OEM and Industry Review—Markets, Strategies and Current Technologies

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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

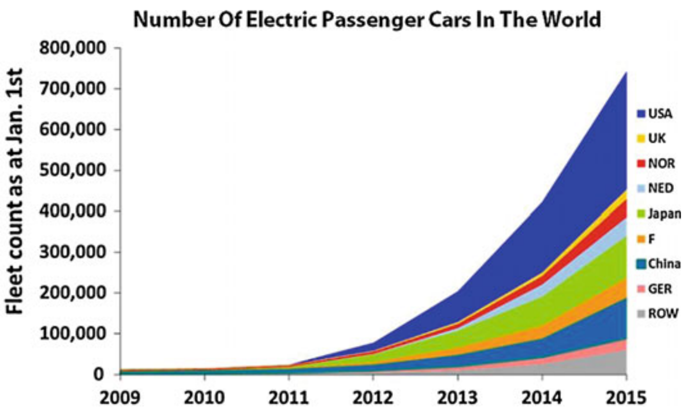

Fig. 1 Number of electric passenger cars worldwide [1]

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).

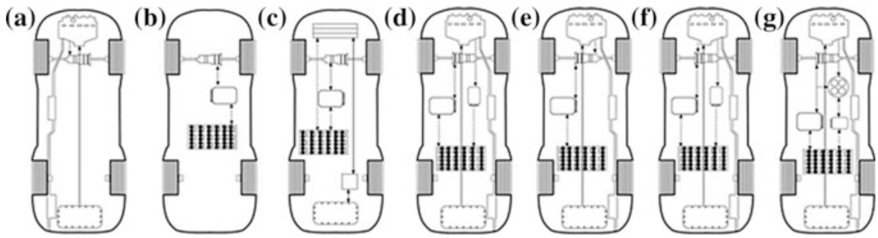

Fig. 2 Schematic drawings of seven types of vehicle classes [11]

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 gCO_2/km (gasoline)** and **131 gCO_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.)

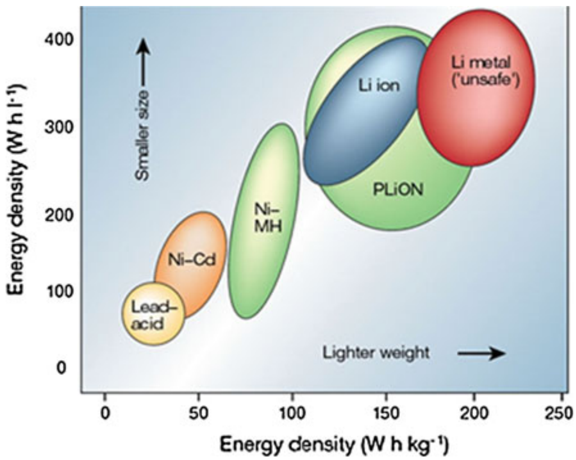

Fig. 3 Battery technologies in terms of volumetric and gravimetric energy density [15]

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.

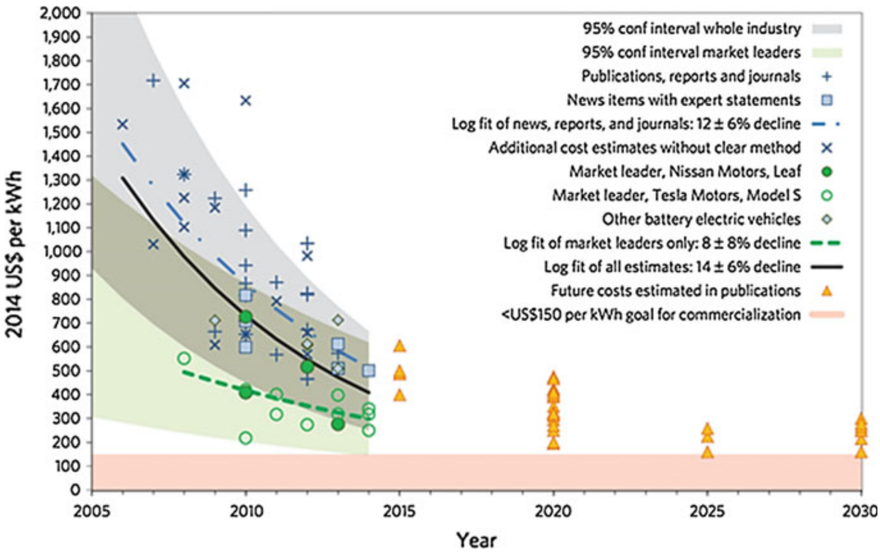

Fig. 4 Cost estimates and future projections for EV battery packs (image courtesy of Nykvist [20])

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: 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: 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: 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: 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: 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: 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: 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**

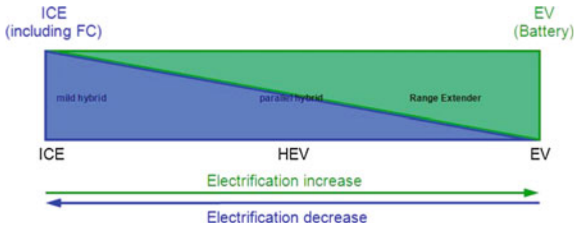

Fig. 5 Vehicle technology spectrum

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

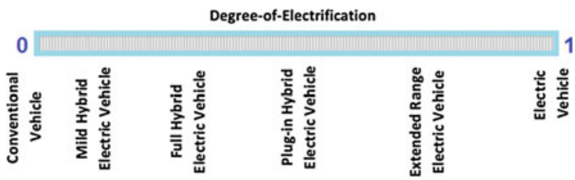

Fig. 6 Degree-of-electrification with relationship to HEVs classifications

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: 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: 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: 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: OPEL AMPERA CHEVROLET CHEVROLET 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 Reference vehicle	Conventional VW Golf VI	Hybrid Toyota Prius III	Hydrogen Honda FCX Clarity	Battery Nissan 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]|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|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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