WORKING PAPER 2016-14

Electric vehicles: Literature review of technology costs and carbon emissions

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Date: 15 July 2016
Keywords: Electric vehicles, well-to-wheel greenhouse gas emissions, technology costs, lithium-ion battery, fuel cell, plug-in hybrid, renewable electricity

1. SUMMARY

The European new vehicle CO_2 regulation (with a mandatory target value of 95 grams of CO_2 per kilometer by 2021 for passenger cars) is currently in the process of being extended to 2025. In this context, one of the key questions is at what point a significant uptake of the electric vehicle market is to be expected. In order to help inform this debate about how electric vehicle technology could fit in a lower-carbon 2020–2030 new vehicle fleet in Europe, this paper focuses on collecting, analyzing, and aggregating the available research literature on the underlying technology costs and carbon emissions. In terms of technologies, this paper concentrates on the three electric propulsion systems: battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), and hydrogen fuel cell electric vehicles (HFCEVs).

The collected cost data is used to estimate the technology cost for automotive lithium-ion (Li-ion) batteries and fuel cells. The cost of battery packs for BEVs declined to an estimated €250 per kWh for industry leaders in 2015. Further cost reductions down to as low as €130–€180 per kWh are anticipated in the 2020–25 time frame. The costs of fuel cell systems are also expected to decrease considerably, but cost estimates are highly uncertain.

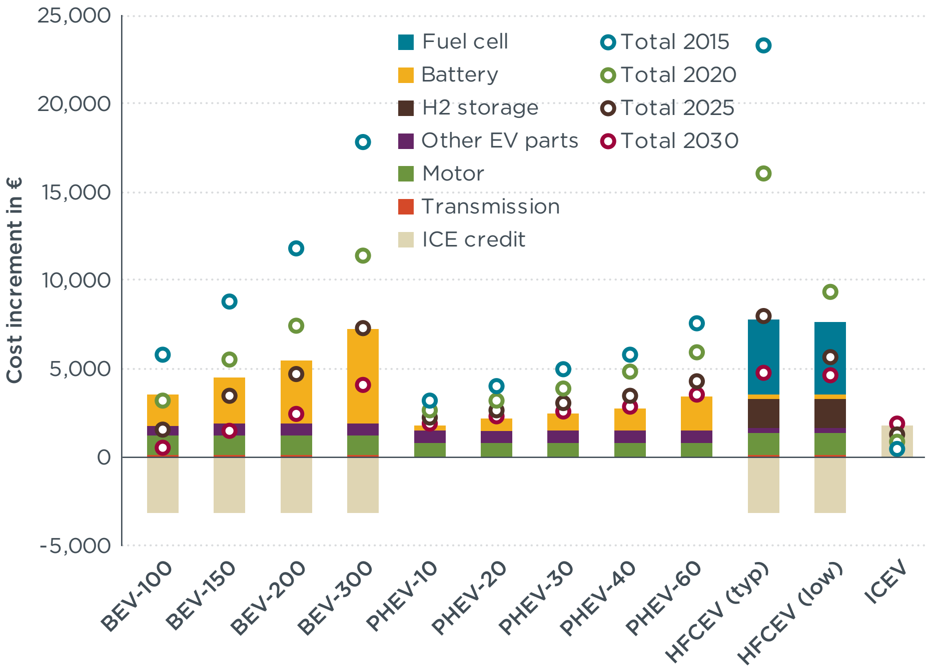

Figure S 1. Cost breakdown of different power trains for a 2030 lower medium car. Circles show total incremental costs over a 2010 internal combustion engine vehicle (ICEV).

Furthermore, the application of fuel cells and batteries in HFCEVs, BEVs, and PHEVs is approximated using a bottom-up cost approach. Overall, the different power train costs largely depend on battery and fuel cell costs. This paper concludes that the costs of all power trains will decrease significantly between 2015 and 2030 (Figure S 1). As shown, power trains for PHEVs will achieve about a 50% cost reduction, compared with approximate cost reductions of 60% for BEVs and 70% for HFCEVs. Costs for hydrogen and electricity chargers are estimated separately.

Greenhouse gas (GHG) emissions and energy demand for electric and conventional vehicles are presented on a well-to-wheel (WTW) basis, capturing all direct and indirect emissions of fuel and electricity production and vehicle operation. The results are

Acknowledgements: *The authors thank Peter Mock, Uwe Tietge, John German, Vicente Franco, and Joshua Miller from ICCT for reviewing and contributing to this paper, which greatly improved its quality.*

based on former analyses, and are updated and refined with real-world fuel consumption levels. Real-world fuel consumption is commonly about 20%–40% higher than official type-approval measurements. Finally, WTW estimates for electric and conventional vehicles are put in the context of the 2021 CO_2 standard for European passenger vehicles.

It is found that carbon emissions of BEVs using European grid-mix electricity are about half of average European vehicle emissions, whereas HFCEVs and PHEVs have a lower emissions reduction potential. In the 2020 context, electric vehicle WTW emissions are expected to continue offering greater carbon benefits due to more efficient power trains and increasing low-carbon electric power. A lower-carbon grid and higher power train efficiency by 2020 could cut average electric vehicle emissions by one-third again.

However, the expected cost reductions and potential CO_2 emission cuts will not be achieved without targeted policy intervention. More stringent CO_2 standards, and fiscal and non-fiscal incentives for electric vehicles, can help the electric vehicle market to grow and costs to fall. Also, efforts need to be combined with activities to decarbonize the grid, or emission reductions will not be as great as they could be. Although the analysis is focused on the European context, similar dynamics with electric vehicle technology, policy, and market development are prevalent across major markets in North America and Asia.

2. BACKGROUND

Governments in Europe and other world regions are focused on greatly reducing the transport sector's carbon emissions. The European Union (EU) and its member states are using vehicle and fuel regulations, substantial financial and nonfinancial incentives for consumers, and other policies to replace petroleum with lower-carbon alternatives. The infrastructure for alternative fuels is also being funded to promote lower-carbon mobility. One of the most difficult questions is when EV technology will improve to the extent that it becomes a mainstream competitive option for consumers and automobile manufacturers facing carbon emission requirements.

2.1. MARKET OVERVIEW

The first EVs were introduced as early as 1838—or 52 years before internal combustion engine vehicles (ICEVs) entered the market. Despite recent growing interest, EVs have remained a relatively small market until today (IEA, 2015). However, the global share of EVs is expected to increase significantly, driven by substantial battery technology improvements and a variety of policies that are accelerating the development of the electric vehicle market. Overall, the market has grown from just hundreds of EV sales in 2010 to more than 500,000 sales worldwide in 2015 (EV Sales, 2016). The early development of markets for electric vehicles is seen predominantly in parts of China, Europe, and the United States, where electric vehicle support policies are helping promote the technology, while costs are still relatively high compared with conventional vehicles.

Table 1 shows the global and regional estimated stock of BEV and PHEV passenger cars as of 2015, and electric vehicle supply equipment (EVSE) as of 2014. EVSE includes semipublic or public charging points or outlets, but not private charging points.

Most of the electric vehicles on the road today are registered in the United States, with about half of those in the state of California. The United

Table 1. Estimated total vehicle fleet as of 2013, EV passenger car fleet as of 2015, and EVSE stock as of 2014 (EIA, 2015; Mock, 2015; EV Sales, 2016; AFDC, 2015; OICA, 2016)

Region	Estimated total fleet[a] (2013)	Estimated passenger electric vehicle fleet[b] (2015)	Estimated EVSE stock[c] (2014)
World	1.2 billion	1.2 million	110,000
United States	252 million	400,000	31,000[d]
California	30 million	190,000	9,000[d]
Japan	77 million	134,000	12,000
China	127 million	290,000	30,000
India	25 million	3,000[e]	300
EU-28	295 million	340,000	50,000
Netherlands	9 million	46,000	12,000
Norway	3 million	75,000	6,000
France	38 million	57,000	9,000
Germany	47 million	51,000	3,000
UK	36 million	49,000	3,000
Italy	42 million	6,000	3,000
Denmark	3 million	8,000	3,000

(a) Includes passenger cars, sport-utility vehicles, pickup trucks, minivans, and two- and three-wheelers.
(b) Includes passenger cars and sport-utility vehicles, but excludes lightweight trucks, quadricycles, utility vehicles, buses, and two-wheelers; includes cumulative sales/stock until 2014 (from EIA, 2015 or Mock, 2015, plus 2015 sales from EV Sales, 2016); retirement numbers are assumed to be negligible.
(c) EVSE is counted by semipublic or public charging points or outlets, not by charging stations; private charging is not included.
(d) 2015.
(e) 2014.

