a primary task. The ICE's dominating factor, it used petrol/diesel as a fuel. Most automobiles in use today are propelled by an ICE fueled by deflagration of gasoline (also known as petrol) or diesel. They have an **average tank volume of 60–70 L (15–18 gal lqd).** Thus, they are **able to drive around 1,100 km (690 mi.)**. That means an average **fuel efficiency of 6.2 L/ 100 km**. Many diesel versions are much more expensive than petrol variants. Thus, the average price for a conventional car is around 28,330 EUR (30,995 USD) (in Germany 2014) [13].

The average $CO_2$ emissions in 2014 for new city cars in Austria have been **127 g$CO_2$/km (gasoline)** and **131 g$CO_2$/km (diesel)** [14].

**Current trends: vehicles, based on ICE, are getting more environmentally friendly and economical. The ICE will be further optimized (e.g. downsizing of the engine and waste heat recovery).**

The data sheet of a Ford Focus 2.0 is listed in Table 1. This car was chosen due to the fact, that it has been used in a study conducted by the U.S. ANL (see Chap. 5).

## *4.2 Technology Extreme—Battery Electric Vehicles (BEVs)*

BEVs are using an e-motor for traction instead of an ICE. Instead of liquid fuels, they use batteries for their energy source. BEVs battery packages have high specific energy, while the HEVs battery packages have high specific power.

The battery vehicle drive train consists of:

- **e-motor propulsion system**,
- **battery system** (charging unit, battery management system, …) and
- **auxiliary system** (heating/cooling, pumps, etc.)

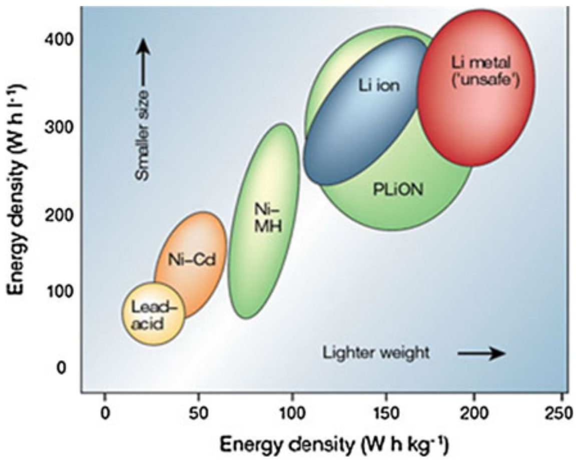


**Fig. 3** Battery technologies in terms of volumetric and gravimetric energy density [15]

The two main types of battery used in BEVs are **nickel metal hydride (NiMH)** and **Li-ion batteries.** While Li-ion batteries are used as primary energy sources in BEVs, NiMH batteries are in most cases used as a secondary energy sources in HEVs. Li-ion batteries store more energy than NiMH (compare Fig. 3), but they suffer from major issues such as high costs, safety, materials availability, environmental impact and wide operational temperature ranges.

In the area of BEVs, a variety of EVs from small to compact up to the premium class are already available. Today's passenger BEVs, have an **average (electric) driving range from 90 km (55 miles (mi.))** (minimum) [16] **to 520 km (323 mi.)** (maximum) [17]. **Most of the common models are in the range of 170 km** (105 mi.). The **charging time** depends on the type of charging station (normal or quick charging) and takes between 0.5 h (400 V) and 20 h (220 V), **mostly 4–8 h.** The *battery capacity* is in the range between 7 and 85 kWh, **mostly in the range of 22 kWh**. The **average price is about 30,000 EUR** (32,820 USD), the cheapest model (Renault Twizzy) is available for 7,150 EUR (7,823 USD) [18].

Especially the BMW's i3 has to be highlighted because of its new technologies mainly used in vehicle construction. The vehicle is separated into two main modules, the life module made of carbon fiber reinforced plastic (CFRP) and the drive module with the battery and the drive unit. The standard use of CFRP is an enormous technological progress. Thus, the BMW i3 is the only vehicle concept, which has been developed from scratch and is not based on an existing vehicle model.

**In case of energy storage, a major trend can be seen in decreasing costs**. **Studies show that the cost per kWh will fall sharply by 2020, or have already fallen sharply.** In their study "Battery technology charges ahead" McKinsey predicts a price of about 182 EUR (200 USD) per kWh for 2020 [19].

Car manufacturer Tesla mentions that the current price is at a rate of 216 EUR (238 USD) per kWh for its Model Tesla S.

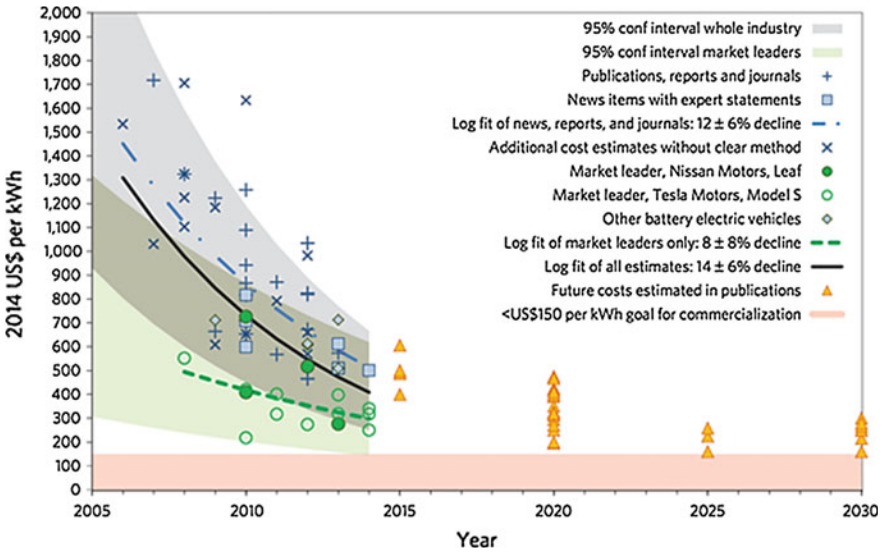


**Fig. 4** Cost estimates and future projections for EV battery packs (image courtesy of Nykvist [20])

*According to a study in Nature Climate Change, the cost of electric vehicle battery packs is falling so rapidly they are probably already cheaper than expected for 2020.*

*In 2013 the IEA estimated cost-parity could be reached in 2020, with battery costs reaching $300 per kilowatt hour of capacity. But market-leading firms were probably already producing cheaper batteries last year, says today's new research. It says its figures are "two to four times lower than many recent peer-reviewed papers have suggested". The new research is based on a review of 85 cost estimates in peer-reviewed research, agency estimates, consultancy and industry reports, news reports covering the views of industry representatives and experts and finally estimates from leading manufacturers.*

*As it can be seen in* Fig. 4 *industry-wide costs have fallen from above 915 EUR (1,000 USD) per kWh in 2007 down to around 375 EUR (410 USD) in 2014, a 14 % annual reduction (blue marks, below). Costs for market-leading firms have fallen by 8 % per year, reaching 274 EUR (300 USD) per kWh hour in 2014 (green marks).For the market-leading firms, shown in green on the chart above, costs last year were already at the bottom end of projections for 2020 (yellow triangles).*

*The paper estimates prices will fall further to around 210 EUR (230 USD) per kWh in 2017–2018, "on a par with the most optimistic future estimate among analysts". The crossover point where electric cars become cheapest depends on electricity costs, vehicle taxes and prices at the pump* [20].

**Table 2** Data sheet of a BEV (1)—Nissan Leaf [21]

| | | |
|---|---|---|
| NISSA:<br>NISSAN LEAF |  | |
| Type: Compact car | **Drive:** Front-wheel | **Top speed**: 145 km/h (90 mph) |
| Production: Series | **Motor**: Synchronous AC | **Battery**: Li-ion |
| Length**: 4.445 m (175 in)** | **Distance** between wheels: 2.7 m (106.23 in) | **Torque**: 280 Nm |
| Width**: 1.770 m (72.2 in)** | **Base curb weight**: 1,525 kg (3,362.1 lb) | **Charging (time)**: 110 V/220 V— 0.5 h/8 h |
| Height**: 1.409 m (69.69 in)** | **Motor weight**: 130 kg (280 lb) | **Battery weight:** 300 kg (660 lb) |
| | **Battery capacity**: 24 kWh | **Electric range:** 121 km (75 mi) |

This trend is directly reflecting the **decreasing vehicle costs**. In 2010 the Mitsubishi i-MiEV cost about 35,000 EUR (39,400 USD). At the beginning of 2014 the purchase price was about 23,790 EUR (26,000 USD). That means a **price reduction of −32 % in three years**! [18].

**Current trends include: decreasing costs of energy storage, increasing number of vehicles, car manufacturers come up with new technologies and concepts like BMW and a strong trend towards autonomous driving.**

Table 2 shows the data sheet of the Nissan Leaf, the first all-electric vehicle to be built on a massive scale by one of the major automakers. A total of 48 battery packs are located centrally in the chassis, which helps provide a good balance and decent handling. Nissan compares its performance to that of a similar car fitted with a 2.0 L gasoline engine. Special aerodynamic underbody panels and diffusers to help reduce parasitic drag. Nissan has broken new ground with the Leaf. Unlike the Tesla S (see Table 3), this electric car has room for five person, and it's being built on a much more massive scale, 20,000 were planned to be built in 2011, as of March 2013, Nissan has an installed capacity to produce 250,000 Leafs per year.

Renault, a key player in the field of e-mobility started an alliance together with Nissan to move forward the market introduction of electric vehicles. Table 4 shows the data of the smallest electric vehicle on the market available and Table 5 the data of one of the most common e-vehicles—the Renault ZOE.

The Mitsubishi i MiEV (data are shown in Table 6) utilizes high energy density Li-ion batteries: a module consists of 4 cells, and 22 modules make one battery pack. The structure of the modules allows them to be installed in either a vertical or transverse position; each high-capacity battery pack can fit under the floor.

The introduction of Li-ion battery technology in 2004 made the EV a viable mobility option. Assembled in series of 100, they were able to provide the currents that electric drive trains require. BMW Group seized the opportunity the new technology presented by initiating the so called "project I"—a think tank whose

**Table 3** Data sheet of a BEV (2)—Tesla Model S [22]

| | | |
|---|---|---|
| TESLA:<br>MODEL S |  | |
| Type: Full-size Luxury | **Drive:** Rear-wheel | **Top speed**: 201 km/h (125 mph) |
| Production: Series | **Motor**: Three phase, four pole AC induction motor with copper rotor | **Battery**: Li-ion |
| Length**: 4.976 m (196.1 in)** | **Distance** between wheels: 2.96 m (116.54 in) | **Torque**: 600 Nm |
| Width**: 1.963 m (77.2 in)** | **Base curb weight**: 2,108 kg (4,643 lb) | **Charging (time)**: 110 V/220 V—0.5 h/4 h |
| Height**: 1.435 m (59.7 in)** | **Motor weight**: 130 kg (280 lb) | **Battery weight:** 1200 kg (2646 lb) |
| | **Battery capacity**: 85 kWh | **Electric range:** 120 km (75 mi) |

**Table 4** Data sheet of a BEV (3)—Renault Twizzy [23]

| | | |
|---|---|---|
| RENAULT:<br>RENAULT TWIZY URBAN 45 Z.E. |  | |
| Type: Microcar | **Drive:** Rear-wheel | **Top speed**: 50 km/h (31 mph) |
| Production: Series | **Motor**: Synchronous AC | **Battery**: Li-ion |
| Length**: 2.337 m (92,2 in)** | **Distance** between wheels: 1.7 m (66.5 in) | **Torque**: 57 Nm |
| Width**: 1.191 m (47.3 in)** | **Base curb weight**: 350 kg (772 lb) | **Charging (time)**: 220 V—3.5 h |
| Height**: 1.461 m (57.5 in)** | **Motor weight**: 130 kg (280 lb) | **Battery weight:** 100 kg (220.5 lb) |
| | **Battery capacity**: 6.1 kWh | **Electric range:** 80 km (50 mi) |

task is to develop sustainable mobility solutions for the future needs of the world's drivers. One such initiative was the MINI E, which has been gathering the feedback of customers involved in its field trials since mid-2009. This trial program allowed the BMW Group to become the world's first major car manufacturer to deploy a fleet of more than 500 all-EVs for private use. The second market test was a larger one, by involving the BMW ActiveE concept in summer of 2011. This generated feedback provided an opportunity to test an early version of the BMW i3 powertrain.

**Table 5** Data sheet of a BEV (4)—Renault ZOE [24]

| | | |
|---|---|---|
| RENAULT:<br>RENAULT ZOE |  | |
| Type: Supermini | **Drive:** Front-wheel | **Top speed**: 140 km/h (87 mph) |
| Production: Series | **Motor**: Synchronous AC | **Battery**: Li-ion |
| Length**: 4.086 m (160.87 in)** | **Distance** between wheels: 2.59 m (101.96 in) | **Torque**: 222 Nm |
| Width**: 1.788 m (70.47 in)** | **Base curb weight**: 1,392 kg (3,068 lb) | **Charging (time)**: 220/400 V—0.5–6/8 h |
| Height**: 1.540 m (60.63 in)** | **Motor weight**: n.a. | **Battery weight:** 290 kg (640 lb) |
| | **Battery capacity**: 22 kWh | **Electric range:** 200 km (15 mi) |

**Table 6** Data sheet of a BEV (5)—Mitsubishi iMIEV [25]

| | | |
|---|---|---|
| MITSUBISHI:<br>MITSUBISHI IMIEV |  | |
| Type: Subcompact car | **Drive:** Rear-wheel | **Top speed**: 130 km/h (80 mph) |
| Production: Series | **Motor**: Permanent synchronous | **Battery**: Li-ion |
| Length**: 3.475 m (136.8 in)** | **Distance** between wheels: 2.55 m (98.52 in) | **Torque**: 180 Nm |
| Width**: 1.475 m (58.08 in)** | **Base curb weight**: 1,185 kg (2,612 lb) | **Charging (time)**: 110/220 V—0.5–8 h |
| Height**: 1.610 m (63.39 in)** | **Motor weight**: n.a. | **Battery weight:** 200 kg (440 lb) |
| | **Battery capacity**: 16 kWh | **Electric range:** 160 km (100 mi) |

The lessons learned from the MINI E (compare Table 7 for data) and BMW ActiveE field trials (e.g. range sufficient for most trips (110–160 km or 70–100 mi.); e-mobility doesn't mean an end of driving fun; identified restrictions as lack of standardized vehicle inlet, etc.) was used to launch the BMW i3 and BMW i8 PHEV, under the new sub-brand BMW i, in autumn 2013. The ActiveE technology includes a powerful electric synchronous motor, which enables the 1 Series EV to tap into 170 hp and 250 Nm of torque, ensuring a 0–100 km/h (0–62 mph) acceleration time of 9 s. Thus it was one of the first cars where the cooling system were able to heat the liquid in order to bring the energy storage units up to an ideal temperature of 20 °C (68 °F) during winter months.

With their Mercedes SLS AMG E-Cell (see Table 8), Mercedes demonstrates the use of four synchronous e-motors, positioned near to the wheels. As a result, compared with wheel-hub motors the unsprung masses are substantially reduced. One transmission per axle transmits the power. The issue is the placement of the

**Table 7** Data sheet of a BEV (6)—BMW—Mini E [26]

| | | |
|---|---|---|
| BMW:<br>BMW MINI E |  | |
| Type: Subcompact car | **Drive:** Front-wheel | **Top speed**: 153 km/h (95 mph) |
| Production: Demonstration | **Motor**: Permanent synchronous | **Battery**: Li-ion |
| Length**: 3.713 m (146.06 in)** | **Distance** between wheels: 2.47 m (97.1 in) | **Torque**: 240 Nm |
| Width**: 1.684 m (66.15 in)** | **Base curb weight**: 1,460 kg (3,218 lb) | **Charging (time)**: 110/220 V—3.5–20 h |
| Height**: 1.407 m (67.33 in)** | **Motor weight**: n.a. | **Battery weight:** 259 kg (572 lb) |
| | **Battery capacity**: 35 kWh | **Electric range:** 170 km (105 mi) |

**Table 8** Data sheet of a BEV (7)—Mercedes—SLS AMG E-Cell [27]

| | | |
|---|---|---|
| MERCEDES:<br>SLS AMG E-CELL |  | |
| Type: Sports car | **Drive:** All-wheel | **Top speed**: 317 km/h (197 mph) |
| Production: Series | **Motor**: 4 x synchronous | **Battery**: Li-ion |
| Length**: 4.638 m (181.1 in)** | **Distance** between wheels: 2.69 m (106.3 in) | **Torque**: 880 Nm |
| Width**: 1.939 m (76.38 in)** | **Base curb weight**: 1,620 kg (3,570 lb) | **Charging (time)**: 110/220 V—3–20 h |
| Height**: 1.407 m (49.65 in)** | **Motor weight**: n.a. | **Battery weight:** 550 kg (1212.52 lb) |
| | **Battery capacity**: 48 kWh | **Electric range:** 260 km (160 mi) |

motors for purposes of dynamics. This means a proper integration of the e-motors and a proper communication between components. The clear challenge with the four-motor configuration is programming in proper torque vectoring between all four wheels. Thus, software development is extremely complex.

## *4.3 Hybrid Vehicles (HEVs) Technology—Between ICE and BEV*

**HEV** powertrains can **combine any two power sources** (see Fig. 5). **Typically one component is for storage and the other is for the conversion of a fuel into**

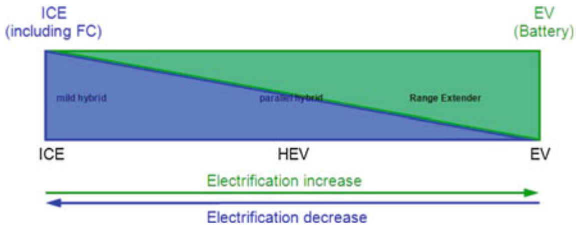


**Fig. 5** Vehicle technology spectrum

**useable energy.** Combinations can include a diesel/petrol ICE with a battery but also a fuel cell with a battery. Every vehicle with not more than two different driving concepts used can be classified in the vehicle technology spectrum shown in this figure. According to the spectrum there are different rates of electrification in the car.

The degree-of-electrification is used to measure the dominance of the electric drive system relative to total drive train power. A bulk degree-of-electrification is often defined for a vehicle design based on component label specifications. The bulk degree-of-electrification is a fraction between 0 and 1. Vehicles with degree-of-electrification = 0 are conventional vehicles, while those with "1" are electric ones (compare Fig. 6). This metric is defined as the amount of power that can be delivered by the electric drive system normalized by the sum of power available from both the electric drive system and the ICE. It is assumed that a PHEV has an electrification rate of around 50 % minimum, whereas the E-REV has an electrification rate of around 80 % minimum. Depending on the energy source it is possible to build an emission free vehicle on the whole spectrum. Starting on the very left with an ICE vehicle using 100 % biofuels, FCEVs, (P)HEVs and BEVs on the very right.

In **general there are four common design options of hybrids** (compare Fig. 2): series, parallel, series- parallel and complex hybrid. However, there are two forms of energy flowing through the drive train: mechanical energy and electrical energy.

The **series hybrid** configuration is the simplest kind of HEV, also called Range Extender. The mechanical power of the ICE is firstly converted into electrical energy (generator). Afterwards the electricity either charges the battery pack or supplies the electric motor directly for traction. One example of this kind of hybrid is the Chevrolet Volt.

**Parallel hybrid**: the parallel HEV allows both the engine and the electric motor to deliver power in parallel to drive the wheels. The propulsion power may be

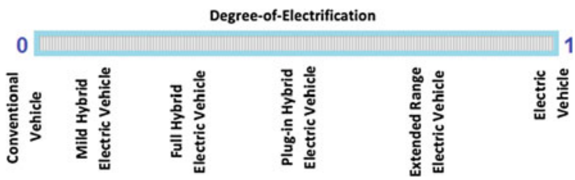


**Fig. 6** Degree-of-electrification with relationship to HEVs classifications

supplied by the ICE alone, by the electric motor alone or by both. One example for a parallel hybrid is the Honda Insight.

**Series-parallel hybrid**: this form incorporates the features of the series and the parallel HEV. Additionally it involves a mechanical link compared with the series hybrid and also an additional generator which is compared with the parallel hybrid.

**Complex hybrid systems**: this hybrid system consists of a bidirectional power flow of the e-motor in the complex hybrid and the unidirectional power flow of the generator in the series-parallel hybrid. One example is the Toyota Prius.

In Tables 9, 10, 11, the key data of different HEVs are shown. The selection of this vehicles has been made due to the fact, that these HEVs have been used for further studies within the report (see chap. 5).

**Table 9** Data sheet of a HEV (1)—Toyota Prius Hybrid III [28]

| | | |
|---|---|---|
| TOYOTA:<br>PRIUS HYBRID III |  | |
| Type: Mid-size car | **Drive:** Front-wheel | **Top speed**: 180 km/h (112 mph) |
| Production: Series | **Motor**: Permanent motor | **Battery**: Li-ion |
| Length**: 4.480 m (176.378 in)** | **Distance** between wheels: 2.7 m (106.3 in) | **Torque**: 207 Nm |
| Width**: 1.745 m (68.71 in)** | **Base curb weight**: 1,490 kg (3,284 lb) | **Charging (time)**: 110/220 V—1.5–3.5 h |
| Height**: 1.490 m (58.66 in)** | **Motor weight**: n.a. | **Battery weight:** 53 kg (118 lb) |
| Engine: **1.8 L 4 cylinders Otto Motor** | **Battery capacity**: 4.4 kWh | **Electric range:** 23 km (14.3 mi) |

**Table 10** Data sheet of a HEV (2)—Hyundai Sonata Hybrid [29]

| | | |
|---|---|---|
| HYUNDAI:<br>SONATA HEV (2011) |  | |
| Type: Mid-size car | **Drive:** Front-wheel | **Top speed**: 195 km/h (121 mph) |
| Production: Series | **Motor**: Permanent magnet motor | **Battery**: Li-polymer |
| Length**: 4.820 m (189.77 in)** | **Distance** between wheels: 2.8 m (110.1 in) | **Torque**: 235 Nm |
| Width**: 1.835 m (72.24 in)** | **Base curb weight**: 1,566 kg (3,454 lb) | **Charging (time)**: 110/220 V—3.5–8 h |
| Height**: 1.470 m (57.874 in)** | **Motor weight**: n.a. | **Battery weight:** 45 kg (96 lb) |
| Engine: **2.4 L 4 cylinders Otto Motor** | **Battery capacity**: 1.43 kWh | **Electric range:** 56 km (35 mi) |

**Table 11** Data sheet of a HEV (3)—Ford Fusion [30]

| FORD:<br>FUSION HYBRID |  | |
|---|---|---|
| Type: Mid-size car | **Drive:** Front-wheel | **Top speed**: 175 km/h (108 mph) |
| Production: Series | **Motor**: Permanent magnet motor | **Battery**: Li-ion |
| Length**: 4.869 m (191.7 in)** | **Distance** between wheels: 2.58 m (101.7 in) | **Torque**: 249 Nm |
| Width**: 1.852 m (72.9 in)** | **Base curb weight**: 1,554 kg (3,427 lb) | **Charging (time)**: 110/220 V—2.5–7 h |
| Height**: 1.476 m (58.11 in)** | **Motor weight**: n.a. | **Battery weight:** 48 kg (106 lb) |
| Engine: **2.0 Atkinson-cycle liter I4** | **Battery capacity**: 1.4 kWh | **Electric range:** 30 km (19 mi) |

**Extended-Range Electric Vehicles (E-REVs)**

**In today's passenger E-REVs, the engine only engages when the battery level drops to a pre-specified point, acting purely as a generator to produce electricity to extend the range** from 130 to 160 km (80 to 100 mi.) to 240 to 300 km (150 to 190 mi.). The tank volume contains 9 L (2 gal lqd). This means an average efficiency of 0.6 l/100 km. According to rules adopted in March 2012 by California Air Resources Board (CARB), the 2014 BMW i3 with a REX unit fitted will be the first car to qualify as a range-extended battery-EV or "BEVx".

The $CO_2$ emissions are 13 $gCO_2$/km. Thus, the figures for fuel consumption and $CO_2$ emission show the enormous savings potential of this technology.

**Current trends: right now there is only one "real" E-REV vehicle available (BMW i3), E-REVs are a bridging technology with regard to acceptance**

One example of an E-REV is shown in Table 12- the BMW i3. Lessons learned from the BMW Mini E (BEV) and the BMW ActiveE field trials were used to

**Table 12** Data sheet of an E-REV—BMW i3 [31]

| BMW: BMW I3 |  | |
|---|---|---|
| Type: Subcompact car | **Drive:** Rear-wheel | **Top speed**: 150 km/h (95 mph) |
| Production: Series | **Motor**: Permanent synchronous | **Battery**: Li-ion |
| Length**: 3.845 m (151.38 in)** | **Distance** between wheels: 2.57 m (101.12 in) | **Torque**: 250 Nm |
| Width**: 2.011 m (79.18 in)** | **Base curb weight**: 1,315 kg (2,899 lb) | **Charging (time)**: 110/220 V—0.5–8 h |
| Height**: 1.547 m (60.63 in)** | **Motor weight**: n.a. | **Battery weight:** 233 kg (514 lb) |
| | **Battery capacity**: 22 kWh | **Electric range:** 161 km (100 mi) |

launch the BMW i3 and BMW i8 PHEV, under the new sub-brand BMW i, in autumn 2013. Unlike BMWs Mini E and ActiveE projects—two vehicles originally designed to be powered by the ICE—the i technology represents totally new development programs that start from the ground up.

The concept is a design that essentially comprises two separate, independent functional units, the drive module and life module. The drive module integrates into one segment the vehicle's suspension, battery, drive system and structural and crash functions in a construction made chiefly from aluminum. The life module consists primarily of a high-strength and lightweight passenger cell made from CFRP. Thus, BMW achieves equal weight distribution for both i vehicles (i3 and i8). By using lightweight materials, BMW was able to offset the additional weight of the battery.

The BMW i3, also known as BMW's Megacity vehicle, consists of a horizontal-split variant architecture, where the drive module provides the basis for the life cell, which is mounted on the top of this arrangement. The key element to the drive module's design is the battery. By making the battery as large as possible, BMW tried to improve the car's driving range.

By placing the battery (lithium-ion cells from SB LiMotive) in the i3's underfloor section, the center of gravity could be improved (by making it lower). Besides that, the weight distribution could be improved too. The space requirements of the motor used in i3 have been reduced by 40 % compared with the motor in the Mini E.

### 4.3.1 Plug-in Hybrid Electric Vehicles (PHEVs)

Since 2013, a lot of new models are available in the segment of PHEVs.

While Toyota has designed its PHEVs Prius especially to the needs of Japanese users (regarding the pure electric range by keeping the battery size as small as possible), other manufacturers like Chevrolet or Opel (both are identical cars), were strongly focused on the American and European markets.

**Today's PHEVs pure electric range is between 23 and 80 km (14 and 49 mi.), by a total average range of 1,200 km (745 mi.) and an average efficiency of 2.1 l/100 km.**

A few German car manufacturers as Porsche, Audi and BMW still started to bring vehicles with plug-in technology to the market or will do so within the next two years.

PHEVs have an enormous potential of saving $CO_2$ emissions and fuel consumption. Compared to similar conventional models, **a reduction of up to 65 % of fuel consumption** and $CO_2$ emission can be achievable. Comparing the HEV technology with PHEV technology (e.g. Toyota Prius Hybrid vs. Prius Plug-In), a further reduction of up to 46 % of fuel consumption and $CO_2$ emission can be achieved.

NiMH batteries are used in over 95 % of all HEVs. Major manufacturers have so far invested substantially in the last 10 years. Compared to Li-ion batteries, the safety aspect of NiMH is a major advantage from a manufacturing point of view.

**Table 13** Data sheet of a PHEV (1)—BMW i8 [32]

| | | |
|---|---|---|
| BMW: BMW I8 |  | |
| Type: Sports car | **Drive:** Front-wheel | **Top speed**: 250 km/h (155 mph) |
| Production: Series | **Motor**: Hybrid synchronous e-motor | **Battery**: Li-ion |
| Length**: 4.869 m (195.27 in)** | **Distance** between wheels: 2.8 m (110.24 in) | **Torque**: 320 Nm |
| Width**: 1.942 m (76.46 in)** | **Base curb weight**: 1,490 kg (3,284 lb) | **Charging (time)**: 110/220 V—1.5–3.5 h |
| Height**: 1.293 m (50.91 in)** | **Motor weight**: n.a. | **Battery weight:** 98 kg (216 lb) |
| Engine: **1.5 L turbo-charged Inline-gasoline** | **Battery capacity**: 7.2 kWh | **Electric range:** 40 km (25 mi.) |

The most important advantages are: environmental acceptability, low maintenance, high power and energy densities, cost and safety in charge and discharge modes.

**Current trends: car manufacturers have different concepts regarding electrical range, PHEVs have a high potential for reduce fuel consumption and $CO_2$ emission**.

One example is the BMW i8, which is shown in Table 13.

Table 14 shows the key data from the Opel Ampera, also known as Chevrolet Volt in the U.S. The Ampera, being known as a true pioneer of what we get now presented by other car manufacturers.

**Table 14** Data sheet of a PHEV (2)—Opel Ampera/Chevrolet Volt [33]

| | | |
|---|---|---|
| OPEL:<br>OPEL AMPERA<br>CHEVROLET<br>CHEVROLET<br>VOLT |  |  |
| Type: Compact car | **Drive:** Front-wheel | **Top speed**: 160 km/h (100 mph) |
| Production: Series | **Motor**: Hybrid permanent motor | **Battery**: Li-ion |
| Length**: 4.498 m (177.08 in)** | **Distance** between wheels: 2.69 m (105.91 in) | **Torque**: 370 Nm |
| Width**: 1.788 m (70.48 in)** | **Base curb weight**: 1,721 kg (3,794 lb) | **Charging (time)**: 110/220 V —1.5–3.5 h |
| Height**: 1.438 m (56.69 in)** | **Motor weight**: n.a. | **Battery weight:** 180 kg (397 lb) |
| Engine: **4 cylinders Otto Motor** | **Battery capacity**: 17.1 kWh | **Electric range:** 80 km (50 mi.) |

## 4.4 Fuel Cell Electric Vehicles (FCEVs)

FCEVs and BEVs both use electric drive trains, but where BEVs power their motors solely with batteries, FCEVs are hybrids, powered by a hydrogen fuel cell with a small battery.

Worldwide, more than 55 million tons of hydrogen is produced, mainly through reformation of fossil fuels. Recent worldwide hydrogen production totals show that 48 % of hydrogen is produced from natural gas, 30 % from oil, 18 % from coal and only 4 % from renewable resources [34].

Hydrogen has the highest energy content by weight (33,320 Wh/kg e.g. about 3 and 7 times more than gasoline (12,700 Wh/kg or 8,760 Wh/l), natural gas (13,900 Wh/kg or 5,800 Wh/l) and coal respectively) but it has a very low energy content by volume [35, 36].

*This makes storage and the distribution to the point of use costly. The low volumetric energy density can be increased storing the hydrogen either under increased pressure, at extremely low temperatures as a liquid or in metal-hydride systems* [37].

The Proton Exchange Membrane Fuel Cell (PEMFC) is the best choice for automobile use. The PEM fuel cell stack is comparable to the engine in a conventional vehicle. Although this technology has been developed in a good pace there are still the limitations of cost and durability. The cost of an ICE engine is about 23–27 EUR (25–35 USD) per kW, but current fuel cell systems are estimated to be about 5 times more expensive.

*Fuel cell stacks as an automotive "engine" are expected to be as durable and reliable as current automotive engines, e.g. 5,000 h lifespan or 150,000 miles equivalent* [38].

At the end of 2013, several car manufacturers have announced plans to introduce a series production model of a FCEV in 2015. In 2013, Toyota has stated that it plans to introduce such a vehicle at a price of less than 91,400 EUR (100,000 USD). At the beginning of 2014, Toyota announced that sales of its FCEV Toyota Mirai will begin in Japan in early 2015 where hydrogen stations are still in place and in the surrounding areas. Preparations are underway for sales to begin in the US and Europe during the summer of 2015.

In early 2015, Toyota announced the sale of its FCEV Mirai in Germany at the end of 2015 at a price of less than 78,580 EUR (85,920 USD.)

The commercial production of FCEVs started at the end of 2015. Furthermore, fuel cells are being developed and tested in buses, boats, motorcycles and bicycles, among other kinds of vehicles. Automobiles such as the GM HydroGen4, Honda FCX Clarity, Toyota FCHV-and Mercedes-Benz F-Cell are pre-commercial examples of FCEVs.

Current FCEVs have a PEM fuel cell with a range starting from 500–600 km (310–372 mi.) and a top speed of 170 km/h (105 mph). That means an average efficiency of 9.5 kg $H_2$/1,000 km. Currently hydrogen in cars is compressed, either to 350 bar (Honda and Nissan) or more commonly to 700 bar (Toyota).

According to the information available to Ludwig-Bölkow-Systemtechnik, at the end of 2014, a total of 72 hydrogen refueling stations are currently operated in Europe, 67 in North America, one in South America, and 46 in Asia.

Table 15 shows the data for the Hyundai ix35 Tucson and Table 16 shows the Toyota Mirai.

**Current trends: several challenges must be overcome before FCEVs will be a successful, competitive alternative for consumers, like: vehicle cost, onboard hydrogen storage, fuel cell durability and reliability, public education and getting the hydrogen to the consumers.**

**Table 15** Data sheet of a FCEV—Hyundai iX35 [39]

| Hyundai IX35 |  | |
|---|---|---|
| Type: Compact SUV | **Drive:** Front-wheel | **Top speed**: 160 km/h (100 mph) |
| Production: Series | **Motor**: Asynchronous motor | **Battery**: Li-ion-polymer |
| Length**: 4.410 m (173.6 in)** | **Distance** between wheels: 2.64 m (103.91 in) | **Torque**: 205 Nm |
| Width**: 1.820 m (70.8 in)** | **Base curb weight**: 1,850 kg (4,078 lb) | **Pressure**: 700 bar |
| Height**: 1.655 m (65.34 in)** | **Motor weight**: n.a. | **Range:** 600 km (375 mi) |
| Tank volume: **5.64 (12.6 lb) kg hydrogen** | **Battery capacity**: 24 kWh | **Consumption:** 0.95 kg (2.09 lb) hydrogen/100 km |

**Table 16** Data sheet of a FCEV (2)—Toyota Mirai [40]

| TOYOTA MIRAI |  | |
|---|---|---|
| Type: Compact car | **Drive:** n.a. | **Top speed**: 175 km/h (108 mph) |
| Production: Series | **Motor**: Synchronous motor | **Battery**: Nickel metal hydride |
| Length**: 4.890 m (192.5 in)** | **Distance** between wheels: 2.780 m (109.5 in) | **Torque**: 335 Nm |
| Width**: 1.815 m (70.8 in)** | **Base curb weight**: 1,850 kg (4,078 lb) | **Pressure**: 700 bar |
| Height**: 1.655 m (71.26 in)** | **Motor weight**: n.a. | **Range:** 310 km (500 mi.) |
| Tank volume: **n.a.** | **Battery capacity**: 1.6 kWh | **Consumption:** n.a. |

# 5 Comparison of Different Vehicle Specifications

Table 17 [41] compares different types of vehicles in terms of cost, performance and $CO_2$ emissions. The chosen models are representative vehicles within their class, and represent the most advanced technologies to date $CO_2$.

## 5.1 *Cost Factor*

Cost is a key factor for public acceptance of vehicles driven by alternative propulsion systems. Right now it seems that the cost factor for electrochemical energy systems is one of the major challenges to overcome. Nevertheless, technological progress has been impressive and enabled costs to fall rapidly. Toyota for example is working hard on their FCEVs. Right now Toyota has cut the cost of making its FCVEs by 90 % since 2005, from 0.9 Mio. EUR (1 Mio. USD) per vehicle down to around 91,450 EUR (100,000 USD) [42].

Instead, **battery prices are expected to fall less rapidly, by 50 % within 10 years compared to 75 % for fuel cells.** Recent cost estimates for FCEVs show the cost dropping over time from several hundred thousand dollars now to roughly 68,600 EUR (75,000 USD) in 2015 and 45,720 EUR (50,000 USD) or less in 2020. For batteries, most analysts project the cost per kWh for BEV batteries to drop from 590–915 EUR (650–1,000 USD) today to 365–640 EUR (400–700 USD) in 2015 and 275–460 EUR (300–500 USD) in 2020, with some projections for 2020 going as low as 135 EUR (150 USD) per kWh [43].

**Table 17** Comparison of different vehicle specifications from a consumer's perspective

| Specification | **ICE (VW GOLF 1.4TSI)** | **HEV (Toyota Prius III)** | **BEV (Nissan Leaf)** | **FCEV (Honda Clarity)** |
|---|---|---|---|---|
| Power supply | ICE | ICE, e-motor | Battery and e-motor | PEM fuel cells and e-motor |
| Fuel | Petrol, diesel & alternative fuel | Petrol/diesel as main fuel | 'Electricity' | Hydrogen |
| Top speed (km/h)\|(mph) | 200\|124 | 180\|112 | 150\|94 | 160\|100 |
| Acceleration (s) | 9,5 | 10,4 | 7 | 10 |
| Range (km)\|(mi.) | 890\|552 | 1150\|716 | 117-175\| 73-109 | 390\|240 |
| Running fuel price (per mile) | 0.2 EUR (0.22 USD) | 0.12 EUR (0.14 USD) | from 0.01 EUR (0.02 USD) | from 0.06 EUR (0.07 USD) |
| Fuel economy (mpg or mpg equivalent) | 45.6 | 72.4 | 99 | 84 |
| Tailpipe $CO_2$ emission (g/km) | 144 | 89 | 0 | 0 |

## 5.2 Durability

**The calendar life of Li-ion batteries is still a problem, as the rate of capacity loss has not improved in 7 years, at approximately 5 % per year.** Lifetimes for Li-ion chemistries are in the order of 2,000 cycles to 80 % depth of discharge (DoD) before 20 % of power is lost. The number of cycles is approximately reciprocal with the DoD, meaning that around 4,000 cycles to 40 % DoD can be expected. With the 130 km (80 mi.) range of current BEVs, this suggests that the battery should last for at least 160,000 km (100.000 mi.), comparable to an internal combustion engine [44].

Fuel Cells lifetimes are assessed by the number of hours until 10 % power is lost. The latest generation of FCEVs from Ford, Daimler, GM and Honda are projected to last 800–1,100 h, falling short of the DoE's 2009 target of 2,000 h. The reliability of current FCEVs must also be improved, as some vehicles are seen to lose 10–25 % performance within the first 300 h of driving [45].

## 5.3 Energy and Power Density

One of the largest problem for electrochemical storage devices is the energy density itself. The specific energy and energy density of batteries and capacitors are unlikely to ever compete with liquid hydrocarbons holding around 12 kWh/kg [46].

Table 18 demonstrates the impact that system weight and conversion efficiency have on the specific energy of petrol, hydrogen and lithium-ion batteries, using data from four modern vehicles. **In order to compete with conventional vehicles, batteries require a five- fold increase in specific energy, while hydrogen only requires a 30 % improvement.** A better battery that could hold 666 Wh/kg at the cell level, or a hydrogen tank that held 6 % would therefore give comparable performance from the driver's perspective.

## 5.4 Efficiency

With the transition from lead acid (75–85 %) and NiMH (65–85 %) to lithium chemistries, battery efficiency has improved. **Under ideal conditions, cycle efficiencies of Li-ion batteries now rival those of capacitors at 90–94 %** in automotive use [47].

Battery system efficiency is closely related to operating conditions, decreasing with both current and temperature. The desire of consumers to move to rapid charging systems is therefore cause for concern. When charged with a 3 kW household charger the charging efficiency of the Mitsubishi i-MiEV is around 90 %.

**Table 18** Comparison of different storage systems in 4 leading vehicles

| Characteristic<br>Reference vehicle | Conventional<br>VW Golf VI | Hybrid<br>Toyota<br>Prius III | Hydrogen<br>Honda FCX<br>Clarity | Battery<br>Nissan<br>Leaf |
|---|---|---|---|---|
| Fuel weight (kg)\|(lb) | 40.8\|89.9 | 33.3\|73.4 | 4.1\|9 | 171\|377[a] |
| Storage capacity (kWh) | 500 | 409 | 137 | 24 |
| Specific energy (Wh primary/kg fuel) | 12,264 | 12,264 | 33,320 | 140[a] |
| Storage system weight (kg) | 48\|105.8 | 40\|88.2 | 93\|205.1 | 300[b]\|<br>661.4 |
| Specific energy (Wh primary/kg of storage) | 10,408 | 10,261 | 1,469 | 80 |
| Net power (kW) | 90 | 100 | 100 | 80 |
| Power plant and auxiliary weight (kg)\|(lb) | 233\|513.7 | 253\|557.8 | 222\|489.4 | 100\|<br>220.4 |
| Specific energy (Wh primary/kg total equipment) | 1,782 | 1,389 | 315 | 60 |
| Average conversion efficiency | 21 % | 35 % | 60 % | 92 % |
| Effective storage capacity (kWh useable) | 105.0 | 143.1 | 82.0 | 22.1 |
| Specific energy (Wh useable/kg total equipment) | 374 | 489 | 260 | 55 |

[a]Stands for bare laminated lithium-ion cells, [b]Stands for including battery management and cooling systems

Inductive charging is another promising option; although it reduces efficiency by a further 10 % [48].

The US DoE and Japan's NEDO hydrogen energy roadmap both set a target of 60 % efficiency for FCEVs circa 2015. From the latest field trials in California it could be seen, that this target is close to being attained, with fuel cell vehicles from five major manufacturers averaging 52 %, and the top manufacturer achieving 57 %.

## 5.5 *Safety*

Public and media-driven concerns about safety continue to dog the proliferation of FCEVs and BEVs, even though the technologies themselves are inherently and passively safe. Hydrogen cylinders are tested against crushing, impact damage, penetration with armourpiercing bullets, and fire [49].

Similarly, the majority of BEV manufacturers have avoided the use of lithium-cobalt, lithium-manganese and other unstable chemistries. The majority now use lithium iron phosphate, and so the battery packs in today's vehicles cannot experience thermal runaway. Coupled with well pacified cooling systems, precise monitoring of the pack's state-of-charge and individual cell balancing, these should give a robust and fail-safe system [50].

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# International Deployment and Demonstration Projects

**Michael Nikowitz**

**Abstract** Governments around the world have set goals to increase electric vehicles' future market share. Therefore, fiscal policies as well as tax exemptions and subsidies are a famous instrument in spurring electric vehicle markets, but in widely divergent ways. These conditions are highlighted in this chapter. There are clear differences in the taxation benefits and sales of electric vehicles across the major vehicle markets: Asia, United States and Europe. This chapter indicates that fiscal incentives are not the only factor which influences the market growth of these vehicles. Besides that, demonstration projects also play an important role in terms of market growth. The data for this chapter have been collected from various information exchange meetings within the IEA, conferences from the Austrian Association for Advanced Propulsion Systems (A3PS) and from an ICCT report (Mock and Yang, http://www.theicct.org/sites/default/files/publications/ICCT_EV-fiscal-incentives_20140506.pdf, 2015) [1].

In this section international deployment and performance analysis of EVs in real life operation and demonstration projects are described. This section should highlight some of the most important ones, by focusing on different regions, and thus it doesn't include all projects. The data from this section have been collected from an ICCT report Mock and Yang [1], as well as from an international information exchange (IEA-Task 1 Meeting) in Goyang, Korea [2].

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## 1 Worldwide Incentives for EVs

EVs form part of the backbone of worldwide policy to reduce carbon emissions substantially by 2050, but the uptake of EVs and PHEVs is not increasing at the rate that was targeted by many countries. Most governments and legislating bodies continue to provide subsidies and financial incentives to encourage consumers to buy electric vehicles, and while some countries such as Norway and Holland have seen strong growth in the EV sector, most European and worldwide auto markets are lagging behind.

Of course, fiscal incentives and subsidies only represent one part of a bigger picture. There is a clear need for the development of an infrastructure to support e-mobility, and further research and development is required to produce EVs and PHEVs which are more competitive on purchase price, without subsidies. This is a good chance to look at some of the current incentives on offer in the various global auto markets, and at some of the initiatives to develop the supporting infrastructure for the EV market.

Research and development will play an important role in achieving these targets as incentives are phased out over the next decade; but in the short-term, subsidies and fiscal incentives will continue to be crucial to the growth of the market.

Early 2014, the International Council on Clean Transport (ICCT) published a study—"Driving Electrification: A global comparison of fiscal policy for electric vehicles"—which evaluated the response to fiscal incentives in 2013 to incentivize the purchase of plug-in electric vehicles in major vehicle markets around the world. Furthermore, this study offers a synthesis of wide-ranging sales data, national taxation policy information, and direct electric vehicle purchasing rebates to analyze the link between government policy and electric vehicle sales.

The study assessed the difference between taxation costs for electric and ICE vehicles, as well as fuel and electricity prices to determine a total cost of ownership; then evaluated those incentives against the electric vehicle market share and growth in each sector to assess the impact of the different incentive programs.

The study pointed out, that there are clear differences in the taxation benefits provided for electric vehicles and sales of electric vehicles across the major vehicle markets, as it can be seen in Fig. 1.

Figure 1 summarizes the relationship between the equivalent per-vehicle fiscal incentive provided in each region (in percentage of vehicle base price, on the x-axis), and the respective passenger car market share of BEV and PHEV for 2012 and 2013 (y-axis).

Taking into account Norway and the Netherlands—in 2013, Norway had the highest share of BEVs and PHEVs sales, with about 6 % of all passenger cars sold in 2013, while The Netherlands had the second-highest market share, with about 5.6 % (which can be seen in Fig. 2). The structures of the two markets are entirely different, though: while in Norway nearly all EVs sold are BEVs, in the Netherlands PHEVs clearly account for the majority of the market.

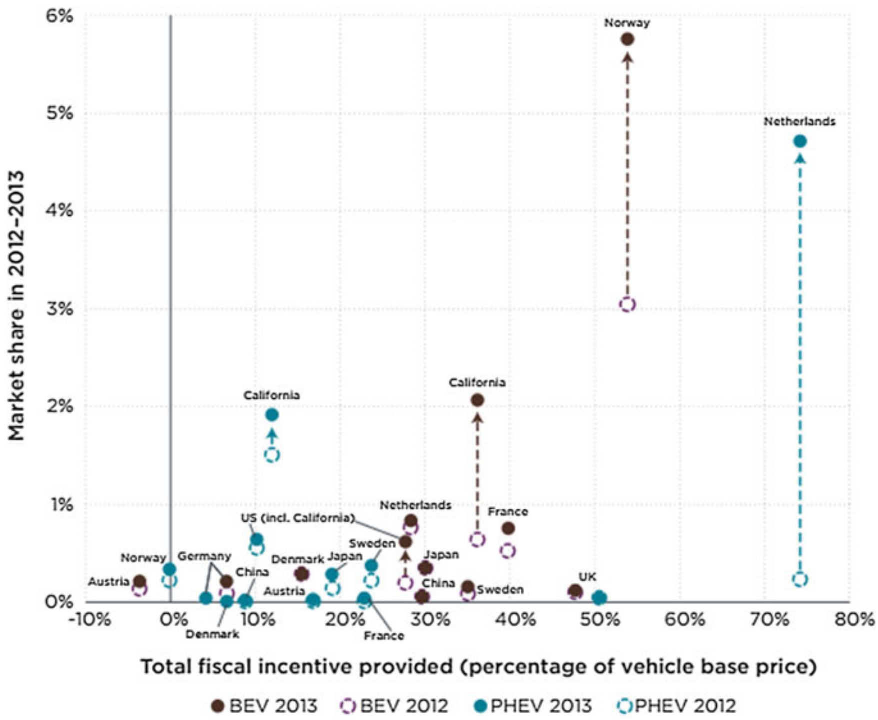


**Fig. 1** 2012/2013 market share versus vehicle incentive for BEVs and PHEVs [1]

Norway's fiscal incentive of about 11,500 EUR (12,970 USD) per BEV (equivalent to about 55 % of vehicle base price) is associated with a 6 % market share for BEV in 2013, and a 90 % market share increase from 2012 to 2013.

Similarly, the fiscal incentive in the Netherlands of about 38,000 EUR (42,840 USD) for PHEV (equivalent to about 75 % of vehicle base price) in 2013 is associated with a 5 % market share for PHEV in 2013, and a 1,900 % market share increase from 2012 to 2013.

These two examples indicate how national fiscal policy can offer a powerful mechanism to reduce the effective total cost of ownership and entice consumers to purchase EVs.

Pushing the sales of EVs can be done by different numerous policy incentives, like:

- **direct subsidies** (defined here as a one-time bonus upon purchase of an EV),
- **fiscal incentives** (defined here as a reduced purchase and/or annual tax for EVs),
- **fuel cost savings** (incentive due to electricity prices being lower than fuel prices as a result of lower taxation and/or lower energy costs, as well as higher efficiency of EVs).

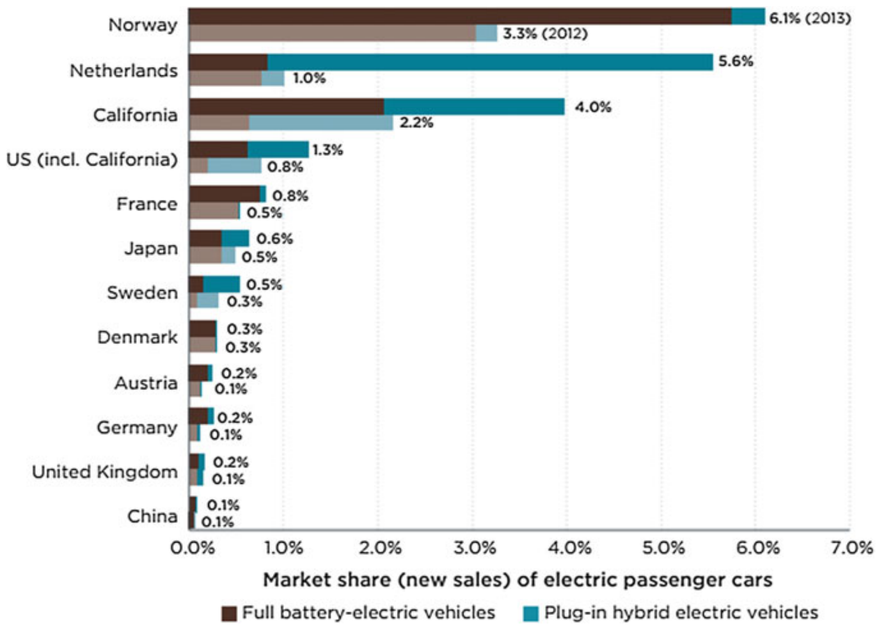


**Fig. 2** Market share of electric passenger cars FY 2012 (*lighter colors*) and 2013 (*darker colors*), in comparison to total sales [1]

## 1.1 Direct Subsidies

There are a number of countries that offer direct subsidies upon purchase of an EV:

- **France**: within the context of the French Bonus/Malus vehicle taxation system, vehicles emitting less than 20 g/km of $CO_2$ receive a one-time bonus of 7,000 EUR (7,904 USD) (the amount of the incentive cannot exceed 30 % of the vehicle purchase price including value-added tax, or VAT, and battery cost). For vehicles in the range of 21 and 50 g $CO_2$/km, the bonus is 5,000 EUR (5,640 USD),
- **UK**: since 2011, customers who purchase a new electric car (emitting < 75 g $CO_2$/km or a FCEV) receive a one-time bonus of 25 % of the car, up to a maximum of 5,800 EUR (6,550 USD),
- **Sweden**: since 2012, cars with a $CO_2$ emission of 50 g/km and less receive a onetime "super green car premium" of 4,500 EUR (5,080 USD). The program will be paid to a maximum of 5,000 cars,
- **US and California**: a federal subsidy program for EVs allows for a one-time bonus, depending on the battery capacity of the vehicle, of up to a maximum of 6,650 EUR (7,500 USD) in form of tax credit. In California, there is another subsidy program at the state level, granting BEV purchasers another 1,800 EUR (2,500 USD) and PHEV 1,100 EUR (1,500 USD) in the form of a one-time bonus payment,

- **Japan**: a government program has allowed for a one-time bonus for EVs and other qualified fuel-efficient vehicles since 2009. The program provides a bonus based on the price difference between the EV and a comparable gasoline car. The bonus is capped at 6,300 EUR (7,100 USD),
- **China**: since 2010, a national program provides a one-time bonus for EVs and FCEVs. The program was recently extended from 2013 to 2015, with some revisions. The bonus is between 4,200 and 7,200 EUR (4,740–8,120 USD) for BEVs, depending on the battery range of the vehicle, and 4,200 EUR (4,740 USD) for PHEVs with battery range no less than 50 km (31 mi.).

## *1.2 Fiscal Incentives*

Another important element of encouraging the purchase of EVs are fiscal incentives, including four main categories of tax breaks:

- **VAT**: all markets for this comparison apply VAT when a vehicle is purchased. The range of the tax is between 5 % (Japan) and 25 % (Denmark, Norway, Sweden) and usually applies to the base price of the vehicle, excluding any purchase/registration tax. (Norway is the only market examined here which excludes BEVs from VAT, the VAT exemption does not apply to PHEVs.) In all other markets, EVs end up paying more VAT than their conventional counterparts. This is because EVs usually have a higher base price and are therefore subject to a higher VAT, even after the bonus has been deducted from the base price of an EV (as in China and Japan),
- **one-time purchase/registration tax**: some markets examined here charge a purchase or registration tax in addition to the VAT, and provide a tax break to EVs. For example, in the Netherlands, registration tax depends on the level of $CO_2$ emission of a vehicle, with higher rates for diesel than for gasoline vehicles. Vehicles with less than 95 g/km (gasoline) or 88 g/km (diesel) are exempt from the registration tax. Other markets with a strong effect of registration tax are Denmark and Norway. In Denmark, registration tax is calculated based on vehicle price, safety equipment on board,
- **annual circulation tax**: some markets charge an annual vehicle ownership tax, and in so doing provide a tax break for EVs. In Germany, for example, annual circulation tax is calculated based on $CO_2$ emissions and engine capacity of a vehicle. BEVs and PHEVs are exempt from circulation tax for a period of 10 years from the date of their first registration. However, the savings are relatively small. In the Netherlands, the effect is larger. The annual circulation tax is generally based on vehicle weight and
- **company car tax:** company cars are very popular in many European countries. For example, in Austria in 2014, only 36.8 % of new passenger cars were registered by private owners, while 63.2 % were registered as company cars (also including short-term registrations from car dealers [3]), this is especially

true for EVs. The basic idea behind the company car system is as follows: Instead of paying a higher salary to its employee, the company offers to provide him/her a car and to pay all related charges, usually including fuel costs. The company can claim the costs for the vehicle and associated charges as business expenditures and is subject to a lower profit tax. The employee, on the other hand, has access to a vehicle that he/she can also use for private trips. In return, the employee has to pay a special company car tax to account for the monetary benefit of having free access to a vehicle.

## *1.3 Fuel Cost Savings*

On a tank-to-wheel basis, EVs are more energy efficient than comparable combustion engines.

Fuel/electricity consumption of a vehicle needs to be multiplied by the price for fuel/electricity to obtain an estimate for annual spending on fuel/electricity. Fuel prices and electricity prices vary significantly across markets. This is also reflected in the estimated fuel cost savings. Norway, for example, has relatively high gas prices but relatively low electricity tariffs, so the resulting cost savings from switching to an EV are larger than in other markets. In Germany, the price of gas is comparably low (for European standards), while household electricity prices are comparably high, hence the estimated savings are lower. In China, the price of electricity is significantly lower than that of gasoline, and therefore the percentage savings of switching to an EV are high—however, because gas prices are low compared to other markets, the absolute savings are at the lower end of the spectrum.

**Conclusion**

Subsidies and incentives have been shown to spur growth in EVs in some markets but have been less successful in others, despite generous incentives. The reasons for this are not easily identified, but it is clear that subsidies are just one part of a wider-reaching approach to accelerating the uptake of EV's.

More can be done in terms of infrastructure and regional legislation, but at some point in the future EVs must be able to compete on price without being subsidized. This is why research and development in the EV sector is every bit as important as incentives for the growth of the market.

Based on the data collected and analysis in this paper by ICCT, it is obvious that there are significant differences between EV markets and the associated fiscal policy.

> Thus, as a conclusion: national fiscal policy is a powerful mechanism to reduce the effective total cost of ownership and entice vehicle consumers to purchase electric vehicles

There are substantial differences in terms of the absolute market share, differences in the growth rate, and differences in the type of EVs predominantly sold (BEVs vs. PHEVs). Electric vehicle market shares range from negligible to 6 %, growth rates vary from zero to more than 400 %, and there are both markets such as Norway and France, where nearly all EVs sold are BEVs, and markets such as Austria, the Netherlands and the US, where most EVs sold are PHEVs.

The analysis demonstrates that there are large differences in the tax structure and also in the level of incentives provided for EVs in the various markets. Linking the level of incentives and the parameters describing market dynamics suggests that there is indeed some link between the incentives provided and the uptake of EVs in a market. Clear examples are Norway and the Netherlands, where high EV fiscal incentives result in a beneficial total cost of ownership for consumers, and this results in high EV market growth rate and market share.

A further conclusion points out: more comprehensive study is needed of the impact of the full portfolio of policy actions to accelerate the early EV market.

A more comprehensive assessment of policy options to spur EV growth would investigate and help understand the importance of vehicle manufacturer policy (e.g., emission standards, electric vehicle requirements), infrastructure policy (residential equipment, public charging), and electric utility policy, along with the consumer EV fiscal policy evaluated here. A more comprehensive and rigorous assessment of these other policy action areas would help designing a longer-term policy path that is not so exclusively dependent upon large initial-year taxation incentives.

A short description of different national taxation systems can be seen in Fig. 3.

# 2 International Deployment and Demonstration Projects

## *2.1 Development Plan for EVs in China (2011–2020)*

**Tens of Cities, Thousands of Vehicles**

In 2009 the Chinese government introduced the “Ten cities, one thousand vehicles Program”, which shall help to encourage the public and private use of electric cars through demonstration projects in these cities. In this plan, 1,000 vehicles will be introduced every year for three years in these ten cities. In 2010 a total of 13 cities were chosen to participate in this program by the Ministry of Finance and the Ministry of Science and Technology, which are jointly running the program. These 13 cities are Beijing, Shanghai, Chongqing, Changchun, Dalian, Hangzhou, Jinan, Wuhan, Shenzhen, Hefei, Changsha, Kunming, and Nanchang, but in the meantime other cities have joined as well. The second group of cities participating is Tianjin, Haikou, Zhengzhou, Xiamen, Suzhou, Tangshan and Guangzhou. Experts reported that in late 2010 another 5 cities joined the project.

Started initially in ten cities, the program has now spread to 25 cities on the mainland.

| Region | VAT | Tax Scheme | | Subsidy |
|---|---|---|---|---|
| | | One-time | Annual | One-time |
| Norway | 25% BEVs exempted | • Registration tax based on vehicle weight, engine power, nitrogen oxide emissions, and $CO_2$ emissions. BEVs are exempted. | • Circulation tax about 350 EUR | |
| Netherlands | 21% | • Registration tax based on the $CO_2$ emission level of the vehicle. BEVs and most PHEVs are exempted. | • Circulation tax based on the vehicle weight, fuel type, and $CO_2$ emission. BEVs and most PHEVs are exempted.<br>• [Company car] Income tax for cars emitting more than 50 g/km $CO_2$ of 25% of the vehicle's catalogue value in 2013. BEVs and some PHEVs are exempted. | |
| US (including California) | 7.3%* (8.4%) | • Registration fee around 33 EUR<br>• Gas-guzzler tax for very fuel-inefficient vehicles | | • Up to about 5,500 EUR based on battery capacity (federal);<br>• About 1,800 EUR for BEVs and 1,100 EUR for PHEVs (Calif.). |
| France | 19.6% | • Registration tax based on engine power. EVs are exempted. | • [Company car] Income tax based on $CO_2$ emission. BEVs and some PHEVs are exempted | • Up to 7,000 EUR for EVs |
| Japan | 5% | • Acquisition tax based on engine displacement and vehicle price. EVs are exempted. | • Tonnage tax based on vehicle weight. EVs are exempted;<br>• Automobile tax based on engine displacement. EVs are exempted 50% | • Up to about 6,500 EUR based on price difference for EVs. |
| Sweden | 25% | | • Road tax based on $CO_2$ emission. EVs are exempted.<br>• [Company car] Income tax partially based on vehicle price. EVs are exempted 40%. | • Up to about 4,600 EUR based on price difference for EVs. |
| Denmark | 25% | • Registration fee mostly based on vehicle price. EVs weighing less than 2000 kg are exempted. | • Annual circulation tax based on fuel consumption. BEVs weighing < 2000 kg are exempted.<br>• [Company car] Income tax based on price. | |
| Austria | 20% | • Registration tax based on fuel consumption. EVs have deductions. | • Circulation tax based on engine power. EVs are exempted.<br>• [Company car] Income tax based on price. | |
| Germany | 19% | | • Circulation tax based on engine displacement and $CO_2$ emission. EVs are exempted for 10 years.<br>• [Company car] Income tax based on price. EVs have deductions. | |
| United Kingdom | 20% | • First year excise duty based on the $CO_2$ emission and vehicle price. BEVs and some PHEVs are exempted. | • Excise duty from second year of purchase based on the $CO_2$ emission and vehicle price. BEVs and some PHEVs are exempted.<br>• [Company car] Income tax based on $CO_2$ emission and price. BEVs are exempted. | • Up to 5,900 EUR for BEVs and some PHEVs |
| China | 17% | • Acquisition tax (10%)<br>• Excise tax based on zvehicle engine displacement and price. | • Vehicle and vessels fee based on engine displacement and price. EVs are exempted. | • Up to 7,200 EUR for EVs |

**Fig. 3** Overview of 2013 national vehicle taxation systems [1]

The project is a demonstration project for new energy vehicles and is meant to promote the technology as well as the industry. The plan aimed to give new energy vehicles a 10 % share of the total auto market by 2012 (compare Fig. 4).

The central government sets some framework conditions for the support, but the local governments need to implement the demonstration projects according to their own local needs and necessities. This leads to each city setting up its own policy to promote new energy vehicles, setting up own industrial alliances, creating its own guidelines for financial support and providing its own (additional) funds. Even though government regulations make open bidding necessary for these

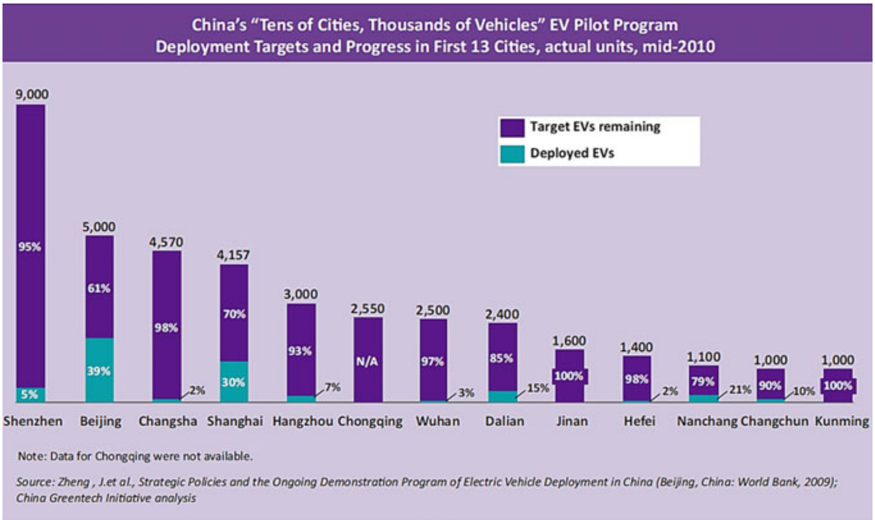


**Fig. 4** China's 'Tens of Cities, thousands of vehicles' (image courtesy of Zheng [4])

demonstration projects, eight city governments (out of the first 13 cities) purchased their first batch of vehicles from their local car manufacturers only.

Some experts are therefore worried that local interests may conflict with the national industrial policies and that local protectionism will violate central policies. There might be a risk of developing the same technologies in many places at the same time and wasting public money. Also, some companies may receive strong support, even though their technology level may never reach the national or the international standard and therefore weakens China's international competitiveness in the long term.

The private vehicle purchase subsidy from the central government was 377 EUR/kWh (483 USD/kWh). The PHEVs (passenger) can receive a maximum subsidy of 6,283 EUR/unit (8,050 USD/unit) and the advanced EVs (passenger) 7,535 EUR/unit (9,660 USD/unit) [5].

In addition to the subsidy from the central government, Shanghai provided a subsidy of 251 EUR/kWh (322 USD/kWh). The PHEVs (passenger) can receive a maximum subsidy of 2,511 EUR/unit (3,220 USD/unit) and the advanced EVs (passenger) 5,023 EUR/unit (6,440 USD/unit).

The year 2011 was a demonstrative year for the development of xEVs in China

Until 2012, the development of EVs was still at an exploratory stage in China. It's predicted that if the past five years can be viewed as a developing period for this sector, then the next five years will be a time for the industry to crack down on key issues

In a conclusion, it seems that the development of the whole EV industry is guided mainly by the Chinese government. In contrary, in Western countries the car manufacturers themselves tend to be playing the key role which could indicate that the Chinese automobile manufacturers should be more aware of the market and perform more actively in its development. The Chinese government should support the domestic car manufacturers moderately to shape a healthy market environment. In spite of all the various financial supporting policies, the Chinese government could formulate an efficient capital and investment platform for xEVs. With a good financing system, the government could attract more international and national capital for the EVs industry, and thus speed up its development pace. At the same time however, it is an undeniable fact that this market is becoming extremely important in China, and that it could create many opportunities for multinational car manufacturers, similarly as it happened with the conventional car market.

**"Development Plan for Fuel-efficient and New Energy Vehicles"**
The currently drafted "Development Plan for Fuel-efficient and New Energy Vehicles" dated 2010 can be seen as the major industrial plan to support the new energy car industry. This plan aims to support the whole industry chain of fuel-efficient and new energy cars, including the development of standards and regulations, and to reach a world level with the three key components of electric engine, drive train and battery. The plan proposes that the sales of China's new energy vehicles will be the number one in the world by 2020. It focuses on the development of BEVs.

The plan is targeted for 2020, but includes 2 different phases. In phase one (2011–2015) Chinese-owned IP for core technologies like battery, motor and electric control will be created and developed. This will be the initial stage for developing pure electric vehicles and plug-in hybrid cars with a total production reaching 500,000 cars. The market volume should reach over 1 million and the government will invest around 14.3 billion EUR (16.1 billion USD) for the development of the whole industrial chain of new energy vehicles.

Phase two (2016–2020) will put more emphasis on developing BEVs and PHEVs. Their total (accumulated) market volume should reach 5 million cars. The key technologies will be broadly diffused in this period and then fuel consumption of new cars should be reduced to 4.5 liters/100 km. By then, Chinese sales of fuel-efficient and new energy vehicles should be number one in the world by 2015 for all the different types of hybrid cars. In this period, Chinese enterprises will manage to produce the necessary key technology, e.g. advanced internal combustion engine, automatic transmission, automotive electronics, lightweight materials etc. All new cars produced by then (with combustion engines or hybrids) need to have a fuel consumption that is below 5.6 liters per 100 km. Chinese industrial experts have been saying that these numbers are not static and will be adjusted during the plan if necessary.

Government officials plan to transform the Chinese automotive industry in the direction of BEVs and PHEVs, yet still looking to the further development and improvement of the traditional car industry and technology.

Besides the investment plans and the division into two major phases, the new plan emphasizes the concentration of the leading-edge enterprises in "national teams". These national teams will build on the existing key auto enterprises in China and the existing energy-saving and new energy vehicle industrial bases in

Changchun, Shanghai, Wuhan, Chongqing, Beijing, Guangdong, Anhui (and others). They will establish pilot bases for the new energy vehicles industry and combine them with demonstration projects. By 2020 the industrial concentration of the bases mentioned above should be 90 %.

The companies will form 2–3 large automobile enterprise groups with a production and sales volume of over 6 million cars per year. Another 1–2 automobile groups with production and sales volume of over 1 million new energy vehicles and 3–5 automobile enterprise groups with a volume of 500,000 cars will be established. The main reason for this concentration is seen in avoiding indiscriminate investments and low-level developments as well as redundant investments.

Industrial plants to produce Li–ion batteries will be concentrated in Tianjin, Shenzhen and Hangzhou. 2–3 leading battery enterprises with production and sales over 20 billion watt-hours (Wh) and the capacity for R&D and production of cell materials' will be established.

The plan mentions establishing and improving standards and regulations for small low speed BEVs. This should give enterprises which are not part of the "national teams" the opportunity to enter the field of electric cars as well [6].

**Shenzen and Wuzhou**

Shenzhen, China has laid claim to the largest fleet of EVs in the world—and they recently (end of 2014) announced the addition of 1,500 EVs to their fleet of 500 EVs, bringing the grand total up to 2,000 EVs. The vehicles—1,300 e-buses and 800 e-taxis—were all bought from Shenzhen-based EV manufacturer BYD. Shenzhen has made some pretty progressive strides to get their residents and government workers behind the wheel of a zero-emissions vehicle—including offering lower energy costs for new electric vehicle owners.

Shenzhen's mission of spreading EV ownership is supported by their all-EV fleet, which transports residents around the city in electric buses and taxis. The purchase of EVs also goes to support jobs provided by BYD manufacturing, which is based in Shenzhen. "Shenzhen is the first city in China to implement a subsidy for new energy vehicles and the first city to launch consumer sales of the BYD e6," noted, Shenzhen Development and Reform Commission (SDRC) Director Xiangzhen Lu.

Shenzhen City will also establish new policies in hopes of encouraging private EV use. The SDRC announced that Shenzhen is formulating measures to impose fees on emissions from gasoline cars while rewarding alternative energy vehicle drivers based on distance travelled. Other incentive policies include allowing pure electric drivers to use the public bus lane during rush hour, insurance privileges, and free annual maintenance checks. China's Southern Power Grid Company has agreed to install free-of-charge, two EV charging poles for each Shenzhen EV driver—one at the home or apartment of the driver and another near the EV driver's place of business. Shenzhen City continues to offer extremely affordable peak and off-peak electricity prices for new energy vehicle users, reducing nightly charging costs to only 0.035 EUR/KWh ($0.04 USD/KWh equivalent) [7].

By the end of Feb. 2013, the largest e-taxi fleet worldwide consisting of 800 e6 in Shenzhen has neared a cumulatively total mileage of 55 Mio. km (34.2 Mio. Mi.) with the maximum mileage of one single e-taxi exceeding 270,000 km (167,770 mi.)—a mileage a common private car will run for 10 years.

By of the end of Feb. 2013, mileage record of the 200-unit e-bus fleet of BYD K9 in Shenzhen has accumulated up to more than 14 Mio. km (8.7 Mio. mi.) with an average mileage of 110,000 km (68,650 mi.) for one single e-bus. In addition, the 5 BYD K9 s serving Shaoguan city have travelled nearly 300,000 km (186,400 mi.) as well.

In operation for more than four years now, the largest fleet in Shenzhen has proved its durability by recently surpassing the 120 million km mark (75 million mi.), putting an average of 400,000 km (248,584 mi.) per taxi with only less than 9 % loss of battery capacity.

In November 2013, Wuzhou started a clean city initiative, in collaboration with BYD. Therefore, BYD Company Ltd has sponsored the first 30 of 200 BYD e-taxi vehicles which were planned to go into operation throughout the year 2014.

30 pure electric e6 (one of the longest range electric cars available today, with the ability to travel over 300 km (186 mi.) under load on a single charge) taxis sponsored by BYD serve as the official car of the Gem Festival, which marks Wuzhou City taking the first step in promoting new energy transportation. After the festival, the first batch of 30 electric taxis will constitute the first local pure electric fleet. In early October 2013, BYD won the bid to supply 200 e-taxis for Wuzhou City. The remainder of the fleet will come in the months following the festival. Haoling Wu, Municipal Party Committee Member and Deputy Mayor of Wuzhou City, outlined in his speech the geographical advantages and investment environment of Wuzhou City. In his speech he discussed the city's admiration for BYD and their world class technologies, as well as describing BYD as the perfect company to help his city open the page to this new chapter [8].

## 2.2 Taiwan

As part of the government's effort to promote the use of EVs in Taiwan, the Ministry of Economic Affairs (MOEA) held a ceremony in Taipei recently to launch two EV pilot projects. The MOEA plans to carry out 10 EV projects in different locations throughout Taiwan over the next few years, putting at least 3,000 of the vehicles on the streets [9].

It took less than three years to get EVs on the road in Taiwan, thanks to the joint efforts of the government and the private sector. Over the past few years (before 2012), Taiwan has built up its own EV supply chain consisting of makers of assembled EVs, EV motors, charging equipment, and other key parts and components. Government policy has guided the industry's development.

Taiwan's EV pilot projects have some features that differ from similar projects in other countries:

- Taiwan's government wants to pour more resources into "intelligent" EVs so as to make use of the island's strong information and communications technology industry to create new driving experiences and new relationships between humans, EVs, roads, and the environment,
- further, Taiwan's EV pilot runs are promoting all types of EVs (including full-electric multi-purpose vans (MPVs), SUVs, and passenger cars, as well as public buses, instead of concentrating on large public buses and small cars as in many other countries) and
- Taiwan's EV industry has been developing around the 80 Ampere charging standard, which is about 2.5 times faster than the international-standard 32 amperes. This faster charging standard could greatly reduce EV charging time and give Taiwan a leading role in the setting of EV-charging standards.

All these factors are expected to propel Taiwan to the forefront of the global EV industry.

**Central Taiwan**

The Taichung City Government was the first regional government in Taiwan to inaugurate an EV pilot-run program, aiming to promote low-carbon transportation, reduce vehicle emissions, and improve the air quality in central Taiwan. This project involved the use of 100 BEVs, mainly for administrative purposes. The city plans to set up 161 charging stations over the next few years, including 64 at the parking lots of government agencies using the vehicles and 97 at EV-only public parking spaces. Parking and charging will be totally free. The city government said that it will continue to subsidize EV purchases, aiming to have 50,000 EVs and 2,000 charging stations in operation by 2020.

Various government agencies are offering incentives to promote the intelligent-EV industry in Taiwan. The Ministry of Finance, for example, has instituted a three-year commodity-tax holiday for purchasers of battery electric vehicles, whether domestically made or imported; the Ministry of Transportation and Communications has worked out special license plates and safety regulations for EVs; the U.S. Environmental Protection Administration (EPA) has mapped out new $CO_2$ emission standards; and the Bureau of Energy under the Economics Ministry has announced more stringent fuel-efficiency rules for internal combustion engine vehicles and is encouraging regional and local governments to provide incentives (free parking, free charging) for EVs.

## *2.3 United States: The 'EV Project' and 'EV Everywhere'*

The EV Project [10] is the largest deployment of EVs and charge infrastructure in history.

On August 5, 2009, ECOtality was awarded a 90 Mio. EUR (99 Mio. USD) grant from the U.S. DoE to embark on this Project. The Project was officially launched on October 1, 2009.

In June 2010, the Project was granted an additional 16.8 Mio. EUR (15 Mio. USD) by the U.S. DoE. With partner matches, the total value of the Project is now approximately 258.6 Mio. EUR (230 Mio. USD).

ECOtality is deploying chargers in major cities and metropolitan areas across the United States. Chevrolet Volt and the Nissan LEAF are partners in The EV Project and drivers who qualify to participate receive a residential charger at no cost. In addition, a portion of the installation cost will be paid for by The EV Project.

The EV Project collects and analyses data to characterize vehicle use in diverse topographic and climatic conditions, evaluates the effectiveness of charge infrastructure, and conducts trials of various revenue systems for commercial and public charge infrastructures. The ultimate goal of The EV Project is to take the lessons learned from the deployment of the first thousands of EVs, and the charging infrastructure supporting them, to enable the streamlined deployment of the next generation of EVs to come.

The EV Project has qualified LEAF and Volt customers for participation based upon home electrical power capabilities. Because a significant amount of vehicle charging takes place at EV driver residences, a portion of The EV Project funding supports home charging units, or more correctly called EVSE. In exchange for allowing the collection of vehicle and charge information, participants receive a Blink wall mount charger at no cost, and in select locations, up to a 450 EUR (400 USD) credit toward the installation. This information includes data from both the vehicle and the EVSE, including energy used and time and duration of charger use. No personal information is being shared or included in the data to be analyzed.

Since the project started more than 71 million miles of data have been collected to date, more than 60 project partners are involved in 21 major cities and metropolitan areas in 9 states and the District of Columbia.

Infrastructure and Vehicle Deployment: 5,700 Nissan LEAF vehicles and 2,600 Chevrolet Volts included in EV Project; 8,300 residential AC level 2 EVSE for participating Nissan, LEAF and Chevrolet Volt customers, 6,350 AC Level 2 public-use EVSE, 125 additional AC Level 2 EVSE in ORNL Solar Project, 310 DC level 2 fast charger ports in cities and on interstate corridors [11].

**EV Everywhere (US)**

EV Everywhere, the latest in a series of Clean Energy Grand Challenges, set ambitious, far-reaching goals for the country. Announced by President Obama in March 2012, the initiative focuses on the U.S. becoming the first nation in the world to produce plug-in electric vehicles that are as affordable for the average American family as today's gasoline-powered vehicles within the next 10 years. The strategic investments to meet these goals will:

- **improve** the **competitive position** of U.S. industry and create jobs through American innovation,
- **enhance energy security** by reducing our dependence on foreign oil,
- **save money** by cutting fuel costs for American families and businesses and
- **protect the health and safety** by mitigating the impact of energy production and use on climate change.

*EV Everywhere* aims to enable American innovators to rapidly develop and commercialize the next generation of technologies to achieve the sufficient PEV cost, range, and charging infrastructure necessary for widespread deployment.

"The EV Everywhere Grand Challenge: Road to Success" report, captures the progress the Department and industry have already made from January 2013 to 2014. Over this period of time, the Department invested 200 Mio. EUR (225 Mio. USD) to address key barriers to widespread adoption of plug-in electric vehicles. The new report describes how the market had rapidly changed:

- DoE research and development reduced the volume production cost of electric drive vehicle batteries to 288 EUR/kWh (325 USD/kWh), about 50 % lower than in 2010,
- more than 50 leading employers joined the Workplace Charging Challenge and pledged to provide charging access at more than 150 sites and
- consumer acceptance rapidly grew 97,000 plug-in EVs were sold in 2013, nearly doubling 2012 sales [12].

## 2.4 European Union

**The European Union (EU) Roadmap for development**

A European Roadmap on the Electrification of Road Transport has been published by three European Technology Platforms. This roadmap, based on the consensus of major companies and organizations from ERTRAC, EPoSS and Smartgrids, is meant to stimulate the debate around the multi-annual implementation of the Green Cars Public Private Partnership. Starting from a general consideration of the potential benefits of the EV a definition of milestones for the next ten years is made that indicates what action ought to be taken in order to ensure the required efforts are made in a well-timed and balanced manner. The focus has been on: energy storage systems, drive train technologies, system integration, grid integration, safety, transport system integration.

To work on these fields, different Milestones have been defined (see Fig. 5); Milestone 1: Introduction (2012); Milestone 2: Intermediate (2015); Milestone 3: Mass Production (2020); Milestone 4: Fully Revised Electric vehicle Concept (2025) [13].

In October 2013 the European Commission established the European Green Vehicles Initiative (EGVI) which is a contractual public-private partnership dedicated to delivering green vehicles and mobility system solutions. It is a continuation of the European Green Cars Initiative which ran from 2009–2013. At the same time the EGVI published the Multiannual Roadmap, which is the reference document for the implementation of the partnership. It takes into account the roadmaps from the three European Technology Platforms involved—ERTRAC, EPoSS, and SmartGrids—and outlines the vision, research and development strategy, and the expected impact and governance model of the EGVI.

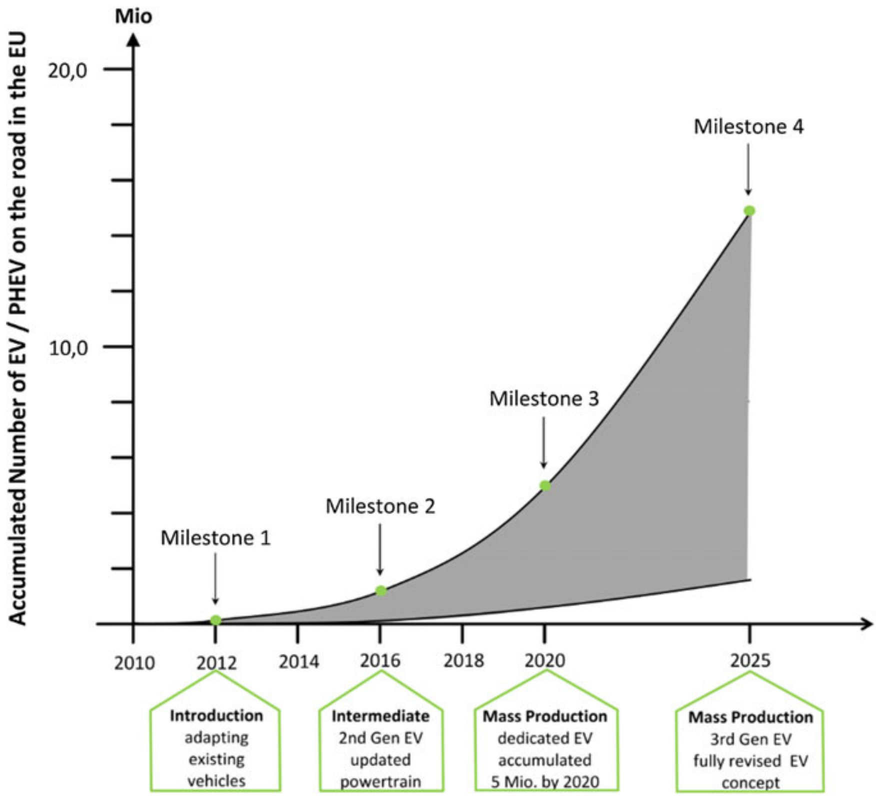


**Fig. 5** European roadmap on the road transport electrification [14]

ERTRAC (the European Road Transport Research Advisory Council), has recently revised its Strategic Research Agenda, setting an objective of an overall efficiency improvement of the transport system by 50 % in 2030 compared to 2010. This will be achieved through research, development and innovation in four key areas; vehicles, infrastructure, logistical and mobility services, and energy and resources.

EPoSS (the European Technology Platform on Smart Systems Integration), is focused on smart systems; defined as intelligent, often miniaturized, technical subsystems with their own and independent functionality evolving from microsystems technology. Research and development in electric vehicles will focus on functionalities provided by smart systems such as: management of energy storage systems, intelligent power electronics, active control of motors and wheels, functional safety of chassis and powertrain systems, smart integration of Range Extenders, and advanced vehicle to grid connection systems.

SmartGrids (the European Technology Platform for the Electricity Networks of the Future), focuses on research topics and priorities necessary for the advancement of the electricity networks and intelligent electric systems.

The EVGI PPP's aim is to contribute to the objectives of major EU policies by delivering innovative technologies which will help to reach the EU's target of reducing $CO_2$ emissions in transport by 60 % by 2050. It also includes milestones for vehicle deployment along its roadmaps, such as an accumulated 5 million EVs and PHEVs on European roads by 2020.

**Green eMotion**

The aim of this project is to develop and to demonstrate a commonly accepted and user-friendly framework consisting of interoperable and scalable technical solutions in connection with a sustainable business platform. 43 partners from industry, the energy sector, EVs manufacturers, municipalities as well as universities and research institutions participate in this project [15].

Smart Grid developments, innovative ICT solutions, different types of EVs as well as urban mobility concepts will be taken into account for the implementation of this framework.

*The four year project started in March 2011*. It has a total budget of 42 Mio. EUR (47 Mio. USD) and will be funded by the European Commission with 24 Mio. EUR (27 Mio USD).

Within this project different ongoing regional and national e-mobility initiatives will be connected leveraging on the results and comparing the different technology approaches to ensure the best solutions prevail for the European market. A virtual marketplace will be created to enable the different actors to interact and to allow for new high-value transportation services as well as EV-user convenience in billing (EU Clearing House).

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# Advanced Vehicle Performance Assessment

**Michael Duoba and Henning Lohse-Busch**

**Abstract** In order to provide answers about the performance of vehicles driven by electrified drivetrains, appropriate test procedures must be developed that are robust and compatible with the technology. In IEA-HEV-Task 17, these results are presented from vehicles tested at the Argonne National Laboratory Advanced Powertrain Research Facility under direction from the U.S. Department of Energy's Vehicle Technologies research portfolio. Chassis dynamometer testing with controlled conditions was employed and included adoption of sophisticated instrumentation, research techniques and considerable staff expertise in testing advanced automotive vehicle technologies. This process was going on for several years, including BEV and PHEV tests with a Nissan Leaf, a PHEV-converted Prius as well as a Chevy Volt (based on the reporting year 2010). This chapter provides comparisons between the different electrified vehicles in terms of their principal configurations and operating modes, charge-sustaining and electric-only and highlights the major findings.

The focus of this section is to provide a review of current state-of-the-art production vehicles (reporting year 2010) with advanced electrified powertrains. The technologies covered are the HEV, PHEV, and the BEV. Vehicles were production versions instrumented with various degrees of signals (some invasive, others minimally invasive) and tested on a chassis dynamometer according to accepted practice and research-oriented procedures to highlight technology capabilities.

Results are presented from vehicles tested at the Argonne National Laboratory Advanced Powertrain Research Facility (Fig. 1), under direction from the U.S. Department of Energy's Vehicle Technologies research portfolio. Chassis

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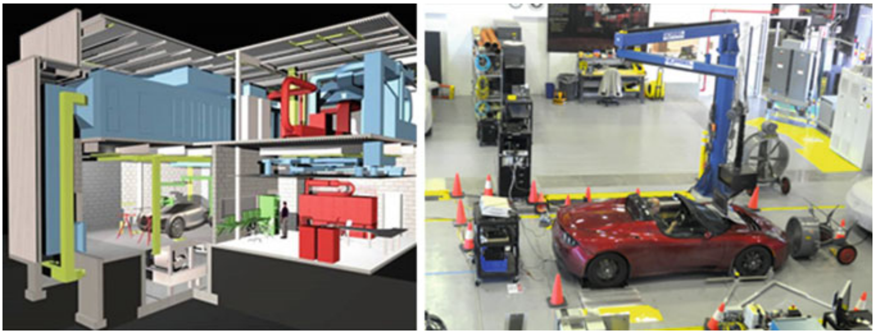

**Fig. 1** Advanced powertrain research facility

dynamometer testing with controlled conditions was employed and included adoption of sophisticated instrumentation, research techniques, and considerable staff expertise in testing advanced automotive vehicle technologies.

ANL, a science and engineering research national laboratory, has five main areas of focus. These goals, as stated by the U.S. DoE in 2008, consist of: conducting basic scientific research; operating national scientific facilities; enhancing the nation's energy resources; developing better ways to manage environmental problems and protecting national security.

## 1 Vehicle Technology Introduction

Five vehicles are highlighted, and the research data and analysis are provided. The highlighted vehicles included Toyota's third-generation (G3) Prius HEV, the Hyundai Sonata HEV, the Ford Fusion HEV, the Chevrolet Volt PHEV, and the Nissan Leaf BEV. More details are shown in Table 1.

Key data of these vehicles are shown in Sect. 2.4 (Current status of low-carbon vehicle technologies (2013–2015)).

### *1.1 Toyota G3 Prius HEV*

The Prius is a "power-split" hybrid configuration that couples the engine through a power-split transmission with two motors (sometimes called an "electric continuously variable transmission") that keeps the engine always running at the best load points for all driving conditions. The power-split also allow seamless start-stop and electric traction assist without state changes or weak operation zones that could be detrimental to drive quality (such as torque delays or abrupt torque interruptions from shifting gears or states).

**Table 1** Vehicle specifications

| |  |  |  |  |  |
|---|---|---|---|---|---|
| Model | Toyota Prius | Hyundai Sonata | Ford Fusion | Chevy Volt | Nissan Leaf |
| HEV/PHEV/BEV | HEV | HEV | HEV | PHEV | BEV |
| Model year | 2010 | 2011 | 2010 | 2012 | 2012 |
| Curb weight (kg) (lb) | 1380 | 1600 | 1690 | 1720 | 1520 |
| | 3040 | 3460 | 3720 | 3780 | 3350 |
| Passenger/cargo volume (cu. ft.) | 94/22 | 104/11 | 100/12 | (N/a)/11 | 98/15 |
| Powertrain configuration | Power-split | P2 with BAS | Power-split | Multi-mode w/power-split | Single gear |
| Rechargeable kWh[a] | N/a | N/a | N/a | 10.3 | 21.2 |
| Max motor/battery kW[a] | 26 | 35–40 | 25 | 111 | 90 |

[a]Derived from dynamometer testing

As a result of years of continuous refinement of its dedicated hybrid platform, the Prius is the benchmark for HEVs efficiency since its introduction at the turn of this century. The third generation of the Toyota Prius features an impressive achievement of 50 Miles per Gallon (MPG) combined city and highway on its U.S. EPA fuel economy label (92 $gCO_2$/km in the new European cycle NEFZ). For the third generation (starting in model year 2010), many systems were refined for lower powertrain losses, and some additional features were added to reduce losses encountered in hot and cold temperatures. More details of these are presented in the following chapters of this report.

## *1.2 Hyundai Sonata HEV*

Whereas many of the full HEVs produced in the past 10 years used the power-split powertrain configuration, the Hyundai Sonata hybrid (starting in model year 2011) is a full hybrid with the "P2" architecture, with an added belt-alternator-starter (BAS) motor. There are many opportunities for cost savings with the "P2" hybrid because the drive motor(s) are smaller and the transmission is similar to existing supply lines. The focus of the analysis will be to compare the hybrid Sonata's performance and efficiency with that of a similar sized, power-split full hybrid (Ford Fusion hybrid).

### *1.3 Ford Fusion HEV*

The Ford Fusion hybrid is a good example of a power-split mid-sized HEV that can be compared to the Hyundai Sonata hybrid to highlight the strengths and differences between the two fundamental design approaches. Data were taken from a model year 2010 vehicle. The efficiency in transient stop-and-go driving is exceptional—of the power-split hybrids available at the time of this report, the Fusion hybrid allows the highest electric-only driving speeds.

### *1.4 Chevy Volt PHEV*

The Chevy Volt is an important example of PHEV technology. Labeled as an E-REV by the manufacturer (GM), the vehicle still matches the definition of a PHEV and is tested according to the same procedures as any other PHEV. The novel power-split architecture allows for driving in various modes. Having two fundamental modes, this vehicle can be compared to the Prius in sustaining mode and to a BEV (Nissan Leaf) in depleting (electric) mode.

### *1.5 Nissan Leaf BEV*

The Nissan Leaf is a good example of a dedicated EV in a similar compact class as the Volt and Prius. (Although the EPA classifies the Prius and Leaf in the same class as the Sonata and the Fusion, the Leaf, Prius, and Volt are more similarly sized.) The Leaf has all the functionality of a typical sedan but is solely powered by the Li-ion battery pack. As expected, the powertrain is fairly simple and will be an excellent vehicle for evaluating electric driving.

## 2 HEV Results (Sonata, Fusion, and Prius, CS Mode Volt)

This section highlights the system-level configuration differences among the hybrids (Sonata, Fusion, and Prius) and the charge-sustaining operation of the Volt.

## 2.1 Introduction to Configurations

There are many ways to couple an engine to one or more e-motors and a set of gears and/or clutches to provide the desired torque and speed at the wheel for driving. The engineering challenge is to use the engine, motor(s), and battery most efficiently. Engine speeds are typically from 600 to 6000 RPM (note that engines to not operate below idle speed). Motor speeds typically spin much faster than engines and can provide positive or negative torque while spinning from −14,000 to 14,000 RPM. A transmission with discrete gear sets can provide a number of ratios to choose from, and one with planetary gears can be used in combination with other planetary gear sets to provide several discrete gear ratios or configured as a power-split device, where the input or output torque is split and the engine speed and speed of the motors are interrelated but with constantly varying ratios. Typically all powertrains have some final drive (FD) gear reduction in order to lower these speeds down to wheel speeds (with high torque).

Figure 2 depicts several simple hybrid powertrain configuration diagrams. The designation "P1" describes the position of the main traction motor. P1 hybrids do not have electric-only propulsion capabilities because of the inability to clutch out the engine. The motor in a P2 configuration can drive the vehicle with the engine

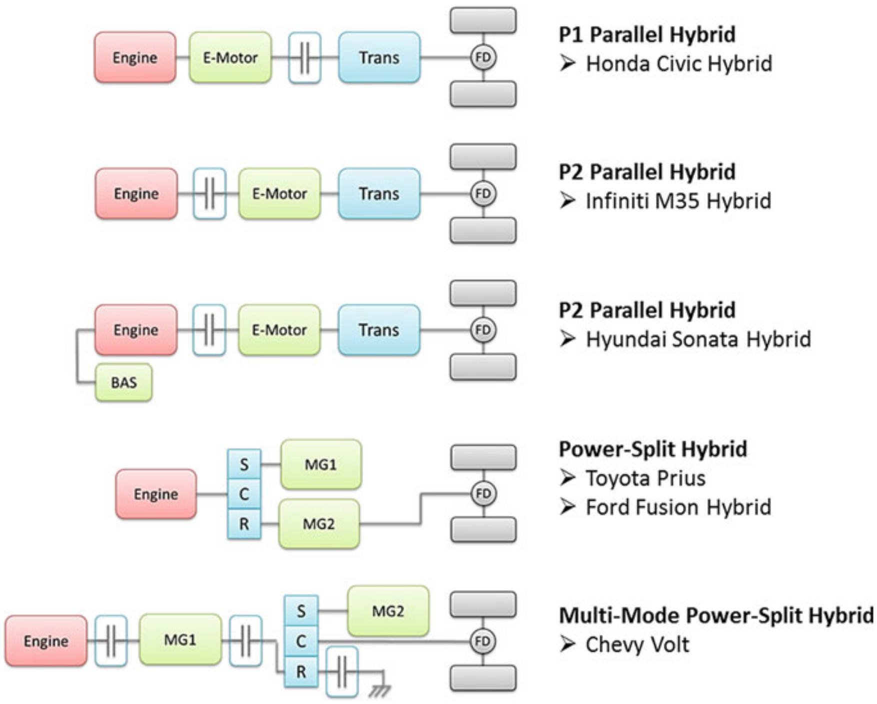


**Fig. 2** Overview about Hybrid powertrain configurations

stopped; however, the torque to start the engine must come from the motor and/or by reflecting vehicle inertia back to the engine (and, as a result, cause interruptions in torque to the wheel). By adding a BAS, the engine can be started while disconnected to the transmission. Also, adding a BAS allows the engine to run in a series mode, which provides more efficient low-speed cruising and better management of battery energy levels. The conventional power-split uses a single planetary gear with two motor-generators to allow infinite driving ratios for all driving conditions and engine start-stop capability. However, once again, the engine torque is always in communication with the wheel, and so engine start-stop must be accomplished with torque pulsation countermeasures to ensure acceptable drivability. Another limitation unique to the simple power-split configuration is that electric-only driving can be limited. Components may over-speed when the engine is at zero speed and the vehicle is at high speed. To remedy this limitation, the engine must run above a set vehicle speed and under coast, or, during braking, the engine must remain spinning (but without combustion) until the vehicle speed is below a safe set point.

### *2.2 Fuel Economy Results*

One of the first observations distinguishing the capabilities of the various HEV powertrain configurations is their variations in fuel economy performance, depending upon type of driving. Using the US EPA's adjusted label results to better indicate real-world performance, both the urban and highway MPG results are shown in Fig. 3 for the vehicles highlighted in this report. Typical conventional vehicles achieve higher MPG in the highway rating (in the range of 1.3–1.5 times higher) than the urban rating. The Sonata hybrid with its fixed gear transmission also follows the same trend as conventional vehicles (higher highway MPG) but to a lesser degree (1.14 times). In contrast, the Prius and Fusion power-split hybrids have the opposite relationship. The highway MPG of the Prius is 0.94 times the urban MPG, and the highway MPG of the Fusion is only 0.88 times the urban MPG.

### *2.3 Engine on-off Capability*

Many factors contribute to the ratio of highway-to-urban MPG. For full hybrids, one important feature is the engine can be left off for low-power driving, thereby increasing average engine efficiency when the engine is on. For deceleration and some cruise periods, the engine can remain off until higher demands better suited for high efficiency are needed in the cycle. In Fig. 4, an excerpt of the Urban Dynamometer Driving Schedule (UDDS) cycle is shown for the Prius and Sonata hybrid. Similar engine operation is seen in the stop-and-go driving, mostly under 65 km/h (40 mi/h).

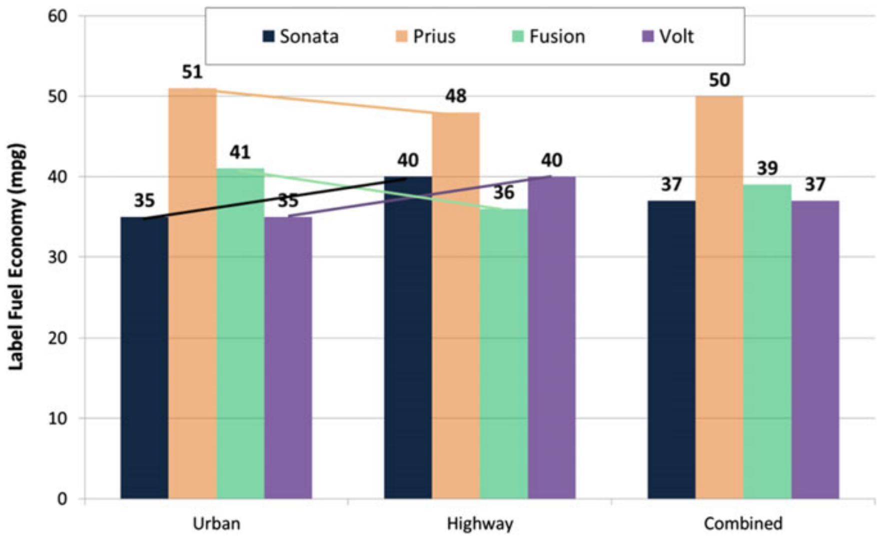


**Fig. 3** Comparison of urban and highway MPG ratings

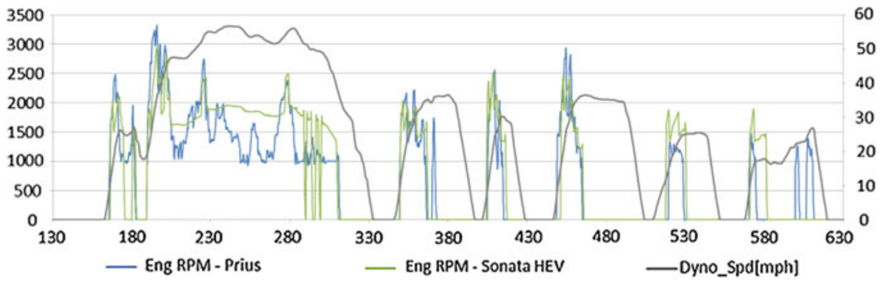


**Fig. 4** Prius and Sonata HEV engine operation comparison (RPM by time (s))

In contrast, however, are the particular hybrid's design capabilities to keep the engine off at higher vehicle speeds. The Sonata configuration does have a benefit of shutting down the engine at virtually any vehicle speed. Thus, during low power periods in the highway cycle, the Sonata does have an efficiency advantage. The Fusion and Prius power-split configurations must keep the engine spinning if the vehicle speed is above 55–65 km/h (35–40 mi/h). This is seen in Fig. 5, which compares the Fusion engine speed to the Sonata's. Notice there are several blocks of time in which the Sonata engine is not being used and is not spinning.

A bar graph indicating the relative percentage of time the engine is off during the urban and highway cycles is shown in Fig. 6. The percentages from hybrid to hybrid for the city cycles are not very different (roughly 60–65 %). However, the

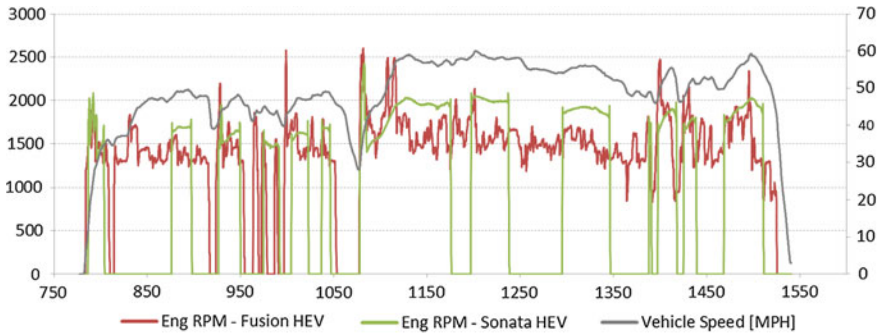


**Fig. 5** Fusion HEV engine speed comparison—note engine-off at high vehicle speed

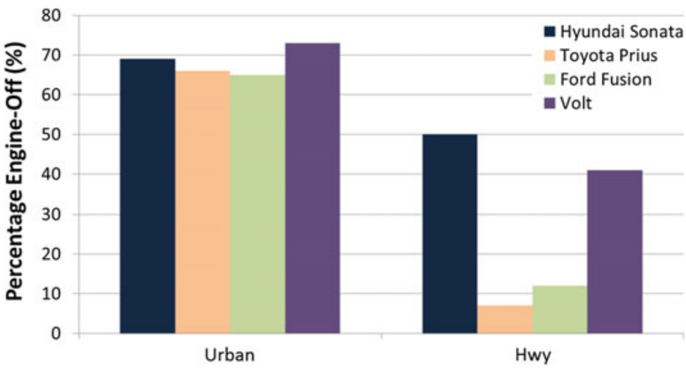


**Fig. 6** Engine-off time comparisons

Sonata is able to keep the engine off for 50 % of the highway cycle compared to only 5–12 % for the other remaining hybrids, with the exception of the Volt.

In the urban cycle, the Volt powertrain mostly runs in series-hybrid mode. The engine comes on to charge the battery and meet road demand. However, in contrast to the Prius, which will start the engine for every "hill" in the UDDS, the Volt only starts 9 out of the 18 hills in the cycle. This strategy can be seen in Fig. 7, which shows a plot of the Volt's engine speed—note that the engine comes on less frequently and, in some places, remains on during deceleration. The engine does not, however, stay on below ~30 km/h (20 mi/h) (perhaps GM engineers wanted to reduce driving noise at speeds below ~30 km/h (20 mi/h)) else this is a matter of driving noise acceptance).

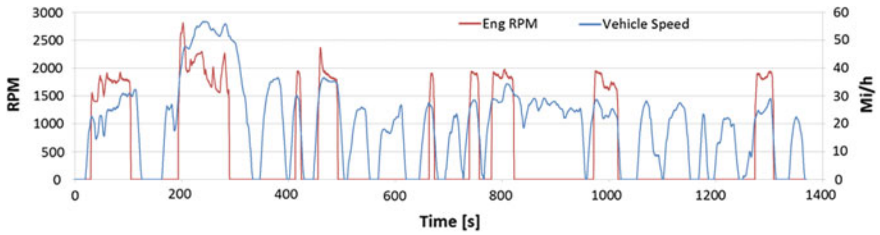


**Fig. 7** Volt engine operation—UDDS

## 2.4 Engine Utilization

Another factor affecting efficient operation is the engine operating points. The plots in Fig. 8 are histograms of engine speed for the Prius, Fusion, Sonata, and Volt in hybrid mode. The Prius engine is optimized for low-RPM efficiency, and so it has the most RPM counts in the 1000–1250 RPM range. The Fusion has the most RMP counts in the 1250–1500 RPM range, which is a much higher range than all the other bins. The Sonata is less capable of running at fixed RPM, and so there is some spread in RPM range. The highest bins are 1500–1750 RPM in the urban cycle and 1750–2000 RPM in the highway cycle. The Volt has a high peak at 1750–2000 RPM and lower peaks on the highway cycle.

## 2.5 Regen

During stop-and-go driving, a vehicle has a good opportunity to recapture kinetic energy through the electric drive system (termed “regenerative braking” or “regen”). Revisiting the earlier point of hybrid urban/highway fuel economy ratio, the effect of recapturing kinetic energy during the cycle is significant. More specifically, as the vehicle captures more energy during braking, it can achieve increasingly higher overall efficiency. One interesting observation about the vehicles discussed in this section is the Volt has a much higher motor and battery capability. Thus, there is a higher potential to capture more regen in the Volt.

Looking at the regen in the aggressive US06 drive cycle for both the Fusion and the Volt, the differences are evident. The total road load power is plotted with the battery power in both Figs. 9 and 10). In the Fusion, road power peaks near 40 kW, but regen levels peak at ~22 kW. With a similar road power (same 1800 kg (4000 lb) test weight), the Volt leaves less regen power untapped by peaking its regen power at ~30 kW.