States also has the largest number of electric vehicle charging points. The Netherlands is the European country with the highest electric vehicle passenger car and charging-plug stock in terms of absolute sales. The following countries have achieved relatively high market sales shares of passenger electric vehicles, as a percentage of all 2014 passenger vehicle sales: Norway (13.7%), the Netherlands (3.9%), Sweden (1.5%) (Mock, 2015), and the United States (1.5%) (Lutsey, 2015b). Most other major automobile markets have EV sales shares at or below 1%.

3. TYPES OF ELECTRIC DRIVETRAINS

3.1. BEVs

Pure battery electric vehicles (BEVs) are also referred to as battery-only electric vehicles (BOEVs). BEVs have no engine and are propelled by electricity that comes from one or several onboard high-energy batteries. Modern models use a regenerative braking system to save energy. Examples include the Renault Zoe and the Nissan Leaf. The Zoe has a 22 kWh Li-ion battery, and an energy consumption of 14.6 kWh per 100 km, which yields a range of about 140 km to 210 km per battery charge on the New European Driving Cycle (NEDC). The 2015 Leaf comes with a 24 kWh battery (plus a 30 KWh option for the 2016 model), and an official consumption of 15 kWh per 100 km.

3.2. PHEVs

Plug-in hybrid electric vehicles (PHEVs) allow electric driving on batteries (in charge-depleting mode), but also conventional combustion-fueled driving (in charge-sustaining mode). Usually, they are equipped with an electric motor and a high-energy battery, which can be charged from the power grid. Modern PHEVs can be driven in electric mode over varying distances before the combustion engine is required. In electric-driving mode, the energy efficiency of the propulsion system is much higher, and is comparable to that of a BEV. Available models include the Chevrolet Volt in U.S. markets (which is the Opel Ampera in EU markets), and the Toyota Prius Plug-in Hybrid. The 2015 Opel Ampera uses a 16 kWh Li-ion battery and consumes 16.9 kWh per 100 km in electric mode on the NEDC. The 2015 Chevrolet Volt has a 16.5 kWh battery, and the 2016 model has an 18.4 kWh battery.

4. BATTERY PRODUCTION

PHEVs and BEVs use similar batteries, with Li-ion being the most common chemistry. There are two primary ways to extract the lithium used in batteries: mining spodumene and petalite ore using evaporation ponds on salt lakes. The majority of lithium is obtained from brine operation (USGS, 2015).

The battery system is the key technology of electric vehicles and defines their range and performance characteristics. The battery works like a transducer by turning chemical energy into electrical energy. Li-ion is expected to be the dominant chemistry for BEVs and PHEVs for the foreseeable future, as most research is done in the field of Li-ion batteries. They provide relatively high power and energy for a given weight or size, and can significantly reduce costs compared with other battery concepts. Energy density of the battery pack is estimated to roughly double, up to about 300 Wh per kg, between 2007 and 2030 (Kromer & Heywood, 2007; Ricardo-AEA, 2015; NAS, 2013). Also, they have a relatively long life cycle and low self-discharging losses. One of their few drawbacks is their sensitivity to over-charging, which is why they require a battery management system.

Other automotive battery concepts include nickel-metal hydride (Ni-MH), sodium-nickel chloride (Na/NiCl2), and non-electrochemical alternatives such as supercapacitors, which allow fast charging but provide low energy density. As a result, batteries with higher energy and power densities are being developed, such as lithium-air (Li-air), lithium-metal or lithium-sulphur (Li-S), but these are far from commercialization (Cookson, 2015; Hacker, Harthan, Matthes & Zimmer, 2009). Li-air batteries may reach energy densities of up to 11,680 Wh per kg (Imanishi & Yamamoto, 2014), which approximates the energetic content of gasoline.

5. HFCEVs

HFCEVs are powered by a fuel cell, which generates electricity from hydrogen and air. Electricity from the fuel cell directly powers the electric motor driving the wheels, and can also be used to recharge the battery pack if necessary. Modern fuel cell vehicles include a battery pack, which is used to capture regenerative braking energy and is also used to assist with acceleration when the fuel cell stack is warming up. The battery size is usually similar to or a bit larger than that of hybrid electric vehicles (HEVs). HFCEVs operate at a higher conversion efficiency than ICEVs, but have a high cost increment. Refueling HFCEVs is considerably quicker than charging batteries. Commercially available models are the Toyota Mirai and Hyundai's Tucson in the United States, or ix35 in Europe. The 2015 Mirai offers an official drive-cycle range of about 480 km, a 114 kW fuel cell stack, and a 113 kW electric motor (Hydrogen Cars Now, 2016c). The Tucson has a battery power output of 24 kW and a 100 kW fuel cell system (Hydrogen Cars Now, 2016b).

5.1. FUEL CELL SYSTEM

The fuel cell system is the key technology of HFCEVs. It principally consists of a fuel cell stack and a range of supporting hardware, which is also referred to as balance of plant (BOP). Several cells sit in one cell stack. The main type of fuel cell stack used for vehicles is the polymer-electrolyte or proton-exchange membrane (PEM). Hydrogen is stored in an onboard storage tank, which is analogous to a fuel tank for ICEVs. With the technology currently available, hydrogen is stored as a compressed gas.

Electricity is produced in the fuel cell through an anode-cathode principle similar to a battery. Hydrogen comes from the onboard storage tank and fuels the anodes, and oxygen comes from the surroundings and fuels the cathodes. Electrons from the hydrogen are forced to follow an external circuit, creating a flow of electricity.

The energy efficiency of fuel cells is between that of batteries for BEVs and combustion engines for ICEVs, and has improved slightly in recent years. A moderate increase in energy efficiency from 53% to 55% (midrange), or 57% (which is optimistic), is expected at the stack level between 2010 and 2030 (NAS, 2013). However, manufacturers are expected to prioritize cost improvements over efficiency in their future development of fuel cell technology.

6. HYDROGEN PRODUCTION

Hydrogen can be produced using a range of different methods, including electrolysis and reforming. Currently, hydrogen is produced mainly from natural gas reforming on a small scale in small generators. Other generation pathways include water electrolysis or biofuels reforming. Future potential large-scale facilities can produce low-cost hydrogen using several methods, for example natural gas reforming or coal gasification (Edwards, Larivé & Beziat, 2011). The lowest cost production of hydrogen, which is also being used by industry, is currently based on fossil fuels. For instance, 95% of hydrogen production in the United States is based on natural gas (U.S. DOE, 2016).

A new development being explored is combining electrolysis with renewable wind and solar energy generation. Such developments allow hydrogen production or charging EVs to offer viable synergistic ways for storing intermittent wind and solar power.

7. CHARGING AND REFUELING INFRASTRUCTURE

There are three types of charging infrastructure for BEVs and PHEVs. Level 1 charging points provide alternate current power to the vehicle via a standard low-power 110 volt circuit, similar to those used in households in the United States or Japan. With these slow-charging points, more than 20 hours of charging are required to fully charge a 24 kWh battery. Residential or public Level 2 charging points in the United States provide alternate current power via a 240 volt (and 30 amp) circuit, and can thus cut charging time by about half. Level 2 charging via a 230 volt (and 15 amp) outlet is common in households in the EU and most other countries. Electrical panel upgrades are necessary in the United States to reach the same voltage. Level 3 charging points convert alternate current line voltage to a high-voltage direct current. Plugged into such a fast-charging point, a battery can be charged up to 80% (which is the recommended maximum level) within half an hour (NAS, 2013). However, the investment cost of Level 3 chargers is much higher than those for Level 1 and 2 (see section 10.5).

Several car manufacturers, such as Honda, Toyota, Hyundai, and Daimler, have already introduced HFCEVs, but primarily in Europe, Asia, California, and Hawaii where the infrastructure exists. Approximately 140 hydrogen fuel stations exist in Europe, with about 18 (AFDC, 2015) to 48 (LBS, 2016) in the United States, which is considerably lower than the number of electricity charging stations. The European countries with the most stations are Germany (41), Italy (21), the United Kingdom (20), Denmark (14), and Norway (10) (Hydrogen Cars Now, 2016a). These numbers vary by source (e.g., compared with LBS, 2016). Germany plans to have an additional 400 stations in operation by 2023 (H2 Mobility, 2015).

Research has been done on indirect hydrogen generation from a liquid fuel onboard reformer, as an alternative to the costly hydrogen infrastructure. Vehicles that are equipped with such small-scale reformers are able to convert gasoline, methanol, naphtha, or even diesel fuel into hydrogen, which is then directly fed to the fuel cell (Edwards, Hass, Larivé, Lonza, Maas & Rickeard, 2014). However, such onboard hydrogen production is more energy- and GHG-intensive than drawing on external hydrogen production, and the reformers are also expensive and take up a lot of space. As a result, all manufacturers have abandoned development of onboard reformers.