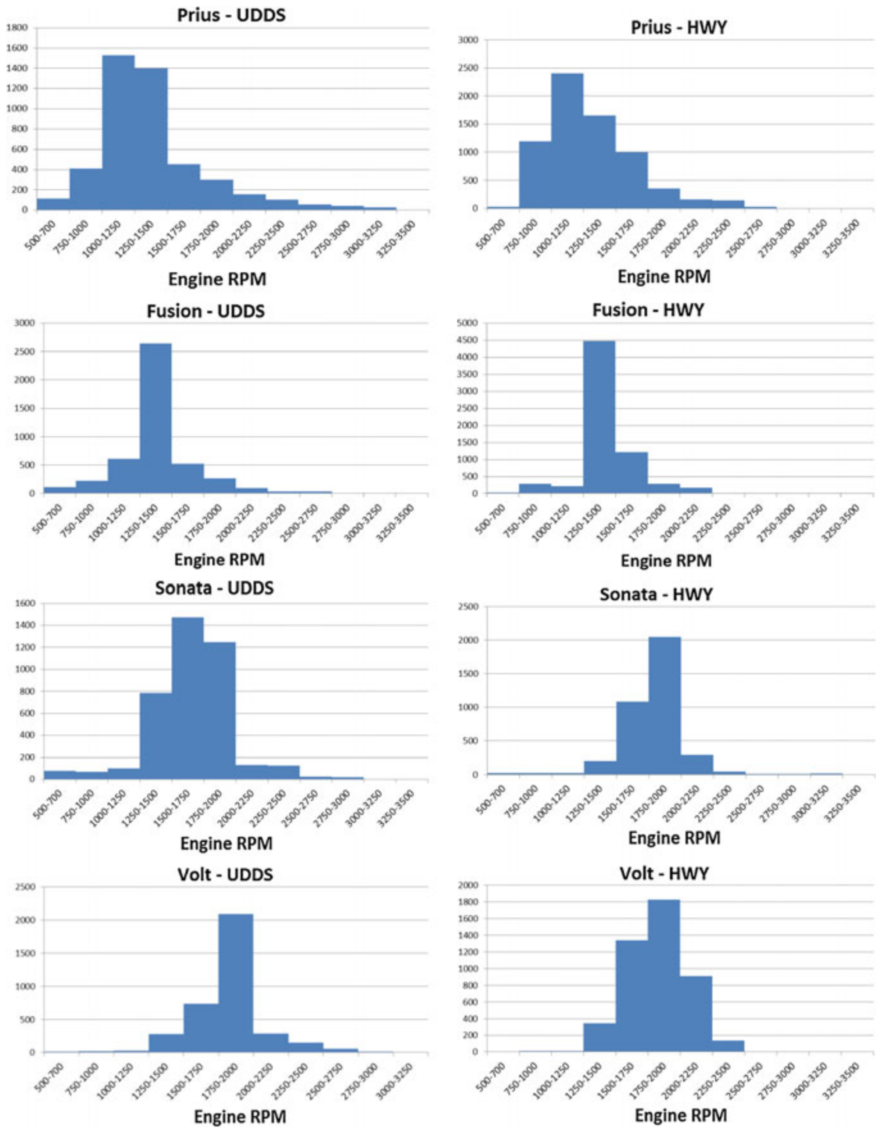


**Fig. 8** Engine RPM histograms for Prius, Fusion, Sonata, Volt Hybrids

## *2.6 Improving Efficiency with Improved Thermal Management*

As U.S. fuel economy ratings have switched to include hot and cold test temperatures, the opportunity for more fuel savings in efficient A/C designs and quicker

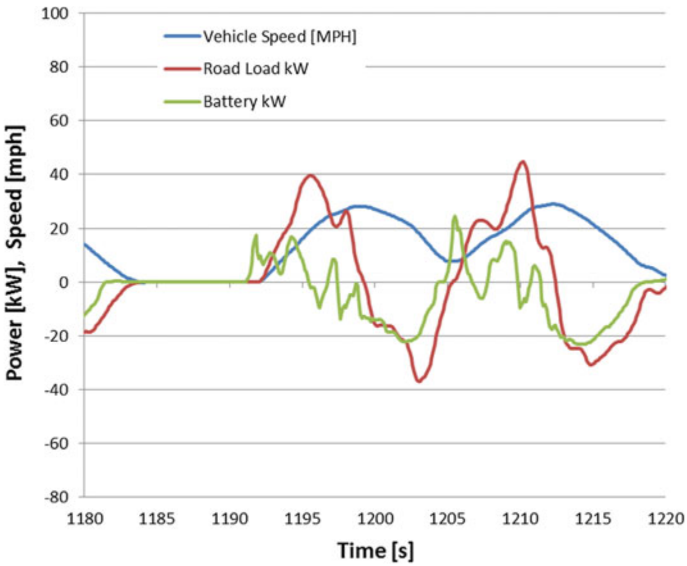


**Fig. 9** Fusion battery power

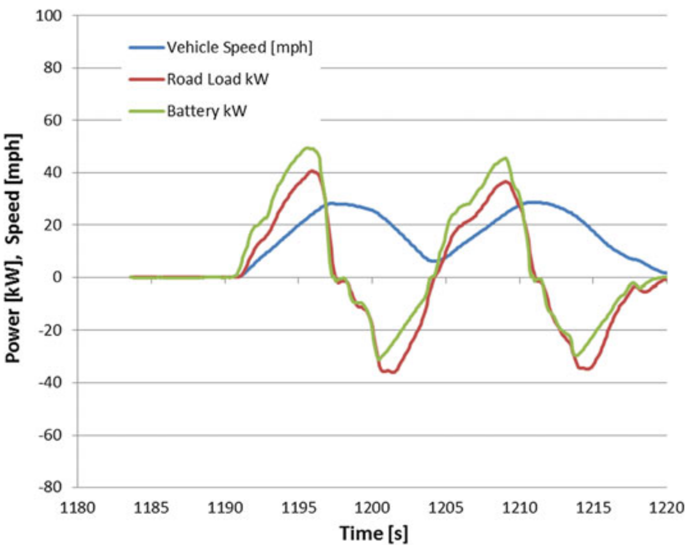


**Fig. 10** Volt battery power

warm-up have prompted manufacturers to add new hardware and controls. The Prius has a special coolant circuit that warms engine coolant with exhaust heat during warm-up. The Prius also has an advanced A/C design that Toyota claims will reduce compressor power consumption by 11–24 % [1].

The Sonata has a transmission oil heat exchanger to take heat from the coolant and warm up the transmission oil. Testing the effects of these particular features is challenging because differences between cold and warm operation are obfuscated by many differences in operation and battery utilization during initial start-up. Testing is ongoing and is expected to help overcome some of the current challenges.

## 3 Electric Vehicle Operation Comparison (Chevy Volt in EV Mode and Nissan Leaf BEV)

### *3.1 Configuration Comparison*

Electric drive powertrains may be the simplest with regard to propulsion component configuration. An e-motor typically has a wide speed range and does not require a launching mechanism (an engine cannot launch a vehicle from stop with fixed gearing without a component or feature that can provide torque at the wheel at zero speed). The Nissan Leaf has a single motor with a single fixed gear. By contrast, the Volt has two e-motors and two electric-only drive modes that can be controlled to provide the best torque or power capabilities at the highest efficiency.

### *3.2 Operational Differences*

The first Volt mode is a one-motor mode. The second mode shares the load between two motors. The Volt uses primarily the first mode, but for part of the time, it uses the second, two-motor mode at speeds above 70 km/h (45 mi/h). However, there are times when the second mode is used at lower speeds. Figure 11 is a plot of vehicle tractive load versus vehicle speed; operation of the second mode is shown in red. Cruise loads at and around highway speeds show use of the two-motor mode and during some accelerations through 15–45 km/h (10–30 mi/h).

### *3.3 Battery Utilization and Recharge Efficiencies*

Taking a well-defined look at various points on the entire energy pathway of a plug-in vehicle helps bring focus with respect to defining efficiencies. "Charger Efficiency" may actually mean several things to various researchers. Figures 12 and 13 show the measured electrical energy flows schematically. The test measurement arrangement for both the Volt and the Leaf did not include a measurement point between the Electric Vehicle Supply Equipment (EVSE) and charger—therefore,

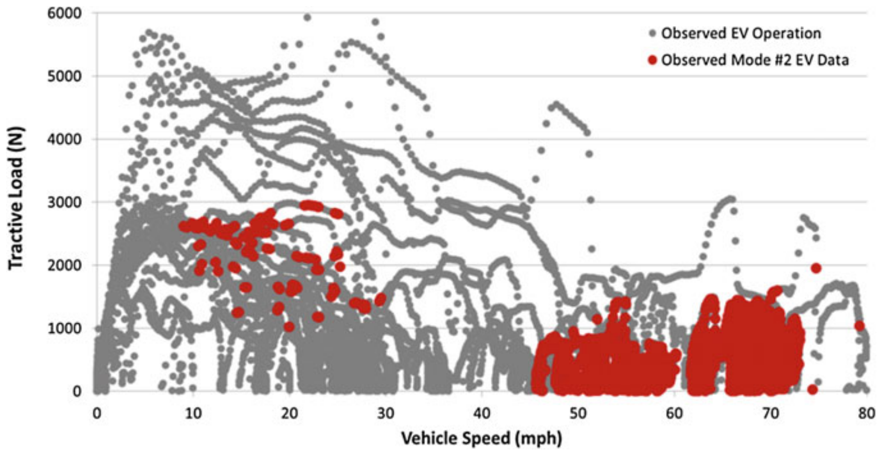


**Fig. 11** Volt operation in "Mode 2" electric-only mode

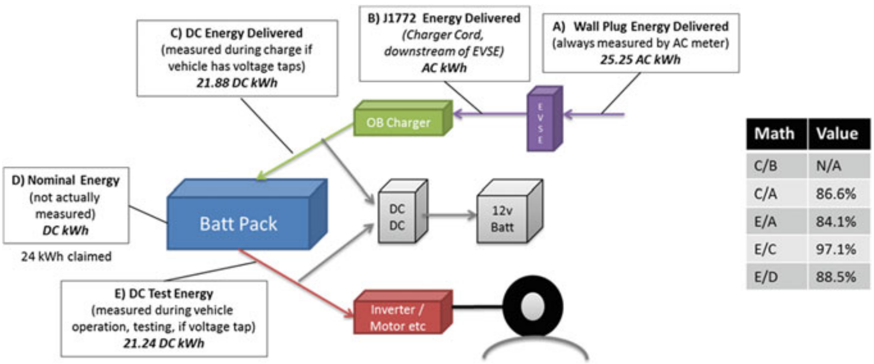


**Fig. 12** Quantifying discharge energy, recharge energy, and efficiency—Leaf

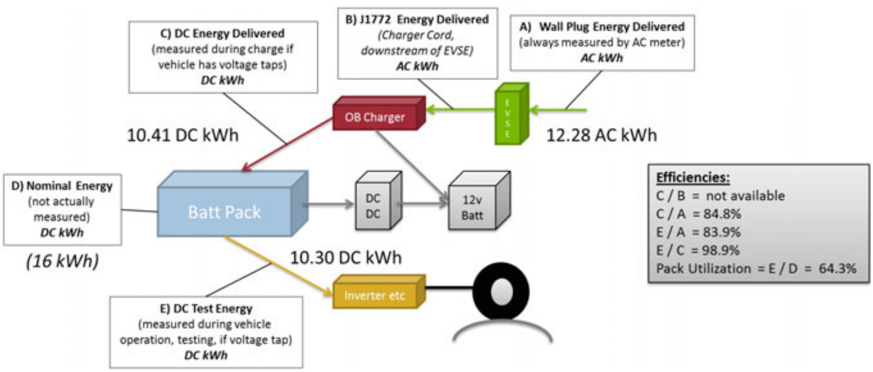


**Fig. 13** Quantifying discharge energy, recharge energy, and efficiency—Volt

**Table 2** Dynamometer settings, energy consumption and cycle energy for Volt and Leaf

| Specification | Volt | Leaf |
|---|---|---|
| Test weight | 4000 | 3750 |
| A (lbf) | 28.66 | 33.78 |
| B (lbf/MPH) | −0.0132 | 0.0618 |
| C (lbs/MPH$^2$) | 0.0202 | 0.0228 |
| | Volt (Wh/mi) | Leaf (WH/mi) |
| UDDS | 211.65 | 199.40 |
| HWY | 223.72 | 231.90 |

only data on AC energy into and DC energy into the pack were available. Note that the efficiency calculation from point A to C includes losses in the EVSE and standby losses of the vehicle during recharge. Sometimes, researchers need to relate the DC watt-hours consumed during driving to the AC watt-hours supplied by the electric grid. This analysis requires the use of the ratio of E to A (not to be mistaken with C to A).

The Leaf and Volt have similar efficiencies at their respective measurement locations. Note to maximize range, the Leaf uses over 88 % of its nominal capacity. However, because a PHEV retains some battery energy for charge-sustaining operation, in terms of pack utilization (the calculation of E/D), the total used energy in the Volt's battery pack is lower than the Leaf's.

## *3.4 Electric Powertrain Efficiency Comparisons*

Table 2 lists the test weight and "target" road load settings for the Leaf and Volt with the UDDS and HWY DC Wh/mi. The data show that the Leaf consumes less DC battery energy per mile on the UDDS than the Volt, but the opposite is the case for the HWY cycle.

There are two competing forces that determine EV watt-hour consumption rate. One is the differences in forces (and energy) required to drive the cycle, and the other is the efficiency at which the drive system can provide propulsion (and recuperate energy during regenerative braking). The Leaf has the advantage of being lighter (and thus less energy is needed to drive stop-and-go), but the Volt has the advantage of having lower driving losses at all speeds (all three terms are lower in the Volt). Closer examination of the consumption rates will require an examination of efficiency.

In Table 3, the tractive energy to drive the vehicles on both cycles is shown. These energies are measured at the chassis dynamometer surface, which is downstream of losses incurred in the driven tire. They are broken out by direction—"Pos Wh" is the integrated positive force at the dynamometer (mostly during acceleration), and "Neg Wh" is the integrated negative force (mostly during braking). All the battery energy going into and out of the battery is tracked during the time steps

**Table 3** Energy consumption and cycle energy for Volt and Leaf

| | Dynamometer | | Battery | | Efficiency | |
|---|---|---|---|---|---|---|
| | Pos Wh | Neg Wh | Wh-Traction | Wh-Braking | Traction (%) | Braking (%) |
| Leaf UDDS | 190.7 | −102.2 | 259.6 | −65.8 | 73.5 | 64.4 |
| Volt UDDS | 180.2 | −113.5 | 280.5 | −67.0 | 64.2 | 59.0 |
| Leaf HWY | 173.1 | −22.8 | 247.0 | −14.1 | 70.1 | 61.8 |
| Volt HWY | 143.3 | −28.4 | 244.1 | −14.9 | 58.7 | 52.5 |

of positive and negative forces. They are also listed in Table 3. Although the total tractive energy required to drive the Leaf on the UDDS is higher, the amount of energy consumed is lower. The Leaf is more efficient at using DC energy to propel the vehicle through the UDDS cycle. However, the Volt's advantage in lower propulsion energy to drive the HWY cycle is more pronounced. This is consistent with the fact that the Volt dynamometer road coefficients are lower, and these forces dominate in the HWY cycle. The positive and negative conversion efficiencies (DC energy to drive energy) of the Leaf and Volt are also shown in Table 3.

## 4 Auxiliary Loads HEV, PHEV, and BEV

### *4.1 Standby Auxiliary Losses*

All of the vehicles discussed in this report take all power for operating low-voltage electronic hardware from the high voltage bus. The amount of standby power can have a significant impact on overall efficiency, especially for cycles with a low average speed. This load includes fans, pumps, actuators, lights, and computers. By looking at the output power flowing out of the main DC bus during a stop near the end of the UDDS cycle, the standby loads can be quantified. The standby losses for several test vehicles are shown in Fig. 14.

Earlier generations of the Prius had multiple management computers in different locations running the powertrains many subsystems. They have since mostly been consolidated, and this could be one of the reasons for the much lower standby power. Compared to the HEVs or Volt PHEV, BEVs do not have as many subsystems to monitor and be powered during standby and therefore could be the reasons for the low losses seen in the Leaf.

### *4.2 Hot and Cold Temperatures*

There are standard temperature conditions for most dynamometer testing. However of great interest in advanced technology vehicle are the effects of hot and cold

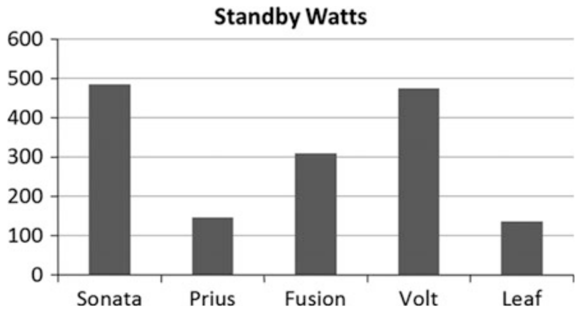


**Fig. 14** Standby electrical loads

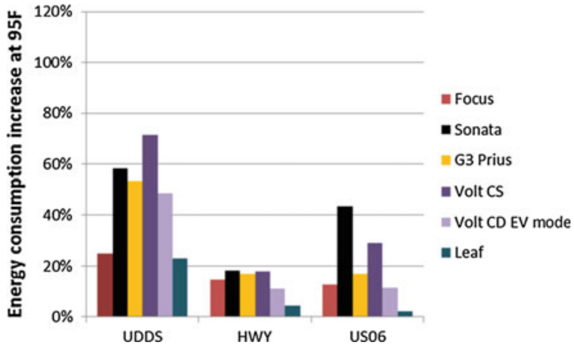


**Fig. 15** Hot temperature consumption penalties for various vehicles

temperatures on the efficiency of various types of vehicle technologies. A number of vehicles were testing hot at 35 °C (95 °F) with a solar load of 850 W/m$^2$ and the vehicle air conditioner in operation and again cold at −7 °C (19 °F) with the vehicle heater in operation. The various consumption penalties are compared in Figs. 15 and 16. Added to the vehicles in this study as a baseline was a conventional model-year 2004 Focus.

The hot temperature penalty does not include the initial temperature cabin temperature pull-down. Most drivers are aware of the penalty in fuel consumption associated with operating air conditioning in a conventional vehicle—especially for stop-and-go driving. But the penalties are much more profound for most of the vehicles studied in the report. The Prius and Volt have consumption penalties of over 50 %.

During cold testing, two UDDS cycles are run, the first initiated after an overnight rest at cold conditions and the second initiated 10 min after the first; results from both are presented in Fig. 16. Of profound significance is the fact that, in the Ford Focus, the additional losses from running at cold temperatures (with the heater) have a relatively low impact on fuel consumption; however, the other vehicles suffer very high penalties under the same operating conditions. HEVs are not able to fully utilize the hybrid function until the cabin and, to some extent, the battery are at operating temperature. Notice the consumption penalties are lower in the second UDDS cycle (after warm-up). The penalties are higher for the Leaf and

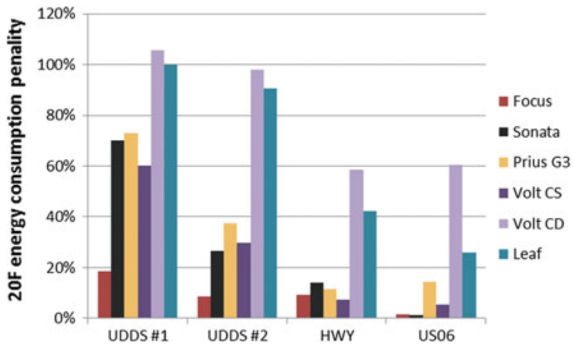


**Fig. 16** Cold temperature consumption penalties for various vehicles

the Volt running electric-only because the heat comes from the battery, not from engine waste heat. As cycle speeds increase, cabin heat power becomes less significant to total energy use and so the penalties are lower. However, the Volt in electric only (Charge Depleting (CD)) and the Leaf have high consumption penalties for all the cycles run. These data suggest that BEV manufacturers should consider equipping vehicles destined for climates with cold winters with alternative technology (e.g., a fuel-fired heater) to avoid an infrequent but likely situation in which a vehicle is stranded without power or heat in a snowstorm. The range of a BEV range could drop by one-half that expected for typical driving if there is an extreme traffic jam during inclement winter weather.

## 5 Conclusions

This report shows various examples of state-of-the art HEVs, PHEVs, and BEVs. Comparisons are drawn between vehicles in terms of their principal operating modes: charge-sustaining (HEVs Sonata, Fusion, and Prius) and electric-only (PHEV Volt and BEV Leaf). The Sonata and Fusion are of similar size, which enables direct comparisons of fuel efficiency. The Leaf, Prius, and Volt are also of similar size for cross comparisons. The Fusion and Prius have essentially the same basic configuration but control approaches that are perhaps unique to each car company. The Volt has a multi-mode configuration transmission with two electric-only modes: a series mode and a power-split mode.

Comparing the design approach used for the Sonata with that used for established hybrids is useful. It is a "full hybrid," and thus from a basic level, the Sonata has all the features of the other hybrids discussed in this report, but it has a "P2" based architecture that reduces the motor size and uses more off-the-shelf automotive components. These features have the potential to reduce vehicle costs and cut initial investment for production. Test data reveal that there are advantages in highway driving with a more direct torque path of the engine and the opportunity to shut down the engine regardless of vehicle speed to save fuel. However, the Sonata step transmission does not have the flexibility of the power-split to optimize engine operation at all times in city driving.

The Volt has a more complex configuration for electric driving than the Leaf fixed gear transmission; however, the efficiency data do not show efficiency advantages over the Leaf. The Leaf has higher efficiencies in terms of DC energy to the propulsion system and loads measured at the dynamometer. Compared to the Leaf, the Volt is heavier and consumes more DC energy driving on the UDDS cycle but because of its lower driving losses, the Volt uses less DC energy driving the HWY cycle. The Volt and leaf have similar conversion efficiencies from the AC wall plug to the battery and out of the battery.

Standby losses were highly varied among the vehicles discussed in this report. The Volt and Sonata losses were similarly three times higher than those of the Prius, with the Volt falling in between.

Highly efficient vehicles can offer very high fuel efficiency, but these benefits rapidly deteriorate in hot and cold conditions. Running the heater off battery energy in electric-only mode of either a PHEV or BEV can double the consumption rate (reducing the range to one-half).

# 6 Future Trends

The degrees of freedom in powertrain design expand exponentially with modern hybrid technology. Integrating motors into transmission systems offers additional design and control levers for automotive designers in the now competitive market for advanced efficient mobility. On the basis of understanding the current vehicles and taking notice of announcements of soon-to-be released vehicles, some trends in the state of the technology can be speculated.

During a Task 17 workshop in Chicago (2013), Valeo presented their forecast for the progress of different drive train solutions (as it can be seen in Fig. 17). Figure 17 shows the expected dominance of mild and full hybrid vehicles in the year 2022. It can be seen, that the ICE will still dominate in the future but the amount of alternative propulsion systems (xEVs) is supposed to strongly increasing, starting from 2020.

## *6.1 Future HEVs*

Toyota engineers have been optimizing their "synergy drive" hybrid powertrain for nearly two decades. From a broad view, little has changed since 1997; however, each motor, gear, subsystem, and electronic system has been refined for maximum efficiency in the last generations. Any shortcomings were identified and addressed with either redesigned or substituted hardware. Inefficiencies found specifically in high-speed driving and from low temperatures were addressed in the 3rd generation

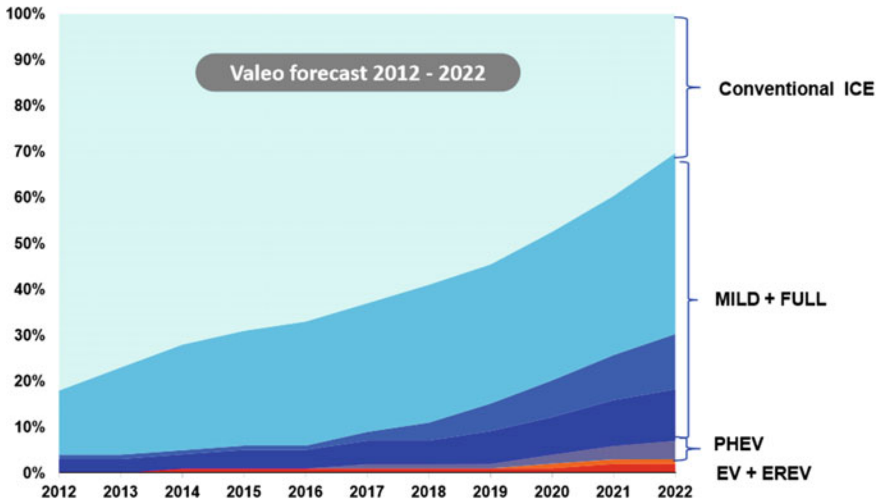


**Fig. 17** Forecast for the progress of different drive train concepts [2]

Prius. Ford has also improved on early hybrid offerings, and its vehicles demonstrate high urban-cycle efficiencies. Ford announcements of next-generation Fusion and C-Max hybrids are on par or perhaps slightly better than the Toyota's in terms of powertrain efficiencies.

More P2 hybrids are becoming available, mostly from European manufacturers, like Audi, BMW, Porsche, VW and Citroen. European OEMs are invested in sequential manual and dual clutch transmissions, and it makes sense that they take this direction for their hybrid designs. Drivability and urban driving fuel economy will be challenges that will be addressed in future revisions. In the United States, planetary gear automatics are still the primary transmission choice, and this type of transmission shares many of the parts and designs of the transmissions used in the power-split type of hybrid. It will be interesting to see if GM will use the "2-mode" hybrid transmission for any future non-plug-in hybrids. It was recently that GM's 2-mode hybrid for trucks applications was cancelled [3].

Because label fuel economy is now according to the "5-cycle" method [4], which includes higher speeds and cold and hot temperatures, manufacturers are starting to include new efficiency features that specifically address these conditions. Expect more thermal recovery devices for quicker warm-up, higher regenerative braking, and improved gearing for economy at high speeds.

## 6.2 *Future PHEVs*

In model year 2013, Toyota and Ford started to release PHEV versions of their HEVs. Both companies are leveraging the existing power-split architectures but are bound to limitations of engine off at higher vehicle speeds and/or road demands. The challenge is to design the system to use electric-only drive capability as much as possible in order to displace the most fuel in everyday driving for a given investment in battery capacity. The more the engine turns on, the more difficult it is to increase the fuel-only MPG. Consider the very mild in-use MPG benefit recorded in fleet testing after-market converted Prius hybrids [5]. The Prius engine turns on under medium to heavy accelerations and at speeds above 100 km/h (60 mi/h).

In 2013 Ford announced the C-Max Energi PHEV to higher power and speed electric-only capabilities than any other blended PHEV offered yet (32 km (21 mi.) range and 140 km/h (85 mi/h) electric-only capability) [6]. Indeed, the C-Max Energi surpassed both the Chevrolet Volt and the Prius Plug-in Hybrid. The overall combined gasoline-electricity fuel economy rating for the 2013 model year C-Max Energi is 4.1 L/100 km (58 mpg) equivalent, the same rating as the Prius PHV and the Ford Fusion Energi, making all three PHEVs the most fuel efficient cars in EPA's midsize class.

A new technology with system-level impacts is wireless charging.

If inexpensive, wireless charge parking spots can be rolled out, battery costs could be cut. For example, if the 2013 Prius with 15–20 km (9–11 mi.) of electric range were to recharge every time it is parked, the total daily miles driven electrically without inconveniencing the driver could be increased significantly. Lower-cost PHEVs could increase their potential market penetration.

For further information please have a look at IEA-IA-HEV **Task 26: Wireless power transfer for EVs** (http://www.ieahev.org/tasks/wireless-power-transfer-task-26/).

## *6.3 Future BEVs*

The first generation of BEVs didn't include systems like thermal management systems or well improved battery management systems, like the first-generation Leaf. The lack of such a system may lower initial costs, but time will tell if the batteries will last as long as customer expectations. Current studies shows that thermal management systems can help to improve the systems performance and therefore increase the driving range, by reducing the energy consumption. The 2013 Ford Focus BEV does include a thermal management system. The impacts of this system and the overall performance will be reported in future work.

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# System Optimization and Vehicle Integration

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**Abstract** This chapter deals with the most important possibilities for improving the overall vehicle performance of electrified vehicles. Thus, it describes the results and the key messages of several IEA-IA-HEV-Task 17 workshops and studies, by focusing on the following topics:

- **E-Motors**: This section is focusing on the advantages and disadvantages of Permanent Magnet Motors with rare-earth permanent magnets, representing one of the most common motors being used so far (based on the reporting year

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2012). Additionally it focuses on alternatives for permanent magnet motors, which are currently at a few level.

- **Battery Management Systems** (**BMS**): A BMS constantly controls the functionality and charge of the battery cells. Therefore, it is necessary to lengthen battery life. This chapter addresses concerns for current BMS, provides an overview about their basics and highlights the most important BMS-Tasks for High Voltage batteries as well as the demonstration of a Lithium-Ion battery performance and cost model for electrified vehicles.

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- **Thermal Management Systems**: The optimization of thermal management has become an important business segment, as it is essential for effective operation of electrified vehicles in all climates. The results and outcomes of a study (Argonne National Laboratory) as well as various workshops addressed innovative methods for Thermal Management Systems. The results are described within this chapter and include specific thermal management technologies, explored innovations on components and Phase-Change-Materials.
- **Simulation Tools**: For many years now numerical simulation has become an essential tool to engineers in the product development process. Computing methods have been refined to such an extent that today simulations are more and more referred to as a basis for important product decisions. This chapter deals with a few simulation tools in the field of system optimization and vehicle integration, including "Autonomie", "Cruise" and "Dymola/Modelica".
- **Functional and Innovative Lightweight Concepts and Materials**: In the future, the proportion of high-tensile steels, aluminium and carbon-fibre-reinforced plastics in vehicles is set to increase from 30 % today to up to 70 % in 2030 (McKinsey & Company, Lightweight, heavy impact, 2013). High-tensile steel will remain the most important lightweight material and carbon-fiber-reinforced plastics are expected to experience annual growth of 20 %.
  As Lightweight construction of the vehicle body has become a very important field of R&D activities, this chapter focus on the outcomes of a study on the impacts of the vehicle's mass efficiency and fuel consumption (Argonne National Laboratory) as well as on various methods of light weighting a vehicle, like simulation tools, advanced "smart" materials, bionic concepts and functional integration.
- **Power Electronics and future Drive Train Technologies**: Around 40 years ago, the first piece of software was used in a vehicle to control the ignition of the engine. Today, up to 90 % of all innovations in a car are realized with electronics and software, based on the customers demand for new safety and convenience functions—Advanced Driver Assistance Systems—which are the basics for autonomous driving. This chapter points out that modular drivetrain topologies are as much important as the requirement of layered, flexible and scalable architectures. The further improvement of the power control unit as well as the E/E-Architecture will play a key role in the future of electrified vehicles.

## 1 System Optimization and Vehicle Integration

*The optimization of vehicle components significantly help to improve the overalls vehicle performance. Especially light weighting the vehicle has a massive impact on the increase of range and on the improvement of energy efficiency.*

*The use of thermal-, and battery management but also the optimal use of power electronics and electronic and electrical architecture will be one of the key challenges and most important steps of the future.*

This chapter describes the most important possibilities for improving the overall vehicle performance. Thus, it describes the outcome and the key messages of several Task 17 workshops, by focusing on:

- overview of different **e-motors** and their abilities,
- management systems like *battery management systems* as well as
- **thermal management systems**,
- **simulation tools**,
- functional and innovative **lightweight components and materials** and
- **power electronics and drive train technologies** for future xEVs

# 2 Electric Motors

In this section electric motors (e-motors) for use in EV's are described. The focus is put on alternatives to Permanent Magnet Synchronous Motors (PMSM). Advantages and disadvantages are pointed out.

This section is hosted by Steven Boyd from U.S. DoE (year 2012).

## *2.1 Introduction*

Currently (FY 2013), permanent magnet (PM) motors with rare-earth (RE) permanent magnets are almost universally used for hybrid and EVs because of their superior properties, particularly power density. However, there is now a distinct possibility of limited supply or very high cost of RE PMs that could make these motors unavailable or too expensive. Since the development of e-motors for vehicle applications is of interest, it should be determined which motor options are most promising and what barriers should be addressed. Currently, the focus is limited to induction and switched reluctance (SR) motors, as these types do not contain PMs and are currently used in electric drive vehicles.

In considering alternatives, cost and power density are two important properties of motors for traction drives in EVs, along consideration for efficiency and specific power.

For each technology, the following aspects can be considered:

- current state-of-the-art performance and cost,
- recent trends in the technology,
- inherent characteristics of the motor, including ones that can limit the ability of the technology to meet performance targets,
- what R&D would be needed to meet the targets,
- potential for the technology to meet the targets

So far, alternatives are few. First, if high-strength Neodymium-Iron-Boron (NdFeB) RE magnets are not available, the following alternative PMs may be considered for use in PM motor designs: Samarium-Cobalt have similar magnetic properties to NdFeB magnets, have better high-temperature stability, but are very costly; Aluminum-Nickel-Cobalt (AlNiCo) magnets have somewhat lower cost but very low coercivity; iron or ceramic magnets are the least expensive but also are the weakest magnets; or new PM materials could be created or discovered. Next, AC induction motors are seen as a viable alternative despite lower power density compared with IPM motors, and are a mature, robust technology that can be less expensive. Alternatively, SR motors are durable and low cost, and contain no magnets. Their peak efficiency is slightly lower than that of PM motors, but the flatter efficiency profile of SR motors can give higher efficiency over a wider range of operation. Significant concerns about SR motors are torque ripple and acoustic noise. Finally, there are other alternative motor designs that have not been completely researched or characterized at this time, and further insight into these designs and reports from ongoing R&D projects may prove useful.

## 2.2 PM Motors

A PM motor is a hybrid motor design that uses both reluctance torque and magnetic torque to improve its efficiency and torque. These motors are created by adding a small amount of magnets inside the barriers of a synchronous reluctance motor. They have excellent torque, efficiency, and low torque ripple. They have now become the motor of choice for most EV applications. PM motors have high power density and maintain high efficiency over their entire torque and speed range except in the field-weakening speed range. This translates into a challenge to increase the constant power speed range without a loss of efficiency. Other major issues are failure modes and the relative high cost of the motor due to the cost of the (currently favored) RE PMs and rotor fabrication. Major R&D challenges are to develop bonded magnets with high energy density capable of operating at elevated temperatures and motor designs with increased reluctance torque. These developments may result in reducing the magnet cost. Other challenges include thermal management and the temperature rating of the electrical insulation.

## 2.3 Induction Motors

The induction motor was invented by Nicola Tesla in 1882 and is the most widely used type of e-motor. Mostly because of its ability to run directly from an alternating current (AC) voltage source without an inverter, it has been widely accepted for constant-speed applications. For vehicle applications, recent developments in low-cost inverters have made variable-speed operation possible for traction drives.

Induction motors have the advantages of being the most reliable, possessing low maintenance, high starting torque, and a wide manufacturing base due to high acceptance by industry. These motors offer robust construction, low cost, and excellent peak torque capability. However, their power density is somewhat limited, and increasing speed is one of the few available paths to increase power density. So, many AC traction drives run at high speeds of 12,000–15,000 RPM at maximum vehicle speeds. This use of high motor speeds results in smaller, light-weight traction motors, but it requires a high-ratio gear box that also has associated mass and losses.

There are few recent improvements to the AC motor for vehicle applications. One of these is the use of a copper rotor instead of aluminum. Depending upon the size of the motor, the use of copper can increase the efficiency of an AC induction motor by one to three percentage points. Although this may seem like a small increase, it is significant in reducing the losses generated by the motor, easing thermal management. Depending on the vehicle, this could also add some distance to all-electric driving range as well. Another improvement that has been studied is determining the effect of different pole numbers, and it has been shown in several studies by Allen Bradley, Reliance Electric, General Electric, and Siemens that the optimum pole number for AC induction motors below 1000 NM is four poles. Increasing the pole numbers for smaller motors reduces the power factor, but is the torque density is increased in the same frame size by increasing the number of poles. For ac induction motors driven by inverters, the number of poles should be increased from 4 to 6 for motors above 1000 NM torque.

As an alternative to PM motors, induction motors are not as efficient or power dense. Furthermore, because AC motors are considered a mature technology, the likelihood of achieving the required additional improvements in efficiency, cost, weight, and volume is low. However, if PM motors become infeasible for reasons of cost or availability, induction motors seem to be the consensus next choice, and therefore remain a relevant technology for EVs.

## *2.4 Switched Reluctance Motors*

The SR motor uses a doubly salient structure with toothed poles on the rotor and stator. Each set of coils is energized to attract a rotor pole in sequence so it acts much like a stepper motor. With current technology, SR motors have inherently high torque ripple and the high radial forces generated can create excessive noise levels if not carefully designed. These motors are currently best suited in high-speed applications where torque ripple is not an issue. In comparison with mature motor technologies such as the AC induction motor and the relatively recent brushless PM synchronous motor, the SR motor offers a competitive alternative to its counterparts despite these aforementioned issues. The basic concept of the SR motor has been around for over 100 years, but recent advances in power electronics, digital control, and sensing technologies have opened up the possibilities of the SR motor and provide some novel design opportunities which can be suited for vehicle propulsion.

Unlike most other motor technologies, both the rotor and stator of the SR motor comprise salient teeth such that torque is produced by the tendency of its rotor to move to a position where the inductance of an excited stator winding is maximized and reluctance is minimized. This condition generally occurs when the corresponding stator tooth is fully aligned with a rotor tooth. The non-steady state manner in which torque is produced in the SR motor introduces the requirement of a sophisticated control algorithm which, for optimal operation, requires current and position feedback. In addition to non-steady state operation, the SR motor often operates with the rotor and stator iron in saturation, increasing the difficulty of optimal control and making the motor very difficult to accurately model without the aid of computer processing and modelling techniques. Therefore, since the SR motor is very technologically demanding in terms of design, modelling, and control, the evolution of SR motor technology has been limited until these demands were adequately addressed. Furthermore, the progression of other motor technologies such as the induction motor and PM motor have not been as limited by the state of other technologies. Since the torque of an SR motor is based on reluctance, no excitation is required from within the rotor, making it more simple, mechanically resilient, and cost effective than other motor technologies. The absence of PM material, copper, aluminum or other artefacts in the rotor reduces the requirement of mechanical retention needed to counteract centrifugal and tangential forces. This causes the SR motor to be especially well suited for rugged applications or high-speed applications wherein high power density is desired. As there are no conductors in the rotor, only a low amount of heat is generated therein, and most of the heat is generated in the stator, which eases motor thermal management requirements. In addition to having low material costs, the simplicity of the SR motor facilitates low manufacturing costs as well.

In regards to electric drive vehicles, the primary issues with SR motors are the torque ripple and acoustic noise that is associated with the fundamental manner in which torque is produced. When current is supplied to the coil of a SR motor stator tooth with proper respect to rotor position, torque is created until the nearby rotor tooth is fully aligned with the stator tooth. Thereafter, torque is created in the opposite direction if the rotor continues to rotate and if current is still supplied to the coil. Therefore, it is typically desirable to reduce the current to zero prior to generating an undesirable torque. However, the inductive behavior of the coil and corresponding magnetic path prevent rapid evacuation of current in the coil, and thus a torque transient occurs and provokes the issue of acoustic noise and torque ripple. Perhaps the second most significant problem with the conventional SR motor is that it cannot be driven with a conventional three-phase power inverter. Nonetheless, a unipolar inverter for a three-phase SR motor contains three diodes and three switching elements, as is the case with a conventional three-phase power inverter, so similarities do exist.

Having lower material and manufacturing costs, the SR motor presents a competitive alternative to the PM motor. And while the power density and efficiency of the PM motor may not be surpassed, the SR motor can approach meeting similar metrics. Various comparison studies have shown that the efficiency and power density of the SR motor and AC induction motor with copper rotor bars are roughly equivalent, while the AC induction motor with aluminum rotor bars falls slightly behind these two types of motors.

### *2.5 Conclusions and Future Work*

Due to the importance of electric traction drive motors to the future of EVs, motor R&D will continue to play an important aspect in the development of these vehicles. This is now further emphasized with the recent uncertainty in the future price and supply of RE magnets.

A proposal for alternatives and future work is to concentrate efforts in three distinct areas:

- continued development of PM motors with RE magnets,
- develop novel motor designs that use non-RE PMs or no magnets at all,
- develop novel magnet materials that could be used in PM motor designs.

Continuing the development of PM motors using RE magnets could result in motor designs that use less RE magnet material, and maintains the technology development path with the consideration of possible future material availability through expanded RE supply or increased recycling. Developing other novel motor designs could potentially use other existing PM materials, improve upon existing motor technologies to better rival PM motor performance, or even develop new motor designs entirely. Finally, PM magnet material development could reduce the cost of existing RE PM magnets through reduced processing cost, reduce RE PM cost by reducing heavy RE content, or develop new magnets through the investigation of novel inter-metallic compounds.

## 3 Battery Management Systems in EVs

In this section the relevance of Battery Management Systems (BMS) (FY 2013) for system performance and costs are evaluated.

This section was partly provided by **Mr. Andrea Vezzini** and **Ms. Irene Kunz** from Bern University of Applied Sciences (BFH).

Content of this section:

- general information and Tasks of BMS,
- battery requirements for different configurations including: HEV, PHEV, BEV,
- battery type considered (Li-ion),

- information from a workshop (technology trends and open points) and information provided by BFH and ANL

**In general the main electrical components of EVs can be summarized as**:

- **e-motor**,
- **e-motor drive (inverter)**,
- **(Li-ion) battery cells**,
- **regenerative brakes**,
- **Vehicle Control Unit (VCU) or board computer**,
- **access to standard vehicle electronics systems (regular ABS,ESP, etc.) and**
- **Battery Management System (BMS)**

A detailed look at the components which have been used for one of the first generation BEVs (Ford) is shown in Fig. 1.

The **VCU** is a board program which reads the actual accelerator position and translates it to the actual torque of the motor. This value is sent to the inverter which drives the motor. Further, the VCU is responsible for monitoring the measured values which are relevant for the vehicle user (e.g. speed, battery SoC, etc.).

The VCU generally exchanges information with all the units in the vehicle. This means that the communication takes place with inverters, chargers, DC/DC converters, BMS and monitor devices over a Controller Area Network (CAN) Interface.

Figure 2 shows an overview of the different block modules in an EV. It is obviously, that it is very important that the BMS has access to most of these modules.

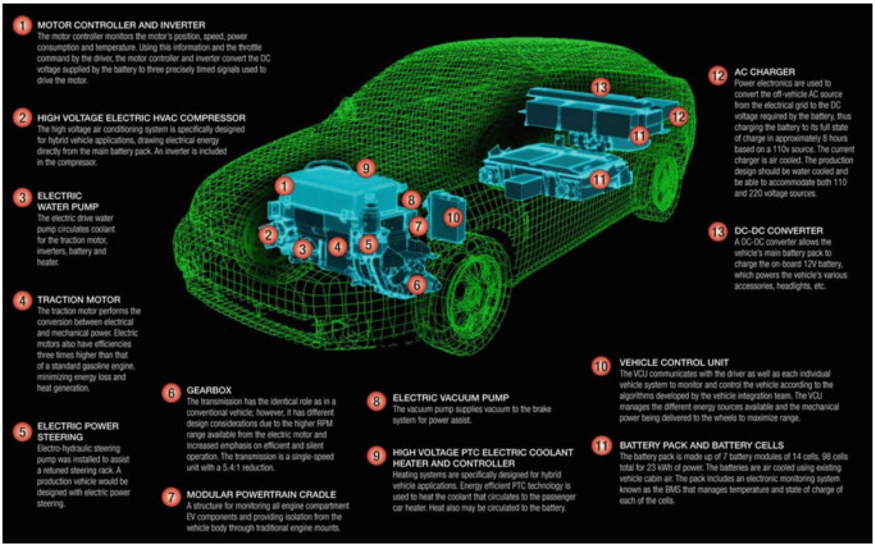



**Fig. 1** Components that will make up a BEV [1]

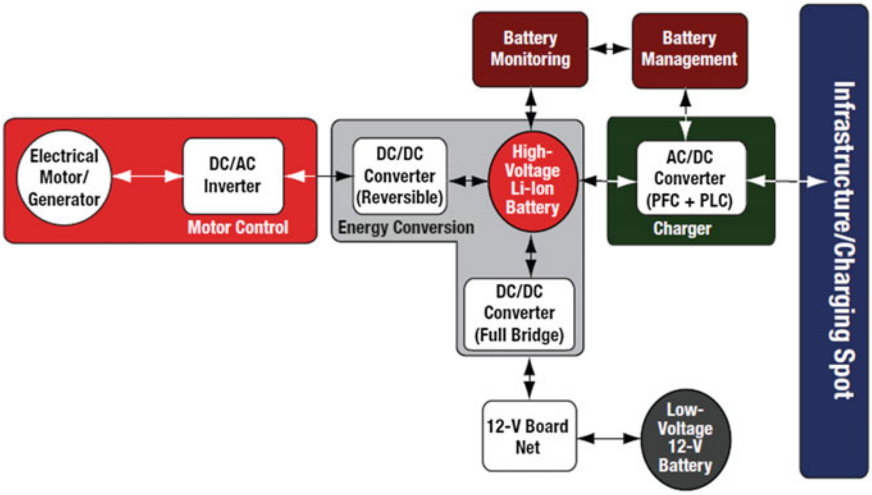



**Fig. 2** Scheme of block modules in an EV [2]

The new market segment of EVs sets off an increasing demand for battery storage systems (see Fig. 3). To guarantee a safe operation of these systems, batteries need to be protected from several malfunctions. This protection is realized with battery management systems.

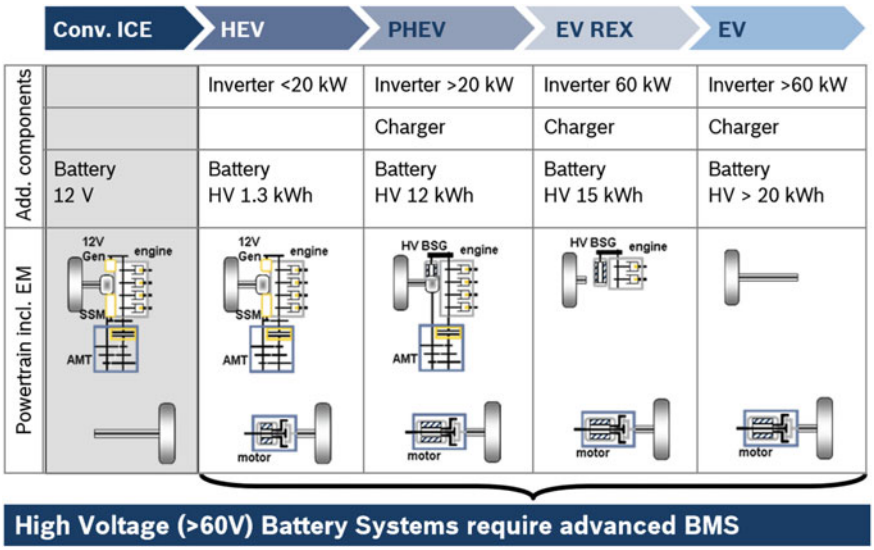



**Fig. 3** High voltage battery systems require advanced BMS (image courtesy of Bosch [3])

*A battery management system (BMS) is any electronic device that manages a rechargeable battery pack. The BMS is required to ensure that the cells in a battery are operated within their safe and reliable operating range. The BMS monitors voltages and temperatures from the cell stack. From there, the BMS processes the inputs, making logic decisions to control the pack performance, and reporting input status and operating state through communication outputs. Concisely, a BMS turns a collection of "dumb" cells into an intelligent, safe and more efficient battery pack* [4].

**Definition of the terms "battery", "module" and "cell"**:

**A "battery" is the complete assembled pack of singular cells**. It may consist of several modules, wired in series. **In a module, single cells are connected in series or parallel** (Fig. 4).

It is possible to obtain higher currents if the cells or the modules are connected in parallel. A series connection leads to higher voltages. **The module controls every cell to guarantee a proper function in the desired operating range by monitoring voltage, current and temperature**. **The control of these modules and battery packs is realized with a BMS**. The process from the material towards the batteries prototype can be seen in Fig. 5.

## *3.1 Description and Tasks of a BMS in an EV Application*

An intelligent implementation of a BMS will extend the battery's lifetime and the driving range of the vehicle. The operation of a BMS in an EV includes normal protection functions like charge control and cell protection against limit-exceedance (voltage, current, temperature). BMS used in EVs have to interact with several on-board systems. Further, there is the requirement to act as a real-time application.

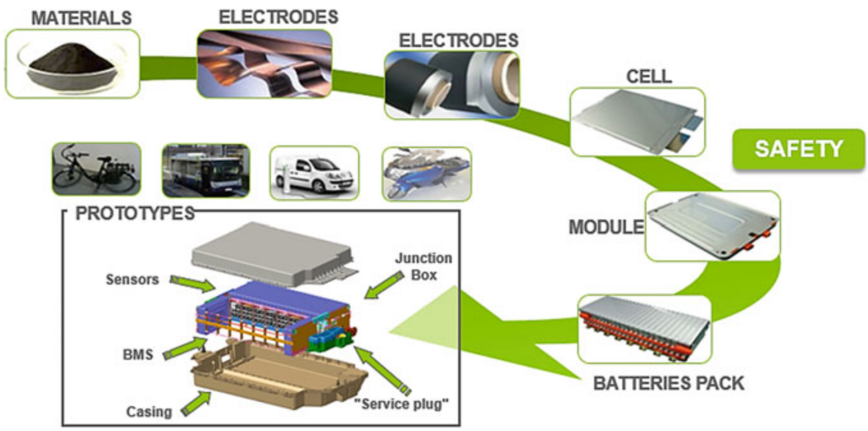



**Fig. 4** From powder to system integration (image courtesy of CEA [5])

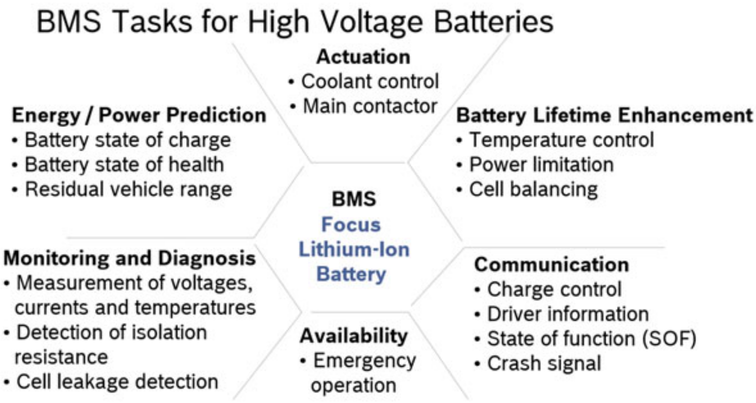



**Fig. 5** BMS-Tasks for high voltage batteries [6]

This means that the safety-relevant applications are handled as prioritized functions and thus should never be blocked due to other less relevant functions of the electric car (like air-conditioning control).

The main functions of a BMS (for high voltage batteries, focusing on Li-ion batteries) are depicted in Figs. 5 and 6 and can be summarized as follows:

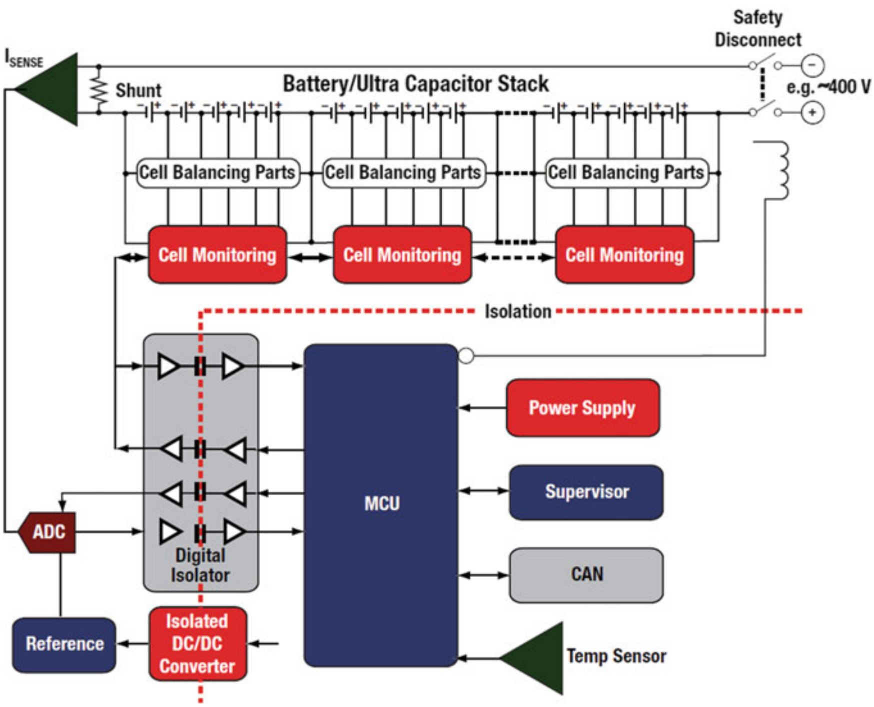



**Fig. 6** Scheme of a BMS in an EV application [7]

- **battery monitoring**: BMS monitors key operational parameters, such as voltages, currents, and temperatures, during charging and discharging of batteries. Based on these values, BMS estimates the state of the battery [e.g. state of charge (SoC) and the state of health (SoH)]. Information which is relevant for the car driver has to be sent over CAN-Interface to the VCU. Here the data will be forwarded to the dashboard where it can be monitored. This information includes the SoC, SoH, error messages and available driving range,
- **energy/power management and prediction**: BMS prevents the battery from operating outside its safe operating area such as: over-current, overvoltage, over-temperature and under temperature. The main goal of the energy management is to guarantee a constant supply of energy for the important vehicle functions. The vehicle can fundamentally be in three states: drive, park or charge. For each of these three states the priority of the different functions change:
  - in drive state, all devices which control the vehicle are to be preferentially treated;
  - if the vehicle is parked, the management system enters a sleep mode with the BMS being turned off for a period of several minutes after which, it becomes repowered to control important parameters of the battery for safety reasons;
  - in charge state a system detecting mechanical collisions on each side has to be active. If such a collision takes place, the connection between battery and vehicle will be immediately interrupted,
- **battery's performance optimization**: in order to maximize battery capacity, and to prevent localized under-charging or overcharging, the BMS ensures that all cells that compose the battery are kept at the same state of charge, through balancing and
- **communication**: BMS communicates the above data to users/external devices. In EVs, the BMS interfaces with other on-board systems such as engine management, climate control, communication and safety systems, responsible for communications with the world outside the battery pack. The BMS transmits the measured and calculated values to the VCU which processes the data and forwards it to the right target component in the car. The SoC of the battery as an example, is forwarded by the VCU to the dashboard monitor.

These tasks are managed by the VCU, which can be seen as the ‘heart’ of the system.

It is important, that the program of the BMS never reaches a deadlock. Therefore the software should be implemented with a real-time operating system (RTOS). Moreover, sensitive tasks like overvoltage protection can be set to high priority in order to be processed first. On the other hand, the BMS involves also less important tasks like sending the actual SoH value to the dashboard monitor. For this task, the priority is set low.