8. CURRENT COSTS

8.1. BEVs

Even though a BEV has no engine, which implies significant cost savings compared with PHEVs, substantial costs arise from the large battery packs currently required. In a study by Ricardo-AEA (2015) it is assumed that the battery pack determines about 75% of BEV power train cost, due to the relatively high battery cost. The authors of the study calculate additional manufacturing costs of about €12,400 for a lower medium passenger car in 2013, with a 24.9 kWh battery at €375 per kWh. The authors do not specify assumed production volumes for BEVs, PHEVs, and HFCEVs. The report, however, suggests that lower production volumes (in the low thousands) are assumed for HFCEVs, with a significantly higher scale for BEVs (in the mid-ten thousands).

Based on an assumed production scale of 300,000 units per year and a 37.6 kWh-rated battery at €356 per kWh, the National Academy of Sciences estimates a similar cost incremental of a BEV-130 (130-miles test-cycle range) of about €12,600[1] over a €20,800 (small to lower medium segment) conventional car in 2010 (NAS, 2013). This incremental was estimated to drop to €9,300–€8,200 by 2015, mainly due to declining battery costs down to €280–€300 per kWh, and a smaller battery size of 34.4 kWh. The authors assume the battery to have a smaller size due to increasingly lower electric energy consumption of the vehicle. Similarly, the present work assumes a downsizing of 1% per year for the motor and the fuel cell system, and 2% per year for the battery pack for all future years, according to the midrange scenario presented in the NAS study (see section 10.4).

A bottom-up cost approach is used in this paper to estimate the component costs associated with different electric power trains over a conventional vehicle. Using the BEV cost figures provided by Ricardo-AEA, and updating with a more recent battery cost estimate of €250 per kWh (see section 10.1), leads to a cost addition of about €5,700 for a BEV-100 (with a drive-cycle range of about 100 miles/160 km) over a conventional passenger car (see Figure 1). Cost subtractions are made for the non-existing combustion engine, exhaust pipe, and conventional transmission and are referred to as ICE credits.

1 Throughout this paper, an average currency exchange rate of €0.79 per US$1 is assumed, based on averaging the average annual exchange rates for 2009 to 2014, and the actual exchange rate from October 1, 2015 (€0.89 per US$1).

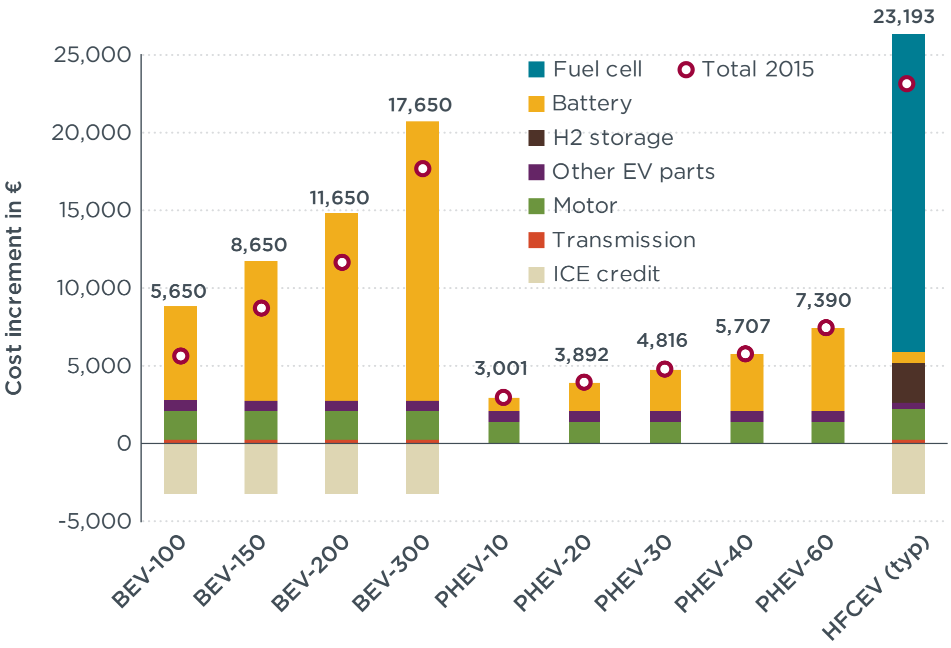

Figure 1. Cost breakdown of different electric power trains for a 2015 lower medium car. Assumed battery production volume is in the mid-ten thousand units, and fuel cell system production is about 1,000.

At the mentioned battery pack price, the battery pack determines about 68% of power train cost. Assuming a BEV with a range of 300 miles/480 km and a 72 kWh battery results in a cost increment of about €17,700 (with an increasing battery share up to 86%). This calculation assumes that all other specifications, such as engine power, remain constant for the BEV-100, -150, -200 and -300 (see Table A 6 and Table A 7 in the Annex for details).

For 2015 battery pack costs, the latest estimates are taken into account, arriving at €250 per kWh, as outlined in section 10.1. This estimate is in line with findings by Nykvist and Nilsson (2015), who estimate €240 per kWh for leading car manufacturers such as Tesla or Renault-Nissan, producers of 50,000 units or more per year. It also largely agrees with the cost of the U.S. Department of Energy (DOE)-funded batteries of €230 per kWh (Faguy, 2015). A U.S. consultancy (Bain & Company, 2015) also estimated €260 per kWh in 2015.

8.2. PHEVs

The National Academy of Sciences assumes that incremental car costs of a 2015 PHEV-30 (with a 30-mile or 50-km drive-cycle range on electric energy) range between €5,100 and €5,800 over a conventional ICEV (NAS, 2013). The authors assume a production of 300,000 units per year, and a battery size of 9.8 kWh at €356–€375 per kWh. Ricardo-AEA assumes much higher additional manufacturing costs of about €9,900 for a lower medium PHEV-30 in 2013, with an assumed 10.2 kWh-rated battery at ~€790 per kWh (but without clarifying production scale).

PHEV cost figures provided by Ricardo-AEA are used in this paper and updated with an assumed PHEV battery cost of €330 per kWh (€250 per kWh as estimated in section 10.1, plus €80 per kWh incremental cost of PHEV batteries over BEV batteries, as pointed out by the NAS study). A simple bottom-up cost calculation taking this battery price into account leads to a total cost increment of about €3,000 to €7,400 over a conventional passenger car, depending on battery size or electric range (see Figure 1). A 16 kWh battery is assumed for a PHEV-60 (with a 60-mile or 96-km electric drive-cycle range), and is scaled down accordingly for a PHEV with a lower range. For simplicity's sake, all other specifications are assumed to remain equal. See Table A 6 and Table A 7 in the Annex for details. Cost subtractions for the smaller combustion engine are assumed to be negligible.

8.3. HFCEV

Current fuel cell production is considerably lower than battery production. Toyota produced 700 fuel cell vehicles in 2015 (Toyota, 2015), whereas most BEV manufacturers produced more than 25,000 units in the same year. The lower production scale increases costs. Ricardo-AEA estimates additional manufacturing costs of HFCEVs over a 2013 conventional ICEV at about €52,270, assuming a production volume in the low thousands. The authors assume fuel cell costs at €600 per kW (fuel cell size is not specified), and a 1.4 kWh battery at about €1,500 per kWh. This suggests significantly higher costs compared with BEVs and PHEVs. Oak Ridge National Laboratory (ORNL, 2013) estimates a 2015 HFCEV power train to cost an additional €30,100 at a production volume of 20,000 units per year, and an 85 kW fuel cell stack at €220 per kW. NAS estimates a car increment of only €5,000–€5,500 over an ICEV (as of 2010). The authors assume 2010 costs of the fuel cell to be about €40 per kW, due to a hypothetical large-scale production of 300,000 units per year. This would imply a total cost of about €3,600 for a 90 kW fuel cell. HFCEV batteries are assumed to cost about €1,010 per kWh in 2010, and €770–€780 per kWh in 2015.

According to NAS, the fuel cell determines about 50%–60% of the costs for the whole car, while Ricardo-AEA assumes costs to be about 85% of the power train (at lower production volumes). The relatively small battery of about 1.4 kWh only contributes to about 4% of the cost increment.

As done above for BEVs and PHEVs, a simple bottom-up cost estimate for HFCEVs is performed based on figures provided by Ricardo-AEA, and updated by using recent DOE (U.S. DOE, 2014) fuel cell system cost estimates for a production volume of 1,000 units (€225 per kW power output) and battery cost estimates from the NAS study. Because battery costs have declined much faster than previously expected, the cost estimate for 2020 batteries from the NAS study is assumed for 2015 (€632 per kWh energy storage).[2] These modifications lead to an HFCEV cost increment of about €23,200, which is roughly half the Ricardo-AEA figure. Cost credits for the non-existing combustion engine, exhaust pipe, and conventional transmission are subtracted from the HFCEV power train costs (as has been done for the BEV). Moving to a production volume of 10,000 units at €83 per kW power output (as in U.S. DOE, 2014) would cut the cost increment by half again, down to €10,200. These simple calculations assume that the specifications of the components remain constant for the sake of simplicity. See Table A 6 and Table A 7 for more details.

A simple uncertainty evaluation is performed by varying costs of the fuel cell systems and battery packs, which both have the highest influence on total costs, by ±20%. The result on power train cost (excluding ICE credits) varies between ±5% to ±17%. As expected, the PHEV-10 is at the low end of that range, and the BEV-300 (±17%) and the HFCEV (±16%) are at the high end.

2 High-power batteries, as used for HEVs and HFCEVs, are much more costly than high-energy batteries used for BEVs and PHEVs, as they require higher power density and different characteristics

9. CURRENT ENERGY USE AND EMISSIONS

Energy consumption of vehicles is typically measured on drive cycles. Accordingly, the BEV Nissan Leaf has a consumption of 15 kWh per 100 km on the NEDC. With 14.6 kWh per 100 km, the Renault Zoe has a comparable consumption. The PHEV Opel Ampera consumes 16.9 kWh per 100 km in electric mode, and 1.2 L of gasoline per 100 km in combustion mode. Real-world or on-road fuel efficiencies are usually considerably lower than driving-cycle efficiencies (Tietge, Zacharof, Mock, Franco, German, Bandivadekar, Ligterink & Lambrecht, 2015).

More comprehensive figures for the energy requirements and emissions of electric and conventional vehicles may be achieved using well-to-wheel (WTW) analysis. WTW analysis is a technique to account for all direct and indirect emissions and energy requirements during the whole life cycle of a fuel. WTW analyses are usually composed of a well-to-tank (WTT) and a tank-to-wheel (TTW) fraction. WTT includes fuel and electricity production, and TTW includes vehicle operation. Vehicle production and recycling is usually not included. Even though WTT analyses capture direct and indirect emissions and energy requirements of different fuels, results can vary widely, because the ISO 14040 and 14044 life-cycle assessment standards only provide general accounting guidelines. Also, different studies may use different assumptions on vehicle lifetime, battery size, distance traveled over the lifetime, the GHG intensity of the electricity mix, and the usage of different models and methods. In addition, WTW studies tend to omit the mentioned real-world fuel efficiencies.

Figure 2 shows WTW GHG emissions and energy use of the three depicted electric power trains compared with conventional and hybridized ones. It can be seen that ICEVs have the highest emissions and energy intensity. More efficient hybrid electric vehicles (HEVs) can lower energy use and GHG emissions substantially down to 155 g CO_2e per km for diesel, respectively 161 g CO_2e per km for gasoline. Taking only typical electricity conversion pathways into account (grid-mix electricity for BEVs and PHEVs, natural gas reforming for HFCEVs), it can be seen that BEV power trains offer the highest energy use and GHG emission-abatement potential. Using the EU electricity grid mix, BEVs can save 37% GHG emissions over diesel ICEVs, and 46% compared with gasoline ICEVs.

The energy efficiency of the electric drivetrain is up to 66%, compared with ICEVs with 14%–19%. HFCEVs are characterized by a conversion efficiency of up to 42% (Lutsey, 2012). The German Aerospace Center (DLR, 2015), on the other hand, estimates the energy efficiency of BEVs at 60%–80%, including charging losses and self-discharge of the battery.

Results from Figure 2 are based on a thorough WTW analysis by the European Commission's Joint Research Centre (Edwards, Larivé, & Beziat, 2011; Edwards, Hass, Larivé, Lonza, Maas & Rickeard, 2014), but are updated by taking into account real-world fuel and electric energy consumption levels, as explained in the following. The authors of the analyses simulate a conventional European reference vehicle in the lower medium passenger car segment. Based on this baseline vehicle, further simulations are performed to reflect different electric power train configurations. All modeled results are based on official NEDC consumption levels. However, earlier research has shown that official type-approval fuel consumption levels of ICEVs were about 24% lower than actual on-road fuel consumption in 2010 (Tietge et al., 2015). The average observed discrepancy for HEVs has been even higher, with 41%. In this paper, the

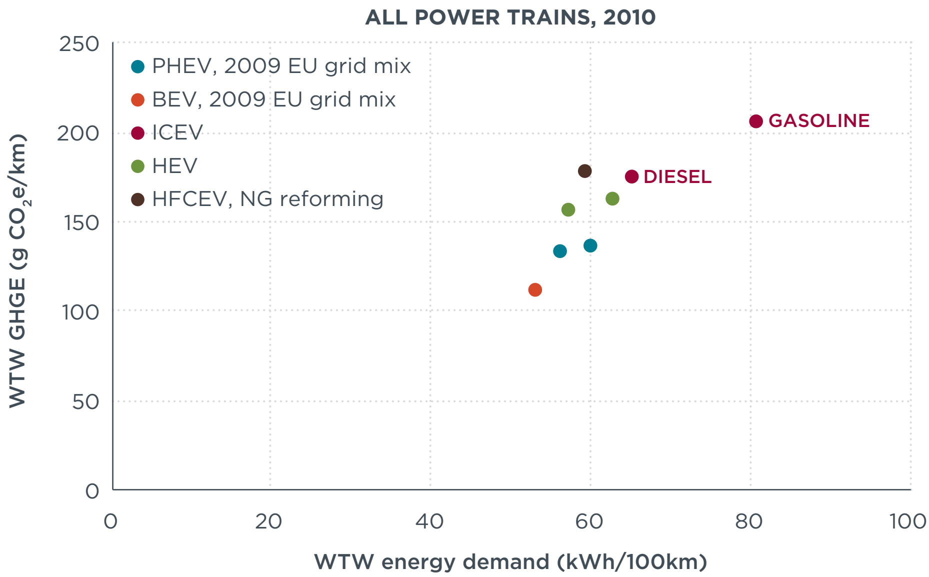

Figure 2. WTW greenhouse gas emissions (GHGE) and energy demand of 2010 passenger cars using different energy sources. For ICEVs, HEVs, and PHEVs, the higher estimate is for gasoline, and the lower one is for diesel.

Table 2. Assumed electric energy and fuel consumption levels of 2010 power trains

2010 power train	Fuel consumption kWh 100km^{-1}	El. energy consumption kWh 100km^{-1}	2010 Adjustment factor	Adjusted fuel consumption kWh 100km^{-1}	Adj. el. energy consumption kWh 100km^{-1}
ICEV, gasoline	56.7	-	1.24	70.3	-
ICEV, diesel	45.2	-	1.24	56.0	-
HEV, gasoline	39.4	-	1.41	55.5	-
HEV, diesel	35.6	-	1.41	50.2	
BEV	-	14.5	1.41	-	20.4
PHEV, gasoline	39.4	14.5	1.41	55.5	20.4
PHEV, diesel	35.6	14.5	1.41	50.2	20.4
HFCEV	26.1	-	1.41	36.8	-

same discrepancy level is assumed for BEVs and HFCEVs.

In the European Commission's analyses (Edwards, Lonza, Maas & Rickeard, 2011; Edwards, Hass, Larivé, Lonza, Maas, & Rickeard, 2014), PHEVs are modeled in accordance with European regulation UNECE R101, leading to overly optimistic fuel consumption levels, and an average discrepancy level of 100% and more between official type-approval and real-world values (Stewart, Hope-Morley, Mock & Tietge, 2015). For this study, an approach more in line with the real-world usage of the vehicles is assumed by applying the average discrepancy level for HEV fuel consumption when the PHEV is operated on fuel (charge-sustaining mode), and BEV electric energy consumption when operated on electricity (charge-depleting mode).[3] Thus, the discrepancy is assumed to be 41%, which is the same as for BEV and HEV (and HFCEV). All fuel consumption levels and their adjusted values are shown in Table 2.

3 It is acknowledged, though, that real electric energy consumption will be slightly above that of a BEV, and fuel consumption will be above that of a HEV due to the combined higher weight of an electric power train and a combustion engine. However, values are not altered due to the absence of further information.