*In high power applications, around ten to over one hundred high-capacity elementary cells are series connected to build up the required battery voltage. The overall cell string is usually segmented into modules consisting of 4–14 series* *connected cells. Thus, the battery can be composed by three layers: namely, the elementary cell, the module and the pack.*

*Within each module the cells are connected together to complete the electrical path for current flow. Modern BMS systems for EV applications are typically distributed electronic systems. In a standard distributed topology, routing of wires to individual cells is minimized by breaking the BMS functions up into at least 2 categories, pack management unit and module management units (as it can be seen in* Fig. 7*). The monitoring of the temperature and voltage of individual cells is done by a BMS "sub-module" or "slave" circuit board, which is mounted directly on each battery module stack, (in a normal passenger car the number would be 10–15 modules). Higher level functions such as computing state of charge, activating contactors along with aggregating the data from the sub modules and communicating with the engine control unit are done by the BMS 'master' or 'main module'. The sub-modules and main module communicate on an internal data bus such as CAN (controller area network). In an electric vehicle, the pack management unit is linked to the vehicle management system through the external CAN bus. Almost all electronic functions of the EV battery pack are controlled by the BMS, including the battery pack voltage and current monitoring, individual cell voltage measurements, cell balancing routines, state of charge calculations, cell temperature and health monitoring, which ensures overall pack safety and optimal performance, and communication with the vehicle management system* [8].

In general the BMS consist of several Module Control Units, which protect the battery cells, and a top level control, which supervises the modules. Generally it includes at least voltage, temperature and current measurements. These values are processed with an Electronic Control Unit (ECU) in order to protect the single cells against malfunctions.

This protection includes the following points:

- **charge control**: limitation of the rate at which the electric current is fed into or drawn from each battery cell to hold the battery in the safe operating area. This includes additional protection of the battery cells against overcharge, overvoltage and deep discharging and

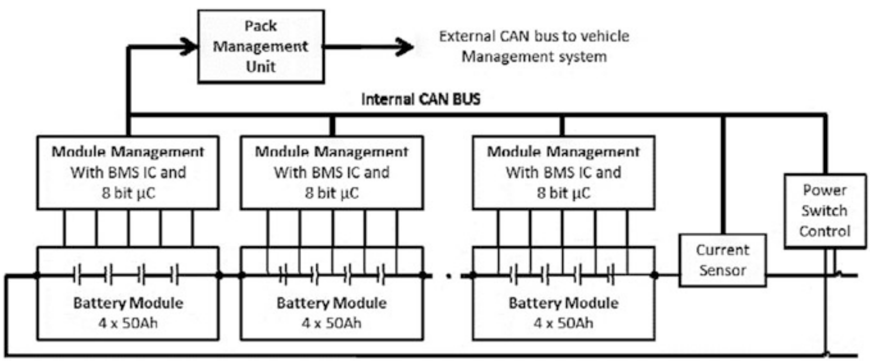



**Fig. 7** BMS structure scheme [9]

- **cell balancing**: in a multi-cell battery (serial connection) small differences between the cells appear due to production tolerances or different operating conditions and tend to increase with each charging cycle. Weaker cells become overstressed during charging and this causes them to become even weaker, until they eventually fail. Without cell balancing, the individual cell voltages will drift apart over time. Cell balancing is a way of equalizing the charge of all cells in the chain.

The overall control of the different modules is realized with a Battery Control Unit (BCU). This unit has the following functions:

- **precharge function**: this function is needed, when the battery is connected for the first time with a system which has a high capacity (e.g. EV). In this case, a very high inrush current is flowing for a short time. To reduce these current peaks, there are two switches needed in parallel (compare Fig. 8). The switch above includes a resistor, which attenuates the current peak (precharge relay). After a while, the main switch below can be closed to reduce the connection resistance to a minimal value and
- **module protection**: in the case of a battery parameter exceeding the allowable range, the unit will open immediately the main switch (compare Fig. 8).
- **SoC determination**: the SoC indicates the proportion of the charge currently available in the battery compared to the fully charged battery pack (100 %). This

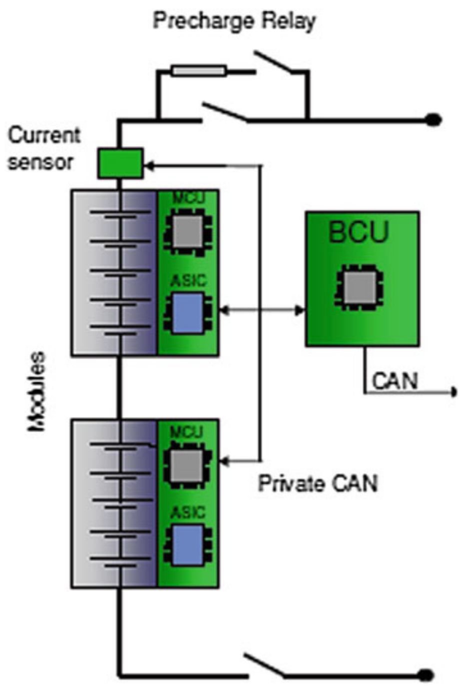



**Fig. 8** Structure of a BMS

function is comparable with a fuel gauge in a car. Chapter 6.3.2 describes different calculation methods to determine this SoC,

- **SoH determination**: the SoH is a relative figure of merit. It provides the actual condition of the battery compared to the completely new battery (100 %) whereas 0 % corresponds to a completely worn out battery pack. The SoH can be determined by the decrease in the capacity of the battery with increasing age. More information on the determination methods for the SoH is provided in Chap. 6.3.3,
- **demand management**: this function provides an intelligent energy management system, which stores the energy amount in the battery as long as possible. The energy management system has to be adapted individually to each specific application,
- **communication with host**: the BMS transmits data to a host computer or an external device. The data can then be stored or plotted in a Graphical User Interface and
- **history (log book function)**: monitoring and storing the data over an extended period of time is another possible function of the BMS. Parameters such as number of cycles, maximum or minimum voltage, temperature and maximum charging and discharging current can be tracked.

**BMS topology**

*BMS technology varies in complexity and performance*:

- *active regulators intelligently turning on and off a load when appropriate, again to achieve balancing further a complete BMS also reports the state of the battery to a display, and protects the battery*,
- *simple passive regulators achieve balancing across batteries or cells by bypassing charging current when the cell's voltage reaches a certain level. The cell voltage is a poor indicator of the cell's SOC, thus, making cell voltages equal using passive regulators does not balance SOC, which is the goal of a BMS. Therefore, such devices, while certainly beneficial, have severe limitations in their effectiveness.*

*BMS topologies fall in 3 categories*:

- *centralized*: *a single controller is connected to the battery cells through a multitude of wires. They are most economical and least expandable*,
- *distributed*: *a BMS board is installed at each cell, with just a single communication cable between the battery and a controller. These are the most expensive, simplest to install, and offer the cleanest assembly*,
- *modular*: *a few controllers, each handing a certain number of cells, with communication between the controllers. Modular BMS offer a compromise of the features and problems of the other two topologies* [10].

## *3.2 SoC Determination Algorithm*

At the moment no direct way of measuring the SoC is provided. There are indirect ways of estimating it but each has limitations. This session deals with several indirect determination methods:

- voltage based SoC estimation,
- current based SoC estimation,
- combination of the current and
- voltage based methods and SoC estimation from internal impedance measurement.

### Voltage based SoC estimation

Several cell chemistries show a linear decrease of voltage with decreasing SoC. This characteristic is used to determine the actual SoC. It is possible to estimate the actual SoC by measuring the open circuit voltage of the battery. Figures 9 and 10 show the discharge voltage of two different battery chemistries. The characteristics are dependent on the temperature and the discharge rate.

In Fig. 9, it can be seen that the voltage in a lead acid battery decreases significantly as it is discharged. By knowing this characteristic the battery voltage can be used to estimate the SoC. A drawback of this method is that the battery voltage is dependent on the temperature and the discharge current. These effects have to be compensated in order to increase the accuracy of the estimation.

In the case of Li-ion batteries in Fig. 10, the voltage changes only slightly. So the estimation of the SoC is nearly impossible. However the voltage of a Li-ion cell changes at both ends of the characteristic abruptly. This effect can be used to detect if the battery cell is fully charged or depleted. But in most systems an earlier alert is required, because a completely discharge of a Li-ion cell will significantly reduce its life span.

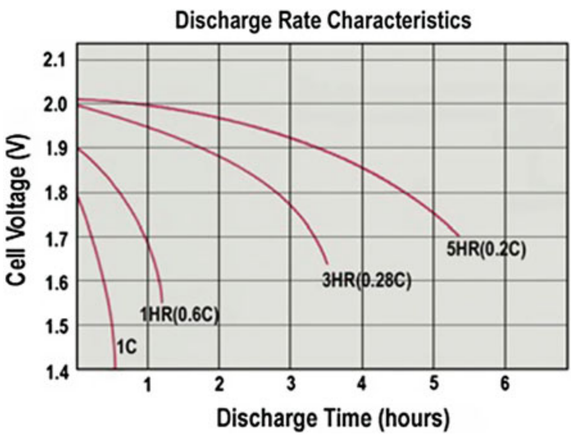



**Fig. 9** Open circuit voltage vs. remaining capacity for a lead acid cell [11]

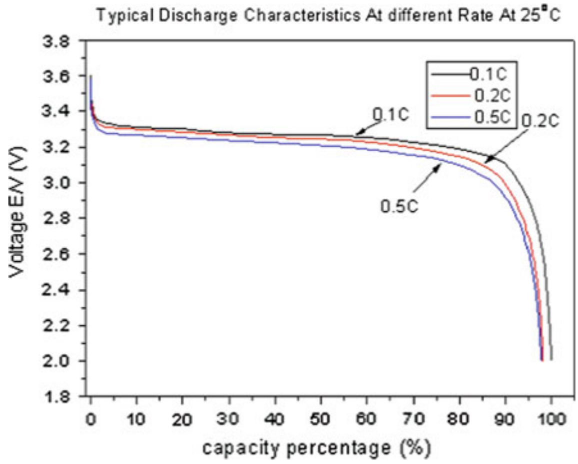



**Fig. 10** Open circuit voltage versus remaining capacity for a Li-ion cell [12]

### Current based SoC estimation (coulomb counting)

With the coulomb counting method the charge which flows in and out of the battery is measured. It is not possible to measure the charge directly. Therefore a measurement of the current is needed, which will be integrated over time.

The start of the measure has to be in a defined initial state, for example if the battery is fully charged. Then the determined charge value is measured relatively to the fully charged battery cell. The drawback of this method is that in case of even a very small current sensor offset, the SoC determined will show a deviation from the real value. Due to the fact that this error is integrated over time it leads to significant estimation errors in longer time periods. This effect is shown in Fig. 11.

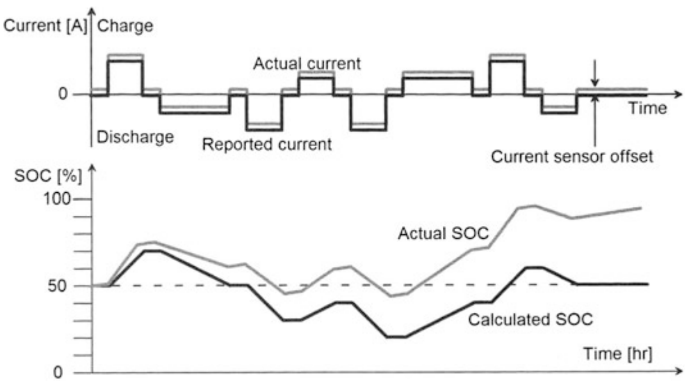



**Fig. 11** Drift of the SoC due to a current sensor offset [13]

### Combination of the current and voltage based methods

A calibration of the integrator's output can be realized if the coulomb counting variant and the voltage based method are combined:

- the battery current is integrated to get the relative charge in and out of the battery,
- the battery voltage is monitored to calibrate the SoC when the actual charge approaches either end.

This method is a more accurate and reliable way to estimate the SoC (compare Fig. 12).

A drawback of this method is that the application in HEVs is not possible. Because the normal SoC range in a HEV is between 20 and 80 %. It never reaches the threshold voltage on either end.

### SoC estimation from internal impedance measurement

In a discharging cycle the cell impedance varies with the SoC. Therefore by measuring the internal impedance it is possible to determine the SoC (compare Fig. 13).

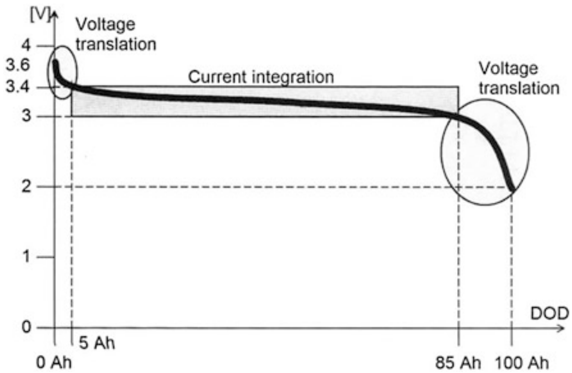



**Fig. 12** Combining current and voltage based SOC-algorithm for higher accuracy [14]

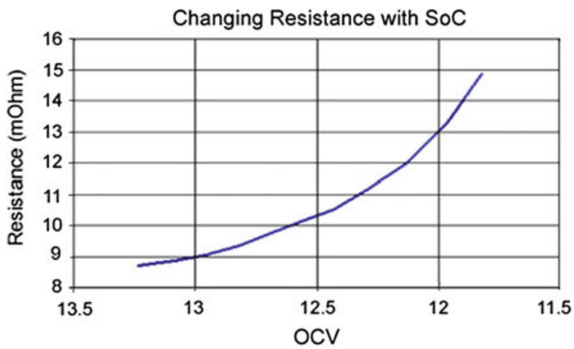



**Fig. 13** Internal resistance of a lead acid battery versus OCV—Open Circuit Voltage [15]

In all battery technologies the internal resistance will increase at the end of a discharging cycle. This effect can be used to determine the actual SoC. This method is rarely used because the battery has to be disconnected from the system to measure the internal resistance. Moreover the results are very temperature sensitive.

If changes of the voltage and current can be measured, then it is possible to calculate a dynamic approximation of the internal resistance with the following formula:

$$r_{i,dyn} = \frac{\Delta V}{\Delta I}$$

With this variant it is possible to estimate the resistance online, this means without disconnecting the battery.

A further effect, which is observed in Li-ion batteries is that the internal resistance also changes at a SoC of 100 % (bathtub function in Fig. 14). The largest change of the internal impedance occurs in the range of 0 to 30 % and from 80 to 100 % SoC.

## 3.3 SoH Determination Algorithm

There are several battery parameters which change significantly with increasing age:

- increase of the resistance,
- decrease of capacity.

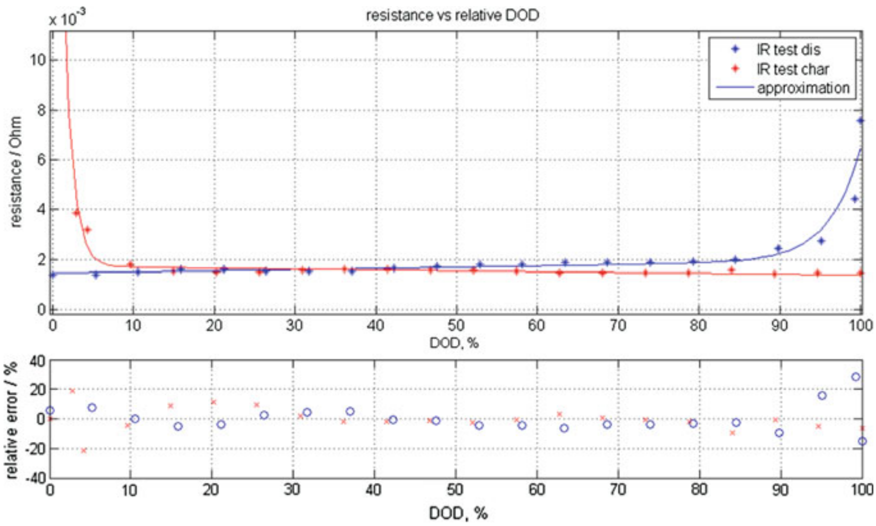



**Fig. 14** Internal resistance of a Li-ion battery versus cell capacity (DoD) [16]

The SoH can be determined from one of these values. Basically the SoH describes the actual condition of the battery in relation to the new battery pack. But actually every BMS manufacturer defines the SoH differently. For a new battery it is necessary to fully charge and discharge the battery in order to determine the initial capacity. This value has to be permanently stored in the BMS, because this value determines 100 % SoH.

After an arbitrary number of cycles, i.e. 100 cycles a correction of the SoH is required, based on a new reference measurement.

First the battery should be fully discharged and in the next charging cycle the capacity of the battery is determined. By comparing this value with the capacity of the completely new battery it is possible to determine the SoH of the battery.

A plot of the capacity versus the number of cycles is shown in Fig. 15. In this graph the Depth of Discharge (DoD) is 100 % (the battery was fully discharged in each cycle). A decrease of capacity with increasing number of cycles is observed.

## 3.4 *Integration of BMS into the EV—State of the Art*

In EVs, the battery system has to be developed as an integral part of the vehicle to avoid malfunctions (see Fig. 16). In the planning phase of the vehicle design, it is important to reserve space for all the battery systems and the BMS. The best solution is to design the system in modular blocks which could then be placed in different locations within the vehicle allowing an optimal use of the available space.

These modular blocks consist of the BMS, charger unit and battery modules. The voltage of the battery pack can be determined from the number of battery modules connected in series.

Two additional points which have to be considered:

- one critical point is the integration of a thermal management in the vehicle. The battery can be cooled down either by air or water flow. An advantage of the water-cooling version is the higher thermal cooling capacity. Moreover the battery can also be heated through the cooling water if other heat sources are

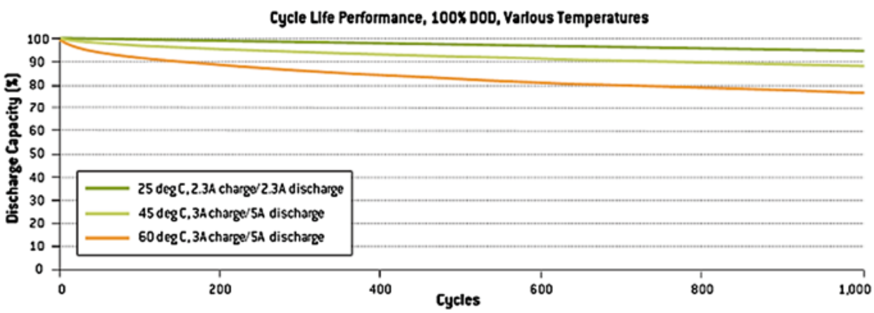



**Fig. 15** Cycle life time of Li-Ion Phosphate cell, 2.3 Ah [17]

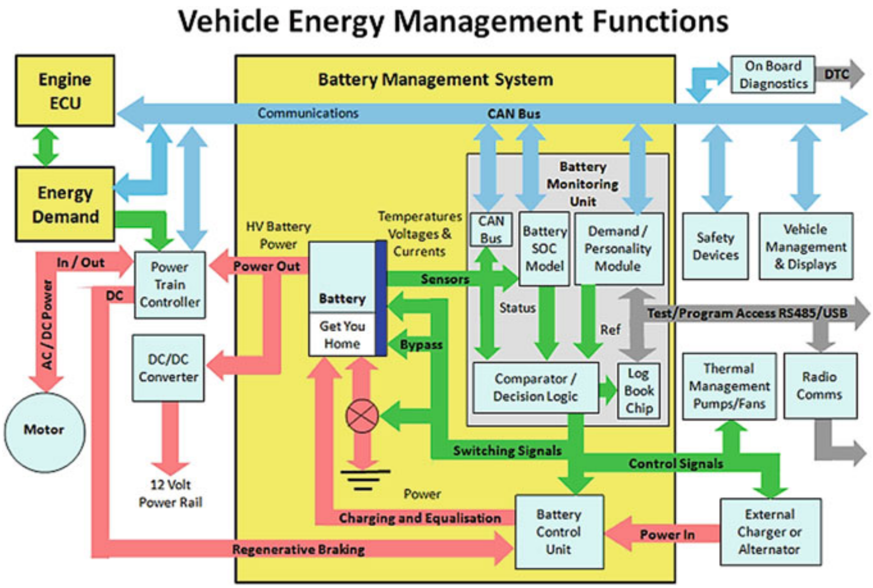



**Fig. 16** Implementation of BMS [18]

included in the same coolant loop (e.g. e-motor, power electronics). Often liquid cooling uses special heating elements and the water is a good medium to distribute that heat,

- the second issue is to protect the battery in case of an accident. Attention has to be paid to the fact that the battery is not located in the crash zone, where the battery can get mechanically damaged (Fig. 17).

The weight of the whole battery pack should be reduced as much as possible. Figure 18 shows that the Li-ion technology is well applicable in EVs due to its high energy density compared to other cell chemistries. In the current EV models, often a combination of Li-ion batteries and supercaps is used. The supercap can provide high power for short-time periods. This power is used to accelerate the vehicle.

The lithium content in a high capacity lithium battery is actually quite small (typically less than 3 % by weight) [20]. Lithium batteries used in EVs and HEVs weigh about 7 kg (15.4 lb)/kWh. Thus their lithium content will be about 0.2 kg (0.4 lb)/kWh. Current EV passenger vehicle use batteries with capacities between 30 and 50 kWh (lithium content will be about 6 (13 lb) to 10 kg (22 lb) per EV battery).

The capacity of HEV batteries is typically less than 10 % of the capacity of an EV battery and the weight of Lithium used is correspondingly 10 % less.

Several BMS structures (compare Fig. 19) are currently offered on the market and differ in simplicity and price.


**Fig. 17** Integration of a battery system in an EV [19]

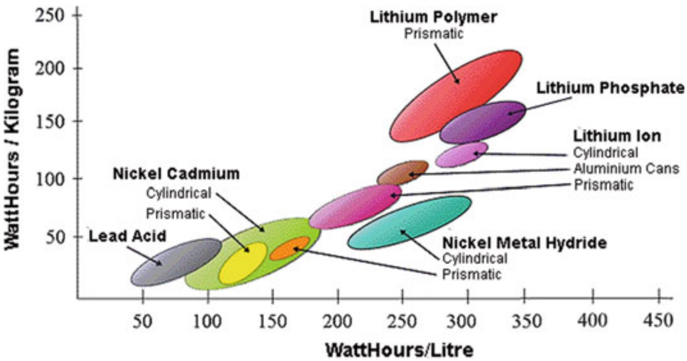



**Fig. 18** Energy density of different battery chemistries [21]

As it can be seen in Fig. 19, the different BMS structures can be divided into:

- **single board**: this is the low cost variant, the BMS is assembled on one single printed circuit board (PCB). The battery modules do not require any special electronics beside voltage, current and temperature sensing devices. The BMS board consists of several application specific integrated circuit (ASICs) which controls the battery modules. The top-level control is supervised by the BCU. This unit disconnects the battery from the application as soon as one battery parameter exceeds the predefined range. Advantage: low cost BMS;

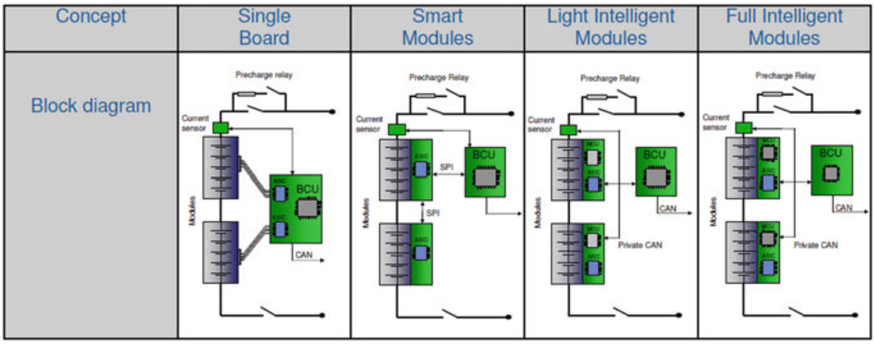



**Fig. 19** State of the art of BMS

Disadvantage: each measurement point has to be connected individually to the BMS board,

- **smart modules**: in this case, each battery module has its own ASIC, which protects the module directly. The ASIC's are able to communicate with the battery control unit over a serial peripheral interface (SPI). All connections from the single board structure can be reduced to one SPI bus common for all modules. Advantage: less wire connections than in the single board structure; Disadvantage: the module control unit can only send information if the BCU (Master) is requesting it which could lead to data loss,
- **light intelligent modules**: in this case, the communication disadvantage of the smart modules has been resolved. The Module Control Unit (MCU) in this case communicates over a private CAN interface with the BCU; in this way errors can be prevented. To initialize this way of communication on each module is a microcontroller needed. In this configuration, the MCU performs the following tasks: measure and supervise the voltage, measure temperature and balance the cells. The BCU includes the determination of SoC and SoH, the thermal management and the control of the precharge relay. A further task is to connect the BMS with the rest of the vehicle via CAN bus and
- **full intelligent modules**: The only difference of this configuration, compared with the light intelligent module, is that some functions of the BCU will be taken over by the MCU. This includes for example determination of SoC and SoH.

## *3.5 Examples of Integrated BMS in EVs and HEVs*

**Daimler MILD-HYBRID S400 (Reporting Year 2009)**

The S400 BlueHYBRID (see Fig. 20) was the first series-production model to be equipped with a Li-ion battery. Continental and Johnson Controls Saft (JCS) were teaming on the pack, with JCS was providing the cells. The compact hybrid module

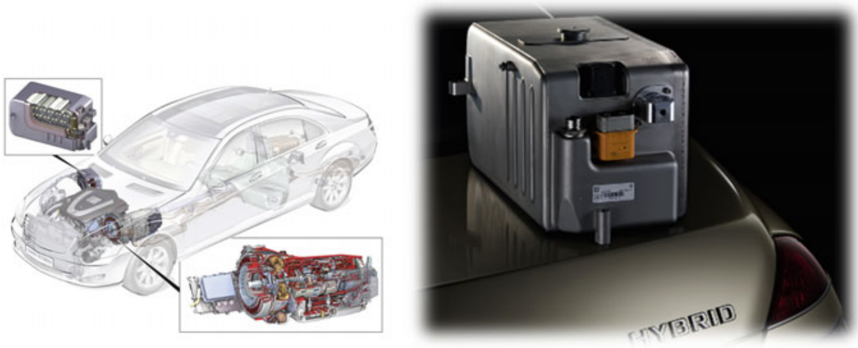


**Fig. 20** Daimler Mild-S400 BlueHYBRID with Li-ion battery pack [22]

is a disc-shaped e-motor that also acts as a starter and generator. The hybrid module also has a start/stop function, and supports regenerative braking.

The high torque of the e-motor at low speeds offsets the reduction in low-end torque resulting from applying the Atkinson cycle to the combustion engine.

Moving to a more powerful e-motor increased the weight of the hybrid system and decreased the fuel consumption. Furthermore, at a higher electrical to combustion power ratio, the e-motor operates increasingly in less favorable areas of the performance map as maximum requirements increase. Although relatively low in power, the e-motor delivers rated torque of 160 Nm (118 lb-ft), contributing to a combined system torque of 385 Nm (284 lb-ft).

The power electronics comprise a control unit which acts as the master of the E-drive system and a power unit that converts the direct current generated by the battery. The power electronics can cope with continuous currents of 150 A, and short-term as high as 310 A. Power is supplied to the e-motor by a bus bar.

The power electronics are situated in the engine compartment in the location of the conventional starter motor and are cooled by a separate circuit.

**Li-ion battery pack**: the compact Li-ion pack (compare Table 1), developed by Continental and JCS Saft, comprises 35 cells and provides 19 kW of power, with a capacity of 6.5 Ah. The battery is connected to the vehicle air conditioning circuit so it can be cooled independent from the engine. Cut-off valves are integrated into the system that allows the customer to switch off the air conditioning without

**Table 1** Key data of the battery system from Daimler

| Description | Characteristic |
|---|---|
| Battery | 35 cells, 1 cellblock (cells + cooler) |
| Voltage | Nominal 126 V, max. 144 V, min. 87.5 V |
| Power | 195 W/10 s (EoL, 50 % SoC) |
| Energy | Min. 0.8 kWh |
| Capacity | Min. 6.5 Ah |
| Cooling | R 134a |
| Lifetime | 10 years (mean temperature 40 °C) |

interrupting battery cooling. When the engine is not running, the electric A/C compressor not only provides air conditioning but also guarantees that the battery's operating temperature limits are not exceeded. Battery pack temperatures do not increased above 50 °C (122 °F) in any operating state to prevent serious damage.

**Operating strategy**: the operating strategy of the S400 hybrid is based around start/stop, regenerative braking, boost and load point shifting. When providing support for load-point shifting, the operating strategy only allows shallow discharge cycle of the Li-ion battery to maintain the cycle strength. Fuller deployment of the electrical support is only provided based on the driver's request, as indicated by accelerator pedal position and a large pedal value gradient. The focus of SoC swings is in the range of 5 %. Values of up to 10 % occur less frequently, while SoC cycle of more than 10 % are rarely observed. This contributes to the 10-year expected service life.

### GM Chevrolet Volt (2012)

At the heart of the Chevrolet Volt, a sophisticated battery-stack management system ensures the safety and reliability of the multi-cell Li-ion battery stack (see Fig. 21) that delivers power on demand to the Volt drive system. Within the management system, battery-monitoring boards use two key subsystems to reliably monitor cell health and deliver digital results to a host processor that orchestrates system operation. Separating those subsystems, a signal interface ensures isolation between high voltage battery-sensing circuitry and communications devices on the boards.

The Chevy Volt was described as an example of an extremely sophisticated vehicle. Over 100 microprocessors were used among in the various subsystems, to control each system. The majority of these controlling microprocessors were in the battery pack (for the BMS) and the inverter controlling the motor.

The Volt's BMS (compare Fig. 22) runs more than 500 diagnostics at 10 times per second, allowing it to keep track of the Volt's battery pack in real-time, 85 % of which ensure the battery pack is operating safely and 15 % monitor battery performance and life.

The battery installed in this vehicle has the following characteristics, as shown in Table 2.

**Fig. 21** GM Chevrolet Volt (view of battery) [23]

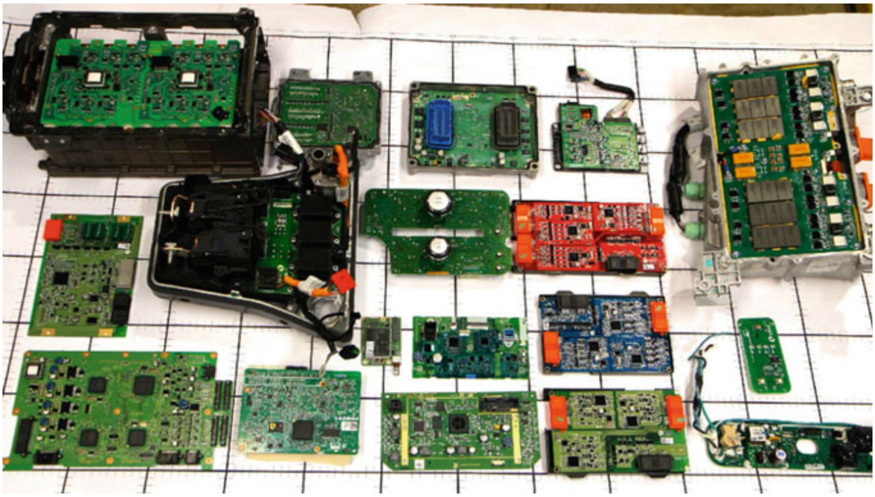


**Fig. 22** The Chevy Volt BMS [24]

**Table 2** Chevrolet Volt (battery data)

| Category | Requirement |
|---|---|
| Max. discharge Power (2 s)/(10 s) | 115 kW/110 kW |
| Max regen power (10 s) | 60 kW |
| Usable energy (end of life) | >8 kWh |
| Max. discharge current | 400 A |
| Nominal voltage | 360 V |
| Round trip efficiency (reference cycle) | >90 % |
| Calendar life | >10 years |
| Cycle life (EV cycles) | >4700 |
| May system weight | 160 kg (352 lb) |

In a PHEV, the battery will be discharged with the full vehicle power over a longer period (e.g. highway driving in pure electric mode). Therefore the battery has therefore to be sized accordingly. In this example of the Chevrolet Volt the pack is arranged in tunnel and under the seat.

### Nissan Leaf (2014)

Perhaps the best known and highest selling EV on the market is the Nissan Leaf. The all electric Nissan Leaf was the first affordable, mass produced, lithium battery EV. Key to the Leaf's success was a battery design that balances safety, performance, cycle life, calendar life, energy density, power density, charge rate, discharge rate, weight, structural integrity, and thermal management.

The Nissan Leaf's battery is made of 48 modules. Each module is made with 4 large surface area laminate Lithium Manganese/Lithium Nickel batteries. The module battery configuration is 2p 2s, meaning that two of the cells are wired in parallel and then this pair of cells is wired to the other pair in series. The results in a 7.4 V nominal voltage battery module with approximately 33 Ah. The modules are encased in an aluminum enclosure. Together these 48 modules form a string that produces between about 290 V empty and 400 V full. The total energy storage capacity of this battery system is approximately 24 kWh.

Each module is essentially sealed, with no active thermal management system installed in the pack. Here, the thermal management is done via passive means, with the heat of the cells being transferred to the metal enclosure of the modules and then to the external pack enclosure.

The Leaf is using a centralized BMS, with a single control unit and a wiring harness that extends to each module (Fig. 23).

**Renault ZOE (2015)**

In early 2015, Renault announced that due to an improved BMS, as well as to the motor, Renault is able to increase the ZOEs range. The new "more compact" motor (10 % less volume)—including improved BMS—will reportedly increase the range of the ZOE by around 8 %, roughly 20 km (12.5 mi.) on the generous European testing cycle. It also accelerates quicker but consumes less power than the original motor. The ZOE uses a 22 kWh Li-ion battery (see Fig. 24).

Renault has been granted 95 patents for its passenger car e-motor. Innovations include replacing the previous liquid cooling with air cooling (the power control


**Fig. 23** Nissan Leaf BMS [25]

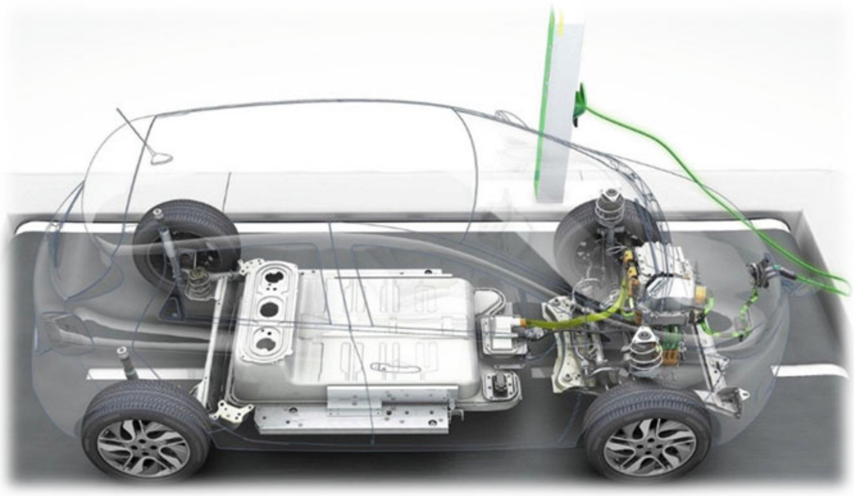


**Fig. 24** Battery module of Renault ZOE [26]

unit is still liquid cooled) and reducing the size of the power control unit by 25 %. The ZOE now features a built-in Chameleon charger that can recharge at either 3 kW or 11 kW. The charger is now built into the power control unit and charging times have been reduced.

One aspect of EV that is largely ignored by ordinary drivers is the BMS. Electric car batteries are composed of many individual cells. It is possible for some cells to become fully depleted sooner than others or to be fully recharged sooner. The BMS constantly monitors the SoC of each individual cell to maximize power and to prevent overcharging [27].

The Renault engineers have substantially upgraded the BMS for the ZOE to better manage battery usage. Those changes play a major role in the car's improved performance and longer range. In essence, the new software uses the stored electrical energy more efficiently.

Especially this example highlights the key role of a BMS.

## *3.6 Technology Trends of BMS*

BMS have a significant potential for improvement regarding the determination of the SoC. As discussed in this chapter, there are several methods available to measure the actual charge, but none of the options are accurate concerning Li-ion batteries.

One of the main problems is that the batteries will exhibit different characteristics depending on their history (temperature, charge/discharge cycles).

The current trend therefore is to implement an observer (Fig. 25), which compares the actual values of the battery with a state space model running in parallel. Using a Kalman Filter Feedback several internal parameters of the battery (SoC, SoH etc.) are tracked and corrected if necessary.

An improvement of the SoC determination is mainly needed in HEVs, because there the battery operates only within a limited SoC range (20–80 %). As discussed above the coulomb counting method is not accurate enough in this SoC range over extended periods of time.

In order to accurately determine the SoC and therefore achieve an optimal performance of the system it is important to obtain an exact characterization of the battery. Therefore a detailed battery model is needed (compare Fig. 26).

Basically, the battery model can be split into two parts:

- electrical battery model and
- thermal battery model

With the application of this determination method, the system is suitable for on-line calculation. The disadvantage in this case is the high complexity of the model which has to cover also the complete operating temperature and dynamic range of the battery. The dynamic range takes into consideration different chemical phenomena taking place within the cell over a wide frequency spectrum. The model also should cover pulsating currents (pulses of several seconds) as well as constant currents over minutes. Moreover, the aging of the battery has also to be taken into account within the battery model.

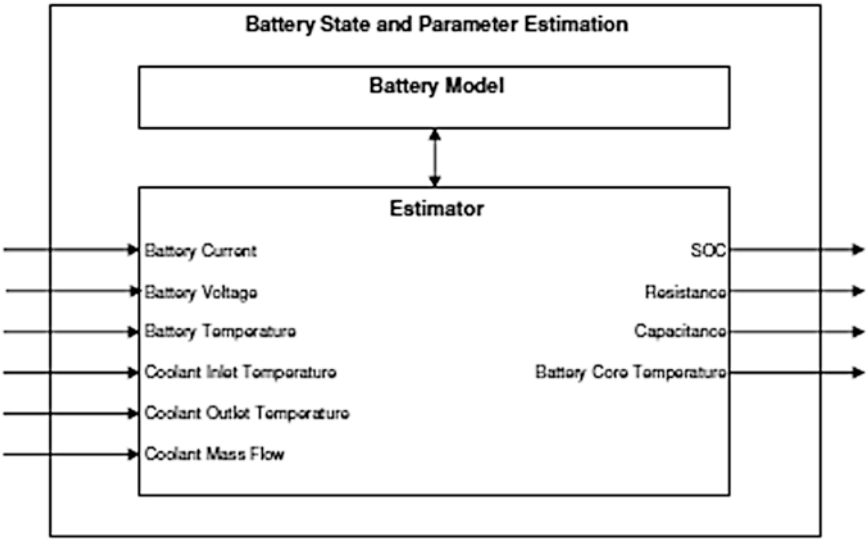



**Fig. 25** Implemented observer estimates the current SoC

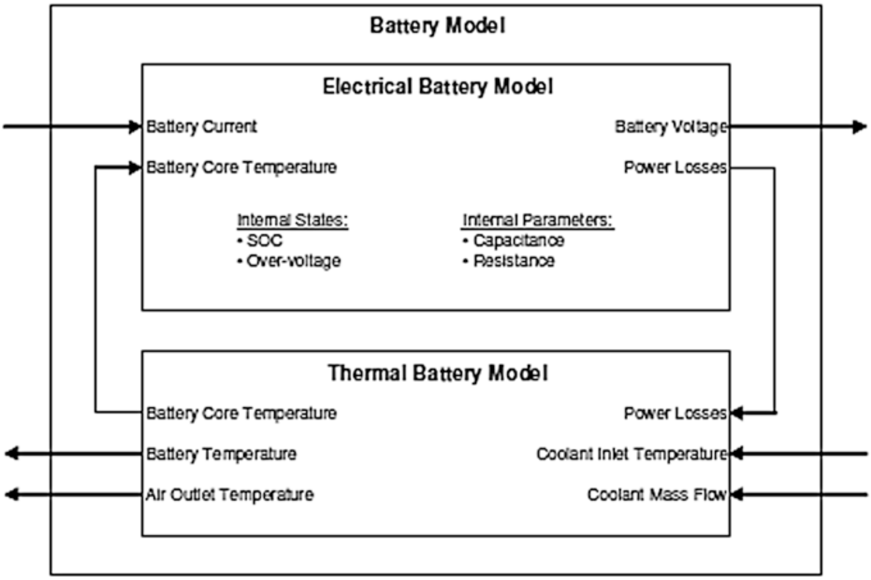



**Fig. 26** Implementation structure of a coupled electrical and thermal observer

Bosch presented their development scenario and future trends for BMS at a Task 17 workshop (Geneva, 2011). Figure 27 highlights where future BMS will focus on. State of the art BMS are focusing on safety, while next generation BMS will have their focus on optimized generation and further more on extended functionality.

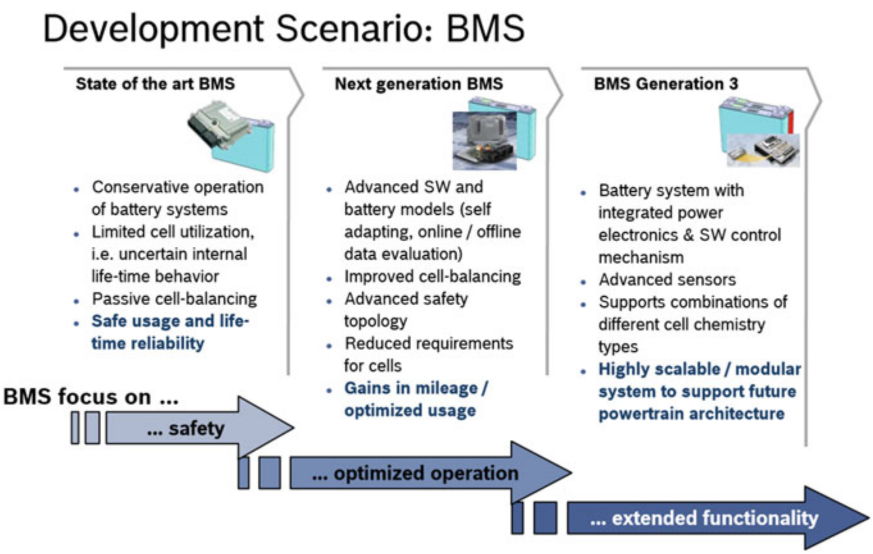



**Fig. 27** State of the art and development scenario of BMS [28]

## 3.7 BatPaC: A Li-Ion Battery Performance and Cost Model for Electric-Drive Vehicles

The information for this section have been provided by a revised final report [29]: "Modeling the Cost and Performance of Lithium-Ion Batteries for Electric-Drive Vehicles" and by the information on a Task 17 workshop in Chicago (2011) on battery performance and cost by Kevin Gallagher from ANL.

*The United States Vehicle Technology Office has supported work to develop models that help researchers design and calculate potential costs of batteries. One major model is the bottom-up Battery Performance and Cost Model (BatPaC) at ANL. This model was developed utilizing efficient simulation and design tools for Li-ion batteries to predict: precise overall (and component) mass and dimensions, cost and performance characteristics—understand how performance affects cost—battery pack values from bench-scale results*

*The recent penetration of Li-ion batteries into the vehicle market has prompted interest in projecting and understanding the costs of this family of chemistries being used to electrify the automotive powertrain. The performance of the materials within the battery directly affects the end energy density and cost of the integrated battery pack. The development of a publically available model that can project bench-scale results to real world battery pack values would be of great use.*

*This first version of the model, the battery performance and cost (BatPaC) model, represents the only public domain model that captures the interplay between design and cost of Li-ion batteries for transportation applications.*

*BatPaC has more accurate predictions than previous models and allows vehicle manufacturers to choose the best and smallest battery for the application. Based on expert recommendations of this model, the U.S. EPA used BatPaC to develop its most recent round of fuel economy standards. In addition, work at the National Renewable Energy Laboratory led to a multi-scale multi-dimensional framework for battery design that uses computer-aided engineering tools.*

***Approach to understanding cost and energy***

*BatPaC is built on a foundation of work by Paul Nelson at Argonne. It Designs Li-ion battery and required manufacturing facility based on user defined performance specifications for an assumed cell, module, and pack format (power, energy, efficiency, cell chemistry, production volume). Thus, it calculates the price to OEM for the battery pack produced in the year 2020. Therefore, it isn't modeling the cost of today's batteries but those produced by successful companies operating in 2020; some advances have been assumed while most processes are similar to well-established high-volume manufacturing practices. BatPaC efficiently completes calculations in fractions of a second* [30].

**Assumed battery format: cell**

Various cell and battery design concepts are under development of battery manufacturers. ANL found out that the exact design of the battery doesn't have an import effect on the cost for a set cell chemistry; the amounts of electrode materials and the number, capacity and electrode area of the cells are the determining cost factor. The most common cell designs for batteries nearing large scale production are cylindrical wound cells, flat wound cells, and prismatic cells with flat plates.

Some previous efforts were based on flat-wound and cylindrical cells. The assumed format of ANL scientists is most likely not the best design, however those successful in producing batteries in the year 2020 will reach similar energy densities and costs through other means.

To provide a specific design for the calculations, a prismatic cell in a stiff-pouch container was selected (compare Fig. 28).

**Battery Pack Design**

The cells are placed on their sides in the module. The model designs the battery pack in sufficient detail to provide a good estimate of the total weight and volume of the pack and the dimensions of the battery jacket so that its cost can be estimated. The modules in a row are interconnected, negative to positive terminals by cooper connectors. The modules (Fig. 29) are supported by a tray that provides space for the heat transfer fluid (ethylene glycol-water solution) to flow against the top and bottom of each module.

**Modeling of battery design and performance**

The design portion of the model calculates the physical properties of a battery based on user defined performance requirements and minimal experimental data (compare Fig. 30). The user is asked to enter a number of design parameters such as the battery power, number of cells and modules, etc. In addition, the user must enter one of the following three measures of energy: battery pack energy, cell capacity or

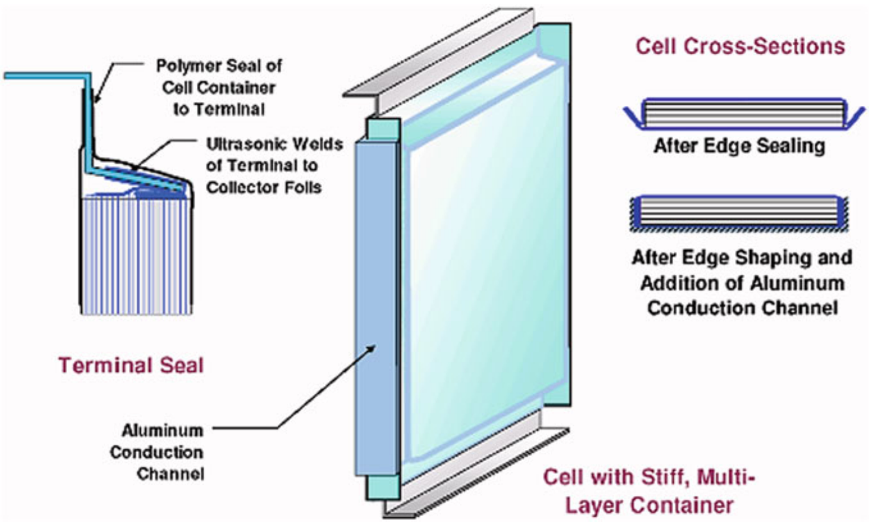



**Fig. 28** Prismatic cell in a stiff-pouch container, to enable calculations [31]

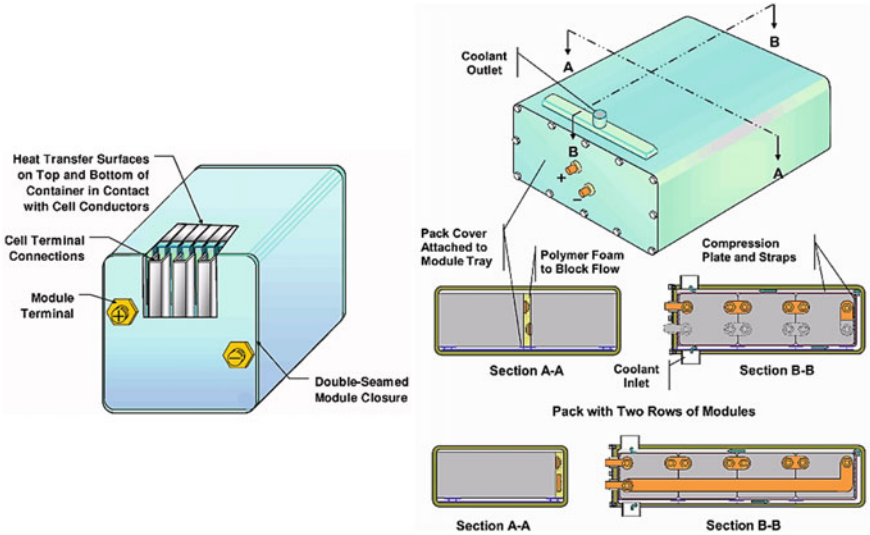



Fig. 29 Assumed battery format: module and pack [32]

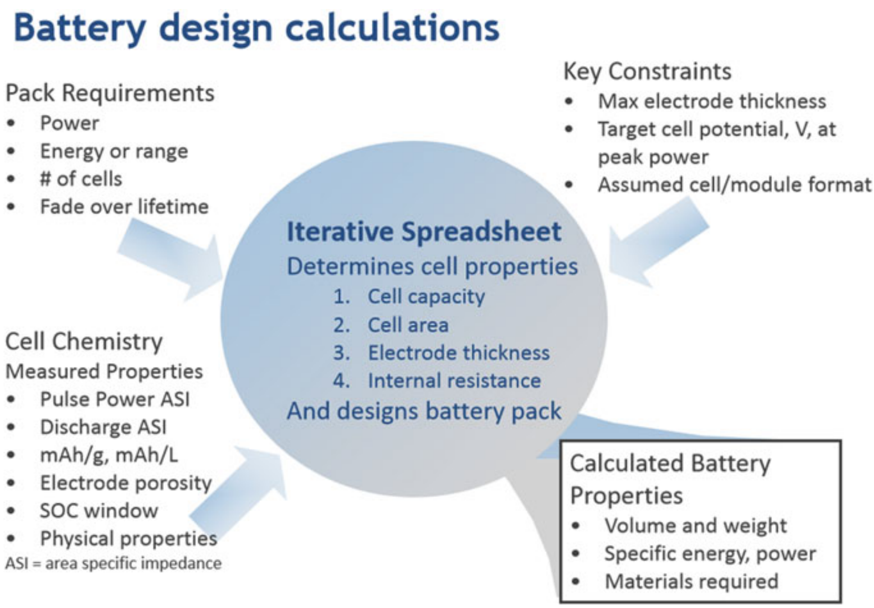


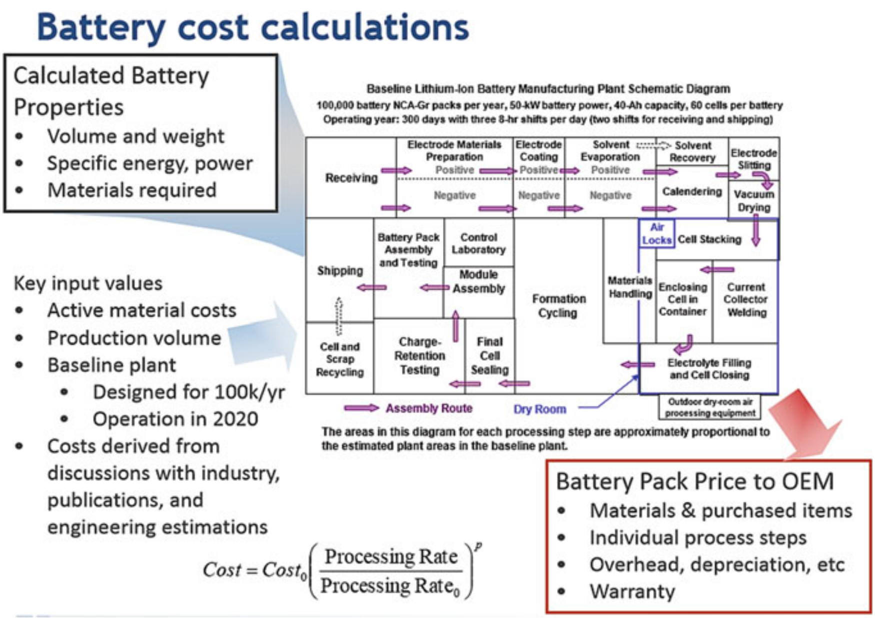

Fig. 30 Summary flow of the design model [33]

vehicle electric range. The model of the battery cost calculations is shown in Fig. 31. This figure shows the baseline Li-ion battery manufacturing plant schematic diagram. This baseline plant is designed to produce 100,000 battery NCA-Gr packs per year. This figure highlights also the adjustment of costs for varying production volumes.

**Illustrated results**

For a set battery pack power, the number of cells in the pack has substantial effects on the price of the pack, the pack voltage and the maximum current. These effects are illustrated in Fig. 32 for NMC441-Gr PHEV25 batteries (providing 40 km (25 mi.) electric range) with 60 kW power at a V/U = 0.8. The price of the pack increases by 17 % in changing the number of series-connected cells in the pack from 32 to 96 and the entire pack integrated cost increases by 15.7 %. The integrated cost includes additions to the vehicle air-conditioning system to provide for battery cooling and the BMS with disconnects. The change of the maximum current, resulting from differing pack voltages, would also affect the cost of the motor and the electronic converter and controller, but in the opposite direction.

Thus, BatPac demonstrates how to reduce the cost of today's batteries by lowering the cell count, moving to large cell formats (from 15 to 45 Ah) and by increasing the maximum achievable electrode thickness. Further, it quantifies the benefits of the future chemistries, as it can be seen in Fig. 33.




$$Cost = Cost_0 \left( \frac{\text{Processing Rate}}{\text{Processing Rate}_0} \right)^p$$

**Fig. 31** Battery cost calculations [34]

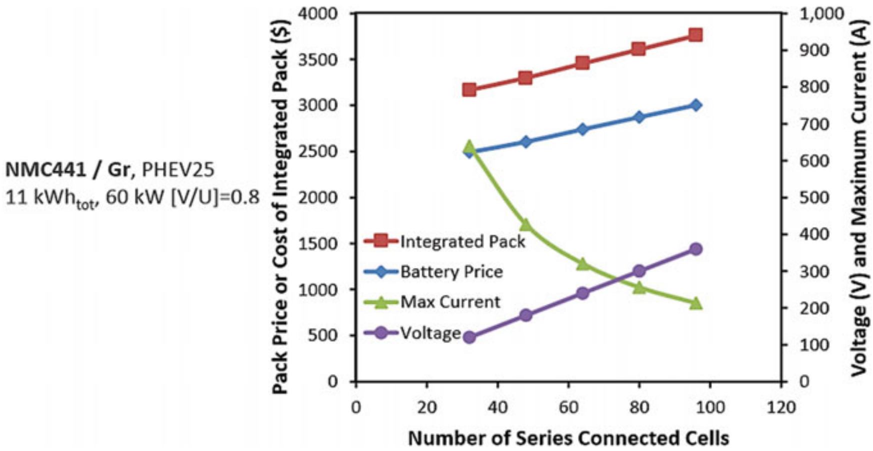



**Fig. 32** Optimization of system costs [35]

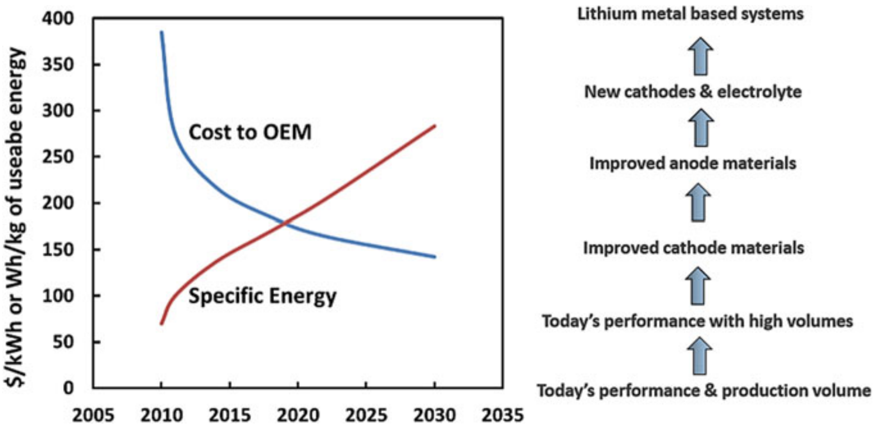



**Fig. 33** Path forward for Lithium battery research [36]

The developed BatPaC model may be used to study the effects of battery parameters on the performance and the manufactured cost of the designed battery packs.

BatPaC can be downloaded by the following link: http://www.cse.anl.gov/batpac/download.php.

## 3.8 Selection of BMS Suppliers and Manufacturers

As this Task started in 2010, where e-mobility was not so familiar and common as it is today, one of the key activities of this Task was the collection of different suppliers and manufacturers. During the last five years of reporting a lot of business fields have been changed, modified, extended or have been removed. Thus, quiet a lot of suppliers and manufacturers which have been reported from the first Operating Agent in 2011, are not existing anymore, due to financial crises, a wrong business plan or the weak demand for e-mobility.

This section of the report tries to show a selection of common suppliers, in order to enable an overview of different model and concepts.

**AVL List GmbH**

The Austrian company AVL is the world's largest independent company for the development of powertrain systems with internal combustion engines as well as instrumentation and test systems.

*AVL Software and Functions offers, among others, innovative and automotive-compliant solutions for the following core functions of different battery types: the determination of the loading and health condition (SoC and SoH), the provision of different functions (SoF), active and passive balancing and cell failure detection.*

*The BCU consists of both, a low voltage and a high voltage part. The low voltage part includes a powerful 32 Bit floating point CPU, and several output drivers to control auxiliary components like HV contactors, water pumps, LV relays, fans or charge sockets. A variety of digital and analog input ports ensure enough flexibility for additional sensors and signals.*

*The high voltage part of the BCU includes high voltage measurement inputs and an integrated isolation guard, capable of up to 800 V total system voltage.*

*The vehicle interface is designed to be simple and easily understandable. The battery activation can be done by a discrete wake-up signal or a combination of wake-up signal and a single CAN request. The internal battery control (switching contactors, contactor weld diagnoses, balancing, isolation monitoring, SoC calculation, and much more) is handled by the BCU and does not need external algorithms. The BCU outputs the necessary CAN signals like pack and DC-link voltage, pack current flow (100 Hz), voltage and current limits, temperatures and SoC.*

***Hardware***

*The BCU features a 32-bit microcontroller including a wide variety of I/Os to manage and communicate with various sensors and actuators as well as to interface with the module control units. The BCU supports up to 3 CAN networks which are typically used for vehicle communication, internal CAN between BCU and MCUs and optional CAN for such items as instrumentation CAN or service CAN. There is also a redundant digital synchronization and fault circuitry for BCU/MCU network safety monitoring.*

*The MCU is an 8-bit controller that supports up to 12 cells in series. The MCU senses cell voltage (every cell) and temperature (up to 4 temperatures per module) and reports these values to the BCU. There are different MCU HW design sizes available, from minimal sized MCU (passive balancing, XX communication) to* *smart-MCUs for 48 V packs incorporating all necessary features for standalone operation.*

***Software functions***

*The in-house developed BMS software comprises basic and application layer software. Many functions are model based. Supported functions include: Battery Core Functions, BCU State Control, Contactor Control, Electrical Hazard Protection, Thermal Management, Battery Protection, Module Control, BCU Communication, Charge Control, Diagnostic Event Handling, Diagnostic Event Manager and Balancing Control: Control cell balancing* [37] (Fig. 34).

**A123 Systems**

A123 Systems, LLC develops and manufactures advanced Nano phosphate lithium iron phosphate batteries and energy storage systems that deliver high power, maximize usable energy, and provide long life, all with excellent safety performance.

A123's system design takes advantage of the patented Nano phosphate® cell technology which delivers high power, excellent safety, and long life. This high-performance cells are incorporated into battery modules which serve as the building blocks for advanced energy storage systems. All modules and systems are built with high-grade components, battery management systems, and thermal management for long battery life and retained capacity.

A123 has developed and validated an automotive-grade electronics and software set for battery management, designed to ensure the safe and reliable operation of large battery systems. The distributed system consists of a battery control module, current sense module, monitor and balance electronics, and an electrical distribution module. Features of the BMS include industry standard CAN and diagnostic

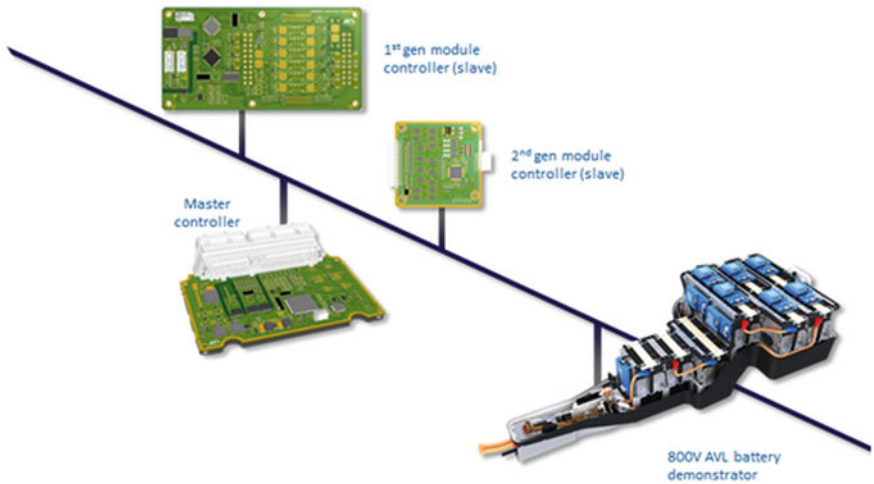



**Fig. 34** Overview of AVL module system [38]

interfaces, SoC and SoH algorithms, charge management, and safety management. The BMS components can be reused use across energy and power systems to enable rapid design and development of a cost effective system.

Figure 35 shows the Nano phosphate® Energy Core Pack (23 kWh) module, which is designed for PHEV and EV applications as ready-to-use sample packs for rapid deployment into powertrains for testing and development purposes. Off-the-shelf energy core packs offer an already finished design to facilitate early vehicle development with less lead time and no engineering charges. Each pack comes equipped with battery management electronics, thermal management, and standard vehicle communication and control interface.

**AKASOL Engineering**

The German company AKASOL, develops and produces innovative Li-ion battery systems for the automobile and commercial vehicle industries, as well as for wind energy, hydropower, and solar industries as well as for the shipbuilding industry. Thus, this company is working on battery systems like *AKASYSTEM* (previously known as AIBAS), which is one of the world's most powerful battery solutions for BEVs or (P)HEVs. The system is freely scalable, automotive-certified, standardized, and ready to order and made in Germany. AKASYSTEM operates with passive and active thermos management using liquid cooling. Cell temperatures therefore always remain within the recommended range even under heavy use. This promotes high performance values and prolongs service life.

The basis of the modular scalable Li-ion AKASYSTEM (compare Fig. 36) battery systems is formed by the highly integrated module *AKAMODULE* (see Fig. 37).

One of the decisive advantages: despite the extremely high functional integration on a modular level, the AKAMODULE achieves energy density of more than 140 Wh/kg. This enables long vehicle range with simultaneously exceptional durability. Every AKAMODULE is cooled with a water-glycol fluid mix and it provides an extremely compact and lightweight solution here with an intelligent combination of housing and cooling structure. The technical data of the battery module is shown in Table 3.

**Fig. 35** Cell (*left*), module (*middle*) and system (*right*) [39]


**Fig. 36** AKASYSTEM is regarded as one of the most powerful battery solutions [40]


**Fig. 37** Battery system and module by AKASOL [41]

## Bosch

Bosch Battery Systems develops, manufactures and markets battery systems for all kind of xEVs (see Fig. 38). As well as providing individual components, Bosch Battery Systems also offers a full range battery system—all from a single source. The areas of operation are including: battery systems for HEVs, PHEVs and BEVs,

**Table 3** Key data for Akasol Engineering battery module

| Product design | AKAMODULE 53 NMC | AKAMODULE 46 Nano NMC |
|---|---|---|
| Chemistry | Li-ion NMC | Li-ion Nano NMC |
| Energy | 2.35 kWh | 2.04 kWh |
| Weight | 17.5 kg | 17.5 kg |
| Energy density | 134 Wh/kg, 240 Wh/l | 117 Wh/kg, 201 Wh/l |
| Discharging performance nom./max. | 11.8 kW/18.8 kW | 11.8 kW/25.0 kW |
| Charging performance nom./max. | 4.7 kW/11.8 kW | 10.2 kW/16.3 kW |
| Capacity | 159 Ah/106 Ah/53 Ah | 138 Ah/92 Ah/46 Ah |
| Voltage | 14.8 V/22.2 V/44.4 V | 14.8 V/22.2 V/44.4 V |
| Service life @ 80 % DoD | >3100 cycles | >5,600 cycles |
| Dimensions (W × H × L) | 260 × 232 × 168 mm | 260 × 232 × 168 mm |

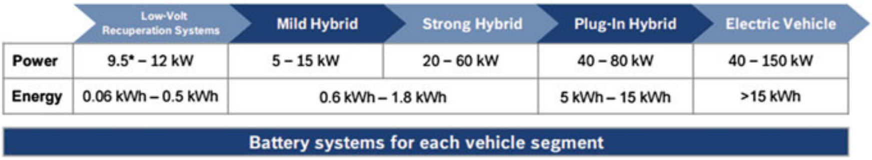



**Fig. 38** Overview of different battery systems by Bosch [42]

modules for systems, hardware and software for BMS as well as thermal management systems. Thus, it covers all types of applications including Li-ion battery technology for automotive powertrain applications.

Bosch is working on smart Li-ion BMS and is developing a system that sends data through the cell connectors rather than a dedicated communications network. The system, designed for EVs and PHEVs, should boost performance, safety and battery service life as well as reducing weight in Li-ion packs. Bosch is researching the innovative system, which uses the path travelled by the electricity in the battery to carry data. The data is then sent to a central control unit, eliminating the need for costly data-transmission wiring (see Fig. 39).

Bosch's intention is to constantly monitor and to control each battery cell individually. This will allow optimum use of the battery's energy. If a single cell in the battery is no longer operating efficiently, then only that single cell will have to be replaced, not the whole module. Migrating data transfer to the internal wiring would allow the battery pack's energy use to be optimized, and would also help to reduce costs.

## I+ME ACTIA

I+ME ACTIA performs research of new battery technologies based on Ni- MH and Lithium Polymer (LiPo) batteries. They have also been working on the development of BMS since 1995. The BMS are mainly designed for the implementation of NiMH or Li-Po batteries in mobile applications.

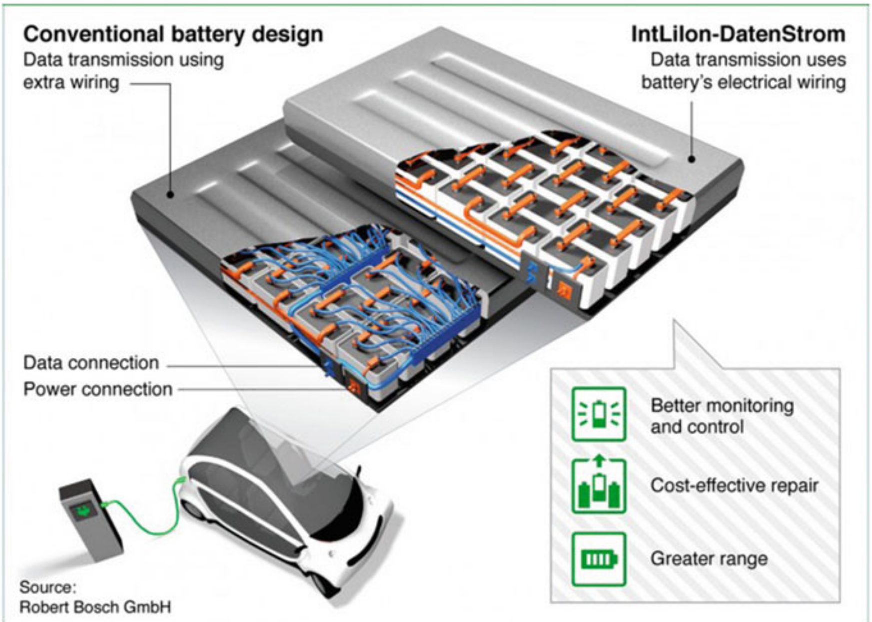



**Fig. 39** Using a battery's internal wiring to send data [43]

The BMS of I+ME ACTIA consists of one master and up to 20 slaves (compare Fig. 40).

The master function includes the voltage measurement for the whole battery and the communication with the slave modules. The master takes control over the protective relay, if a limit is exceeded. Further, the SoC and SoH were determined and can be sent over a CAN Interface to the vehicle controller. Thus, the master consists of 8 digital inputs with different characteristics, 8 digital outputs for activation of contactors or relays, CAN bus for communication with other control units, an Ethernet interface for representation of system data and status RS232 interface for communication with a PC.

**Fig. 40** Master (*left*) and slave (*right*) unit of Actia [44]

Whereas the slave module is responsible for measuring the cell voltages, it includes also the cell balancing of the battery module. Here we have an accuracy of maximum ±5 mV.

The slave consists of a microprocessor controlled part of the BMS, the measuring and monitoring of 5–10 cells on a Li-ion basis, the measuring of voltage and temperature of cells and control the voltage balancing, 10 differential analogue inputs and 3 analogue inputs for measuring of temperatures.

Moreover the slave measures the temperature and sends all data to the master unit for the top-level control. The limit values of the BMS can be configured by software.

The battery systems of this company are often used in hybrid vehicles, bicycles, forklifts, wheel chairs and robots. The technical details of the Master and Slave unit are online available [45].

### Johnson Control

Johnson Control supplies complete battery systems covering activities from design to manufacturing and is the leading independent supplier of hybrid battery systems to make vehicles more energy-efficient (see Fig. 41). It was the first company in the world to produce

Li-ion batteries for mass-production HEV. The BMS from Johnson Control is well suited for applications in the automotive sector. Battery systems using the Johnson Control BMS are able to interact with other automotive systems and adjust their performance to go with the ever-changing conditions. This is realized with the help of microprocessors and hardware adaptations. Further in this BMS a thermal management is included. Thus, Johnson Controls has expertise in designing, developing, and integrating fully integrated air- and liquid-cooled battery thermal management systems.

Electronic Management-Johnson Controls' system electronics integrate cell balancing for extended driving range and battery life. Diagnostics and voltage monitoring can be run on each individual cell which includes temperature controls. Johnson Controls has the capability to design and produce the cell supervision circuit and balancing electronics in our global Li-Ion battery technology centers and facilities. The technical specifications are listened in Table 4.

The functionality of the Johnson Control Battery management system is shown in Fig. 42. This figure shows that the BMS gains on the one hand information from

**Fig. 41** Product portfolio of Johnson Control (batteries from *left* to *right*: advanced start-stop vehicles; micro HEVs; (P)HEVs and EVs) [46]

**Table 4** Technical specifications of Johnson Control batteries for HEVs and PHEVs/EVs [47]

| Specification | Battery for HEV | Battery for PHEV and EV |
|---|---|---|
| Dimensions | 657 × 383 × 191 mm (25.9 × 15.1 × 7.5 in) | 1184 × 498 × 296 mm (46 × 19.7 × 11.6 in) |
| Capacity | 6.8 Ah | 41 Ah |
| Voltage: | 259 V | 345 V |
| Total energy | 1.5 kWh | 14.4 kWh (45-mile range @ ~250 Wh/mile) |
| Weight | 46 kg (101 lb) | 149 kg (328 lb) |
| Thermal management | Parallel-flow water/glycol liquid cooling system | Parallel-flow water/glycol liquid cooling system |

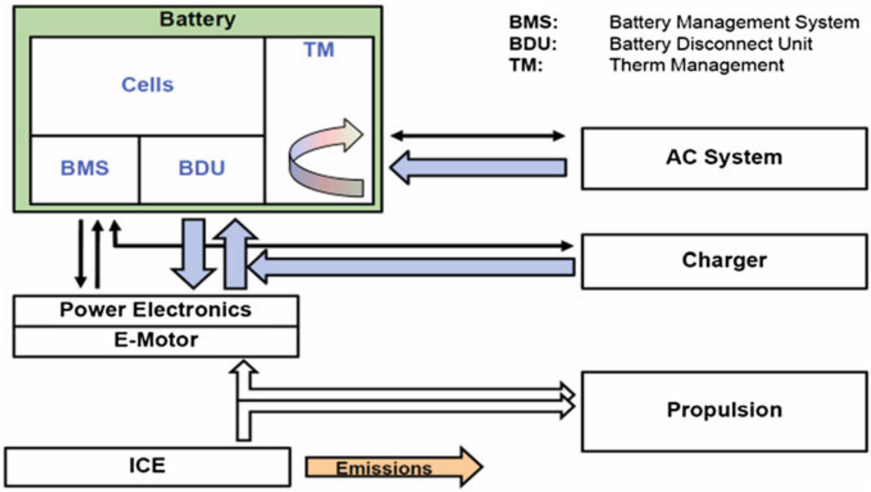



**Fig. 42** BMS functionality of the firm Johnson Control [48]

the power electronics and the motor, while on the other hand the BMS controls the power output stage. Over the battery disconnect unit, the battery can be suspended from the electronic. This is for secure, if a failure occurs. Further the charger gives information of the battery to the BMS, which adapts the characteristics to the actual battery. The thermal management is important, due to the fact that the temperature of a Li-ion battery does not exceed the temperature limitation. Else the life expectancy of the battery will decrease.

The BMS (compare Fig. 43) measures the battery voltage and current. With this information the system is able to control the secure of the system. Moreover the cell balancing is supervised and also the temperature.

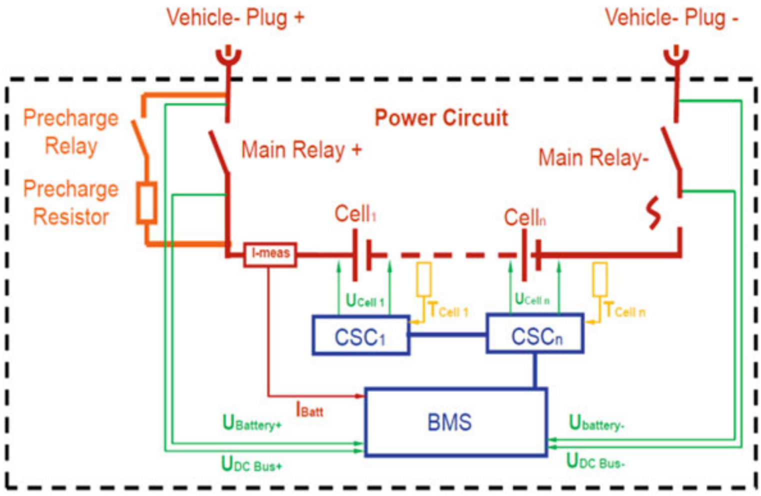



**Fig. 43** Schematic of the BMS [49]

# 4 Thermal Management

During the last years strong attention has been paid to increase the energy density of EVs batteries or to improve the energy consumption of the electric powertrain as well as of the auxiliary components of the vehicle. For BEVs, heating and cooling the cabin is an issue, many people have been working on since years.

> *Thermal management has a high potential for improving fuel economy and reducing emissions of HEVs and BEVs. Thus, thermal management of batteries is essential for effective operation in all climates. During the last years, the optimization of thermal management of vehicles has become an important business segment* [50].

**Thermal Management effects** (compare Fig. 44):

- **fuel/energy consumption** (e.g. friction losses, combustion process, recovery of energy losses, efficiency, etc.),
- **emissions** (e.g. cat-light-off, EGR/SCR strategies, etc.),
- **engine performance** (e.g. effective cooling, engine efficiency, reduction of friction losses, etc.),
- **comfort and safety** (e.g. cabin conditioning, windscreen defrosting, etc.)

Compared to a conventional vehicle in a HEV there are additional heat sources like e-motors, power electronics, batteries, etc. which have to be kept in a certain temperature range to generate high efficiencies and protect components against overheating. Due to the interaction between different subsystems like the combustion

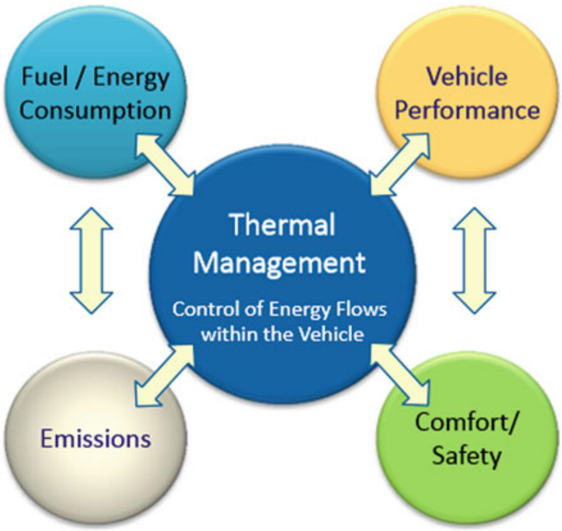



**Fig. 44** Thermal management and its impact

engine, e-motor/generator, energy storage and drive train for hybrid systems a comprehensive simulation model is necessary.

Figure 45 gives an overview about different drive train configurations, including the ICE, micro HEV, mild HEV, full HEV and PHEV/BEV and their requirements concerning new vehicle constraints; new thermal needs and new systems and components. This picture demonstrates the need for further thermal management systems.

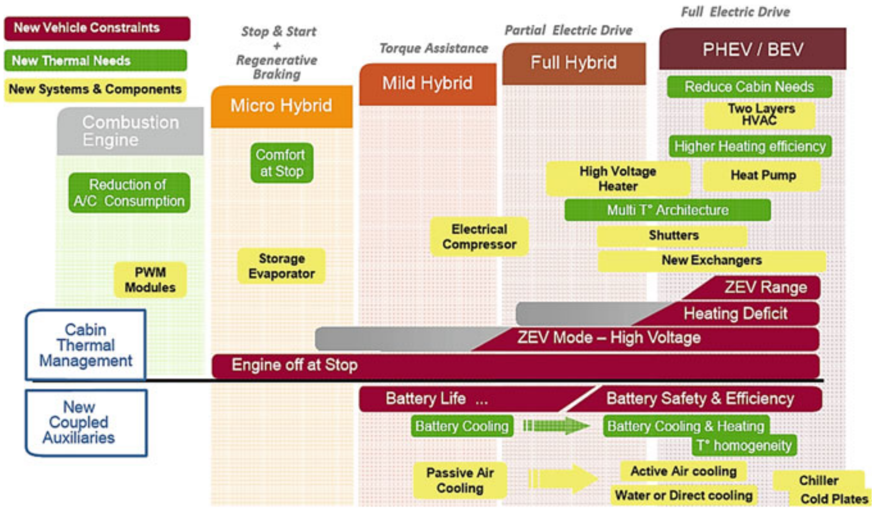



**Fig. 45** HEV/EV thermal management activities [51]

During the last years a lot of companies and R&D institutions realized the demand for thermal management solutions. Therefore two Task 17 workshops were held in Chicago (2013) and Vienna (2014), focusing on Thermal Management Systems (TMS) and concepts for HEVs.

Companies and Research Institutes as ANL, Austrian Institute of Technology (AIT), Delphi, Fraunhofer, qpunkt, Valeo presented their results and concepts.

A selection of the most imported ones are mentioned in this section.

**Overview of ambient temperature impact and drive pattern on energy consumption for HEVs, PHEV and BEV**

The ANL highlighted the ambient temperature impact and drive pattern on energy consumption. Thus, they compared a BEV (Nissan Leaf 2012), HEV (Toyota Prius 2010) and a conventional one (Ford Focus 2012).

The study included a comprehensive thermal study: 7 vehicles spanning conventional vehicles (CV) (gas and diesel), HEVs (mild to full), a PHEV and a BEV, which have been tested on cold start UDDS, hot start UDDS, HWFET and US06 at ambient temperature of −7 °C (20 °F), 22 °C (72 °F) and 35 °C (95 °F) with 850 W/m$^2$ of sun emulation (compare Fig. 46).

The output of this study demonstrates the following facts:

- **−7 °C (20 °F) cold start** has the largest cold start penalty due to high powertrain losses and frictions. Once a powertrain reached operating temperatures, the energy consumption is close to the 22 °C (72 °F) results again (see Fig. 47),
- **35 °C (95 °F) environment** requires a constant A/C compressor load which impacts the energy consumption across all vehicle types on hot and cold starts,
- **worst cases scenarios** for the different vehicle types:

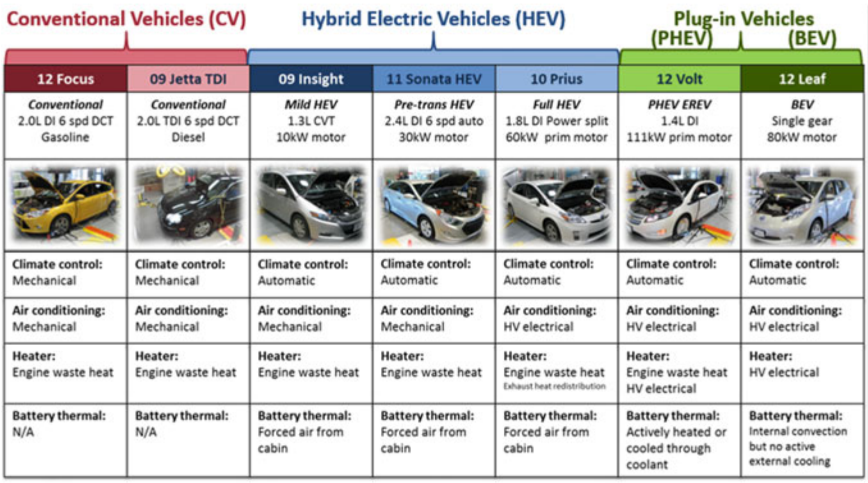



**Fig. 46** Wide technology spectrum of research vehicles [52]

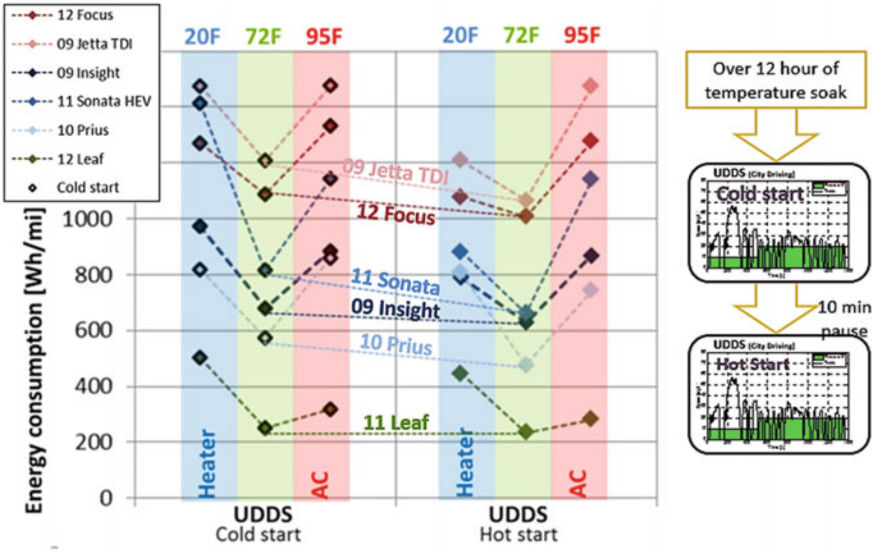



Fig. 47 UDDS energy consumption for cold and hot start [53]

- **CV**: 35 °C (95 °F) environment due to 4–5 kW of extra air conditioning load,
- **HEV**: both −7 °C (20 °F) and 35 °C (95 °F) have a large range of increase due to a change in hybrid operation (fuel and electricity trade off),
- **PHEV**: −7 °C (20 °F) where the PHEV uses both the engine and the electric heater to warm up the powertrain and the cabin,
- **BEV**: −7 °C (20 °F) due to 4 kW of heater which can double the energy consumption on a UDDS,

- **Battery system resistance** doubles from 35 °C (95 °F) to −7 °C (20 °F) for all battery chemistries in the study

Looking in more detail into the study, as it can be seen in Fig. 48, using the heater in an electric car may double the energy consumption in city type driving. Figure 49 shows that driving at higher speeds and aggressively will increase the energy consumption in an electric car.

By comparing the cold start energy function and the hot start energy consumption it is obviously that the cold start energy consumption is larger than the hot start one (see Fig. 50).

Figures 51 and 52 are showing the largest energy consumptions increases for a BEV and for a conventional one. Thus, the largest energy consumption increase for an EV occurs at −7 °C (20 °F) and for a conventional at 35 °C (95 °F), while a conventional vehicle has the largest absolute energy consumption penalty on a cold start.

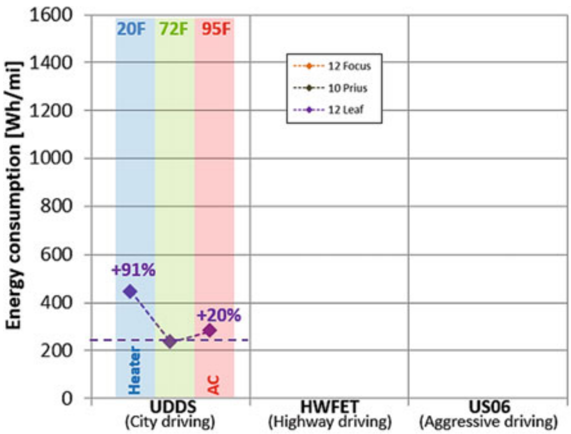



**Fig. 48** Using the heater in an electric car may double the energy consumption in city type driving [132]

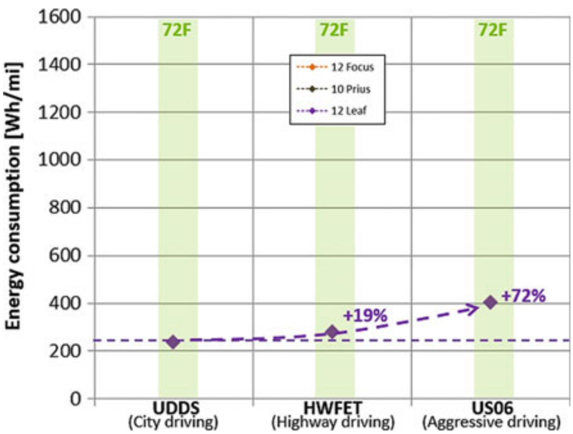



**Fig. 49** Driving at higher speeds and aggressively will increase the energy consumption in an electric car [54]

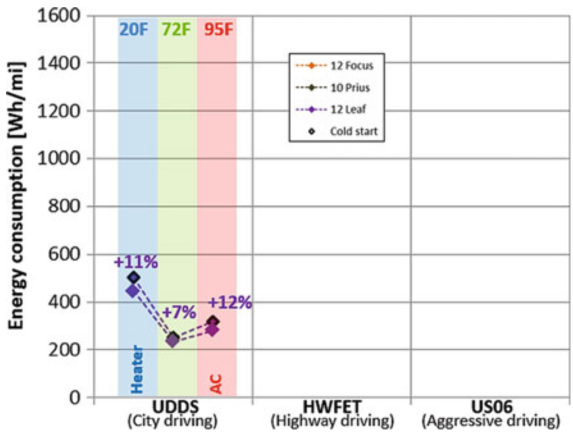



**Fig. 50** Cold start energy consumption is larger than the hot start energy consumption [55]

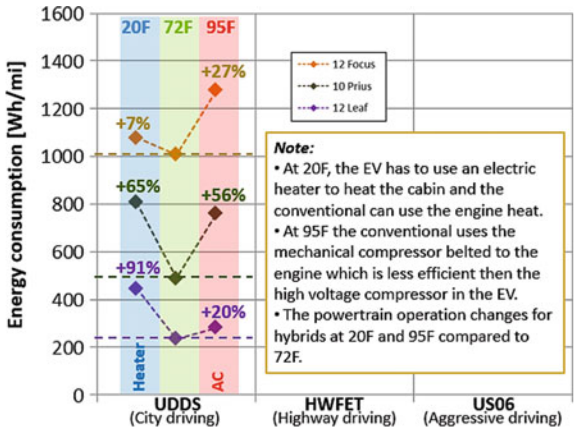



**Fig. 51** Largest energy consumption increase for an EV occurs at −7 °C (20 °F) and for a CV at 35 °C (95 °F) [56]

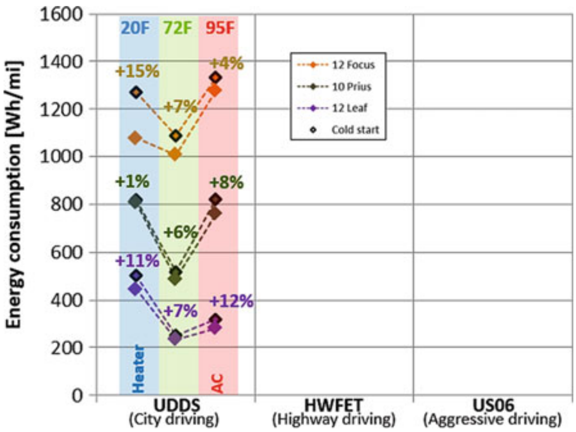



**Fig. 52** A conventional vehicle has the largest absolute energy consumption penalty on a cold start [57]

Figure 53 shows that generally increased speeds and accelerations translate to higher energy consumption, except for the conventional due to low efficiency in the city.

For more information of this study refer to Journal of Automobile Engineering [59].

*Driving at higher speeds and aggressively will increase the energy consumption in an EV.*
*Cold start energy consumption is larger than the hot start energy consumption.*
*Largest energy consumption increase for an EV occurs at* −7 °C (20 °F) *and for a conventional at* 35 °C (95 °F).
*A CV has the largest absolute energy consumption penalty on a cold start.*
*Generally increased speeds and accelerations translate to higher energy consumption except for the conventional due to low efficiency in the city.*

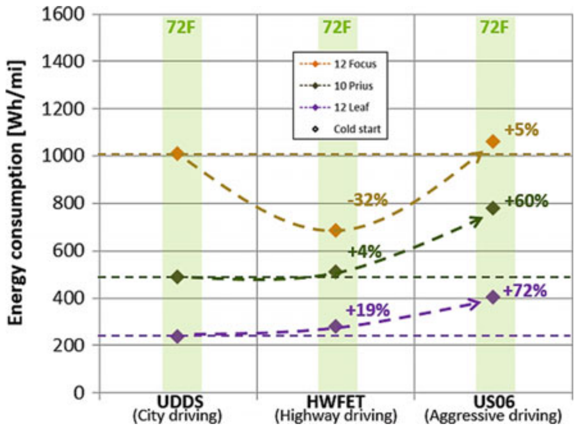



**Fig. 53** Generally increased speeds and accelerations translate to higher energy consumption except for the CV due to low efficiency in the city [58]

## 4.1 Heating Technologies

**In** **conventional vehicles** (driven by an ICE) **the heating system is usually fed by the waste heat of the combustion engine**. The ICE has a relatively low efficiency of about 30–40 % so that a lot of waste heat has to be dissipated to the cooling system. **One part of these heat losses is then transferred to the vehicle cabin by a heat exchanger** and forced convection due to a fan, the other part is dissipated to the surrounding environment by a cooler. The usage of this heat has no direct influence on the driving range of the vehicle because it is generated as part of the combustion process.

**In BEVs, this waste heat is not available, the heat for heating the passenger compartment has to be taken from other sources**. **Due to the high efficiency of the drive components, as the electric machine, the power electronics and the battery, only little waste heat is generated, which is not enough to heat the cabin**. Hence, the heating system has to be powered by another source. If heat is generated electrically by energy taken from the traction battery, the driving range of the vehicle may be reduced by up to 50 % (compare visualization Figs. 54 and 55).

Qpunkt, an Austrian company, evaluated the range losses due to vehicle heating (average for January), based on a 1D Matlab Simulink Simulations with a given, average driving power for urban and overland cycles depending on the ambient temperature (compare Fig. 56).

qpunkt is a specialist in the fields of thermal management, computational fluid dynamics (CFD) and acoustics, in automotive engineering and in other areas such as aviation, railway, research and development.

In BEVs heat has to be generated instead of using waste heat.

The easiest way is to use the electrical energy stored in the traction battery of the vehicle by using a positive temperature coefficient element (PTC) to generate heat (reduction of the driving range). Another possibility for a heating is based on burning a $CO_2$ neutral fuel like bioethanol and thus generating heat (bioethanol tank, which has a negative influence on the vehicle weight).

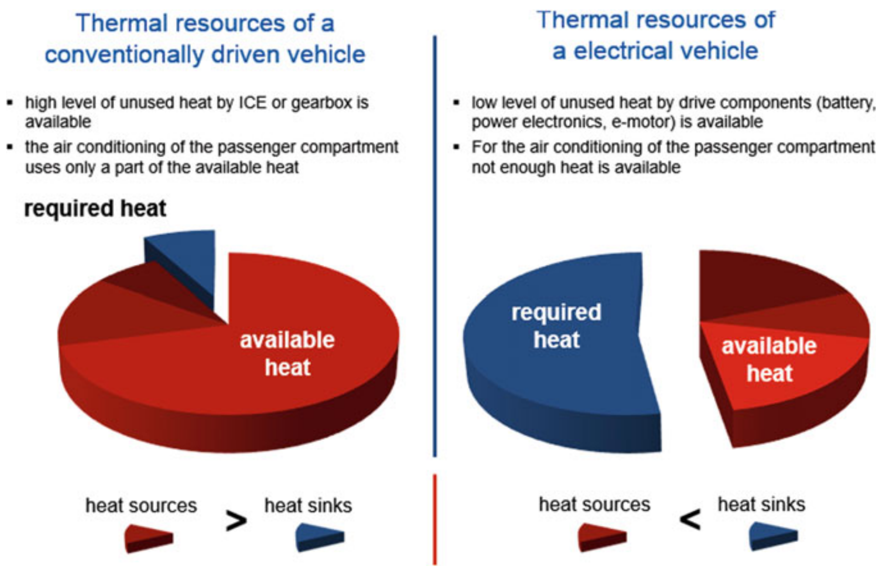



**Fig. 54** Thermal resources of a CV (*left*) and of an EV (*right*) [60]

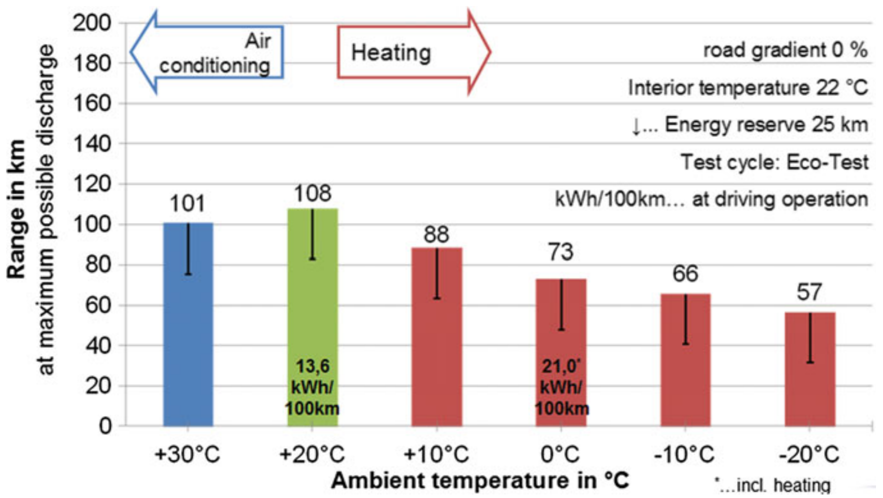



**Fig. 55** Influence of heating and cooling an EV on the range anxiety [61]

Cold weather conditions affect the battery, notably in terms of:

- **capacity**: a very cold battery doesn't fully charge. It can be compared to a fuel tank that contracts in the cold. The result is, of course, reduced range,
- **power**: a cold battery cannot provide all the power required by the motor, reflected in weaker acceleration. These batteries are highly sensitive to temperature changes

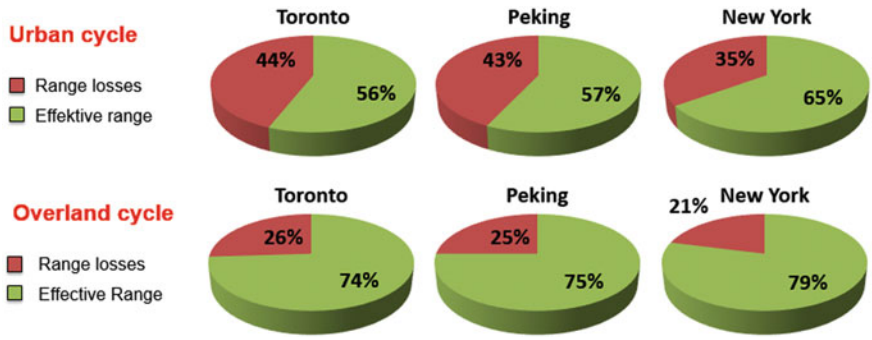



**Fig. 56** Range losses due to vehicle heating (average for January)—bases on 1D Matlab Simulink Simulations with a given, average driving power for urban and overland cycles depending on the ambient temperature [62]

and can be negatively impacted if improperly designed. Depending on where the climate control system is located, the battery life can be either positively or negatively impacted by the climate control design of the vehicle and

- **charge**: an overly cold battery cannot be charged too fast, making for longer “quick” charging times. Cold, however, has no impact on standard charging, via a Wall-Box.

One of the emerging technologies being used to solve cooling and heating problems for EVs and HEVs is the heat pump. This technology has been around for decades—but heat pumps are just now coming into their own in the automobile industry. They transfer heat to and from a working fluid (a refrigerant in most cases) to the air. As such, heat pumps can be used to both heat and cool the cabin of a vehicle and are estimated to increase battery range substantially.

By introducing the Renault ZOE, Renault presented the first EV, which uses a heat pump in addition to an air conditioning. The heat pump fitted on ZOE (compare Fig. 57) is a reversible air conditioning system.

The following subsections listen different concepts and technologies which have been demonstrated during the Task 17 workshops, mentioned above.

## *4.2 Automotive Thermal Comfort by Valeo*

**Valeo** started to implement the thermal systems business group into their portfolio. This business group develops and manufactures systems, modules and components to ensure thermal energy management of the powertrain and comfort for each passenger, during all phases of vehicle use. Therefore they are focusing their work on: climate control, powertrain thermal systems, climate control compressors and the front end module.

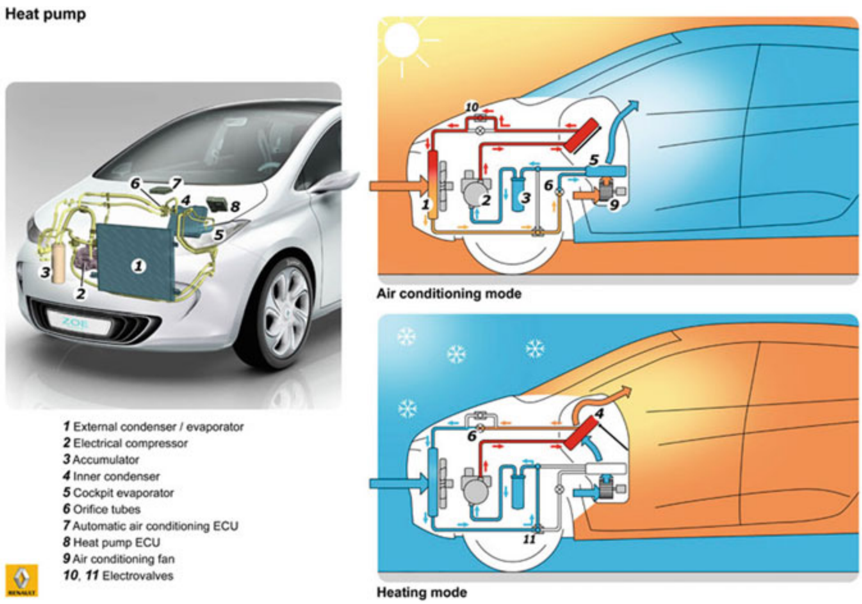



**Fig. 57** Heating system of the Renault ZOE [63]

Valeo offers a wide range of different technologies for thermal management solutions.

**Stop Stay Cool (SSC) Evaporator**: this evaporator consists of an Embedded Phase Change Material (PCM) to store and recover energy when the engine is off. This enables the benefits of thermal comfort at stop (with engine off) and no changes to the module architecture are required. The SSC enables a longer engine shut off at high heat loads (see Fig. 58).

**Front-End Integration (Active Shutter)**: front-end has an impact on overall power efficiency (emissions and fuel economy). Active Shutters improves heat pump deicing and lowers the drag coefficient. The front-end design and integration is a key to leverage: system efficiency; compressor downsizing and operating range (see Fig. 59).

**Cooling technologies: depending of the vehicle itself, different cooling techniques are available, like: passive air cooling, active air cooling, liquid cooling and direct cooling** (Fig. 60). **Passive air cooling** systems is suitable for low performance city vehicles with low mileage per day and no fast charging. Compromises with vehicle performances have to be accepted. **Active air cooling** is used for average driving conditions with sufficient battery capacity. Fast charging is one of its limitations. Liquid cooling is used by high performance EVs, which depend on 100 % availability in all driving, charging and ambiences. **Liquid cooling** can also be used for easy heating. **Direct cooling**, also known as refrigerant direct cooling is used by high performance hybrids, which do not depend on 100 % availability under all ambient conditions (specifically winter conditions).

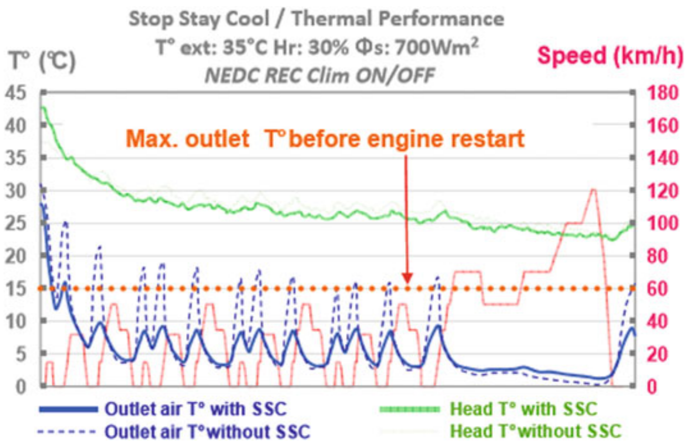



**Fig. 58** Performance and benefits of the SSC evaporator [64]

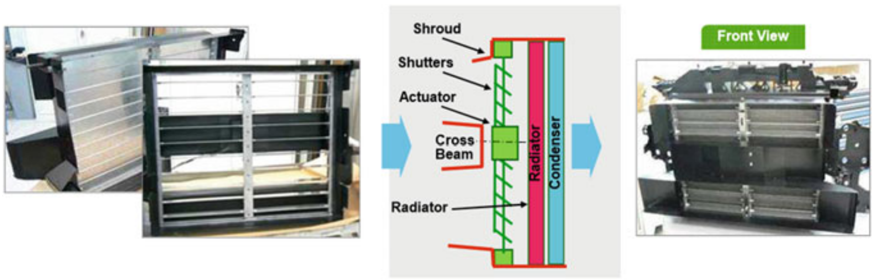



**Fig. 59** Front-end integration—active shutter (image courtesy by Valeo [65])

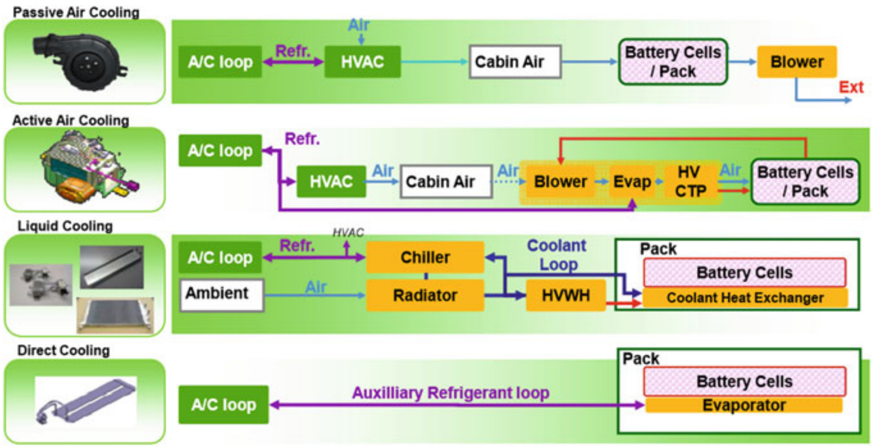



**Fig. 60** Different cooling techniques for xEVs [66]

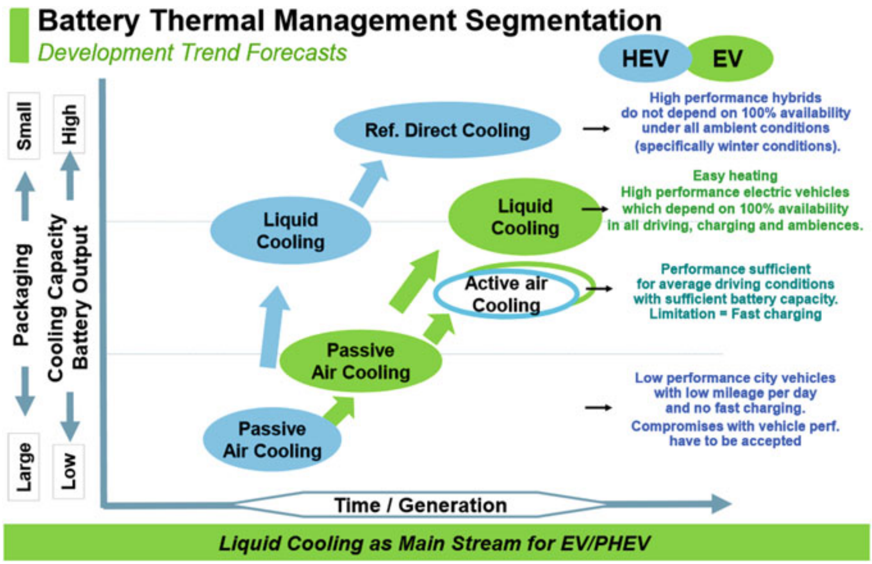



**Fig. 61** Battery TMS—development trend forecast [67]

Depending on the future trends, EVs and PHEVs are gaining more and more on popularity. Therefore cooling methods, especially liquid cooling can be seen as a main stream for EV/PHEV. This main stream in shown in Fig. 61. Thus, refrigerated direct cooling and liquid cooling might be the future cooling methods.