As a result of taking into account these adjustment factors, WTW energy consumption figures are higher compared with the results from the European Commission researchers (Edwards, Larivé, Beziat, 2011; Edwards, Hass, Larivé, Lonza, Maas, & Rickeard, 2014), of between 13% for BEVs, to 35% for HEVs and PHEVs. The following subsections detail WTW figures for all electric power trains using different feedstocks.

9.1. BEVs

Figure 3a shows that energy requirements and GHG emissions of BEVs are highly dependent on the electricity source used. Electricity from wind power is the least GHG- and energy-intensive option, resulting in 6 g CO_2e per km. Coal and gas power combined with CCS options can save GHG emissions, but are also less energy efficient. If fueled with electricity from coal power, BEVs can reach emission intensities up to 243 g CO_2e per km, exceeding ICEVs with 204 g CO_2e per km for gasoline, and 174 g CO_2e per km for diesel (see Figure 2).

9.2. PHEVs

Unlike BEVs and HFCEVs, PHEVs are partially powered by the combustion of fossil fuel in an engine. Thus, PHEVs release tailpipe emissions into the air. On a WTW basis, differences in emissions between different electricity sources are thus less clear compared with BEVs and HFCEVs. As for PHEVs, in which fuel use is supplemented by electricity use, data points in Figure 3b are quite close together. In this study, a 50–50 share of fuel and electricity use is assumed, which is in agreement with earlier research (Stewart, Hope-Morley, Mock & Tietge, 2015). For each feedstock, the higher estimate is for gasoline PHEVs, and the lower is for diesel.

Typically, PHEVs have higher energy requirements and GHG emissions than BEVs. However, if powered with

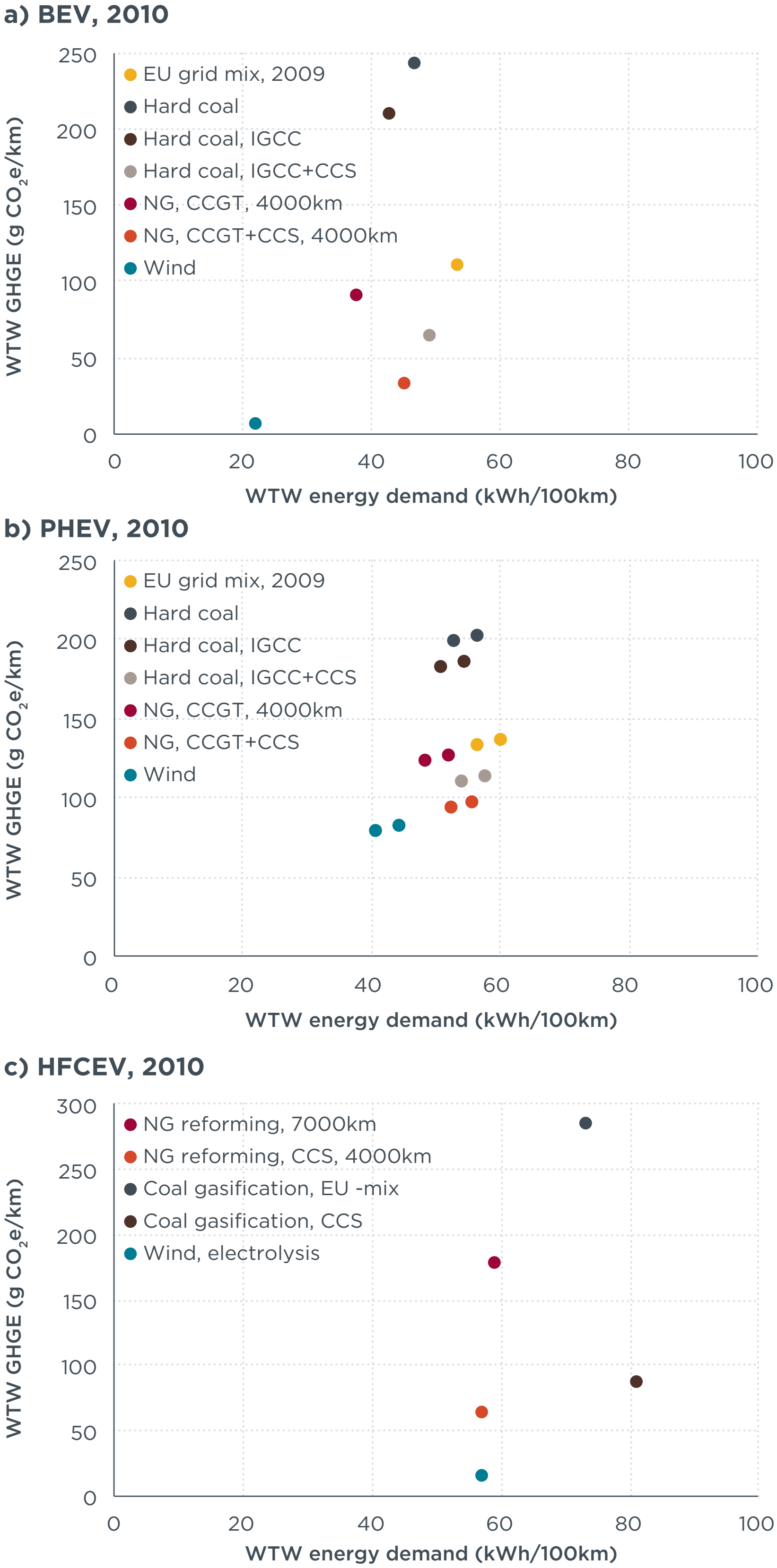

Figure 3. WTW GHG emissions (GHGE) and energy requirements of (a) BEV, (b) PHEV, (c) HFCEV (2010 passenger car) using different electricity sources and conversion pathways

electricity solely from coal, BEVs and PHEVs reach similar values. This can be explained by the high GHG intensity of coal power. Conversely, if electricity from wind power is used, BEVs emit considerably less GHG emissions than PHEVs, because the low GHG intensity of wind power is outweighed by the use of fuel.

Figure 4 shows how the share of driving in charge-sustaining mode influences WTW energy demand and GHG emissions. The higher the share of fuel use (20%–50%–80%), the closer the data points move together. In general, lower fuel use decreases WTW emissions and energy demand. Yet, in combination with coal-powered electricity, higher fuel use reduces overall GHG emissions.

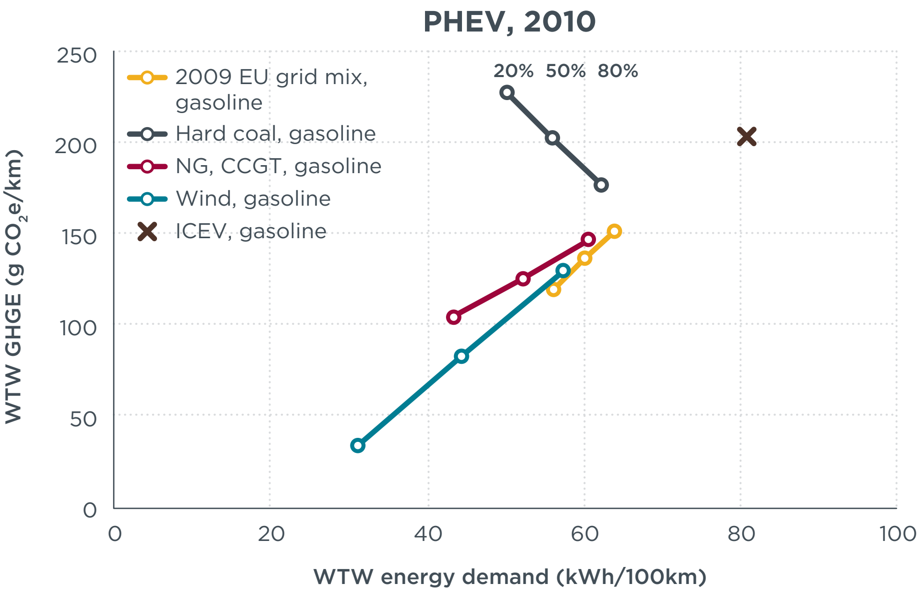

Figure 4. Influence of fuel use on WTW GHG emissions (GHGE) and energy demand

9.3. HFCEVs

HFCEVs are free of tailpipe emissions other than water vapor. WTW GHG emissions and energy consumption can differ substantially, depending on how hydrogen is created, the GHG intensity of the feedstock, and the type of hydrogen storage (onboard or central). The lowest GHG emissions can be achieved with wind-powered electrolysis; however, this is currently too expensive to be a viable option. Another future large-scale option for hydrogen production is coal gasification, though this has a GHG and energy balance in the region of gasoline ICEVs: 284 g CO_2e per km and 73 kWh per 100 km (Figure 3c).