## 4.3 Development of Nanofluids for Cooling Power Electronics by Argonne

This project report is hosted by E. V. Timofeeva, D. Singh, W. Yu, D. France, from Argonne National Lab.

Two cooling systems are currently used for HEVs, higher temperature system for cooling the gasoline engine and lower temperature system for cooling the power electronics.

The DoE started a project with the goal to eliminate the lower temperature cooling system, such that all cooling is done with a single higher temperature cooling system. In order to reach this goal, the cooling fluid needs to have better heat transfer properties and the DoE proposed to use Nanofluids as coolants. Nanofluids have a proven ability to increase thermal conductivity and heat transfer and promise to reduce the size, weight, and number of heat exchangers for power electronics cooling.

### Definition of Nanofluids

*Nanofluids are fluids containing nanoparticles (nanometer-sized particles of metals, oxides, carbides, nitrides, or nanotubes). Nanofluids exhibit enhanced thermal properties, amongst them; higher thermal conductivity and heat transfer coefficients compared to the base fluid* [68].

Simulations of the cooling system of a large truck engine indicate that replacement of the conventional engine coolant (ethylene glycol-water mixture) by a Nanofluid would provide considerable benefits by removing more heat from the engine. Additionally, a calculation has shown that a graphite based Nanofluid developed by Argonne could be used to eliminate one heat exchanger for cooling power electronics in a HEV. This would obviously reduce weight, and allow the power electronics to operate more efficiently.

To develop Nanofluids for heat transfer (e.g., cooling), team used a systems engineering approach. This method enables scientists to look at how Nanofluid systems work by analyzing the behavior of the whole system, which is different than looking at each individual property of the system, such as nanoparticle material, concentration, shape, size and more.

### Nanofluids improve performance of vehicle components

Researchers from ANL have been working with industrial partners to create and test Nanofluids which improve the cooling of power electronics in HEVs. Fluids, containing nanoparticles, can lessen the need for heat exchangers by increasing the heat transfer efficiency. The results are smaller cooling systems and lighter vehicles.

During a Task 17 workshop researchers from ANL presented silicon carbide nanoparticles and ethylene glycol/water Nanofluid that carries heat away 15 % more effectively than conventional fluids. Further they've developed a graphite-based nanofluid that has an enhanced thermal conductivity 50 % greater than the base fluid, which would, under specific conditions, eliminate the need for a second heat exchanger for cooling power electronics. To develop nanofluids for heat transfer, the Argonne team used a systems engineering approach (compare Fig. 62). Using the systems engineering approach they discovered that particle size and shape in combination with particle concentration were key to designing effective Nanofluid coolants.

The project concentrated on further development of graphitic based nanofluids for hybrid electronic cooling that result in higher heat transfer coefficients while keeping the viscosity low.

Figure 63 shows the thermal conductivity mechanisms in Nanofluids. The project was focusing on development of graphitic nanofluids. ANL scientist developed surface modification of nanoparticles that uses electrostatic repulsion for achieving good dispersion, low viscosity and stability of suspensions, while percolation of nanoparticles provides high thermal conductivity.

**Accomplishments**: Study of particle shape effects in graphitic nanoparticles on thermal conductivity and viscosity of suspensions, in particularly graphitic platelet diameter and thickness (Fig. 64), allowed identification of promising graphitic

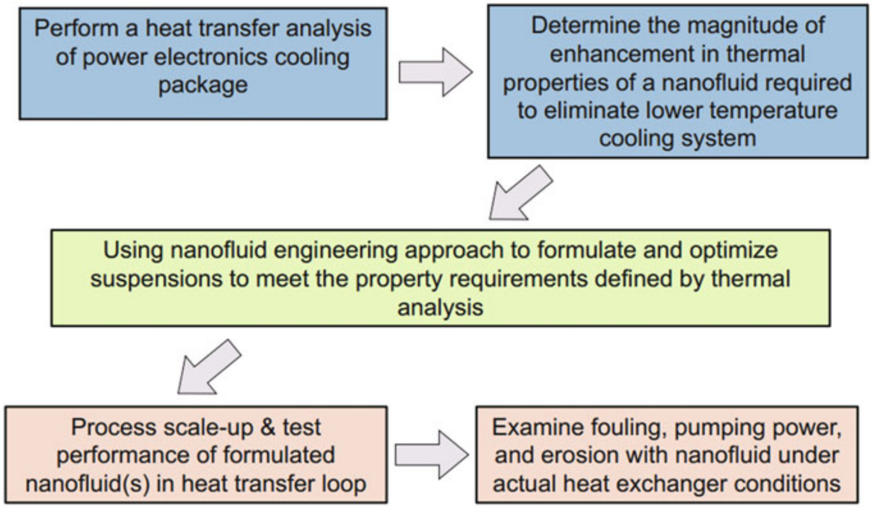



**Fig. 62** Approach for using nanofluids to replace heat exchangers [69]

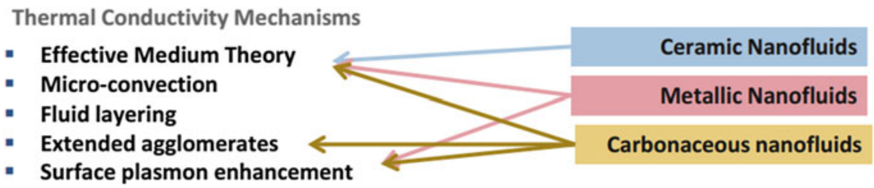



**Fig. 63** Thermal conductivity mechanism [70]

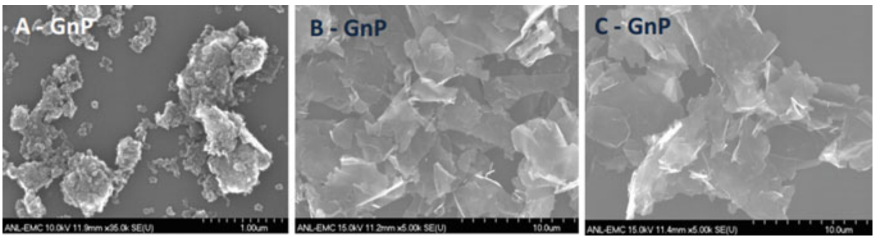



**Fig. 64** Various grades nanoparticle selections GnP [71]

additives (graphite nanoflakes or multilayered graphene), which are low cost and commercially available at large scale. Surface modification procedure was developed to overcome poor dispersibility of graphite in water and ethylene-glycol - water mixtures.

Thermal conductivity ratio between 1.5 and 2.3 at 5 wt% of nanoparticles (room temperature) enables possibilities for dramatic improvement in power electronics cooling. Figure 65 shows the calculated heat flux at double sided cooling, while Fig. 66 shows the heat flow at single-sided cooling.

**Project in a summary**:

- analysis of power electronics cooling system allowed establishing criteria for efficient nanofluid coolant such as thermal conductivity ratio of more than 1.5,
- such enhancements are possible with graphitic nanoparticles that are commercially available at reasonable costs (20 % added cost to coolants),
- graphitic nanofluids in 50/50 mixture of ethylene glycol and water showed:

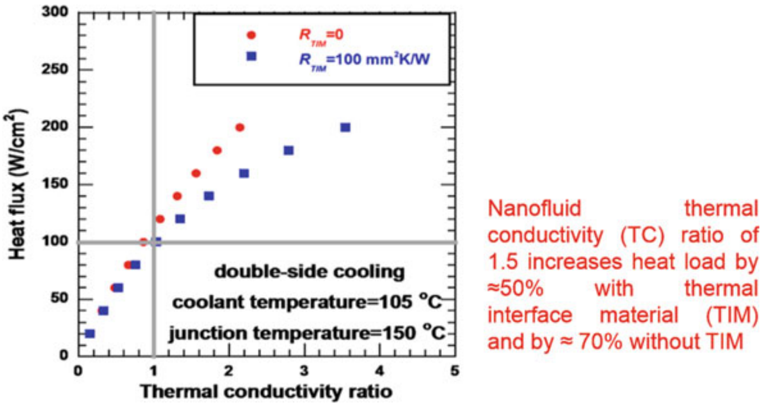



**Fig. 65** Heat flux—double sided cooling [72]

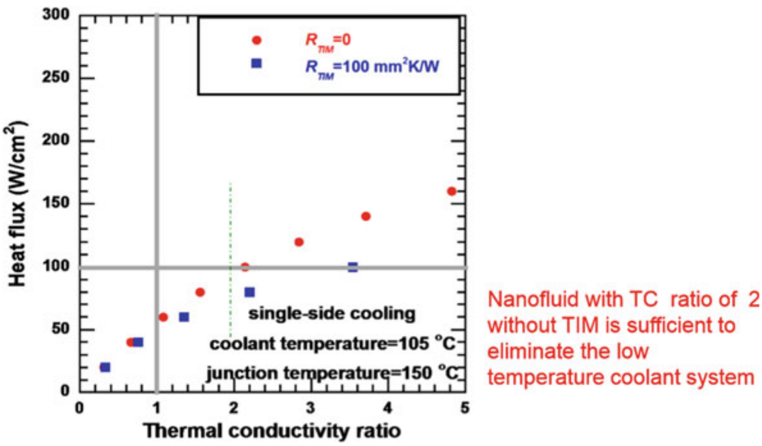



**Fig. 66** Heat flux—single sided cooling [73]

- morphology dependent thermal conductivity;
- 50–130 % increases in thermal conductivity at 5 wt% (room temperature)—possibilities for dramatic improvement in liquid cooling nanoparticle;
- surface treatment provides better dispersion stability, lower viscosity, and higher thermal conductivity;
- enhanced performance with temperature,
- the optimized and scale up nanofluid tested in a heat transfer loop, fouling and erosion tests further validated the commercial viability of the graphitic GnP nanofluid technology.

### *4.4 Eko-Lack: Simulation and Measurement of an Energy Efficient Infrared Radiation Heating of a Full EV by AIT and Qpunkt GmbH*

This project report is hosted by Bäuml T., Dvorak D., Frohner A., Simic D. from AIT.

Together with some other Austrian institutions and companies the AIT (Austria's largest non-university research institute, is among the European research institutes a specialist in the key infrastructure issues of the future) worked on a project, which was focusing on the simulation and measurement of an energy efficient infrared radiation heating of a BEV.

As mentioned in the beginning of this chapter, heating up an EV leads to a loss of range. One possible conventional approach would be the reduction of demanded heat, which would improve the total vehicle efficiency. On the other side that fact leads to a conflict of targets between efficiency versus comfort.

The target comfort within an EV increases a high costumer perception, while the target of reduced heating costs decreases the costumer's perception.

Thus, the approach for a new heating system has been taken from civil engineering technology to increase the heating efficiency. The aim of the project was to heat up the interior of an EV through a special varnish based heating system which can be applied to different surfaces and components, and requires less energy than conventional heating concepts while increasing the range and the passenger comfort. This special heating varnish was subjected to various durability tests. A major challenge was to maintain a durable contact between the electrodes and the varnish layer. A 1D and 3D simulation of the varnish based heating system in the vehicle passenger compartment was implemented and linked with an intelligent control concept. Heating elements were manufactured and embedded in a test vehicle, which was evaluated during several test runs.

## Infrared Heating System

Conventional heating systems of EVs are very inefficient. A cheap method is to use PTC heaters in EVs. There, the electric resistance of the heater rises with the temperature of the element and reaches a certain stable operating point. Around this PTC element, the air is heated up and then transported to the cabin by a fan. At low ambient temperatures this inefficient heating method uses up to 6 kW of electrical power for heating the cabin. In Fig. 67 this power consumption can be seen in a vehicle on a chassis dynamometer at an ambient temperature of −7 °C (19 °F) and a vehicle speed of about 50 km/h (31 mph). The power needed for heating up the cabin is about as much as the used driving power for a small vehicle at a constant speed of 50 km/h (31 mph). The proposed infrared heating system has a much higher efficiency. Only a small electrical power is needed and thus the consumed heating energy can be reduced. It takes about 20 min to reach a comfortable climate in the cabin.

Figure 68 shows a comparison between a conventional heating system and an infrared heating system. Thus, the infrared system is independent, locally separated and high efficient.

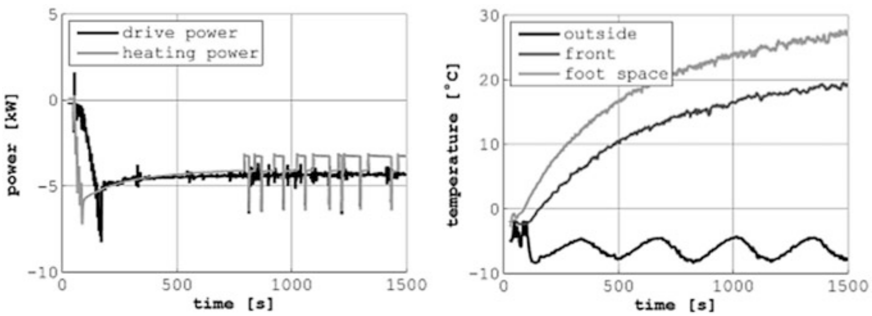



**Fig. 67** Comparison of drive and heating power (conventional convective heating) measured in a BEV test vehicle on a climatized vehicle dynamometer [74]

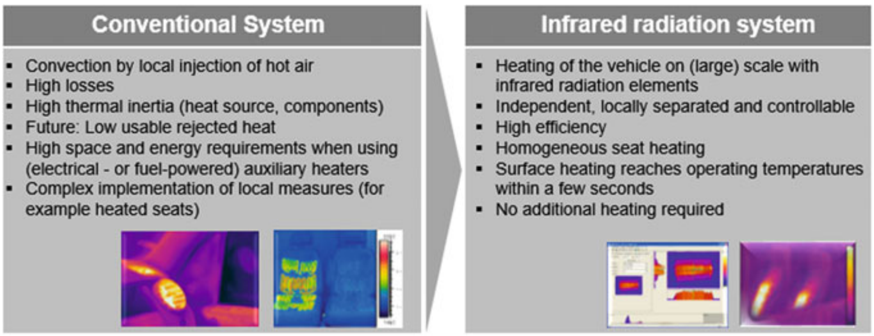



**Fig. 68** Conventional versus infrared heating system [75]

The infrared radiation system is based on an electrically conductive coating. When an electric current flows through the coating, heat is generated and dissipated directly as infrared radiation to the passenger. Because the heating elements are very close to the passenger, and infrared radiation is commonly reckoned as very comfortable heat, the air temperatures in the vehicle cabin can be kept lower while preserving or even increasing the thermal comfort of the passenger.

Infrared radiation provides a very quick thermal sensation and comfortable feeling. The heating system can be designed either as large-area coating for infrared heating or as contact heating. It can be applied to different carrier materials and structures in a vehicle environment like the dashboard, door coverings, A- and B-pillars, to the center console, the steering wheel and to many more objects.

For choosing the right carrier and covering materials which have different properties, several test have been carried out to optimize the heat dissipation and radiation capabilities. Isolating and reflecting carrier layer materials prevent a heat dissipation to the backside and optimize a heat transfer to the desired front side. Kevlar Honeycomb layers as used in aviation, as well as fiber glass sheets covered with silicone and a reflective coating layer have been used to manufacture samples for the used heating elements. The behavior of the element covers (leather or textiles for automotive applications) is very important, especially in the case of partial damages of the heating coating. Small damages have a big influence on the electrical resistance, but do not create dangerous hot spots on the heating coating. Different types of electrodes for contacting the heating elements have been tested for durability and conductivity. Aluminum electrodes have turned out to have the best compromise between electrical conductivity and mechanical stability. For analyzing the long-term behavior under automotive conditions (vibrations, UV-radiation, heat, etc.) a special test box was set up where vibration tests could be performed. Also UV-radiation tests and operational tests in different ambient temperatures were performed, to determine the long-term reliability of the heating coating itself, the carrier and covering layers as well as the electric contact surfaces.

For this project the heatable coating “radheat” of qpunkt has been chosen. Base of the product “radheat” is an electrically conductive coating layer which consists of a semiconductor material-polymer dispersion (w/o carbon nanotubes or ceramics).

Basic facts of “radheat”:

- **weight**: $\sim$200 g/m$^2$,
- **typical film thickness**: 0.5 up to 1 mm (0.02–0.04 in),
- **voltage**: from 0 to 400 Volt (AC/DC),
- **maximum temperature**: 400 °C (752 °F) and
- **maximum power**: 40 kW/m$^2$ (depending on coating thickness).

The areas of application for this heatable coating are shown in Figs. 69 and 70.

**Thermal Measurement and Simulation**

Through a simulative design of the coating based heating system the energy saving potential can be estimated in advance. Therefore a simplified 3D model of the vehicle cabin was created including in- and outflow ports of the cooling system (Fig. 71).

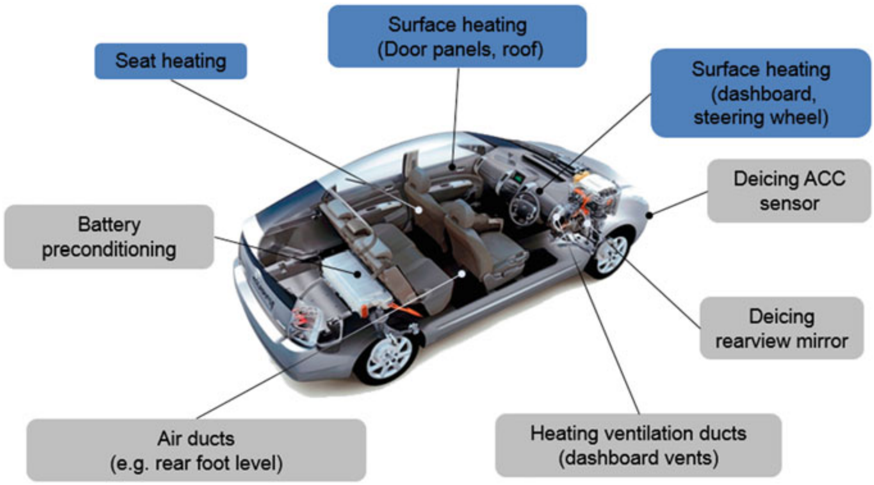



**Fig. 69** Application areas for "radheat" (*blue colored*) [76]

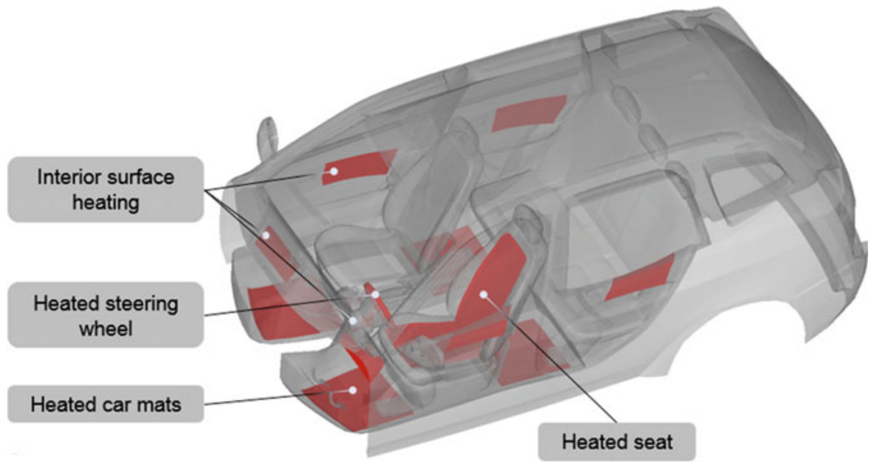



**Fig. 70** Application areas for "radheat" in detail [77]

The vehicle Computational Fluid Dynamics (CFD) model itself consists of around 1.1 million computation cells, with boundary layers resolved for all surfaces. A convection boundary condition was used for all cabin walls. The external heat transfer coefficients were defined as a function of the vehicle velocity. Material properties for the car body were defined in order to achieve a total thermal transmittance of 0.5 $W/m^2K$. A Surface-to-Surface (STS) radiation model was used to calculate the radiation heat exchange between all surfaces of the model. For all flow inlets, velocity and temperature were defined. Turbulence was modelled using the

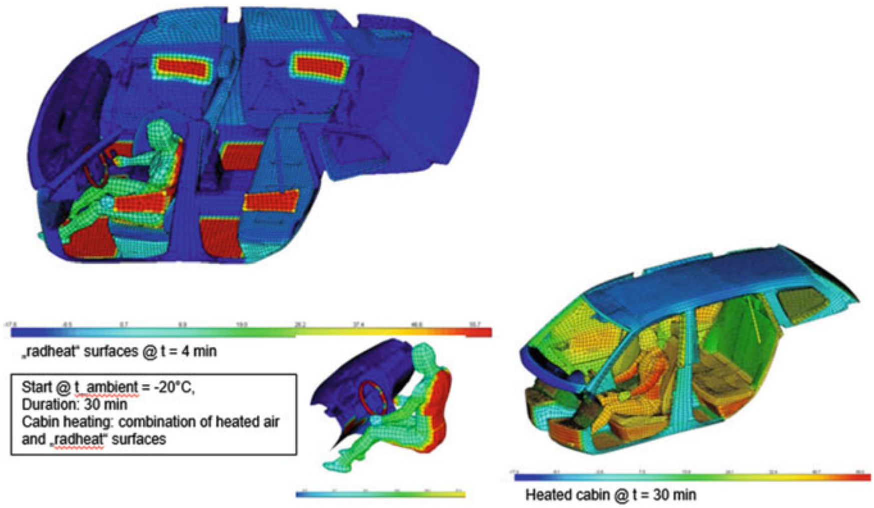



**Fig. 71** Simulation of the heatable surfaces [78]

k-omega SST model. On the driver's seat, a human dummy model was seated to assess the skin temperatures and thermal comfort of the passenger. The internal heat gain of the dummy was taken into account using a heat flux boundary condition for the dummy surface with a total heat transfer rate of 100 W.

In a first step, a 3D CFD flow simulation of the conventional convective heating system was performed, to determine reference values for the energy consumption of the conventional system. For validating these simulations, measurements in the climatic wind tunnel at a temperature of −7 °C (19 °F) have been performed (see Fig. 72). Measurement data included electrical currents and voltages of the drive system and the auxiliary components as well as about 20 temperature values inside the vehicle cabin. The sensors were positioned according to VDA220.

In a second step, the infrared heating elements have been positioned in the vehicle simulation as depicted in Fig. 74 as purple (dark colored) elements. This CFD model was coupled to a 1D model of a controller for the infrared heating

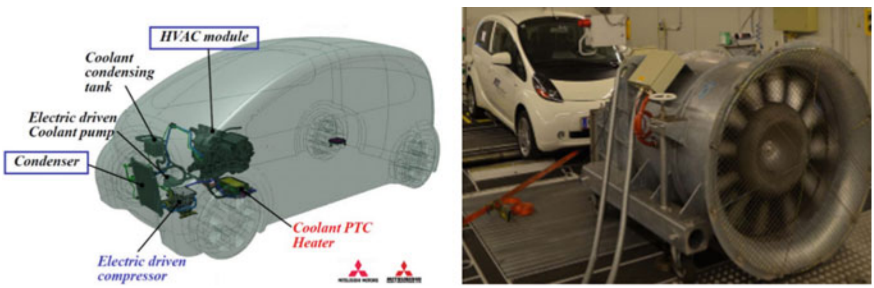



**Fig. 72** Flow measurement of the test vehicle [79]

elements. The control concept takes into account the current ambient and cabin temperature, as well as the vehicle velocity. For these three variables, correction terms apply. The higher the ambient or cabin temperature gets, the lower the temperature of the heating elements has to be to get the same thermal comfort in the cabin. On the contrary, the higher the vehicle velocity gets, the higher the heat transfer coefficient to the ambient and hence, a higher desired temperature on the heating elements is demanded. Furthermore maximum power and temperature values for each heating element are defined. A PI controller with anti-windup controls the desired temperature of the elements.

The thermal comfort of the simulated driver dummy was determined and evaluated using comfort indicators gained by a human thermoregulation model.

In the first simulation with heating elements with a total maximum power of 200 W were installed and convective heating was deactivated. The power of the heating elements was increased until a surface temperature limit of 70 °C (158 °F) was reached. In Fig. 74 it can be seen, that the skin temperature of the human dummy does not reach comfortable values between 25 °C (77 °F) and 36 °C (97 ° F). The maximum value of the human dummies skin temperature is about 22 °C (71 °F), a maximum cabin temperature of 2 °C (35 °F) was reached. This shows, that infrared radiation heating alone is not enough to create a comfortable environment in the cabin, because the surrounding air in the cabin is not heated up sufficiently (compare Fig. 73).

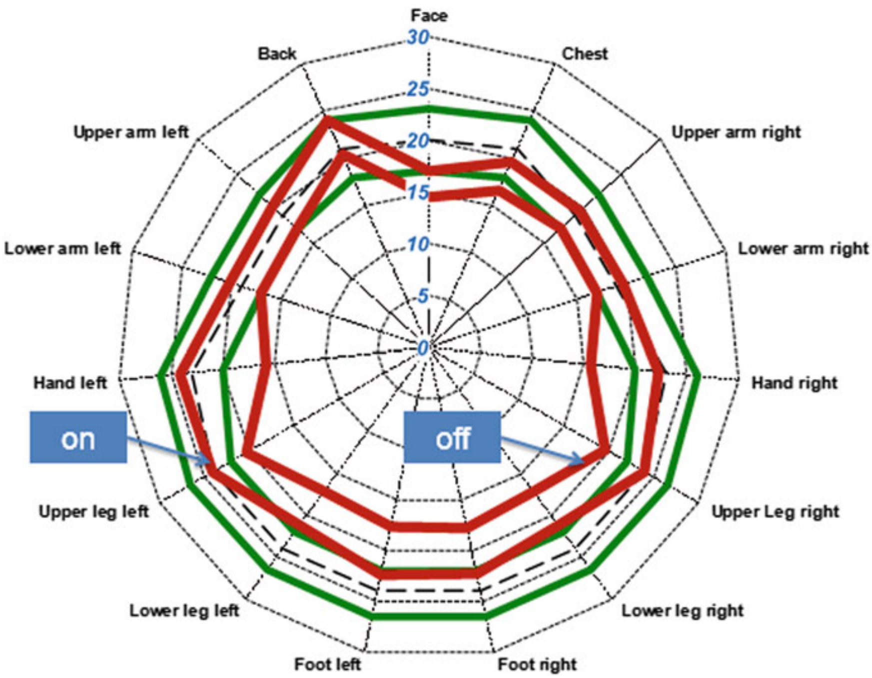
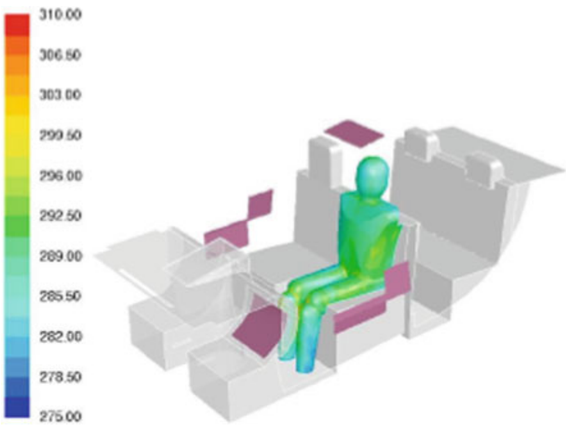



**Fig. 73** Simulation results driver's comfort [80]

**Fig. 74** Temperature distribution on the human dummy during heating with the infrared heating elements (indicated as purple elements) only [81]

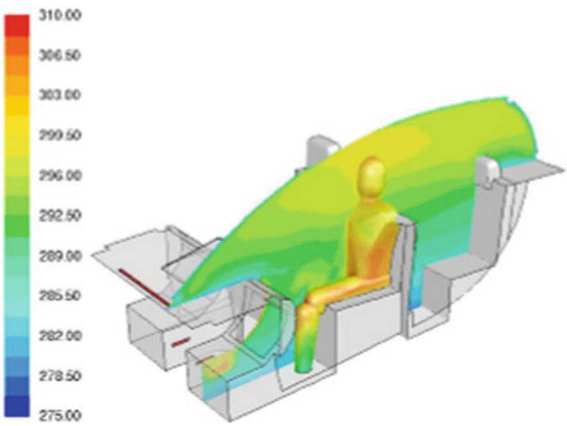



In a second simulation, additional convective heating with a power of approximately 2 kW was switched on. An outlet temperature of about 55 °C (131 °F) was assumed. Figure 75 shows the skin temperature of the human dummy again, that is now closer to the comfort temperature. Also the cabin temperature is higher and between 10 °C (50 °F) in the foot space and 30 °C (86 °F) around the head (compare Fig. 76).

### Validation Results

The simulation was validated by putting the EV, equipped with six infrared heating elements and numerous temperature, voltage and current sensors, in a climatic chamber. The ambient temperature in the climatic chamber was cooled down to a constant value of −7 °C (19 °F). The vehicle was conditioned to this temperature to simulate warm-up of the vehicle during operation in cold weather conditions. During the first test phase, only the infrared heating elements with a total maximum

**Fig. 75** Temperature distribution on the human dummy and on a surface through the cabin during heating with the infrared heating elements and additional convective heating [82]



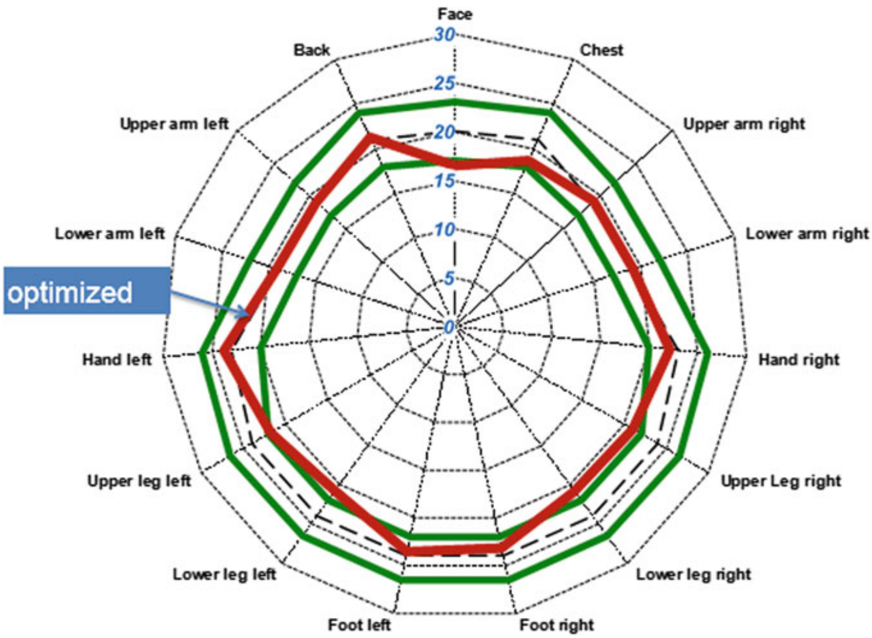



**Fig. 76** Simulation results driver's comfort—optimized [83]

power of 200 W were active, without additional convective heating. Test persons were asked to sit in the vehicle for an hour and assess their thermal comfort and sensation every 5 min. Like the simulations showed before, the body parts directly warmed by the heating elements were regarded as comfortable very quickly by all test persons. Whereas most of the test persons observed cold feet, because there are heating elements under the steering wheel pointing to the knees and thighs but not near the feet. The cabin temperature after about 30 min rose to only 2 °C (35 °F), because the infrared radiation of the heating elements warms up the human body directly, but not the surrounding air, which shows a good correlation with the simulated results. The heat-up of the inner air happens mostly by the dissipated heat of the passenger. In a second test run, additional convective heating with reduced power of around 2 kW was switched on. Here as well, body parts exposed directly to the heating elements were warmed up very quickly. Despite of an additional convective heating, the feet needed nearly 30 min to be regarded as comfortable for most of the test persons.

The project team expects a cut of the losses in range due to the heating system by half. The most important advantages are: the heating effect, available after 1 min; the quietness of the system; the possibility to focus the heat output locally; the reduction of vehicle weight; the usage in conventional and hybrid vehicles.

***Thermal Management Systems means a challenge***:

*Energy management has to be understood as a topic for vehicle and powertrain. A thermal management strategy has to be developed and implemented (ECU, VCU, BCU). Thus, thermal management can't be threaten in an isolated view as it is a multi-disciplinary development task (many departments involved)! The increasing system complexity means an early integration of simulation into the development process.*

## 5 Simulation Tools—Overview of International Research Groups

Simulation has become an essential tool to engineers in the product development process. The challenge of reducing costs and time along the product development cycle creates a growing demand to replace physical prototypes with virtual prototypes applying frontloading.

The growing number of closely interacting powertrain components and control systems and the increasing complexity of these control functions, requires the analysis and testing of an extensive number of powertrain combinations.

In order to keep vehicle development costs low, while still being able to eliminate quality issues, for example due to overlooked test cases, test and calibration methods are being adjusted to incorporate simulation in all analysis, hardware test, function development and calibration tasks.

Ideally the same system and sub-system simulation models should be used for as long as possible in the whole vehicle development process (from concept to test), in order to guarantee consistency by generating comparable results in offline and real-time applications.

The following chapter includes several approaches to simulation by highlighting three examples of different simulation tools:

- Cruise by AVL List Gmbh
- Autonomie by Argonne National Laboratory
- Dymola/Modelica by Austrian Institute of Technology

### *5.1 CRUISE—Vehicle System Simulation (by AVL)*

This section was mainly provided by Mr. Engelbert Loibner from AVL List GmbH.

**From concept studies to calibration and testing**

AVL CRUISE [84] offers all required flexibility to build up a system model, whose fidelity may easily be adjusted to various application requirements through the entire powertrain development cycle. It supports everyday tasks in vehicle system and driveline analysis through all development phases, from concept planning and design in the office, to calibration and verification on hardware test systems. Starting with only a few input data in the early phases, the model maturity grows throughout the vehicle development process according to the continuously increasing simulation needs in xCU software and calibration development. CRUISE models improve the flexibility and the productivity of platforms that are implemented in Hardware in the Loop (HiL) procedures: AVL InMotion, IPG CarMaker, dSPACE, ETAS, National Instruments, Opal RT, as well as AVL PUMA Open testbeds. Model reuse in consecutive or iterative development approaches ensures consistent decision making processes and saves valuable engineering time, keeping the project focus on the target: optimizing vehicle fuel efficiency, emissions, driving performance and drivability.

Today's vehicle powertrain concepts, electrified and conventional, are pushing the complexity of system simulation models to extremes. The highly adaptable System/Sub-system structure of CRUISE, allows an easy changing of drive train concepts.

Vehicle hybridization and adapting the model to alternative application needs in different phases are carried out within minutes, saving time to focus on value adding engineering, calibration and testing tasks, without a need to look into mathematical equations or re-program simulation model code.

**Solution oriented open concept**

CRUISE is more than a vehicle simulation model. Streamlined workflows are realized for all kinds of parameter optimization, component matching and sub-system integration. CRUISE powertrain integration system simulation platform features a modular structure, with a wide range of interfaces to other simulation tools, like Matlab/Simulink, CarMaker, CarSim, etc., ready to use analysis tasks and data management capabilities.

**AVL CRUISE Application Examples**

Today software developers must save time and money while delivering increasingly complex controllers that function correctly in all applications. A key approach to address these challenges is so called 'frontloading' or 'model based development' (see Fig. 77). Here, to reduce software development effort and risk it is necessary to start testing the software, as soon as executable software parts are available, typically well before real hardware exists. Therefore realistic, computationally fast, flexible and affordable simulation plant models are required (see Fig. 78).

AVL CRUISE has wide ranging capabilities and flexibility to support this advanced software development process. For example, CRUISE models can easily be compiled and used directly in the Matlab Simulink environment, a widely used software development environment. Furthermore, the modular architecture of a CRUISE powertrain model means that the CRUISE plant models can easily be adapted or improved to match the actual requirements of each software development status. For example, it is possible to simulate the whole powertrain, or just those sub-systems which are required to test the chosen software part.

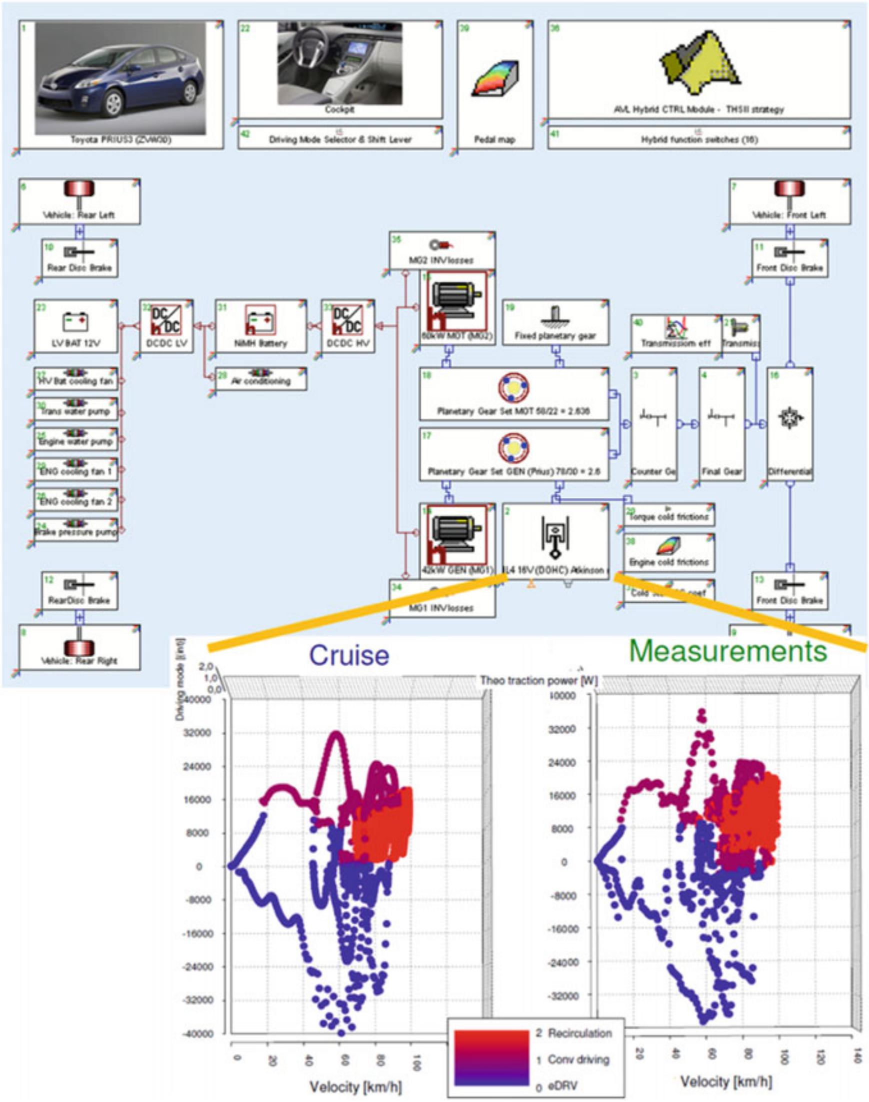



**Fig. 77** Model based development with Cruise [85]

For software testing, various test cases are defined and therefore it is also necessary to re-parameterize parts of the AVL CRUISE vehicle model, like for example alternative clutch characteristics to consider the aging and wear of a clutch. CRUISE offers a simple way to change predefined vehicle parameters without the need to recompile the model.

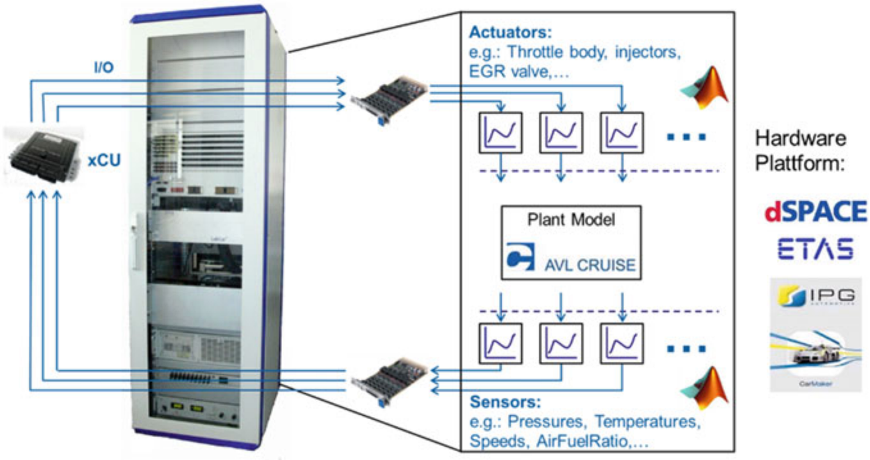



**Fig. 78** Plant modeling for xCU software development [86]

Depending on the software development process status, the testing environment is changed from Model in the Loop (MiL), to Software in the Loop (SiL) and to HiL. In all three environments essentially the same CRUISE powertrain model is used. The complete powertrain model remains the same for all test environments. Only two parts, the interface type and the compiler, need to be adapted to the chosen target environment.

**HEV powertrain modeling and validation**

With AVL CRUISE it is possible to generate very detailed and advanced models of HEVs. If those models are also validated against measurements, the result is a very detailed reflection of the real vehicle behavior with respect to fuel consumption, $CO_2$ emissions, internal energy flows and vehicle performance.

CRUISE simulation models allow very detailed analysis of each powertrain component. This approach is very useful to optimize the complete system by virtually optimizing single components. The effect of a modified or changed powertrain component (e.g. electrical machine) can be simulated in CRUISE without time consuming adaptations to the powertrain model: CRUISE offers the opportunity to investigate parameter, component or even system variations to provide a detailed sensitivity analysis.

Beside the component optimization, a second major benefit of highly sophisticated simulation models of HEVs is the possibility to virtually generate detailed requirements and load profiles for each component in the system. Such an output is fundamental for successful and efficient component design, especially for novel and hence more unknown powertrains. By simulating various driving cycles (real world and legislated) the CRUISE model delivers detailed information regarding the maximum load (mechanical or electrical), from which the expected life-time of various components can be derived.

AVL CRUISE can be used as a standalone model, but it also provides the opportunity to be used as a development platform since it can easily be connected with various other tools. For example, using the direct connection between AVL CRUISE and AVL Concerto tools, it is readily possible to handle extremely large simulation result data, filtering out superfluous information to display only the relevant parts.

The architecture of advanced HEV models contains beside the CRUISE powertrain and vehicle, highly complex xCU control logic, typically modeled in Matlab Simulink. Both parts are easily connected via a standard interface defined in AVL CRUISE. This control logic reflects exactly the control algorithm re-engineered from the measurements and used for CRUISE model validation. To allow further optimization of the model parameters and to better calibrate the control logic, well-known 'Design of Experiment' techniques can be virtually applied through a coupling with AVL Cameo.

## 5.2 *Autonomie (By Argonne National Laboratory)*

This section was mainly provided by Mr. Aymeric Rousseau from ANL.

Many of today's automotive control-system simulation tools are suitable for simulation, but they can provide rather limited support for model building and management. Setting up a simulation model requires more than writing down state equations and running them on a computer. Detailed knowledge of vehicle performance, controls, architecture configuration, component technology, system integration, fuel economy benefits and cost is required.

With the introduction of electric-drive vehicles, the number of components that can populate a vehicle has increased considerably, and more components translate into more possible drive train configurations. In addition, building hardware is expensive. Traditional design paradigms in the automotive industry often delay control-system design until late in the process—in some cases requiring several costly hardware iterations. To reduce costs and improve time to market, it is imperative that greater emphasis has to be placed on modeling and simulation. This only becomes truer as time goes on because of the increasing complexity of vehicles and the greater number of vehicle configurations.

Because of the large number of possible advanced vehicle architectures and time and cost constraints, it is impossible to manually build every powertrain configuration model. As a result, processes have to be automated.

Autonomie (Argonne National Laboratory 2011a; Rousseau, n.d.) is a MATLAB©-based software environment and framework for automotive control-system design, simulation, and analysis. The tool is designed for rapid and easy integration of models with varying levels of detail (low to high fidelity) and abstraction (from subsystems to systems and entire architectures), as well as processes (calibration, validation, etc.). Developed by Argonne in collaboration with General Motors, Autonomie was designed to serve as a single tool that can be used to meet the requirements of automotive engineering throughout the development process from modeling to control. Autonomie was built to accomplish the following:

- support many methods, from model-in-the-loop, software-in-the-loop, and hardware-in-the-loop to rapid-control-prototyping,
- integrate math-based engineering activities through all stages of development, from feasibility studies to production release,
- promote re-use and exchange of models industry-wide through its modeling architecture and framework,
- support users' customization of the entire software package, including system architecture, processes, and post-processing,
- mix and match models of different levels of abstraction for execution efficiency with higher-fidelity models where analysis and high-detail understanding is critical,
- link with commercial off-the-shelf software applications, including GT-Power©, AMESim©, and CarSim©, for detailed, physically-based models,
- provide configuration and database management and
- protect proprietary models and processes.

By building models automatically, Autonomie allows the simulation of a very large number of component technologies and powertrain configurations. Autonomie can:

- simulate subsystems, systems, or entire vehicles,
- predict and analyze fuel efficiency and performance,
- perform analyses and tests for virtual calibration, verification, and validation of hardware models and algorithms,
- support system hardware and software requirements,
- link to optimization algorithms and
- supply libraries of models for propulsion architectures of conventional powertrains as well as electric-drive vehicles.

Autonomie is used to assess the performance, fuel consumption and cost of advanced powertrain technologies. Autonomie has been validated for several powertrain configurations and vehicle classes using Argonne's Advanced Powertrain Research Facility (APRF) vehicle test data, among other data sources.

With more than 400 different pre-defined powertrain configurations, Autonomie is an ideal tool to analyze the advantages and drawbacks of the different options within each family, including conventional, parallel, series, and power-split (P) HEVs. Various approaches have been used in previous studies to compare options ranging from global optimization to rule-based control.

Autonomie also allows users to evaluate the impact of component sizing on fuel consumption for different powertrain technologies as well as to define the component requirements (e.g., power, energy) to maximize fuel displacement for a specific application. To properly evaluate any powertrain-configuration or component-sizing impact, the vehicle-level control is critical, especially for electric drives. Argonne has extensive expertise in developing vehicle-level controls based on different approaches, from global optimization to instantaneous optimization, rule-based optimization and heuristic optimization.

The ability to simulate a large number of powertrain configurations, component technologies, and vehicle-level controls over numerous drive cycles has been used to support many U.S. DoE as well as manufacturers' studies, focusing on fuel efficiency, cost-benefit analysis, or greenhouse gases. All the development performed in simulation can then be implemented in hardware to take into account non-modeled parameters such as emissions and temperature.

## 5.3 Dymola/Modelica (By Austrian Institute of Technology—AIT)

This section was provided by Mr. Dragan Simic and Thomas Bäuml from AIT.

Simulation is state of the art in automotive development but up to now the simulation efforts mainly focused on the analysis and optimization of individual components. For realization of optimized and efficient vehicles the optimum tuning of the different powertrain components is essential, but especially the high complexity of alternative vehicle powertrains requires the balancing of different components, like internal combustion engine, electric machine, and electric energy storage systems. Based on that, new simulation and testing tools on systems level are necessary to analyze and optimize the complex system "vehicle" as a whole and to realize innovative and competitive vehicles.

This development environment on systems level has to meet different requirements, like interdisciplinary, flexibility and real-time capability. Especially in the context of alternative drive train vehicles the complexity of the powertrain increases due to the complex interaction of the ICE, the e-machine, the inverters, the energy storage system, electric auxiliaries, etc. For simulation and optimization of such complex systems the development tools have to provide the possibility to combine mechanical, electric, thermal, etc. models. For that purpose the AIT has set up an advanced simulation and development environment based on Dymola/Modelica. Several Modelica libraries have been developed covering the mechanical, electrical and thermal behavior of components. The libraries have been realized in such a way that the entire vehicle can be modeled in an easy and flexible manner and different vehicle concepts can be compared.

Furthermore, looking at the vehicle concepts of today a broad spectrum of different drive technologies, vehicle and fuel concepts is considered and developed. The efficient analysis, comparison and optimization of different vehicle concepts require flexible development tools that support modularity and fast exchangeability of parts of the vehicle models.

Finally today's development environment has to cover the entire development process—from the concept and design phase up to the testing phase. The support of the entire development chain by just one simulation tool highly improves the usability and efficiency. For that purpose the efforts necessary to integrate the simulation and the test environment as well as the availability of real-time models define the applicability of a simulation tool.

In addition, to not only the design phase but also support the entire development process, a Hardware in the Loop test environment has been established. The Modelica simulation environment can be coupled via in-house developed interfaces to a high performance energy storage system as well as an electric drive test bed. By that a virtual development environment has been established that allows an efficient design of EV components and their controls as well as their testing and optimization without time and cost intensive vehicle integration and tests.

At the AIT for modeling, the object oriented simulation language Modelica [87] in the modeling and simulation environment Dymola [88] is used. Modelica (see Fig. 79) is an object oriented, multi domain modeling language for component oriented modeling of complex physical systems. Systems in Modelica are modeled in a way an engineer builds a real system. Each component is physically described by algebraic and ordinary differential equations with respect to time. Systems containing mechanical, electrical, electronic, hydraulic, thermal, control, electric power or process-oriented subcomponents can be simulated simultaneously and interactions analyzed. In Modelica there is no predefined causality. The modeling and simulation environment Dymola decides by using complex algorithms which

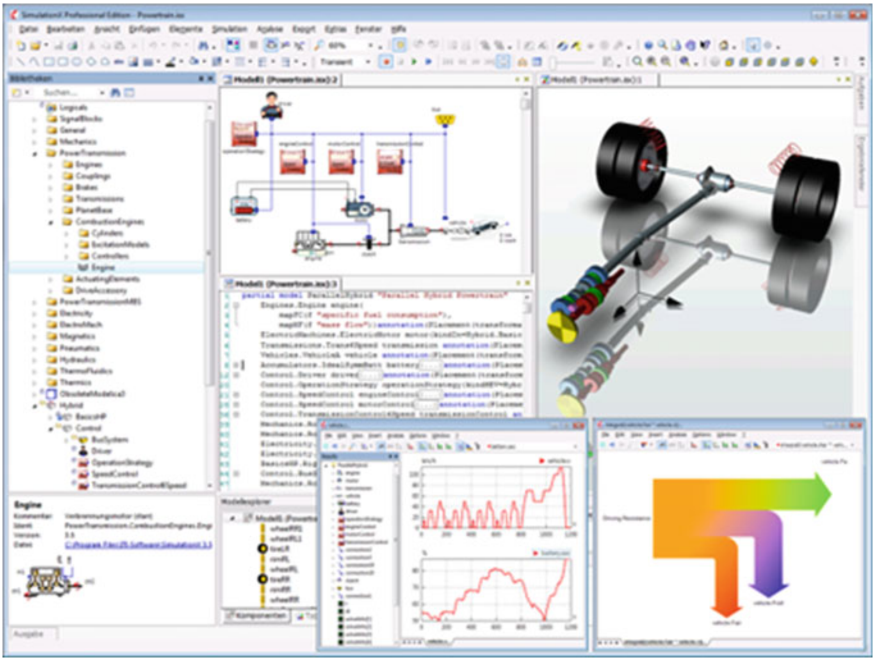


**Fig. 79** Screenshot from the simulation tool 'Modelica' [89]

variables are known input or unknown output variables and how the equation system has to be solved in the most efficient way. The structure of the simulation model defines the set of equations and hence the variables to be solved for. Symbolical transformations and optimizations of the equation system drastically reduce simulation time. Each component in Modelica is handled as an object which can inherit equations and parameters from other classes. Each object representing a physical component has interfaces. With these interfaces, components are able to interact with other objects having the same type of interface.

In a typical vehicle simulation model all desired components can be integrated into the overall system. At the AIT primarily subsystems and systems as far as the entire vehicle are modeled. Main focus is on the design and sizing of drive components as e-machine, battery and power electronics. Other tasks include the prediction and investigation of driving range, efficiency, thermal behavior of components. The libraries used in these simulations have all been developed at AIT. These include libraries for analyzing the electrical behavior of controlled e-machines as well as the thermal characteristics. Libraries for electric energy storage systems and power electronic devices are also used. These can be combined in vehicle system models for longitudinal and lateral dynamics. Modeling the cooling system of a vehicle connects all components thermally. For optimizing the air flow in air conditioning systems aeroacoustic 1D flow models are available. Most of the models are modeled in more than one level of abstraction focusing on different purposes. While the full physical model of an e-machine includes switching effects and electrical transients, the abstraction is a quasi-stationary machine without electrical transients which is suitable for most of the issues regarding energy consumption simulations and driving range analyses. By choosing a model with the right level of detail for the right purpose, simulation time can be drastically reduced.

Simple control systems like basic operating strategies for EVs or HEVs can also be modeled in Modelica. For more detailed strategies or plant control systems MatLab is the tool of choice. Control systems developed in MatLab can be easily used in Dymola and vice versa. This makes it easy to couple the strengths of these tools and gain a maximum output.

## 6 Lightweight as Overall Method for Optimization

Lightweight as overall optimization method has the potential for a higher energy efficiency and has an impact on safety and end-of-life vehicle.

***The light weighting benefits on fuel/energy consumption depend on the driving type***:

- *in city type driving and aggressive type driving light weighting any vehicle type will reduce the energy/fuel consumption.*

- *in highway type driving light weighting vehicles does not significantly reduce the energy/fuel consumption.*

***Light weighting a vehicle will save the most amount of fuel/energy in a conventional vehicle due to the comparatively low powertrain efficiency of the conventional vehicle.***

**Light weighting the car can be done by**:

- **the intense use of simulation tools**,
- **the use of advanced materials (e.g. sandwich materials)**,
- **the implementation of bionic concepts and by use of**
- **functional integration**.

The main way of achieving the reductions in the consumption and emission values of passenger cars is by improving the efficiency of these vehicles. As well as improving aerodynamics and the powertrain, increasing efficiency is possible through lightweight design, since a large proportion of fuel consumption is generated by the vehicle mass.

The share of consumption due to aerodynamic drag and idling consumption is around 30–40 % of total consumption, whereas the mass-dependent consumption of a vehicle due to rolling and acceleration is up to 70 % of total consumption. These values are irrespective of the total vehicle mass. It is therefore evident that by saving on mass, a large proportion of consumption can be influenced. In vehicles with an alternative drive, a reduction in the mass of the body in white structures is of considerable importance, because electrical energy storage systems are heavy.

**There are various lightweight design strategies for reducing vehicle mass: conditional, conceptual, material and form lightweight construction** [90].

## *6.1 Vehicle Mass Impact on Efficiency and Fuel Economy*

This section was mainly provided by Mr. Michael Duoba from ANL.

The results of a study of the "Vehicle Mass Impact on Efficiency and Fuel Economy", conducted by ANL, have been presented during a Task 17 workshop in Vienna (2012).

It is widely accepted that increased vehicle mass adversely affects vehicle fuel economy. The vehicle has to consume additional energy to accelerate the heavier vehicle, as well as increased rolling drag; therefore, it requires more energy to propel the vehicle. From several literature references of U.S. EPA fuel economy labels of vehicles produced in the past 10 years, a clear trend can be seen showing that vehicle mass directly impacts overall vehicle fuel economy for light duty vehicles. Despite the clear trend, the magnitude of this mass impact on fuel consumption varies significantly between references. The results of the previous studies show that a decrease in mass of 114 kg (250 lb) results in an improvement in fuel economy of 0.53–1.6 mpg for ICE technology.

*Industry assumes that 1.0 % change in vehicle mass is equal to 1.0 % change in vehicle road load.*

This study, initiated by the U.S. DoE's Office of Energy Efficiency & Renewable Energy, conducted coastdown testing and chassis dynamometer testing of three vehicles, each at multiple test weights, in an effort to determine the impact of a vehicle's mass on road load force and energy consumption. The testing and analysis also investigated the sensitivity of the vehicle's powertrain architecture on the magnitude of the impact of vehicle mass.

Therefore, three vehicles have been selected for testing. To accomplish the objectives a BEV, HEV, and ICE vehicle has been chosen (Fig. 80):

- Nissan Leaf (2011),
- Ford Fusion Hybrid (2012),
- Ford Fusion ICE V6 (2012)

* Car and Driver
** OEM website

| | CONVENTIONAL | HYBRID ELECTRIC | BATTERY ELECTRIC |
|---|---|---|---|
| Vehicle | Fusion V6 | Fusion HEV | Leaf |
| EPA label (City/Highway) | 20 / 28 | 41 / 36 | 106 / 92 mpgge |
| Curb weight [lb]* | 3,548 | 3,805 | 3,377 |
| ETW [lb] | 3,750 | 4,000 | 3,750 |
| Engine/Motor specifications** | 3.0 V6 Duratec 24V PI<br>10.3:1<br>240 hp @ 6550 rpm<br>223 hp @ 4300 rpm | 2.5 I4 Atkinson-cycle PI<br>12.3:1<br>156 hp @ 6000<br>136 hp @ 2250 | 80kW AC synchronous electric motor<br>107 hp<br>207 lb.ft |
| Traction Battery** | N/A | NiMH 275-Volt / 36kW | Lithium-ion<br>Capacity 24kWh |
| Transmission** | 6 speed automatic<br>3.56:1 final drive | Power Split | Single speed gear reduction |

**Fig. 80** Data from vehicles tested in the study [91]

### Testing methodology

Testing included a collaborative study with two parts:

- coastdown testing,
- chassis dynamometer testing

**Part 1: Coast down study (test track)**: coastdown testing was conducted on a closed test track (Phoenix area) to determine the drag forces and road load at each test weight for each vehicle. It consisted of a 3.2 km (2 mi.) straight away. Many quality measures were used to ensure only mass variations impact the road load measurements. Thus, for each vehicle, at each test weight, a minimum of 14 coastdown tests were conducted to reduce sensitivity to external variables—7 tests in each direction to nullify any track grade variability.

Acceptable testing conditions for wind, ambient temperature, and humidity limits were strictly adhered to per the SAE J1263 standard. The test weights chosen for coastdown testing included weights heavier and lighter than the U.S. EPA certification test weight. The EPA certification weight was curb weight plus an additional 150 kg (332 lb), which included the driver and typical cargo or luggage.

To reduce testing variability, the vehicle was warmed up for 30 min. prior to testing, the ride height was held to a small tolerance at the various vehicle test weights and temperatures were monitored and recorded to ensure vehicle is functioning at steady state operating conditions. Table 5 shows the test weights used for the three vehicles for coastdown testing.

**Part 2: Dynamometer testing for fuel and electric consumption at Argonne with road load from coast down testing**.

Chassis dynamometer testing was conducted over standard drive cycles UDDS, HWFET and US06 on each vehicle at multiple test weights to determine the fuel consumption or electrical energy consumption impact caused by change in vehicle mass. A chassis dynamometer provides a very accurate and repeatable means of measuring energy consumption. To reduce testing variability prior to the on-dynamometer coastdown and vehicle loss determination, each vehicle was warmed up per dynamometer test procedures. For each vehicle, the same sensors and sensor positioning, but also the same temperatures used during the coastdown testing were also used in the dynamometer testing.

**Table 5** Vehicle test weights utilized for coastdown testing

| | Fusion ICE (V6) (kg\|lb) | Fusion HEV (kg\|lb) | Leaf BEV (kg\|lb) |
|---|---|---|---|
| +227 kg (500 lb) | 1928\|4250 | 2041\|4500 | 1928\|4250 |
| +113 kg (250 lb) | 1814\|4000 | 1928\|4250 | 1814\|4000 |
| EPA cert. weight | 1700\|3750 | 1814\|4000 | 1700\|3750 |
| −45 kg (100 lb) | 1655\|3650 | 1770\|3900 | 1655\|3650 |
| −113 kg (250 lb) | 1588\|3500 | 1700\|3750 | 1588\|3500 |

The road load measurements obtained from the coastdown testing were used to configure the chassis dynamometer. Chassis dynamometer testing also incorporated many quality controls to ensure accurate result.

Table 6 shows the test weights used for the chassis dynamometer testing.

### Testing results and analysis

Coastdown testing: the results shown in Fig. 81 are the average of the 14 coastdown tests at each test weight for each vehicle. Note the progression of increasing coast time for increasing test weight. Two opposing factors were in effect.

With increasing mass, the vehicle inertia increased, which increased the coastdown time; however, also with increasing mass, the rolling resistance forces increased, which decreased the coastdown time. Because the overall coastdown times slightly increased, the vehicle's momentum had a larger impact on the coastdown time than the rolling resistance. Thus, a slightly nonlinear trend of decreasing vehicle mass results in decreased vehicle drag; a slight difference in trends (from vehicle to vehicle) is likely due to tire technology, not due to powertrain technology.

In order to summarize the coastdown testing: the vehicle mass impact on vehicle road load and drag losses was determined. The coastdown testing conducted for: three Vehicles (BEV, HEV, ICE), including five weight classes for each vehicle. The analysis of coastdown testing data provided road load data to enable accurate chassis dynamometer testing.

The mass impact on vehicle road load showed: a slightly nonlinear trend of decreasing vehicle mass results in decreased vehicle drag and a slight difference in trends (from vehicle to vehicle) is likely due to tire technology, not due to powertrain technology

**Table 6** Vehicle test weights for dynamometer testing

| | Fusion ICE (V6) (kg\|lb) | Fusion HEV (kg\|lb) | Leaf BEV (kg\|lb) |
|---|---|---|---|
| +227 kg (500 lb) | 1928\|4250 | 2041\|4500 | 1928\|4250 |
| EPA cert. weight | 1700\|3750 | 1814\|4000 | 1700\|3750 |
| −113 kg (250 lb) | 1588\|3500 | 1700\|3750 | 1588\|3500 |
| −227 kg (500 lb) | 1474\|3250 | 1588\|3500 | 1474\|3250 |

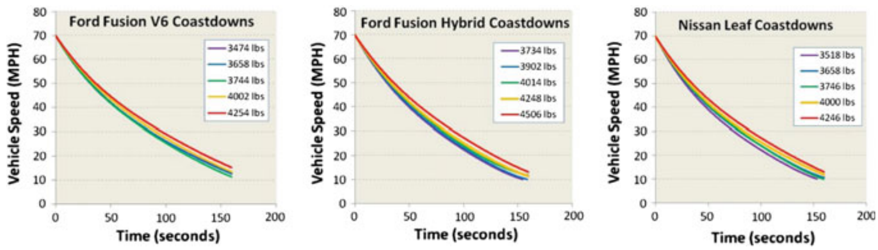



**Fig. 81** Coastdown speeds for the 3 vehicles at each of the five test weights [92]

Dynamometer testing: each vehicle was tested continuously at its different test weights on the same chassis dynamometer. The target coefficients (A, B, and C) utilized for the dynamometer testing were directly derived from the coastdown testing and analysis described above. This was accomplished by curve fitting a three-term equation to each of the five vehicle road load curves for each vehicle (as shown in Fig. 81).

One test weight category was tested per day per vehicle. Each test weight category was tested at least three times to establish a confidence interval in the fuel and energy consumption results from the chassis dynamometer testing. The test cycles used are U.S. certification cycles that represent different driving patterns. The UDDS represents city-type driving, the HWFET represents highway-type driving, and the US06 represents aggressive and higher speed driving (as shown in Fig. 82).

The fuel was measured using a direct fuel flow meter in line with the vehicle fuel pump and the fuel rail at the engine. A Hioki power analyzer was used to measure the DC power and net DC energy in and out of the high voltage battery pack for the EV and the HEV. The power analyzer measurements on the HEV were used to verify that the tests were in charge-sustaining mode.

Raw chassis dynamometer test results: Figs. 83, 84 and 85 present the average fuel consumption as a function of vehicle test weight. Each average fuel consumption test result was framed by a 95 % confidence interval.

The data shows that for all vehicles, fuel consumption increased noticeably on the UDDS and US06 test cycles, which contained higher average accelerations as shown in Fig. 82. Fuel consumption on the HWFET seemed relatively unaffected by the weight change compared to the other drive cycles.

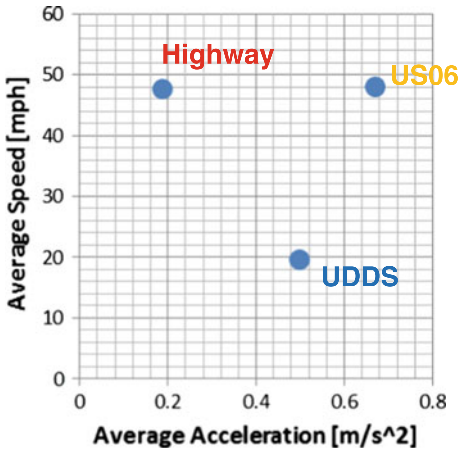



**Fig. 82** Average speed/acceleration distribution of different driving cycles [93]

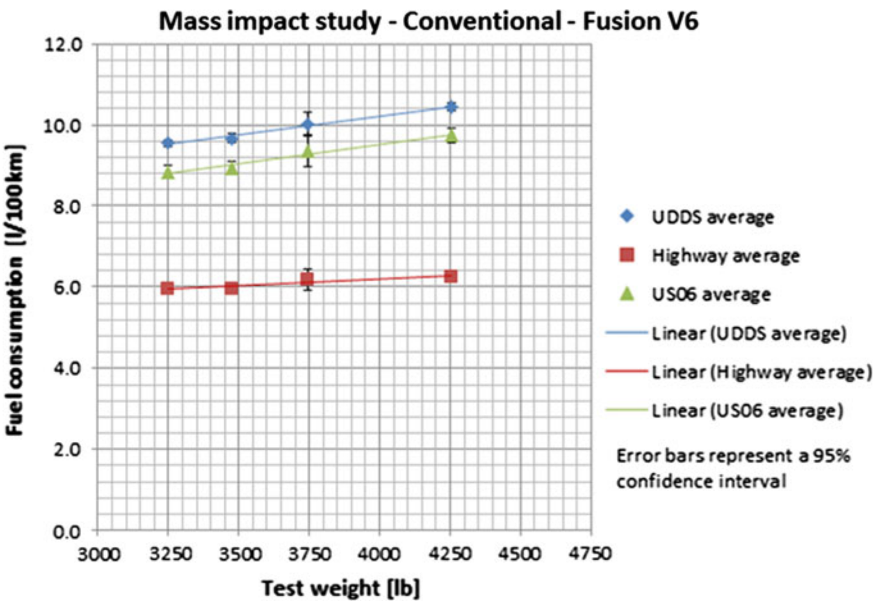



**Fig. 83** Fuel consumption of the Ford Fusion V6 (ICE) [94]

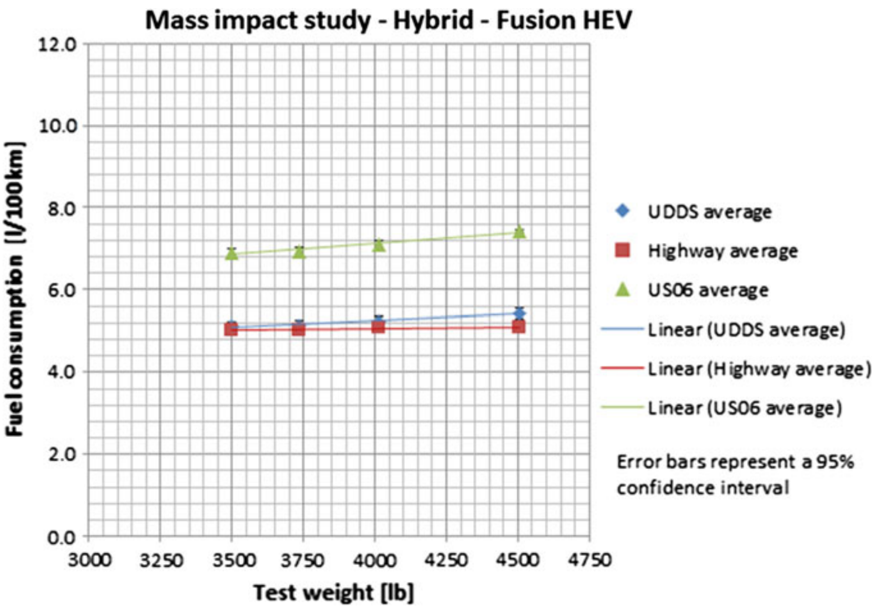



**Fig. 84** Fuel consumption (Ford Fusion HEV) [95]

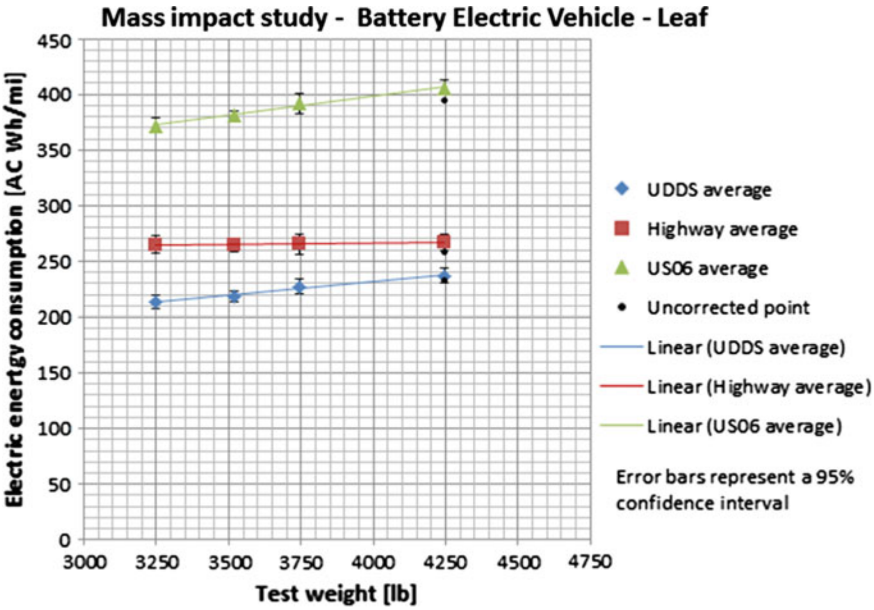



**Fig. 85** Fuel consumption of the Leaf (BEV) [96]

## Energy consumption change in terms of mass change

To compare the results from the three vehicles, percent change in energy consumption over percent change in vehicle mass was chosen as the metric, because fuel consumption (l/100 km) and electrical energy consumption (Wh/mi) were not readily comparable. Additionally, the absolute energy consumption savings is represented in liter of gasoline equivalent, which is calculated for the EV based on the AC energy consumption and the energy content of gasoline.

Figures 86, 87 and 88 show the energy consumption rate of change and the absolute fuel savings as a function of rate of vehicle mass change.

**Figure** 86 **illustrates (note: linearizing loses some of the detail**. **Mass gain and mass reduction seem to have different slopes)**:

- **a lighter vehicle will require less power on average to complete a drive cycle** and thus the load demand on the powertrain is lower **which translates into a lower powertrain efficiency** and
- **in city driving** the average load on the powertrain are relatively low, therefore **an increase in load can significantly improve the powertrain efficiency, perhaps it may appear that light weighting a BEV has the best return in energy consumption gain in this graph, but the absolute fuel gain as a function of mass change shows a different story (see** Fig. 87).

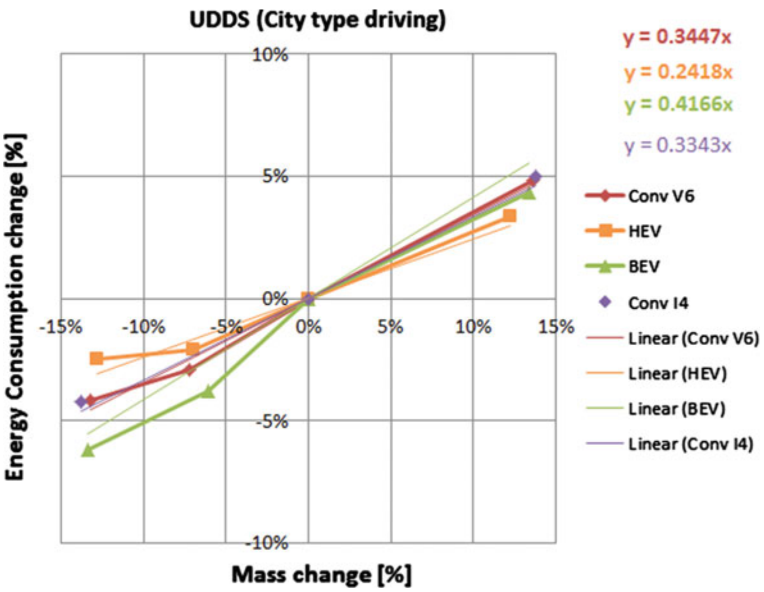



**Fig. 86** Energy consumption rate of change and the absolute fuel savings as a function of rate of vehicle mass change—UDDS [97]

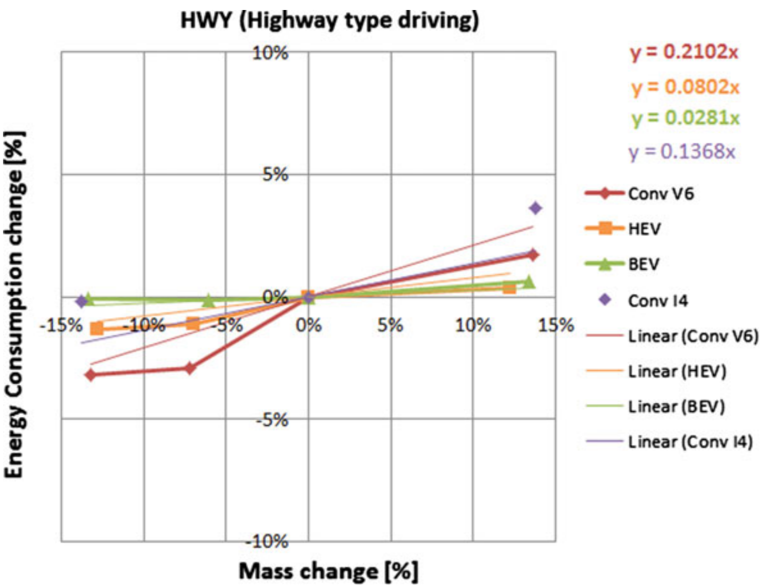



**Fig. 87** Energy consumption rate of change and the absolute fuel savings as a function of rate of vehicle mass change—HWY [98]

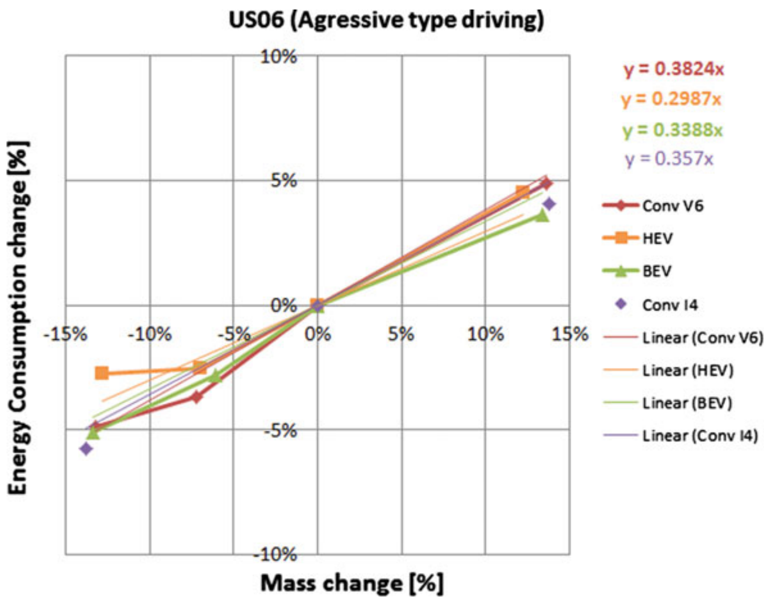



**Fig. 88** Mass impact on aggressive driving—US06 [99]

**Figure** 87 **illustrates (note: linearizing loses some of the detail. Mass gain and mass reduction seem to have different slopes)**:

- **the energy savings from lightweight a vehicle on the highway cycle are relatively low**. Reducing the road load through better tire technology and better aerodynamics would significantly reduce the energy consumption on the highway.

**Figure** 88 **illustrates (note: linearizing loses some of the detail. Mass gain and mass reduction seem to have different slopes)**:

- **the largest proportional energy change occurred in the city and during aggressive-type driving**. In these cycles, where the vehicle accelerated often, the vehicle mass had a direct impact on the inertia energy required to move the vehicle forward. Because the inertial power required to move a vehicle was calculated by multiplying acceleration by mass, any mass change to a vehicle has a direct and proportional impact on the energy required to accelerate the vehicle. This effect was displayed in the data in the cycles dominated by acceleration and
- the highway cycle energy required to move the vehicle was dominated by the road load because the vehicle was cruising at relatively steady speeds. In the energy consumption rate change graphs, all of the vehicles seemed to be clustered relatively closely. **Perhaps the EV might experience the largest benefit in range increase on a full battery per mass saved. In the absolute energy or**

**fuel savings graphs, lightweight conventional vehicles provide the largest fuel savings per mass saved, because the conventional vehicles have the lowest vehicle efficiency**.

**Summary and conclusion**:

This study investigated and quantified the impact of vehicle mass on the road load and energy consumption of three vehicles of varying powertrain architecture, including a Ford Fusion V6 (ICE), the Ford Fusion Hybrid (HEV), and the Nissan Leaf (BEV). Each vehicle was tested at multiple test weights lighter and heavier than the EPA certification test weight. This study investigated the impact of increased vehicle mass and vehicle light-weighting on vehicle road load force and energy consumption.

Coastdown testing and analysis was conducted to measure the impact of weight mass on vehicle road load. For the three vehicles, a slightly non-linear trend in decreasing road load was measured versus decreasing vehicle mass. **The results of the testing and analysis showed that for a given vehicle, the road load shows a slightly non-linear trend of decreasing road load with decreasing mass. This trend appears to be consistent across vehicle powertrain architectures (e.g., conventional powertrain, HEV, or BEV)**.

*Chassis dynamometer testing of fuel consumption or electrical energy consumption showed that in city-type driving and aggressive-type driving, a 10 % mass reduction can result in a 3–4 % energy consumption reduction for the conventional ICE engine, HEVs, and BEVs.*

The energy consumption benefit appeared to be linked to the reduction in inertia energy required to accelerate the vehicle. Vehicle mass change did not appear to have a large impact on energy consumption in highway-type driving. **The largest absolute fuel savings can be achieved by mass reduction in a conventional** vehicle because powertrain efficiency was the lowest of the three vehicles tested in this study; therefore, it had the largest overall energy consumption impact.

**Vehicle mass significantly impacted energy consumption during stop and go driving** [such as city driving (compare Table 7)]. Conversely, **highway driving proved to have little impact from vehicle mass on energy consumption**. The results

**Table 7** Results of percent change in energy per percent change in vehicle mass

| For a 10 % mass reduction | | | | | | |
|---|---|---|---|---|---|---|
| | (%) consumption reduction | | | (Lge/100 km) consumption reduction | | |
| Driving type | City | Highway | Aggressive | City | Highway | Aggressive |
| ICE V6 | ~3.5 | ~3.0 | ~4.5 | ~0.35 | ~0.19 | ~0.40 |
| HEV | ~2.5 | ~1.5 | ~4.0 | ~0.12 | ~0.06 | ~0.19 |
| BEV | ~5.0 | ~0.1 | ~2.5 | ~0.08 | ~0.01 | ~0.10 |

of this study were specific for the three vehicles tested (e.g., the 2012 Ford Fusion V6 ICE, 2012 Ford Fusion Hybrid HEV, and 2011 Nissan Leaf BEV). Though some general conclusions can be drawn from these results, they do not dictate the results for other makes and models of ICE vehicles, HEVs, and BEVs [100].

*The energy savings from lightweight a vehicle on the highway cycle are relatively low.*

Reducing the road load through better tire technology and better aerodynamics would significantly reduce the energy consumption on the highway.

## 6.2 Functional and Innovative Lightweight Concepts and Materials for xEVs

*According to a McKinsey study* [101] *(2014), the proportion of high tensile steels, aluminum and CFRP in vehicles is set to increase from 30 % today to up to 70 % in 2030. High-tensile steel will remain the most important lightweight material (market share: 15–40 %) and CFRP are expected to experience annual growth of 20 %.*

Following the worldwide trend of dealing with the topic of Lightweight in 2014—Task 17 discussed and analyzed this topic in terms of a workshop.

The workshop (2014, Schaffhausen, Switzerland) was hosted by Georg Fischer Automotive AG, a Swiss company specialized in the field of lightweight design, which is well known for their pioneering materials developed in-house, bionic design, and optimized manufacturing technologies, in the automotive sector. About 30 participants included experts from industry as well as research institutes and representatives from government. The workshop enabled good talks and fruitful discussions between experts from different working fields and technologies.

The workshop was focusing on Functional and Innovative Lightweight Concepts and Materials for xEVs and covered four sessions about:

- lightweight activities in Switzerland (hosting country),
- lightweight materials and components,
- simulation and
- functional and innovative concepts and solutions.

The aim of the workshop was an information exchange in order to identify potentials for improvement in the field of lightening xEVs by giving an update on available lightweight materials and prognoses about future materials. Thus, representatives from all kind of materials were invited to share their opinion. **The workshop pointed out, that right at the moment there is no ultimate**

**lightweight material available. Much more, the future of lightweight materials will be a mixture of the best materials on the market available, by combining their benefits: there is a need for the right material on the right place**.

Furthermore, the participants got the possibility to participate at guided tours:

- **Automotive- and R&D-center** of Georg Fischer,
- **Iron Library**: the library's books and periodicals, offers an in-depth perspective like no other in the world. The collection comprises over 40,000 publications that deal with the topic of iron, including classics by masters such as Isaac Newton as well as specialized modern literature.

In order to emphases the bandwidth of different lightweight materials and solutions, which have been covered during a Task 17 workshop. The following section highlights the most important of them: bionic, materials and functional integration.

**Bionic**

**Nature has provided ideas for high-strength materials, dirt-repellent coatings and even Velcro fastenings.** This has led to developing bionic car components, or even full cars like the Mercedes-Benz bionic-car. The Alfred-Wegener Institute designs and constructs vehicle components with an intelligent lightweight construction by using ELiSE- Evolutionary Light Structure Engineering- a new, versatile tool for lightweight optimization. After the technical specification and objectives of a component are defined, the optimization is done by five steps: screening for biological archetypes within 90,000 structures → structure assessment (natural structures are analyzed according to technically boundary conditions) → abstraction and functional transfer of natural structures to CAD model → application of parametric and evolutionary optimization (FEA optimization with focus on feasibility of manufacturing and cost performance) → assembly.

Figure 89 shows the development of the ELiSE process with the example of a b-pillar. Finally a weight reduction of 34 %—from 8.0 (17.5 lb) to 5.3 kg (11.7 lb)—can be achieved.

**Materials**

Despite the above ground-breaking achievements in key areas, OEMs are still searching to develop strategies and technical solutions for cost-effectively integrating

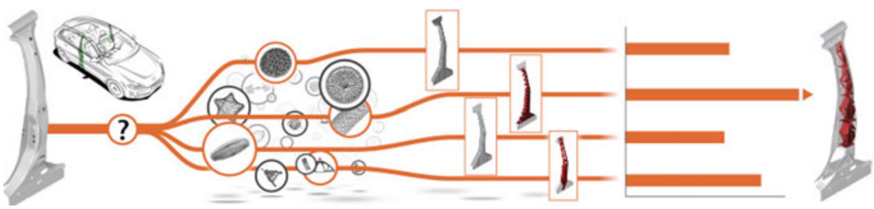



**Fig. 89** ELiSE process with b-pillar development [102]

lightweight materials into multi-material vehicles and securing lightweight materials and components on a global platform. **The combined use of various materials** (also known as multi-materials or sandwich materials) **allows the generation of products displaying a broad spectrum of desired properties**. By selecting the appropriate material many mechanical characteristics can be influenced and optimized. Sandwich structures with three or more layers represent the base technology for lightweight parts. The Austrian company *4a manufacturing* [103] offers the worlds thinnest sandwich structure, used to optimize vehicles weight. Especially, materials can be produced having very high bending stiffness at low weight and total thickness of 0.3 mm (0.01 in) or more and a surface weight of 100 g/m$^2$ or more. Further advantages are good formability and very good damping conditions.

Figure 90 shows the schematic build-up of the sandwich material. Automotive application fields for 'Cimera' are: firewall (−45 % weight reduction compared to aluminum), rear panel (−30 % weight reduction compared to aluminum).

AIREX Composite Structures produces sandwich materials being used in the application field of roofs for buses and trains. A weight reduction by up to 160 kg (352.6 lb) (−20 %) can be achieved by using sandwich roofs (see Fig. 91). Beside

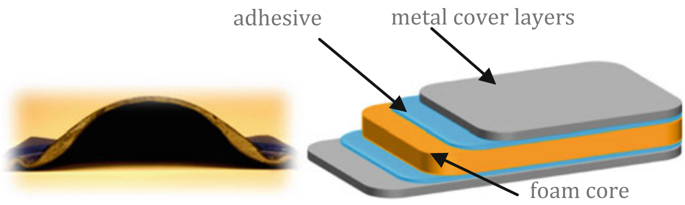



**Fig. 90** Material "Cimera" (*left*), schematic drawing (*right*) [104]

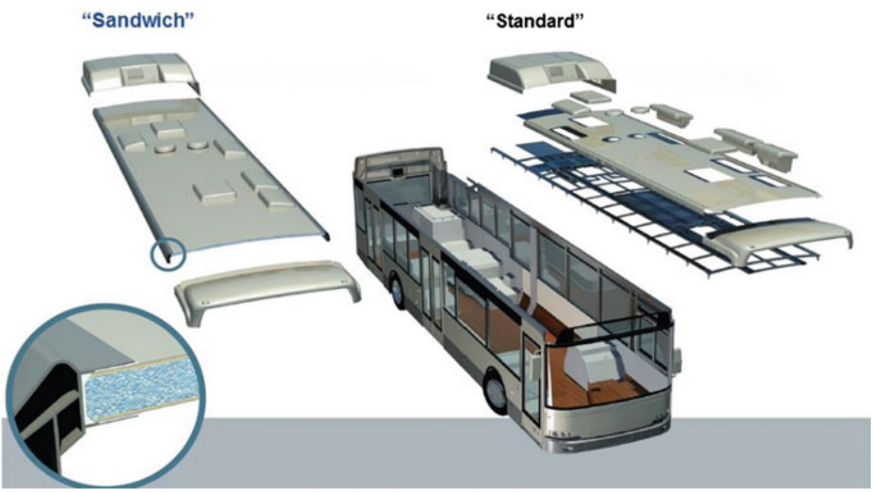



**Fig. 91** Sandwich technology for buses [105]

the benefits of weight reduction, the sandwich roof is stiffer under longitudinal, vertical and torsional loading (5–22 % smaller displacements), in comparison to the steel roof. Also the welded joint bounded joint is 50 % stronger than the steel one. A further benefit results in the saving of manufacturing costs (up to 10 %) and the saving of material costs in the build out through component integration.

Georg Fischer Automotive AG is specialized in the field of lightweight design. They demonstrated the challenges and hurdles between carbon composites and casting materials like iron, magnesium and aluminum. Thus, they showed the differences in the context of recycling, lower energy consumption, corrosion resistance, repair, weight, material cycle, resistance and costs. Table 8 compares the different material abilities between casting and carbon composites (Source: Georg Fischer). Figure 92 points out that carbon fibers have excellent abilities in terms of tensile strength, Young's modulus and weight reduction.

Carbon fibers have a huge benefit in comparison to casting materials, like their ability for weight reduction. Besides that, carbon fibers have a few disadvantages which makes them unattractive at the moment:

- **manufacturing climate balance sheet**:
  - Steel/AHSS (0–5 kg $CO_2$/kg),
  - Aluminum (10–25 kg $CO_2$/kg),

**Table 8** Comparison of different materials

| | GJS 400-15 GJS 450-10 | SIBO-DUR 700-10 | Aluminum | Magnesium | Carbon fiber |
|---|---|---|---|---|---|
| Tensile strength RM ($N/mm^2$) | Min. 400–450 | Min. 700 | 277–338 | 217.5–230 | 3530–4560 |
| 0.2 %—yield stress Rp0.2 | Min. 250–310 | Min. 440 | 142–196 | 112.5–155 | – |
| Elongation (%) | Min. 10–15 | 8–12 | 3.5–12.5 | 3.5–10 | 1.1–1.5 |
| Young's modulus ($kN/mm^2$) | 175 | 175 | 72–77 | 43–45 | 230–395 |
| Density ($g/cm^3$) | 7.1 | 7.1 | 2.6–2.7 | 1.8 | 1.8 |

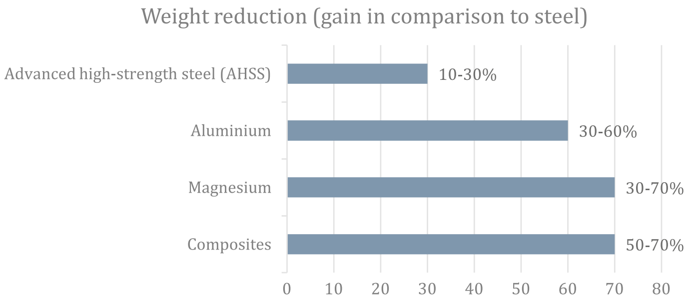



**Fig. 92** Comparison of weight reduction

  - Carbon fiber composites (20–42 kg $CO_2$/kg),
  - Magnesium (11–47 kg $CO_2$/kg);

- **manufacturing energy consumption**:
  - Steel/AHSS (0–25 MJ primary energy/kg),
  - Aluminum (60–200 MJ primary energy/kg),
  - Carbon fiber composites (280–380 MJ primary energy/kg),
  - Magnesium (310–390 MJ primary energy/kg);

- **emission over life-cycle**/change of perspective: Break Even:
  - 0 km High Strength Steel,
  - 90,000 km Aluminum,
  - 120,000 km Magnesium,
  - 170,000 km Carbon fiber;

- **availability**:
  - Magnesium: 8th abundant element in earth's crust;
  - Carbon fiber: uses polyacrylonitrile;

- **recycling**:
  - Metals: fully recyclable, used in new alloys, used as a mixture in new alloys,
  - Carbon fiber: still not sure how to recycle, at least downcycling or scrap;

- **cost comparison:** costs per part (in % of Steel)
  - Steel 100 %,
  - Aluminum 130 %,
  - Magnesium 155 %,
  - Carbon fiber 570 %—Thus, today there are up to 3 times higher costs for carbon fiber. With new precursors and technological progress improving production processes, a decrease of almost 30 % in the global cost of composites is expected between 2015 and 2020;

- **production chain**: Figs. 93 and 94 are showing the different production chains of carbon fiber and magnesium (based on the explanations and data from Georg Fischer Automotive). It can be seen that the production chain for carbon fiber is much longer and complex that the one for magnesium.

Georg Fischer demonstrated that there are a few materials for lightweight design available, all of them with different abilities. Using new materials like carbon fiber can held to reduce the vehicles weight drastically and furthermore to save fuel. But it is also necessary to have a look at the overalls balance sheet.

*Future vehicles will rely on multiple lightweight materials to reduce weight, and increasing use of both High Strength Steel (HSS) and aluminum within new vehicles are likely to continue. There are several advantages of using HSS over aluminum:*

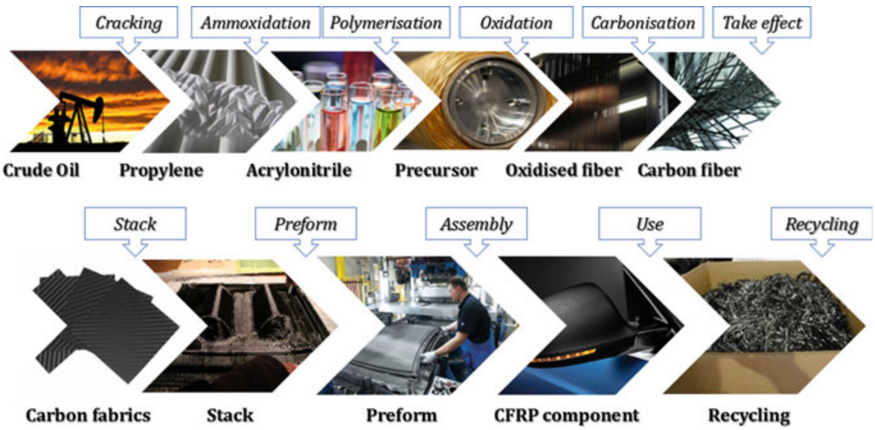



**Fig. 93** Carbon fiber production chain [106]

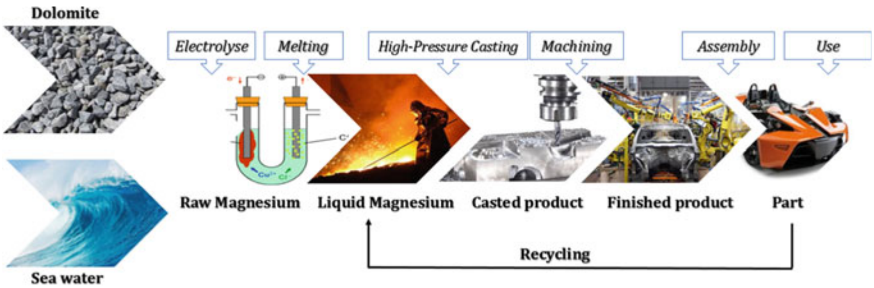



**Fig. 94** Magnesium production chain [107]

*the energy demands for producing HSS are lower, as is the cost per kilogram of total weight savings at high production volumes. HSS-intensive concept vehicles have also demonstrated that it is possible achieve similar degree of weight savings as with aluminum. Aluminum, however, is preferred in cast components like the engine block and wheels, where HSS cannot compete in.*

*This light metal will make some inroads in the body and chassis, but given its higher cost, aluminum content per vehicle is unlikely to overtake steel.*

A comprehensive comparison of all materials can be seen in Table 9.

Further, Georg Fischer showed ways of how to reduce the weight of existing components:

- substitution of sheet metal constructions: e.g. seat frame in casted magnesium up to 30 % less weight than metal sheet assembly, innodoor frame in casted aluminum up to 40 % less weight than metal sheet assembly,

**Table 9** Comparison of abilities of different materials

| Ability | Iron/steel | Aluminium | Magnesium | Carbon |
|---|---|---|---|---|
| Strength | ++ | + | 0 | ++ |
| Costs | ++ | + | 0 | −− |
| Energy consumption | + | 0 | − | − |
| Weight reduction | − | + | ++ | ++ |
| Repair | ++ | + | + | −− |
| Recycling | ++ | + | 0 | −− |

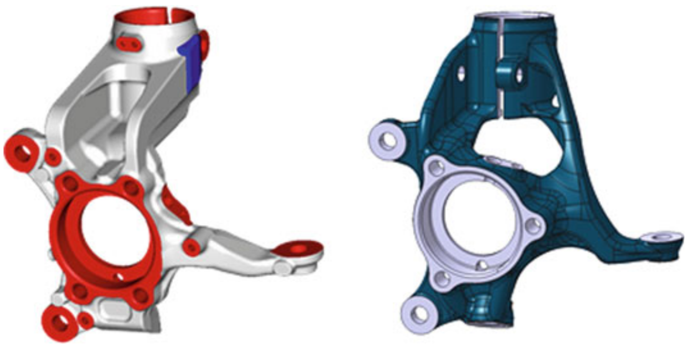


**Fig. 95** *Left* Front knuckle serial production, *right* Bionic front knuckle [108]

- implementing bionic design (see Fig. 95): e.g. weight reduction of up to 35 % in an iron steering knuckle through bionic design,
  substitution of system parts: cross member, completely casted in iron has 17 % less weight than combined assembly out of steel sheet and iron

**Functional integration in the field of lightweight**

**Functional integration provides parts with several functions in order to save on the final number of parts**. For example, replacing plastic interior trim with structural parts suitable designed with laminable, visually attractive surfaces. Individual close-to-the-wheel drives open up new possibilities for vehicle dynamics control strategies. This includes an associated increase of driving safety and energy efficiency through the targeted distribution of power and recuperation. On the other hand, the positioning of the motors close to the wheel increases the unsprung mass. This challenge can only be met by consistent lightweight design for all chassis components. The “LEICHT” concept—by the German Aerospace Centre DLR—presents a novel, drive-integrated chassis concept which in terms of its design and construction offers a significant chassis weight reduction (see Fig. 96). By integrating the motor into the chassis in an intelligent way, easy modularization regarding drive power and steer ability becomes possible. This enables an adoption to a variety of vehicle concepts and an application as front or rear suspension

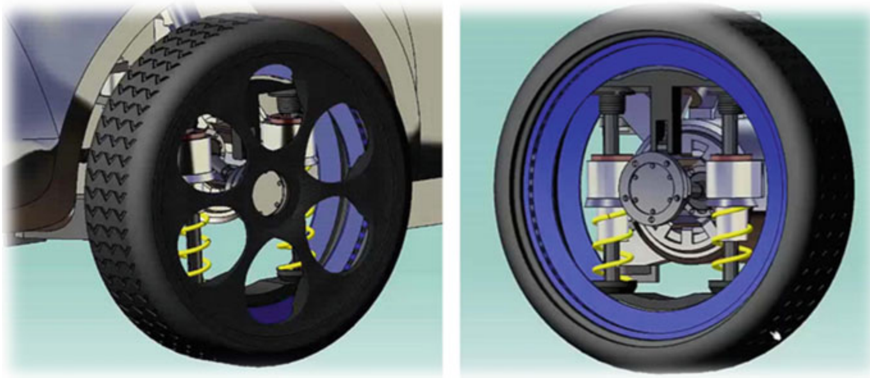


**Fig. 96** Torque transmission (*left*) and wheel travel (*right*) [110]

module, by reaching about 30 % weight reduction in comparison to conventional reference structures [109].

Another innovative concept called ESKAM was presented by Groschopp AG. In 2014 there were no optimized drive axles for BEVs on the market available. They are too heavy, too expensive and too big, measured by the available power. The aim of ESKAM (Elektrisch Skalierbares Achs-Modul) is to develop an optimized electric drive axle module for commercial vehicles, consisting of two motors, transmissions and power electronics (see Fig. 97). All components fit neatly and compactly into a shared housing, which is fitted in the vehicle using a special frame construction also developed by the project engineers.

This innovative concept provides an integration of the drive prior to the axis module by limiting the weight of the drive module to a maximum of 100 kg (220.4 lb). For this purpose, it is necessary to couple rapidly rotating e-machines with corresponding gears and to integrate them in a common housing. In this case, only e-motors are used, which are not dependent on permanent magnets or on ever-increasingly expensive rare earth elements such as neodymium and samarium. The electric drive consists of two identical electrically excited, electronically

**Fig. 97** Project ESKAM. *Left* Front axle, *right* rear axle [111]

commutated motors and transmissions, which are housed together with the power electronics in a housing and fitted to a drive axle module. The power range of the engine is scalable between 20 and 50 kWh. The axle module presents numerous advantages, such as a high power density and a very high torque. For drivers, this means very fast acceleration. Because the module is scalable, it can be used in everything from small vans and municipal vehicles, to buses and trucks. With a wheel hub motor, that would not be possible. While wheel hub motors have definite advantages, they are not suitable for commercial vehicles, as they scarcely deliver more than 2000 RPM. While the speed of most e-motors is approximately 10,000 to 15,000 RPM, the ESKAM motor (from Groschopp) achieves speeds of 20,000 RPM, with maximum torque of 45 Nm (33 lb-ft) and power of 32 kW (43 hp).

As well as designing the axle module, the project researchers and developers simultaneously developed the required series production technologies. As an example, gearbox shafts are usually manufactured from expensive cylinders or by means of deep-hole drilling. In both cases, the excess material is unused. By contrast, researchers have chosen new, short process chains together with methods that allow greater material efficiency. One such method is spin extrusion, which was developed by the project partners.

Magna presented a vehicle called CULT [112] (Cars' Ultra-Light Technologies vehicle), a modern lightweight vehicle fueled by natural gas which shows significantly reduced $CO_2$ emissions (Fig. 98). Lead-managed by Magna Steyr, the Polymer Competence Center Leoben GmbH worked on the development of an ultralight vehicle with minimal $CO_2$ emissions in the CULT project.

Comparable benchmark cars in this segment normally have a curb weight of approximately 900 kg. (1984 lb). By functional integration and cancellation of parts 80 kg (176 lb) should be reduced. Further 100 kg (220 lb) should be achieved by a multi material approach. Downsizing and the use of secondary effects should cut down the curb weight by another 120 kg (264 lb). Overall, this means a weight reduction of 300 kg (661 lb). Finally 672.5 kg (1481 lb) of total weight could be achieved by this holistic approach. The materials, being used can be seen in Fig. 99.

**Fig. 98** CULT, vehicle (*left*) and explosion view (*right*) [113]

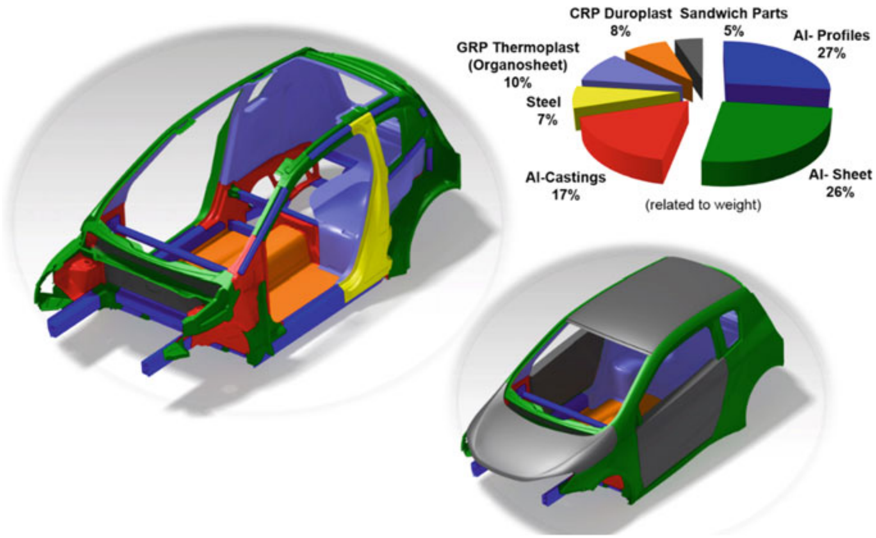



**Fig. 99** Materials concept for CULT [114]

Therefore, aluminum was used for several parts and represents nearly three quarter of the complete weight of the body-in-white structure. In addition steel was used in the side construction to obtain the crash relevant stiffness in this area. Organosheets, duroplasts as well as sandwich parts for the roof, doors and hood represent the rest of the material mix.

One of the methods employed to achieve this objective was exploitation of the properties of thermoplastic fiber composite materials relating specifically to weight in order to reduce the overall vehicle weight by using lighter components. For example, for the bumper beam, which consists of a crossbeam and shock absorbers, thermoplastic continuous-fiber-reinforced semi-finished composites were used.

The Fraunhofer Institute presented the requirements for a composite wheel with integrated hub motor—the development of a wheel of CRFP with an integrated e-motor (see Fig. 100). The main focus of the development was to achieve the optimum of lightweight potential considering structural durability.

During the realization, the technical challenges of multifunctional design were considered in the whole product life cycle. The CFRP lightweight wheel has a weight of approximately 3.5 kg (7.7 lb).

The motor housing is not directly connected to the rim, but to the inner area of the wheel axle. This prevents radial or lateral loads, especially shocks caused by rough road or curbstone crossing, from being transferred directly to the hub motor (4 kW). Another advantage of the separation of the load paths is that the rim can be more flexible than if it were directly connected to the hub motor. For increasing the flexural rigidity at a constant weight, foam cores were inserted into the spokes. A smaller, commercially available hub motor was used as the e-motor.

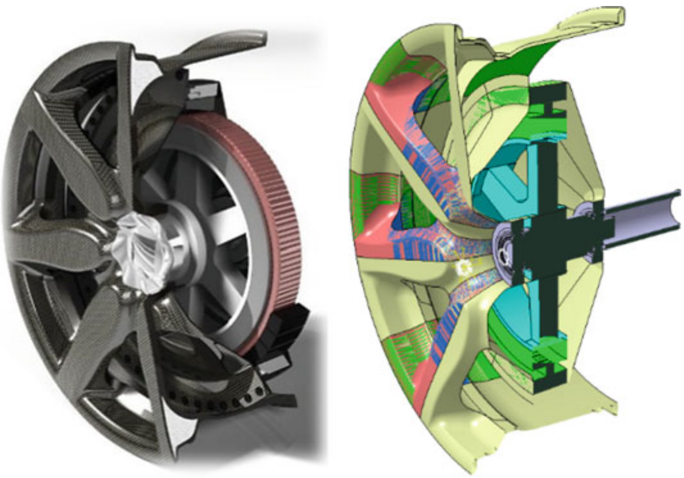


**Fig. 100** Wheel with integrated hub motor [115]

To align the fibers continuously and with the flow of the forces and to avoid stress peaks caused by sharp edges or sudden variations in rigidity, radii that are in line with the material and smooth transitions have been created in the component. The motor adapter flange is connected with the interior area of the wheel axle. To reduce the mass and increase flexural strength, foam cores have been integrated into the spokes. The e-motor is a small, commercially available wheel hub motor. The motor, consisting of a permanent magnet (outer rotor) and a yoke ring with solenoids (stator) has a power of 4 kW and a control voltage of 2 × 24.5 V. Through the use of high module fibers in fiber reinforced plastics, an increased eigenfrequency with improved damping behavior is achievable compared to the use of metal. Higher module fibers would allow still further reduction of mass noise emission.

## 7 Power Electronics and Drive Train Technologies as Overall Optimization Method

Nearly 40 years ago, the first piece of software was used in a vehicle to control the ignition of the engine [116].

The first software systems in vehicles were local and did not have any communication between different systems. Since then a lot has happened and today almost all new functionality involves advanced control of electronics and software.

The automotive industry is traditionally a mechanical based industry. Mechanics is still the foundation of the vehicle, however the amount of software and electronics is increasing rapidly. Thus, the automotive industry faces a challenge.

**In 2004, 23 % of the overall cost of high-end cars was related to the Electrical/Electronic (E/E) system** (Hardung et all. [117]). At this time this figure was believed to increase to 35 % in 2010 [118].