The majority of hydrogen is currently produced by natural gas reforming, resulting in WTW GHG emissions of 177 g CO_2e per km, compared with the direct usage of electricity from natural gas for BEVs, which results in 90 g CO_2e per km (Figure 3a). Similarly, for all other electricity options, it is revealed that intermediate conversion to hydrogen can cause significantly higher energy consumption and GHG emissions compared with the direct use of electricity. Detailed values and assumptions for the WTW meta-analysis are provided in Table A 1 to Table A 4 in the Annex.

It is worth noting that WTW energy use and GHG emissions figures for all vehicle types are static and are average values, because they do not include individual driving behavior, different driving situations where fuel consumption can differ, or potential rebound effects and technology breakthroughs. Future WTW analyses may address these effects. Also, as mentioned earlier, WTW analysis is focused on fuel and electricity production and does not include vehicle production and dismantling/recycling. Earlier life-cycle assessments demonstrated that GHG emissions from the manufacturing phase of EVs are roughly double that of ICEVs (87–95g CO_2e per km vs. 43g CO_2e per km) (Hawkins, Singh, Majeau-Bettez & Strømman, 2012), which somewhat diminishes the WTW balance of EVs (also compare with UCS, 2015, p. 21).

According to another study, the overall life-cycle environmental impact of the Li-ion battery is about 15% as a share of the whole BEV (Notter, Gauch, Widmer, Wäger, Stamp, Zah & Althaus, 2010). The Union of Concerned Scientists (UCS, 2015) states that the battery causes 8%–12% of total life-cycle GHG emissions, but the higher production emissions are quickly offset by use of the vehicle. Options to further decrease the overall environmental impact of EVs include battery recycling, or the reuse of batteries as grid-level electricity storage (Dunn, Gaines, Kelly, James & Gallagher, 2015).

10. COST REDUCTIONS

10.1. Battery Packs

Given the high share of battery costs in total EV costs, it is likely that the success of BEVs, PHEVs, and HEVs will be mainly driven by developments in battery costs. The costs associated with Li-ion batteries are expected to drop dramatically (see Figure 5) due to advancements in battery designs and production techniques. This also includes the replacement of high-cost materials and economies of scale, improvements to the cell and electrode structure design, and high-volume production processes with reduced wastage.

Electric batteries are composed of several electrochemical cells. Cell costs are expected to fall at a slightly slower rate than battery packs because volume-independent costs make up about 30% of cell costs, but only 25% of battery pack costs. Volume-independent costs are the costs of raw materials, standardized parts, labor, and general machinery, and they are assumed to remain relatively constant until 2020 (BCG, 2010).

The highest initial cost estimate of €2,000 per kWh is provided by Syrota (2008), as referenced by Hacker, Harthan, Matthes & Zimmer (2009). The lowest known cost estimate is given by UBS (2014) at €100 per kWh for the battery pack by 2025, based on recent steep cost declines. Estimates by Ricardo-AEA (2015) arrive at about €160 per kWh in 2030. The National Academy of Sciences (NAS, 2013) expects battery pack costs to be in the order of €205 per kWh for PHEVs and €160 per kWh for BEVs in 2030 in the optimistic scenario, or €250 and €200 per kWh in the midrange scenario. Both types have lower relative costs (in € per kWh) compared with batteries for HEVs and HFCEVs, which require higher power density and different characteristics.

Data shown in Figure 5 are collected from various peer-reviewed papers and scientific and consultancy reports dating back to 2007, resulting in a total sample size of 118. However, data sources older than 2013 are not taken into account for the fitted line in the figure, and they are referred to as "background data." The central cost estimate for a 2015 BEV battery pack is roughly €250 per kWh (see fitted curve). Accordingly, BEV battery pack costs would equate to around €6,000 for a 24-kWh rated battery pack.

This estimate is in accordance with a recent report by the U.S. DOE (Faguy, 2015), which states that battery costs of DOE-funded projects declined down to €230 per kWh on average by 2014. Similar results are obtained by Nykvist and Nilsson (2015), who find costs of market-leading

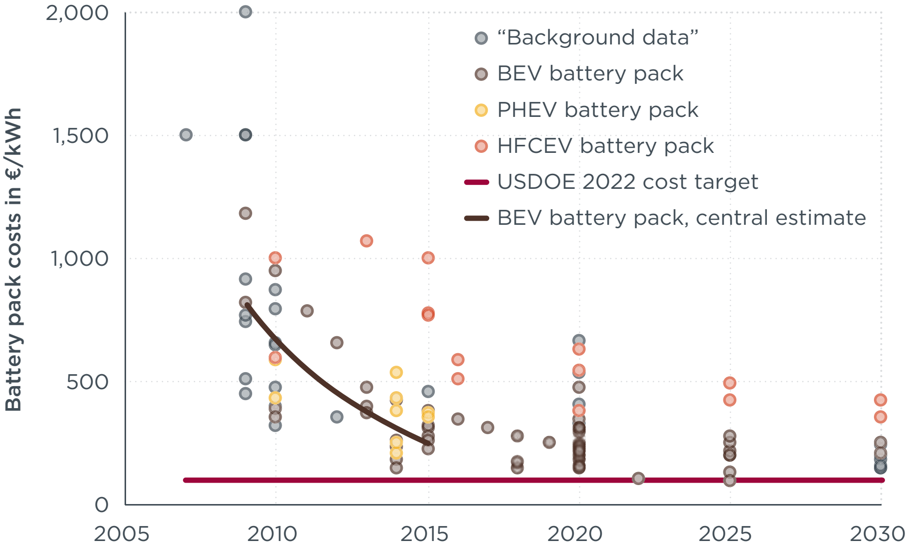

Figure 5. Range of estimated Li-ion battery pack costs for BEVs, PHEVs, and HFCEVs and the 2022 U.S. cost target for BEV battery packs

manufacturers (such as Tesla or Renault-Nissan, which are producers of 50,000 units and more) to be in the order of €240 per kWh, with an average of €320 per kWh for all manufacturers. Bain & Company (2015) also estimate €260 per kWh in 2015.

For the costs in 2020, a study by Daimler engineers (Mayer, Kreyenberg, Wind & Braun, 2012) estimates a range of €310–€410 per kWh, which seems rather conservative by comparison. A more optimistic outlook (Nelson, Ahmed, Gallagher & Dees, 2015) estimates that market leaders may approach €150–€180 per kWh by 2020 at a production volume of 30,000 units or more (BEV battery packs only) in advanced factories. These advanced factories are called flexible plants that can produce different types of batteries for BEVs, PHEVs, and HEVs at varying production volumes up to a total of 235,000 units per year. The authors developed the first freely available, peer-reviewed cost model for automotive batteries, called BatPac.[4]

As of 2015, Renault-Nissan, Tesla, General Motors, Mitsubishi, Volkswagen, BMW, BYD, and Kandi have all produced more than 25,000 EVs per year and are looking to grow their production volume, which indicated that many companies are now reaching the Renault-Nissan and Tesla volume of more than 50,000. General Motors, which began its next-generation BEV production in 2015 for the Bolt, has indicated its battery *cell* production is on the order of €110 per kWh and will be decreasing to as low as €80 per kWh in the 2021 time frame (Cobb, 2015). These estimates indicate that automakers and increasingly competitive battery suppliers are moving toward higher production—up to 500,000 vehicles by 2020 in the case of Tesla (Tesla Motors, 2014)—and potentially further reducing costs toward €130–€180 per kWh at the battery pack level in the 2020–25 time frame, and perhaps to the DOE's target of US$125 (€100) per kWh in the longer term (U.S. DOE, 2015; Faguy, 2015).

10.2. Fuel Cell Systems

Fuel cell systems used in HFCEVs also significantly dropped in costs, and this trend is expected to continue in the future. System costs are highly dependent on production rate and scaling effects, which occur at a

4 Available at http://www.cse.anl.gov/batpac/download.php.

minimum of 30,000 units or higher (see Figure 6). Based on the information that Toyota Motors produced 700 units of the Mirai in 2015, planning to increase production up to 2,000 units in 2016 and 3,000 units in 2017 (Toyota, 2015), the present study assumes a production volume of 1,000 units in 2015 and 5,000 units in 2020 in a typical scenario. The low-cost scenario assumes a production volume of 10,000 units by 2020. Further assumed growth is illustrated in Table 3.