**Today up to 90 % of all new innovations in a car are realized with electronics and software** [119].

*In today's commercial vehicles driven by an ICE, the proportion of electrical, electronic and IT components is between 20 and 35 % (dependent on the vehicles class). In xEVs, this share will increase to up to 70 %. This includes around 70 main control units with more than 13,000 electronic devices.*

*In the future, every second euro/dollar is spent on the production for electronics. Currently, the share of electronic components to the manufacturing cost is around 30 %, by 2017 it will grow to 35 % and will still increase to 50 % in 2030.*

## 7.1 *Reasons for an Increasing Amount of Software and Electronics*

One of the **reasons for the large increase of software and electronics are the customers demand for new safety and convenience functions** such as adaptive cruise control, blind spot detection, forward collision avoidance, lane departure warning and many other **Advanced Driver Assistance Systems (ADAS)**, which means safety becomes one of the key challenges by increasing the amount of software.

ADAS can be seen as a pre-stage of autonomous driving (compare the different pre-steps of autonomous/automated driving at Fig. 101). The current trend towards

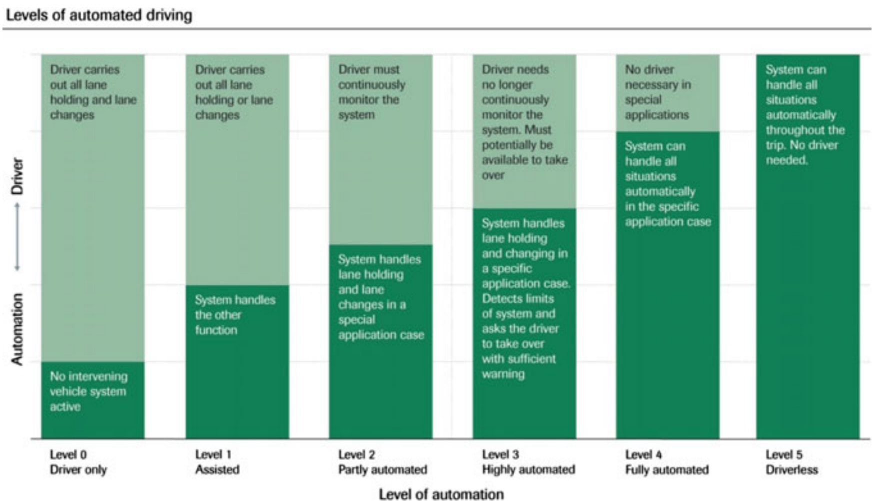



**Fig. 101** Levels of automated driving, including ADAS [120]

autonomous driving requires interconnectivity of modules and systems such as control units, sensors and actuators, which have to communicate in a timely, safe and reliable way. Therefore embedded software, including functional integration, is indispensable.

**Functional integration** plays an important role due to the fact that electric systems and embedded software are increasingly taking over the functional integration role. Today about 80 % of all vehicle innovations are coming from the field of electronics which indicates that future cars will be highly connected but will also consist of complex systems.

Last but not least, to cope with **new regulations on emissions** the use of software and electronics is a necessity.

## *7.2 Electrified Drive Trains Leads to Increasing Complexity*

Powertrains in EVs have to meet demanding requirements with respect to power density, life time and component costs. Thus systems are becoming increasingly complex making the engineering of these software intensive systems more and more difficult.

Especially the change towards electrified technologies—the advanced implementation of HEVs and BEVs—has led to an increased consumption of electrical energy in automotive wiring harnesses. As it can be seen in Table 10 these vehicles require new/additional components like the e-machine, power electronic unit, battery system, etc. which include a massive amount of software and electronic. Such vehicles require a modification of the drive train components which means a fundamental technology turnaround and that leads to complex systems.

Complex systems require software in the powertrain, embedded systems E/E-Architecture, Intelligent Control, which are increasingly taking over the functional integration role in the vehicle development.

The increasing amount of varieties of architecture of current (H)EVs can be seen in Fig. 102, by comparison of Nissan Leaf, Toyota Prius, Renault ZOE and Renault Fluence ZE.

**Table 10** List of components for e-vehicles: not needed/to be adapted/new ones

| Components not needed any more | Components to be adapted | Additional components |
|---|---|---|
| Combustion engine | Transmission | E-machine |
| Fuel-injection system | Wheel suspension | Advanced power electronics |
| Tank | Power electronic | Battery system |
| Clutch | Air conditioning | |
| Exhaust-gas system | Water pump | |
| Auxiliary equipment | Thermal insulation | |
| Combustion engine | Transmission | |

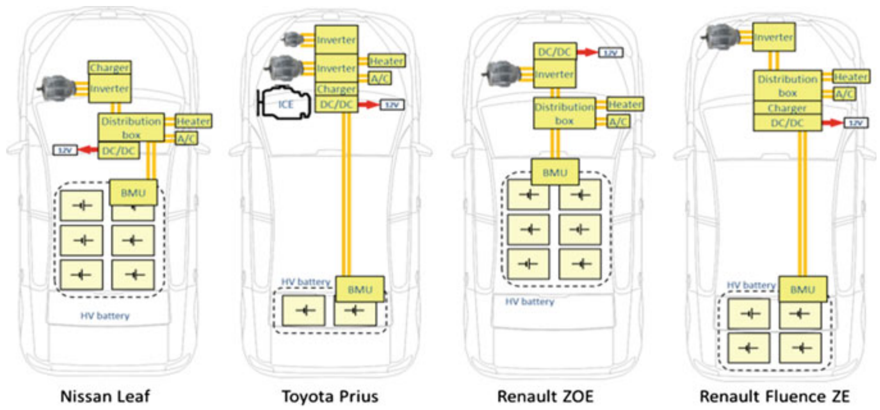



**Fig. 102** Power architecture of current (H)EVs [121]

Furthermore, the comparison of the power architecture of different current (H) EVs demonstrates, the use of different power and high voltage levels can be seen in Figs. 103 and 104. Thus, the highly diverse E/E-Architecture is obviously and will still stay diverse, due to different OEM strategies and different hybridization strategies.

Future power electronics will have to adapt modularization and downscaling in weight and volume. Thus, the optimal use of electronics & software in vehicles is

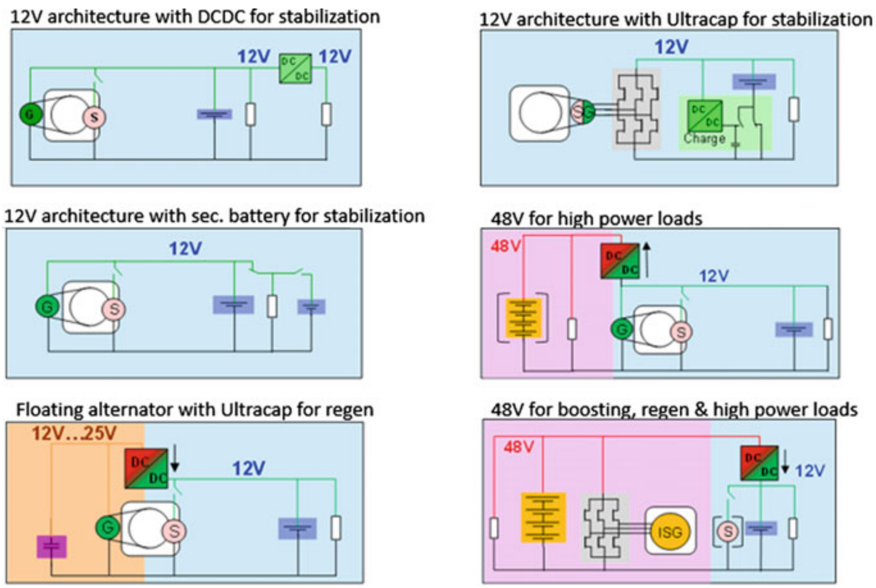



**Fig. 103** Power net architecture [122]

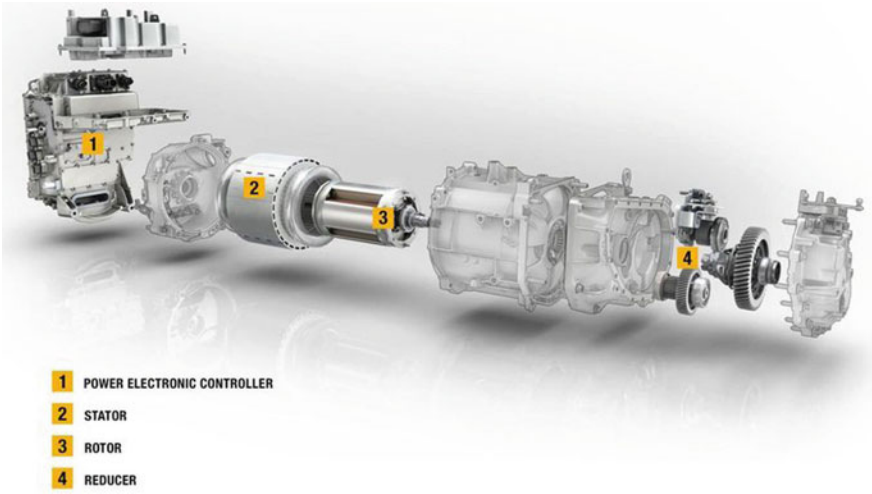



**Fig. 104** Exploded view of the R240 [124]

THE prerequisite challenge in order to meet all requirements of cooperative vehicle safety, the adaptive vehicle management, electrification, automated driving and especially to improve the vehicles performance in terms of efficiency which directly influences mileage and finally it turns into a very real and visible benefit to the customer.

Reducing electrical energy consumption in the complex E/E-Architectures of modern passenger vehicles has increasingly been a topic for discussion over the last couple of years. The E/E-Architecture of EVs consist of at least two voltage domains where vehicle modules are placed in relation to their application.

As mentioned in this section, due to the increasing amount of electrification of the vehicle and thus the upcoming complexity of the vehicle, several questions have to solved, regarding the optimization of the E/E-Architecture, like:

- complex cooling system (up to three different heat exchanger for one car: engine, power electronics, battery),
- design standard modules for various applications to reduce non recurrent engineering cost,
- limited volume under the hood (especially for HEV and PHEV),
- high electrical power for auxiliaries → 12 V and 48 V network,
- connected car system demanding high auxiliary battery capacity (especially for car sharing),
- maintenance: for any repair shop; continuously evolving technologies,
- 1 % energy loss/gain on a 10 kWh battery corresponds to a 43.3 EUR (48.5 USD) loss/gain (according to U.S. DoE) for same EV mileage,
- ensure reliable and safe operation throughout system lifetime.

## *7.3 Benefits Through Optimized Power Electronics and Drive Train Technologies*

**Task 17-workshop on Power Electronics and Drive Train Technologies**
In April 2015, RENAULT announced, that they have been successful by extending the range of its BEV ZOE to 240 km (149 mi.)—a boost of 31 km (19 mi.) or 14.6 %—in the New European Driving Cycle (NEDC) by using a new lighter and more compact R240 e-motor and an optimized electronic management system. The R240 is a synchronous e-motor with rotor coil, with a power output of 65 kW and torque of 220 Nm (162 lb-ft). It also features a built-in Chameleon charger which allows faster charging at home (3 and 11 kW). The R240 (see Figs. 104 105) is an all Renault motor [123].

Two main areas of focus in the development were improved electronic management to cut electric energy consumption on the move and the new charging system to reduce charging times at low power levels.

Due to the fact, that this example of an OEM successfully demonstrated that improving the power electronic unit has a massive impact on the improvement of the overalls vehicle performance, the members of the IEA-Task 17 agreed on a

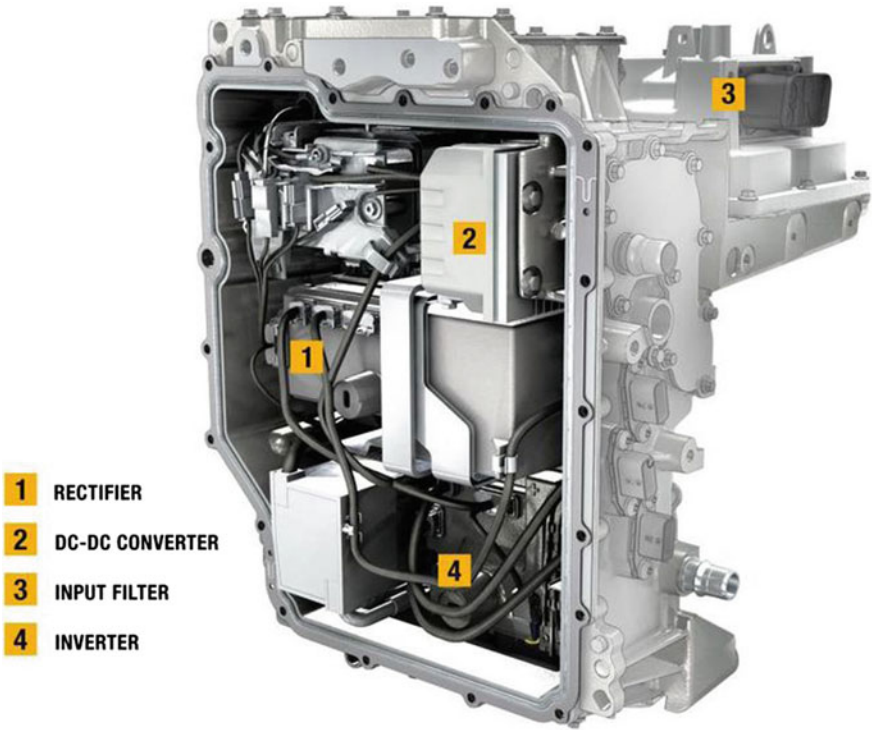



**Fig. 105** Cutaway view of the power electronic controller [125]

workshop about "Power Electronics and Drive Train Technologies for future xEVs".

The workshop was organized by the A3PS and held in Berlin (Germany) in April 2015, hosted by VDI/VDE-IT, a service provider in the field of innovation and technology for customers in Germany and all over the world. VDI/VDE-IT analyses, supports and organizes innovation and technology for clients with political, research, industry and finance backgrounds.

About 20 participants from industry as well as R&D and policy makers followed the invitation and participated at this one-day workshop. Participants from several countries (Austria, Belgium, France, Germany, Switzerland and the USA) have been present.

**Aim of this workshop**: the aim of this workshop was to summarize and communicate on a global level:

- the status and prospects of Power Electronics and Drive Train Technologies,
- to give an introduction about E/E-Architecture and Intelligent Controls in order to enhance the overalls vehicle performance and
- discuss the synergies of fully autonomous vehicles.

**Results of the workshop**

This workshop was focusing on methods to improve the energy efficiency and performance of xEVs. Thus, the following topics have been discussed:

- **virtual design approaches** in the development of powertrain concepts,
- evaluation of **future powertrain architecture** and their benefits on efficiency,
- new **power electronic concepts for online energy management**,
- **cloud data solutions** to improve the intelligence of such vehicles,
- possibilities of improving the e-motor by using advanced E/E-Architecture,
- combined **view of the grid and the vehicle together** as a system,
- **methods to calculate the maximum junction temperature** in a vehicle drive with a combined cooling system, which makes it possible to specify the cooling system with respect to a specific drive cycle, a maximum power rating, as well as a maximum acceleration from standstill,
- benefits of **modular drive train structures** with a flexible drive train topology as better utilization of components, higher production numbers (in terms of economy of scale), an advanced energy management, enhancement of system life time and reliability, additional safety functions and system redundancy and
- **synergies between electric and automated driving** by collecting of new ideas for a follow up Task.

**Focus on power electronics and drive train technologies**

**Virtual Design Approaches in the Development of Electric Vehicle Powertrain Components**

This section was provided by Mr. Johannes Gragger from AIT.

Power electronics, machines and batteries in EVs and HEVs have to meet exceptional requirements with respect to power density, resilience and component costs.

In the design process usually driving cycles are used to assess the performance of an electric powertrain configuration. Due to the typical load play it is of high importance to consider the electrical, mechanical and thermal effects including respective interactions in the individual system components.

Especially thermal EV drive simulations consists of different challenges like real load cycles as well as the largest (thermal) time constants can have several minutes, high switching frequencies vs. large mechanical and thermal time constants and drive models calculating switching events are slow.

The resulting question tries to look at the temperature of the inverter bridge, how hot does the inverter bridge get in the worst-case instance of a presumed drive cycle?

During a task 17 workshop in Berlin (2015), the AIT showed methods as well as benefits and challenges of virtual electric powertrain design and discussed their application in powertrain development projects (based on the data of the conference paper [126]: "*An Efficient Approach to Specify the Cooling System in Electric Powertrains with Presumed Drive Cycles*").

The interactions of the cooling system with the electric drive components of a battery electric bus are assessed by multi-physical domain simulation. A vehicle model with real drive cycle data is applied for the calculation of the torque and speed of the induction machine. These results are then imported to an electro-thermal-mechanical drive model that is fast enough to calculate the thermal conditions of the electric drive throughout an entire drive cycle. With another drive model the maximum values of the junction temperatures that are cooling system and drive cycle dependent, are calculated.

Thus, the AIT showed simulation models to calculate the maximum junction temperatures in a vehicle drive with a combined cooling system. It has been shown that by simulating the vehicle model, drive model A and drive model B one after another, it is possible to assess the influence of the combined cooling circuit on the worst-case junction temperatures in the inverter.

For the initial simulation the EV is modeled considering mechanical and electric effects while transient thermal effects (such as temperature changes in components due to heat dissipation) are disregarded.

In the simulation a virtual driver model controls the vehicle model using a prescribed reference drive cycle. The drive cycle data is found from test rides with a reference vehicle carrying a GPS logger. During these test rides on prescribed public traffic routes the instantaneous local position of the vehicle was recorded. Figure 106 shows the instantaneous vehicle speed and altitude profile corresponding to the public traffic route that is used as the reference for the presented virtual design approach.

In the vehicle model the electric part of the powertrain is modeled with a battery model and a variable-speed electric drive model (comprising the behavior of the two-level inverter, field-oriented-control and the induction machine). Simulating the vehicle model the instantaneous torque requirement and the angular speed of the induction machine are calculated. The respective simulation results are shown in Fig. 107.

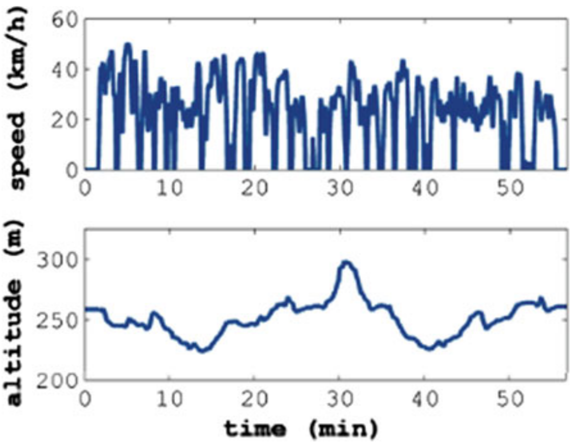



**Fig. 106** Real drive cycle extracted from GPS data [127]

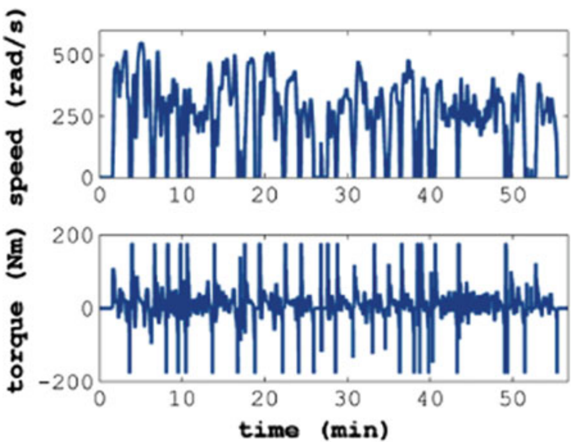



**Fig. 107** Machine speed/torque requirements [128]

Therefore, if applied in a virtual design approach the three models can be utilized to find the cooling system specifications required for a save inverter operation in the electric powertrain with the described cooling circuit topology.

Three simulation models were used (Fig. 108):

- a vehicle model,
- a drive model for drive cycle simulation and
- a refined drive model

In the proposed approach the results of the vehicle model are used as input data to drive model A and the results of drive model A are used in drive model B. The

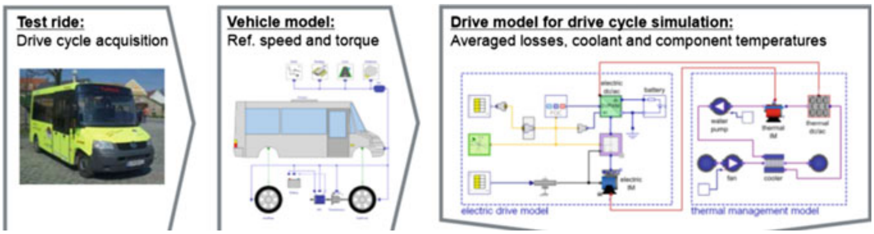



**Fig. 108** Evaluation of the maximum junction temperature [129]

proposed approach makes it possible to specify the cooling system with respect to a specific drive cycle, a maximum power rating, as well as a maximum acceleration from standstill (plus curb climb).

To keep the calculation effort at the lowest in every simulation the three models are consequently rid of physical relations that do not have a significant influence on the calculated results. This makes the presented approach very computation time efficient.

The models showed that the load in real drive cycles changes very often and is low most of the time. Further, a usual result is that the cooler can be smaller than expected [130].

### Efficiency Improvement Potentials for Light-, Medium- and Heavy Duty Trucks via Hybridization and Electrification in Urban and Sub-Urban Traffic

<u>This section was provided by Mr. Peter Prenninger from AVL.</u>

By means of numerical simulations it was investigated how and to what extend future powertrain architectures for three classes of commercial vehicles (light-, medium- and heavy duty trucks (see Table 11)) can contribute to efficiency improvements. Thus it was investigated how to reach the optimal match of powertrain systems of trucks for particular use cases by investigating the typical load profiles for different vehicle classes, mentioned above.

**Table 11** Vehicle classes used for the study (light N1; medium N2, heavy N3 [131])

| Light/N1 ("Sprinter Class") | Medium/N2 ("Atego-Class") | Heavy/N3 ("Actros-Class") |
|---|---|---|
| Max. 3.5t GVW | Max. 12t GVW | Max. 40t GVW |
| 2.1 t tara mass, 0.9 t max. pay load | 4.5 t tara mass | 15 t tara mass |
| Assumption: 0.5 t av. load (volume fully utilized) = 125 parcels à av. 4 kg | Assumption: 4.5 t av. pay load = 9 pallets à av. 500 kg | Assumption: 20 t av. pay load |
|  |  |  |

Particular transport routes in urban and suburban services were selected which are very representative for each class of vehicles and their typical use profiles. Various types of hybridizations as well as different fuel options were taken into account. The results indicate that there is not a single "optimal" solution, but in each vehicle class, a "best solution" always depends very much on the profile of the transport tour and the related load profile for the powertrain (compare Figs. 109, 110 and 111). The study also indicates that Start-Stop and Mild Hybrid offers high $CO_2$-reduction potential at relative modest add-on costs. Furthermore PHEVs are almost as good as pure EVs with advantage of wider range and much lower costs (Fig. 110).

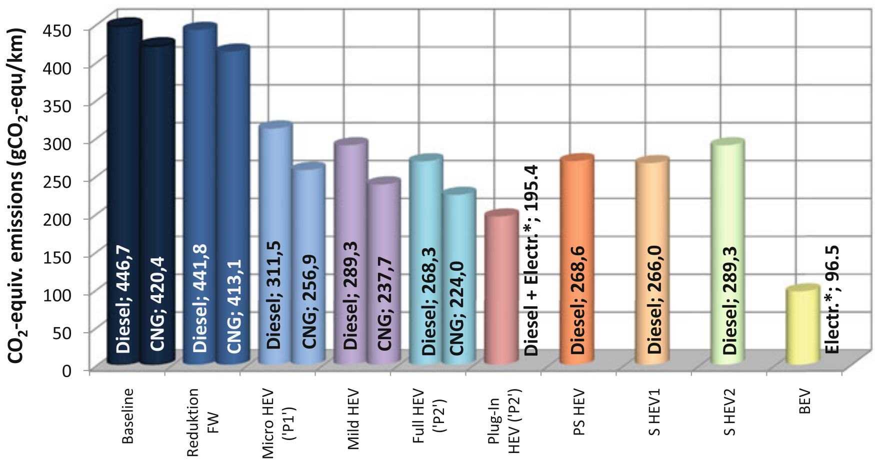



**Fig. 109** Simulation results: light/N1 ("Sprinter-Class") [132]

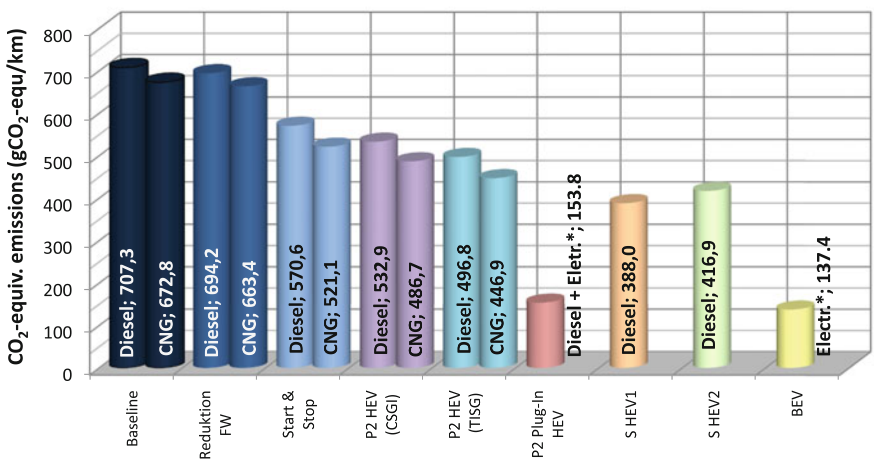



**Fig. 110** Simulation results: medium/N2 ("Atego-Class") [133]

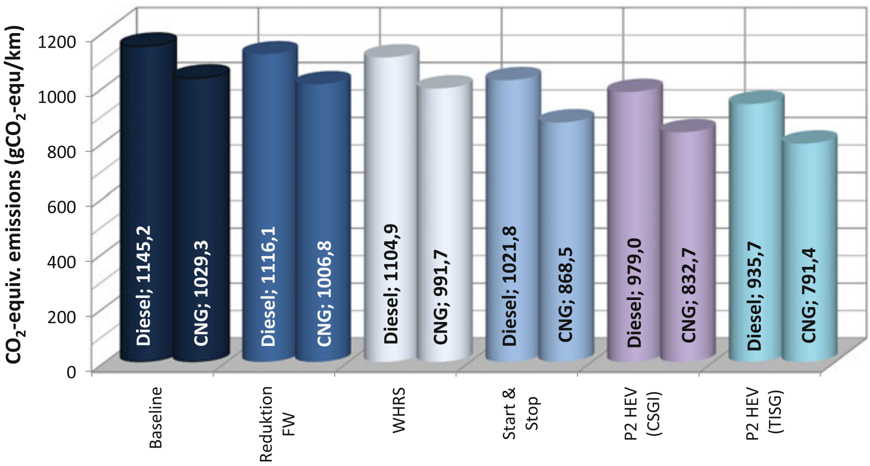



**Fig. 111** Simulation results: heavy/N3 ("Actros-Class") [134]

### Advanced Reluctance Motors for Electric Vehicle Applications

Punch Powertrain is working on a project called ARMEVA, which aims to develop a new rare-earth-free generation of advanced reluctance motors (see Fig. 112), as rare earth supply issues are expected within the next years. Alternatives exist, the challenge is to deliver alternatives that combine the best balance of efficiency, power density, safety, reliability, durability and cost.

*The goal of ARMEVA is to achieve similar power density and NVH-performance (Noise, vibration, and harshness) at lower costs when compared to permanent magnet motors in real EV applications. The focus will be on Switched Reluctance Motors, Variable Reluctance Synchronous Motors and DC exited flux-switching motors which each have been the topic of previous research by the consortium, and offer promising potential.*

*The scientific objectives of the ARMEVA project are: (i) development of multi-physics simulation models for advanced reluctance motors; (ii) comparative assessment to select optimal motor topology for future EV's; (iii) development of an integrated electric drive system based on advanced reluctance motor technology and customized power electronics* [135].

Challenges—are in overcoming the inherent torque ripple and NVH while maintaining high efficiency as well as in developing adequate power electronics for an independent control of each phase at affordable cost. Due to the fact of being a non standardized component, it requires economy of scale.

The ARMEVA project addresses these challenges by CAE based optimization, advanced control methods, integral system design optimization and by further integration of drive train components.

The main scientific objectives of the ARMEVA project are the development of multiphysics simulation models for advanced reluctance motors, comparative

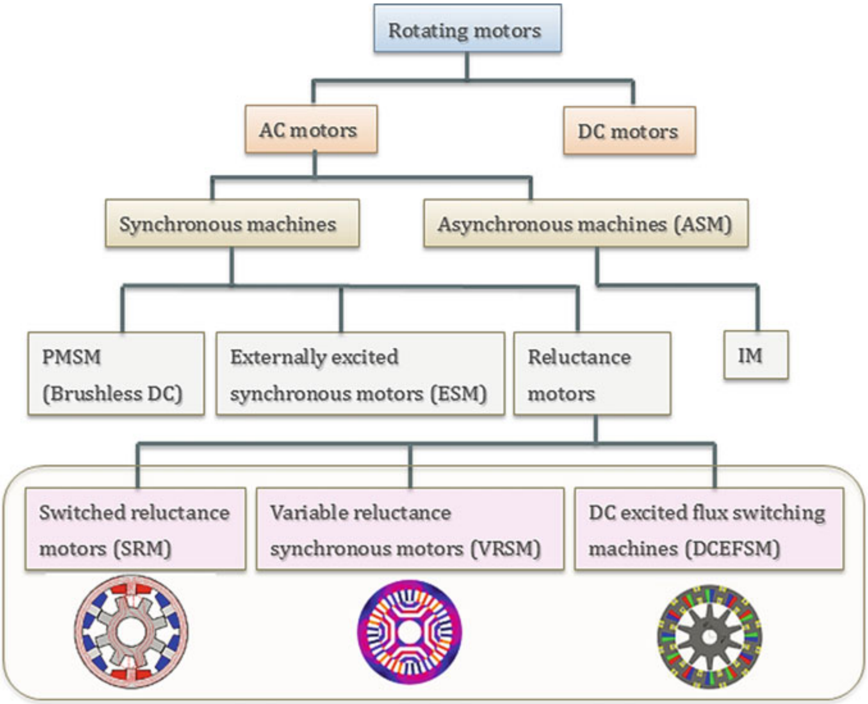



**Fig. 112** Advanced reluctance motors

assessment to select optimal motor topology for future EV's and development of an integrated electric drive system. The entire system consisting of control software, power electronics and a physical e-motor (including high voltage wiring, liquid cooling and a 100 kW SR motor) (Fig. 113) will be integrated and validated in a vehicle platform.

**Fig. 113** Electric drive system of "ARMEVA" [136]

ARMEVA is using a system based approach using multi-attribute techniques to improve the overall concepts and multi-application, multi-operation analysis to optimize vehicle level efficiency in a wide range of realistic conditions.

### Focus on E/E-Architecture and Intelligent Control

### Examples of electric innovative architectures for xEVs

The growth of EVs market encourages car manufacturers to continuously improve the E/E-Architecture of xEVs due to the fact that the classical E/E-Architecture (see Fig. 114) has limitation and has to be challenged. CEA (France) presented two examples, how innovative architectures can enhance service to customers. For example smart Battery Modules, with new integrated functions, are one of the solutions to imagine, design and define new electric architectures.

In terms of requirement for new batteries and architectures there are a few aspects which should be considered, as low system cost; high quantity/low part number; low development cost, re-use, low space requirements. Furthermore the system should be: reliable and safe; flexible and always available. **All these requirements leads to the necessity for standard modules with integrated functions.**

CEA showed two proposals. The first one deals with an innovative balancing solution supplying 12 V auxiliary network, which permits:

- a redundant 12 V supply implying no need for a 12 V battery,
- the ability to have 48 V or 12 V or both with one standard module,
- a better efficiency for the 12 V supply at low power,
- endless energy on the 12 V network when vehicle is off and
- a high power balancing which enables fast charging and compensation of capacity difference between modules.

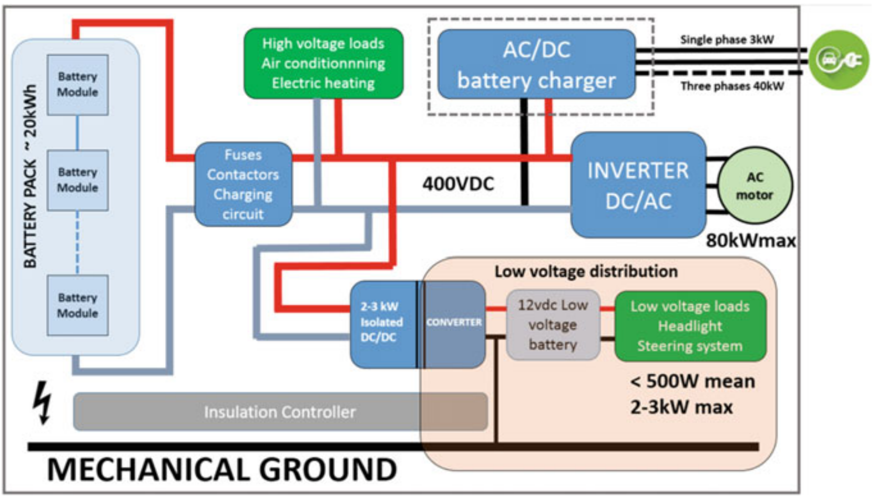



**Fig. 114** Battery pack in the E/E-architecture of an EV [137]

The advantages of the presented balancing solution (supplying 12 V auxiliary network) are:

- compensation of differences of capacities (compare
- Figures 115 and 116). The standard module consists of 2 kW in the drive and 300 W in the auxiliary network, including a (45 Ah + 40 Ah (in serial) = 40 Ah battery pack. The remaining energy in module 1 at the end of discharge consist of 3000 Wh. While the smart module consists of 2 kW in the drive and 300 W in the auxiliary network which is split in 220 W in module 1 and 80 W in module 2. That enables the increase of the energy used at the end of discharge. Thus the energy of the pack is totally used,
- possibility of removing the low voltage battery,
- better efficiency with low power consumption and a
- flexible configuration as it can be seen in Fig. 117.

The second proposal deals with a solution of a switch module (see Fig. 118) which also permits:

- a bypass of one module in case of fault/service continuity in case of fault,

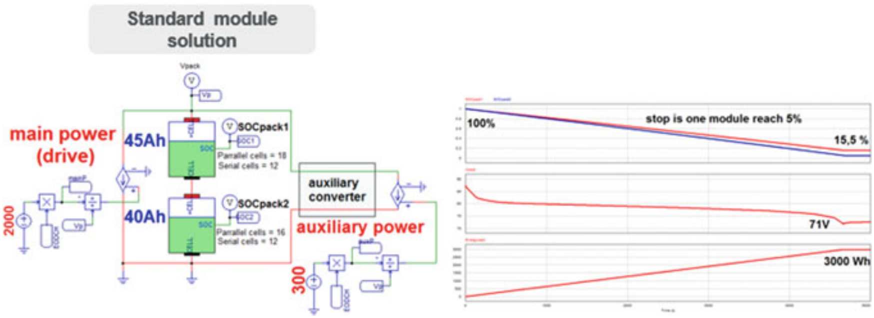



**Fig. 115** Standard module solution [138]

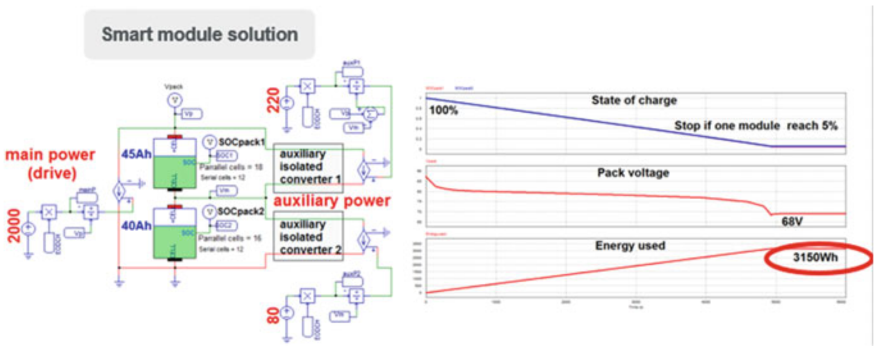



**Fig. 116** Smart module solution [139]

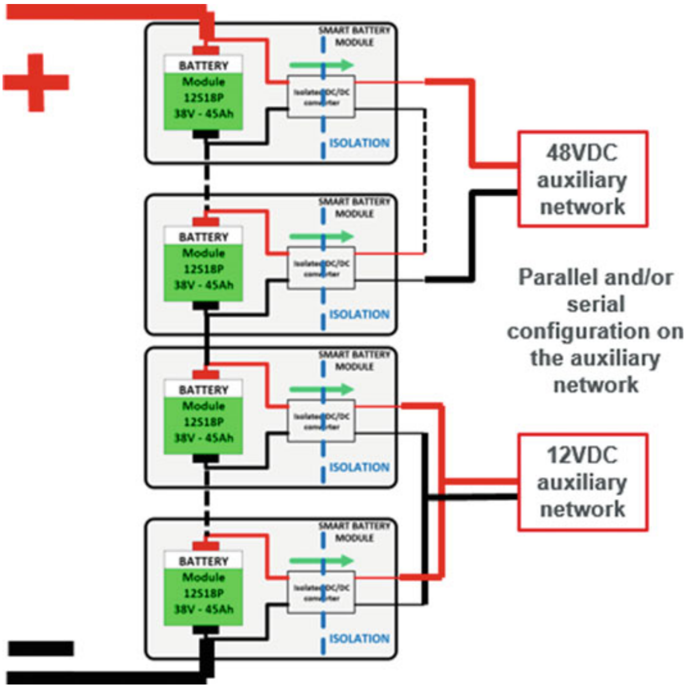



**Fig. 117** Flexible configuration as a big advantage [140]

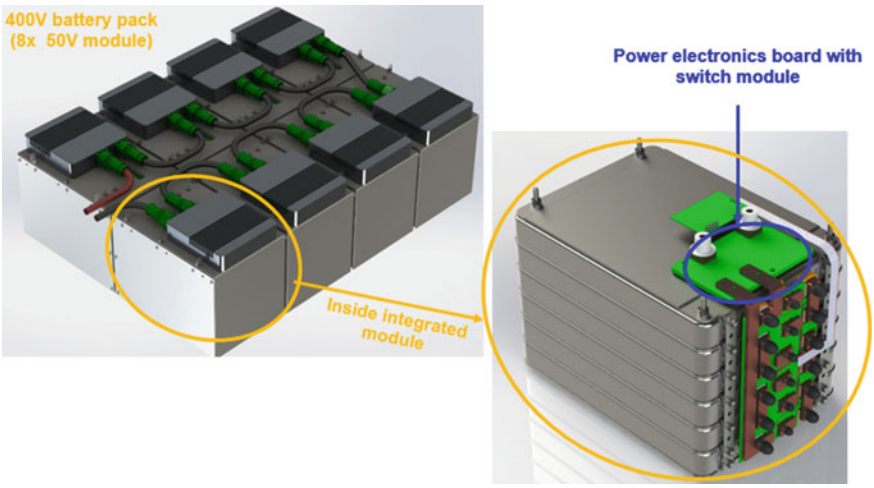



**Fig. 118** Designed prototype for a switch module [141]

- an increasing battery capacity (range) without modifying DC bus voltage,
- standardization becomes easier and
- safety improvements during manufacturing and in case of crash.

**Vehicle Cloud information**

**IMPROVE**—Cloud Data Solution
The IMPROVE main approach is to innovate the intelligence and connectedness of commercial EVs integrated control systems delivering improved connectedness of the vehicles to on-board and off-board data, energy efficiency and drive range while maintaining comfort and safety. IMPROVE focuses on in-vehicle information and communication technologies innovations for commercial vehicles. Within this focus, IMPROVE leverages a set of hardware and software innovations that in combination add a target of +20 % range for the same battery capacity, increase the life of the battery, reduce the cost key components and uses deeply integrated interconnections between subsystems inside the vehicle and between the vehicle (sub-)system and the outside world.

Thus, IMPROVE aims to increase efficiency and range predictability of CEVs (commercial electric vehicles) operated in fleets by:

- employing cloud information for operation and control strategy;
- reuse of waste energy in a holistic, predictive way;
- learning from history (gaining information of several vehicles and using this info for a strategy);
- establishing psychological efficiency incentives through gamification.

IMPROVE will drastically increase the intelligence of the vehicle in two ways: on one hand through the interaction between an integrated control system and on-board and off-board data; and on the other hand by developing in-the-loop local modelling and scenario check capabilities into control subsystems to increase the intelligence of each component.

Algorithms developed in the project will thus involve modelling scenarios of the future before deciding what the best course of action might be. In the case of commercial vehicles, the focus on operation economy and the influence of payload changes during the trip on energy consumption is especially important, and the IMPROVE approach allows to take these parameters into account.

*This workshop demonstrated that improving the power electronics unit, the E/E-Architecture, the introduction of an intelligent control and the modification of the drive train technologies indeed helps to improve the overalls vehicle performance of xEVs.*

*Future generations of xEVs require a layered, flexible and scalable architecture addressing different system aspects such as uniform communication, scalable and flexible modules as well as hardware and software.*

*Future (P)HEVs and BEVs will—apart from some micro hybrids—require a high voltage power net in addition to the conventional power net. This high voltage power net includes at least an electrical energy storage and a single drive inverter.*

*The automotive future is hard to predict, but it is indeed promising for the power electronics and motor drives industry.*

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# Final Results and Recommendations

**Michael Nikowitz**

**Abstract** Task 17 of the International Energy Agency's Implementing Agreement for Hybrid and Electric Vehicles was working on the System Optimization and Vehicle Integration of electrified vehicles to enhance the overall vehicles performance. The Task successfully demonstrated that lightening the vehicle (by using bionic concepts, smart materials and functional integration), improving the electric power control unit (trough improvement of the electrical and electronic architecture), optimizing thermal management solutions and improving the battery management system, can help to improve the energy efficiency and the overall system performance of such a vehicle. These improvements can significantly increase the drive range and reduce costs and therefore can make the vehicle more attractive in terms of customer acceptance. Some of the developed methods and improvements are now being used in current vehicles, which highlight the significant importance and success of this Task.

Worldwide industry and government are forced to consider **alternative and sustainable solutions for transportation**. Vehicles, driven by alternative drive train offer a unique advantage concerning energy efficiency, emissions reduction, and reduced petroleum use and have thus become a research focus around the world.

Studies—conducted by the IEA—pointed out, that there are approximately **700,000 BEVs and PHEVs on the streets** (as per May 1st 2015). It's expected to reach the **1 million mark till the end of 2015**. There are predictions that the EV market will reach 8 % of total car sales by 2020 (2.5 Mio. BEVs, 3.1 Mio. PHEVs and 6.5 Mio. HEVs (Source: Bosch, 2015)).

Electronic systems involved in the operation and monitoring of such vehicles have been the subject of substantial improvements during the past few years. Consequently, these systems not only have gained importance in conventional transport systems, but they also have improved the perspectives for electric drive

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trains. Nevertheless, further optimization of these components and new concepts for their integration in the overall system tuned to the specific requirements of different vehicle applications is necessary.

**Task 17** was running for a period of five years (2010–2015) and **was working on the system optimization and vehicle integration of xEVs to enhance the overall vehicles performance.** During that period **nine expert-workshops** took place on several locations worldwide (including 43 speaker and about 143 participants).

**Task 17 successfully demonstrated that lightening the car, improving the electric power control unit, optimizing of thermal management solutions and improving of the battery management system, helps to improve the energy efficiency and the overall system performance of such a vehicle.**

These improvements can significantly **increase the drive range** and **reduce costs** and therefore makes the vehicle more attractive in terms of **customer acceptance**.

## 1 Batteries

During the past decade, there has been a lot of progress, especially in the field of electrochemical storage devices and FCEVs (see Fig. 1). Beside durability and energy density, cost is one of the main areas where improvements are required to compete with conventional fossil fuels. Within the last years, costs have been falling rapidly and are expected to continue doing so for the next 10 years. The battery's durability is already expected to be sufficient for automotive use, giving ten years calendar life and 150,000 miles of range. Fuel cell stacks appear to still be falling short of the US DoE's 2009 target of 2,000 h operation, corresponding to approximately 25,000 mi. before a 10 % drop in power output. Energy density is still the Achilles heel of batteries. The next generation of lithium-based chemistries are expected to approach the perennial problem of 'range anxiety'.

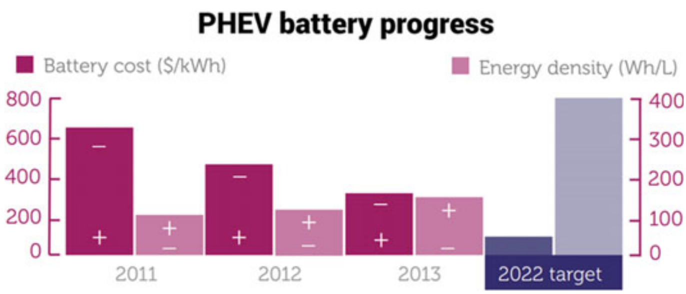


**Fig. 1** PHEVs battery progress: costs have fallen while energy density rose [1]

Currently, 80 % of the total amount of e-drive costs belongs to the battery, while the 10 % attributable to the e-motor and further 10 % to the power electronics.

## 2 Improvements by Thermal and Battery Management

Thermal-, and battery management is playing an important role (and will still play one of the most important roles in the future) as it can increase the range and efficiency through optimized system configurations. Knowing the precise thermal interaction of components is necessary for an optimal design as it influences fatigue, energy consumption, noise, emissions, etc.

Workshops of this Task pointed out that:

- driving at higher speeds but also aggressive driving will increase the energy consumption in an electric car,
- cold start energy consumption is larger than the hot start energy consumption (BEV),
- the largest energy consumption increase for an EV occurs at −7 °C (20 °F) and for a conventional one at 35 °C (95 °F),
- a conventional vehicle has the largest absolute energy consumption penalty on a cold start,
- powertrain type, driving style, and ambient temperatures all impact the energy consumption significantly and
- generally increased speeds and accelerations translate to higher energy consumption except for the conventional due to low efficiency in the city

## 3 Simulation and Virtual Vehicle

With the introduction of xEVs, the number of components that can populate a vehicle has increased considerably, and more components translate into more possible drive train configurations. In addition, building hardware is expensive. Traditional design paradigms in the automotive industry often delay control-system design until late in the process—in some cases requiring several costly hardware iterations. To reduce costs and improve time to market, it is imperative that greater emphasis has to be placed on modeling and simulation. This only becomes truer as time goes on because of the increasing complexity of vehicles and the greater number of vehicle configurations. Thus, the necessary expertise to perform the required sophisticated simulations and calculations becomes more and more complex. Especially predicted future driving information like route based energy management, supported by a mixture between deterministic and stochastic information, will play a key role as they can help to optimize the energy consumption.

The work on Task 17 pointed out, that the demand for companies, focusing on simulation tools for EVs, is still increasing. These companies and R&D institutes will play an important role in the future.

## 4 Lightweight Through Advanced Materials, Bionic Concepts and Functional Integration

Vehicle weight and size reduction is one known strategy to improve fuel economy in vehicles, and presents an opportunity to reduce fuel use from the transportation sector. By reducing the mass of the vehicle, the inertial forces that the engine has to overcome when accelerating are less, and the work or energy required to move the vehicle is thus lowered. A general rule of thumb is that for every 10 % reduction in vehicle weight, the fuel consumption of vehicles is reduced by 5–7 %. Vehicle weight reduction can be effective, but is a challenging way to achieve significantly greater fuel economy gains. Especially light weighting the vehicle has a massive impact on the driving range (depending on the driving type cycle).

The light weighting benefits on fuel/energy consumption depends on the driving type:

- in city type driving and aggressive type driving with many and/or larger accelerations, light weighting any vehicle type will reduce the energy/fuel consumption,
- in highway type driving, where a vehicle will cruise at relative steady speed light weighting vehicles does not significantly reduce the energy/fuel consumption and light weighting a conventional vehicle will provide the largest improvement in fuel consumption due to the relative lower powertrain efficiency of the conventional vehicle, compared to a BEV.

Especially the use of bionic concepts can help to reduce the amount of materials needed. Bionic design can reduce development time, minimizes development costs, identifies new light weight solutions and helps to find efficient concepts in product development.

Also the use of new materials as carbon or sandwich materials (combination of different materials in order to improve the total abilities) contributes to light weighting the car. But it should be kept in mind to have a look at the life cycle assessment too. For example carbon has two main advantages: its low weight and its strength. But the increasing use of carbon in xEVs (e.g. BMW i3) requires the need for new recycling processes.

Comparing HSS versus aluminum in lightweight vehicles: HSS is less costly, and has lower production energy demands. However, aluminum remains competitive in select applications.

Functional integration will play a major role in future vehicles in order to reduce the amount of total parts being used in a vehicle. Functional integration (e.g. CFRP wheel with integrated hub motor) doesn't only have an impact on reducing weight, it can also help to improve the driving abilities and can lead to a fundamental technology turnaround.

Future new vehicles are still expected to become steadily lighter, as automakers seek all means to achieve higher fuel economy. Further, the new fuel economy standards for 2016+ are aggressive, and will require rapid rates of new and improved vehicle technology deployment. More-fuel efficient vehicles, like those with more sophisticated propulsion systems, tend to require more energy during their material processing and production phase. The material production energy demand for a current conventional gasoline car is 5 % of its life-cycle energy impact. The energy expended over its long use-phase in form of fuel use dominates its life-cycle impact at 76 %. However, the total automotive material production energy demand for all new U.S. vehicles was substantial at 0.94 Exajoules in 2010 [2].

Vehicle light weighting and vehicle downsizing, coupled with efficiency gains in material processing over time can greatly reduce the production energy footprint of new vehicles.

## 5 Power Electronics and Drive Train Technologies Require New Software Concepts

The increasing demand for ADAS and autonomous driving results in an increasing amount of software and electronics within the vehicles. Especially in terms of xEVs the amount of embedded systems and software within the powertrain is rapidly growing. This leads to a fundamental technology turnaround which requires adapted software within the powertrain. Thus, the systems are becoming very complex. This results in required embedded systems and E/E-Architecture in order to process all the data and sources. Power Electronics and adaptive drive train technologies are thus playing an important role and will have a massive impact in the future.

In today's commercial vehicles driven by an ICE, the proportion of electrical, electronic and IT components is between 20 and 35 % (dependent on the vehicles class). In xEVs, this share will increase to up to 70 %. This includes around 70 main control units with more than 13,000 electronic devices.

In the future, every second euro/dollar is spent on the production for electronics. Currently, the share of electronic components to the manufacturing cost is around 30%, by 2017 it will grow to 35 % and will still increase to 50 % in 2030.

The Task 17 workshop pointed out, that today's manufacturers are focusing very intense on that field of thematic which indicates the importance on that area. As the future is hard to predict, modular drive train topologies can increase the chances for a market breakthrough of xEVs by providing a better opportunity for high production volumes. Future generations of xEVs require a layered, flexible and scalable architecture addressing different system aspects such as uniform communication, scalable/flexible modules as well as hardware and software. System integration of power electronics is inevitable to fulfill the cost and package volume requirements on future xEVs. New technologies emerge which may greatly improve power density and system integrability. The optimization of a power electronic vehicle component always requires a comprehensive survey of the whole drive train.

Further, this Task successfully demonstrated that **the automotive industry is dealing with two major trends: the electrification of the drive train and autonomous driving**.

## 6 Change Within the Automotive Value Chain

The trend towards e-mobility leads to massive changes along the automotive sector's entire value chain. The new vehicles require a number of technically innovative components and systems to operate. This will impact key parts of the component and vehicle creation value chain, from R&D in specific components like batteries, all the way to integrating and assembling vehicles, down to new fields in the mobility value chain such as new infrastructure and new business models. While the ICE was almost the component with the highest value within the value chain, the introduction of xEVs are changing the hierarchy. Due to the fact that components like ICE, clutch, exhaust system, etc. won't be needed in xEVs any more, new and additional components as power electronics, e-motor, software will be necessary.

It can be foreseen that the power electronic unit and the e-motor will be on the top of the hierarchy and thus will replace the ICE, which won't be needed any more.

This key massage has to be transferred to policy makers and representatives of industry in order to aware them of the upcoming change in value chain. Furthermore the R&D has to be prepared and informed to, to guarantee qualification and education in that kind of fields and to ensure enough qualified employees.

## 7 We Have to Change

The demand for xEVs is still at a low level and far behind expectations (except in a few countries like Norway). However, in order to reach the various global consumption requirements, further hybridization and thus electrification is inevitable.

In the European Union, by 2021, phased in from 2020, the fleet average to be achieved by all new cars is 95 g $CO_2$/km. This means a fuel consumption of around 4.1 l/100 km of petrol or 3.6 l/100 km of diesel. Only in the sub compact class (up to 1,200 kg (2,645 lb) of vehicle weight), petrol engines with consumptions of less than 95 g $CO_2$/km are possible.

For conventional cars there is still potential for optimization like through downsizing, use of alternative fuels, etc. Experts from Bosch Engineering are of the opinion that for conventional cars there are still further fuel savings possible (diesel: 10 % and for petrol up to 20 %). However, in their point of view SUVs and heavy vehicles won't reach the 95 g $CO_2$/km limits though. Here a (partial) electrification is indispensable.

The introduction of xEVs doesn't mean the 'end of the ICE'. These vehicles will still exist for further decades of years. But it is predictable that due to global trends like interconnectivity, autonomous driving, limited resources and global consumption requirements, the electrified drive train—xEVs—will sooner or later dominate the automotive market.

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