Declining fuel cell system costs reflect recent technological advancements, falling material costs, and a more efficient use of precious metals, such as platinum, in fuel cell electrodes. The National Academy of Sciences (NAS, 2013, p. 33) assumes cost reductions of 2% per year between 2020 and 2030 for the midrange case, and 3% per year for the optimistic case. At an assumed production volume of 300,000, the authors arrive at 2020 costs of €28 per kW (optimistic), and €32 per kW (midrange). At a production volume of 500,000 units, the Carbon Trust (2012) expects system costs to drop down to €39 per kW by 2030. Assuming equal production rates, the lowest known estimate is €21 per kW (IRENA, 2014). The DOE (U.S. DOE, 2014) estimates €225 per kW at 1,000 produced units and €83 per kW at 10,000 units. Moving further to 100,000 units may approach about €53 per kW. Compare this with the Ricardo-AEA (2015) study, which estimates 2013 costs at about €600 per kW, at production levels of a few thousand units, with costs coming down to €40 per kW by 2030 (not shown in Figure 6 because the production scale is not further specified). A study conducted for the consultancy Roland-Berger (Bernhart, Riederle & Yoon, 2013) estimates system costs to be €500 per kW in 2015 and €100 per kW in 2025 and beyond at production volumes of 3,000 units in 2015 and 5 million units in 2025 onwards (not shown in Figure 6). Other studies estimate €28–€40 per kW at one million produced units (Mock, 2010; Mock & Schmid, 2009).

Table 3. Assumed production volumes of hydrogen fuel cell systems in a typical and a low-cost scenario (based on Toyota, 2015; U.S. DOE, 2014)

Scenario	2015	2020	2025	2030
Typical	1,000	5,000	10,000	50,000 (30,000–80,000)
Low cost	1,000	10,000	50,000 (30,000–80,000)	100,000

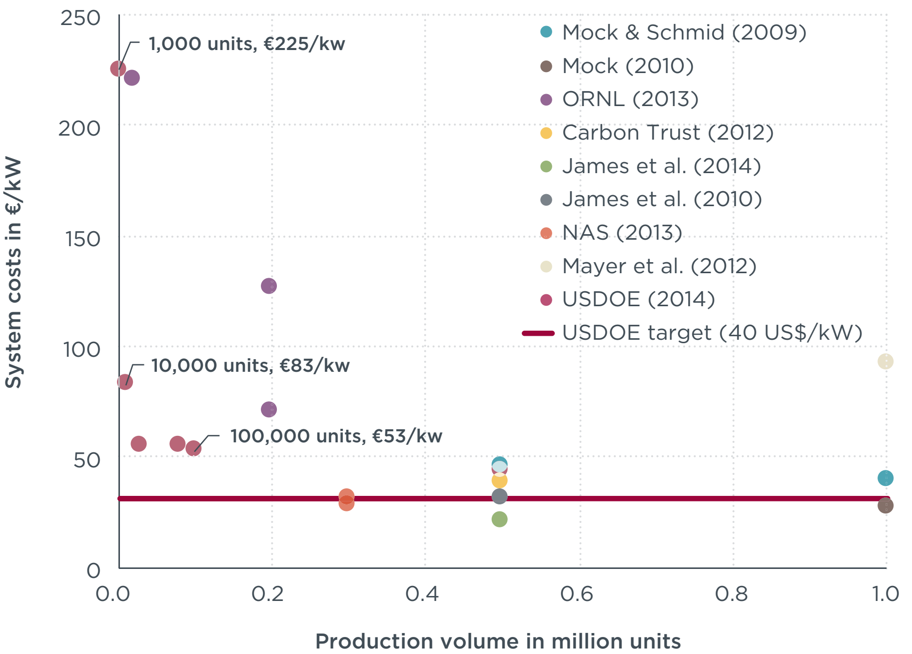

Figure 6. Range of projected fuel cell system costs for HFCEVs as a function of production volume

10.3. Hydrogen Storage

According to the National Academy of Sciences (NAS, 2013, pp. 30ff, p. 293), costs of onboard hydrogen storage are estimated at about €2,700 in 2010 and expected to drop down to about €1,600–€1,900 in 2030. Storage capacity is estimated to decrease from 5.5 kg to 3.8 kg (midrange) or 3.3 kg (optimistic) in 2030, which adds to the cost per kilogram, but reduces the total cost. Fuel savings and new manufacturing techniques can further alleviate these costs. In addition, significant cost improvements in carbon fiber are expected by 2030, resulting in net cost reductions.

10.4. Car Cost Increment

The NAS compares incremental costs of BEVs, PHEVs, and HFCEVs over a small to lower medium ICEV manufactured in 2010. Electric vehicle drivetrains are much more costly initially, with cost increments of about €6,500 for PHEVs, €6,800 for HFCEVs, and €12,600 for BEVs (see Figure 7), at assumed production volumes of 300,000 units per year. Costs of EV power trains decrease significantly over time (at constant production scale), while the costs of ICEVs are growing primarily due to the cost of weight reduction. Hybridization of the power train is not assumed. The study analyses a midrange and an optimistic scenario. Differences between the cases are due to higher weight reductions, higher rolling resistance reductions, better aerodynamics, and

Figure 7. Estimated cost increment of EV power trains over a 2010 ICEV passenger car. Production scales can vary considerably between different studies. Own estimates for 2015 are based on an assumed ~50,000+ produced batteries and ~1,000 fuel cell systems; for 2030 ~500,000+ battery packs and ~50,000 (typical) to ~100,000 (low-cost) fuel cell systems are assumed.

higher accessory efficiencies in the optimistic case. The cost difference between the two scenarios highlights the cost gain of downsizing and improved efficiencies.

According to Ricardo-AEA, for a lower medium car, fuel cell technology leads to the highest additional manufacturing costs (€52,700). The large range of cost estimates reflects the large variances in assumed production volumes. Ricardo-AEA assumes fuel cell system production volumes of a few thousand units. The large cost range between different studies, especially for HFCEVs, reduces as a function of time, as all studies assume increasing production volumes of electric drivetrains, thereby reaping the benefits of scale economies.

The cost reductions in battery packs will especially affect BEV costs because they usually have a larger battery than PHEVs, HFCEVs, and HEVs.[5] Further variable cost reductions in electric motors from around €9 per kW to €5–€5.50 per kW are expected between 2010 and 2030 (NAS, 2013; Ricardo-AEA, 2015). Current high battery costs also explain the significantly higher production costs of BEVs over PHEVs.

5 For a sample of small and compact cars, batteries range between 13–30 kWh for BEVs (n=9) and 4–19 kWh for PHEVs (n=10). HFCEVs and HEVs have smaller batteries, around 0.99-1.6 kWh (n=6).

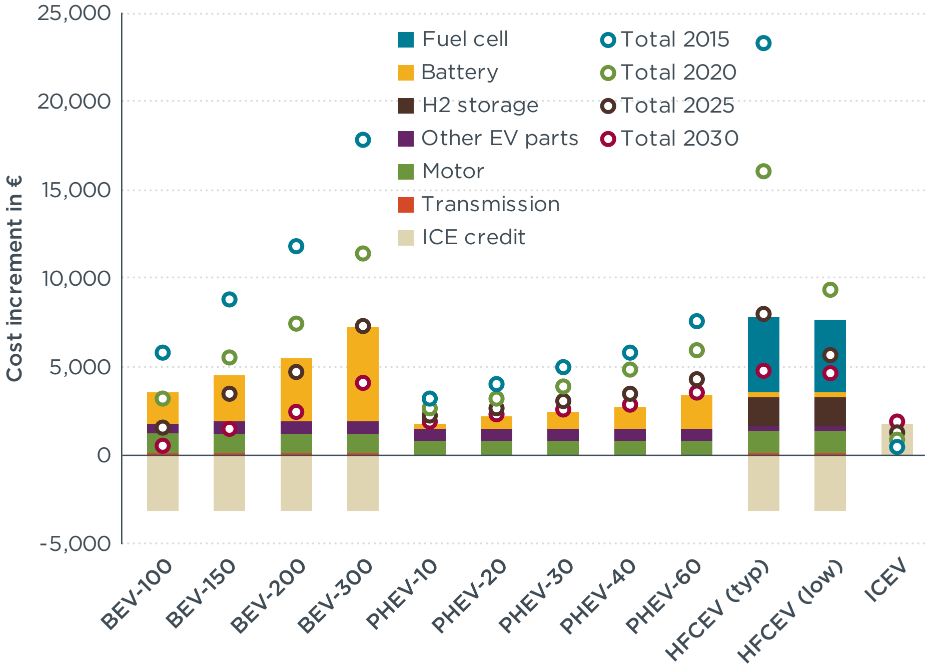

Figure 8. Cost breakdown of different power trains for a 2030 lower medium car. Assumed battery production volume is ~500,000+ units, fuel cell system production is ~50,000 for the typical case and ~100,000 for the low-cost case. Circles represent total incremental costs over a 2010 ICEV.

Total costs of PHEVs are expected to decline at a slower rate because they have smaller batteries that still need to provide high power, and are thus assumed to be more costly (about €80 per kWh) (NAS, 2013). In contrast to electric propulsion systems, ICEVs are expected to grow in costs, primarily due to further drivetrain efficiency improvements and added costs from improved exhaust after treatment. An ICCT study estimates the cost increase to be about €1,000 by 2020 (Mock, 2013), and the NAS estimates it to be about €1,700–€1,900 by 2030.

As indicated in section 10.1, battery pack level prices may decline further from an estimated €250 per kWh down to €130–€180 per kWh for industry leaders between 2015 and the 2020–25 time frame. This would reduce the cost of a 24-kWh rated BEV battery from about €6,000 to below €4,000, which would reduce the incremental cost of the BEV power train accordingly. Similarly, moving from an assumed production volume of 1,000 to 10,000 fuel cell systems may reduce costs from €225 per kW to €83 per kW (U.S. DOE, 2014). This would reduce the cost of a 90 kW fuel cell system from about €20,000 to about €7,500.

Taking into account these component cost estimates, Figure 8 illustrates additional electric power train cost in 2030 and compares these with the costs from 2015 to 2025. All types are characterized by significant cost reductions between 2015 and 2030. The PHEV-30 achieves a 49% cost reduction, the BEV-100 60%, and the HFCEV 70% (excluding ICE credits). This is due to falling component prices and an assumed downsizing of 1% per year for the motor and the fuel cell system, and 2% per year for the battery pack, according to the midrange scenario by NAS (2013). Cost credits are subtracted from BEV and HFCEV power train costs for the non-existing combustion engine, exhaust pipe, and conventional transmission.

Incremental costs for the BEV-100 option fall down to €1,400 by 2025 and thus below the PHEV-10 with €2,100. Incremental costs for the ICEV are still slightly lower with €1,200–€1,300 but the breaking-even point is reached shortly after. By 2030, the costs of BEV-100 and BEV-150 are below ICEV costs and the 10-mile PHEV breaks even with the ICEV. HFCEVs achieve similar but still slightly higher costs than the BEV-300.

Performing a simple uncertainty analysis, as done in section 8, yields a variation in power train cost (excluding ICE credits) between ±2% (PHEV-10) to ±15% (HFCEV). These variations are lower than in 2015, where costs are ranging between ±5% to ±17%, which is due to the falling cost of the battery packs and fuel cell systems.

As seen in Figure 7, the resulting cost estimates for a 2015 HFCEV are at the upper end of previously reported cost estimates. With an assumed increasing production scale, costs fall steeply and eventually reach the lower end of reported values for 2030. Cost estimates for BEVs and PHEVs are below recent estimates. It should be stressed again that this is mainly due to the fact that this work assumes relatively low battery pack cost, but comparably high initial fuel cell system costs (due to low observed production scale). HFCEV cost estimates bear higher uncertainty, as fuel cell system production is still at an early stage and the future production scale is difficult to quantify.

10.5. Charging Infrastructure

The above cost figures do not take into account the new charging infrastructure that will be needed for EV deployment. Differences in cost estimations per type of charger are large (see Figure 9), partly due to the inclusion or exclusion of various cost components, such as planning, installation, authorization, signposting, etc. The National Academy of Sciences (NAS, 2013) estimates Level 1 charging points in the United States to cost about €540 on average, including installation. Costs range between €350 and €1,500. Other sources report costs as low as €116[6] in the United States (HomeAdvisor, 2016). The U.S. Environmental Protection Agency (U.S. EPA, 2012) even cites €62 for a PHEV-20 charger, €327–€416 for a PHEV-40 charger, and €416 for an EV charger in the United States, with an additional installation cost of €806 for all three types. These numbers indicate that costs can be quite low for those only charging at home. Level 2 home chargers in Europe and the United States can be as cheap as €200. The highest known cost estimate for Level 2 residential chargers is €5,300 (INL, 2015), which is driven by the electrical upgrades needed in older houses. The present study finds a median value for Level 1 and 2 residential chargers of about €640–€660.

According to the German National Platform for Electric Mobility (NPE, 2015), Level 2 public chargers (>3.7 kW) in Germany cost €2,200 on average, and are expected to cost €1,700 in 2020, including planning, authorization, installation, signposting, etc. Faster stations (11 or 22 kW) currently cost €10,000 and are assumed to drop down to €7,500 in 2020. Level 3 chargers (50 kW) are by far the most expensive, with a calculated median cost of €32,500 (see Figure 9). Empirical evidence comes from Europe with reported actual costs for fast charging points of about €25,800 per vehicle[7] (EC, 2015). The NPE (2015) also reports that fast charging points in Germany ranged between €20,000 and 35,000 in 2015. Costs for 2020 are expected to be about €24,000 on average.

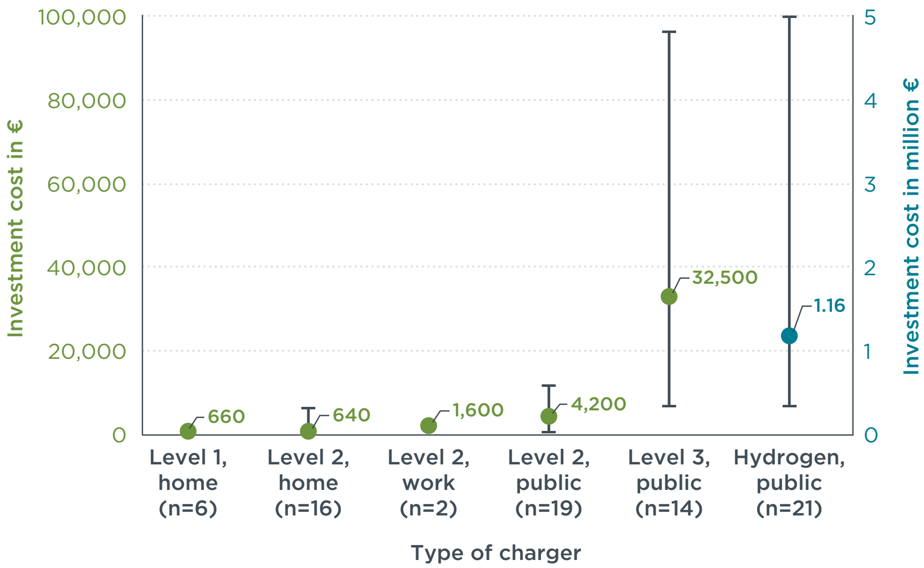

Figure 9. Summary of investment costs for electricity and hydrogen chargers by station type (and for differing regions). Colored dots indicate the median and error bars indicate the range of cited literature values. The left vertical axis is for electricity chargers, and the right one is for hydrogen chargers.

Hydrogen fueling stations are more costly by several magnitudes, ranging from ~€330,000 to ~€5 million, depending on type and cost components included. A study from Shanghai (Weinert, Shajoun, Ogden & Jianxin, 2007) estimates costs for six different station types, including capital cost and operating cost, to range between ~€330,000 and ~€1.1 million. In Germany, costs are estimated at about €1 million per station in 2015 (Hegmann, 2015). The National Academy of Sciences (NAS, 2008) estimates capital costs in the United States to range between €320,000 and €1.7 million per station using on-site natural gas reforming. Per-station costs rise up to €2 million when using on-site electrolysis. Costs are expected to decrease down to an average of €970,000 in 2020, and to €350,000 by 2035.

On a per-vehicle basis, costs are very uncertain, as relatively little is known about how many cars can be served by one station, and which charger types are preferred by users. Costs for PHEVs are assumed to be lower, as these rely less on the new infrastructure. Even though hydrogen chargers are considerably more expensive, per-vehicle costs of BEVs and HFCEVs are expected to be similar as refueling is quicker, and investment costs are therefore spread over more vehicles.

The National Academy of Sciences (NAS, 2013, pp. 45, 307) calculates electricity infrastructure investment costs for the United States in 2010, 2020, and 2030 on a per-vehicle basis, including costs for home and public chargers, but not costs for electricity generation, transmission, distribution, grid expansion, or parking spaces. For each vehicle, a mix of charging stations is assumed. For example, for a PHEV-10 one Level 1 home charger and 0.25 of a Level 1 charger at work (NAS, 2013, p. 319). As a result, infrastructure investment costs are the highest for BEVs (€3,350 in 2010) because they fully rely on the new fuel infrastructure that is largely yet to be built. Infrastructure costs go down with decreasing battery usage. Thus, costs are lower for PHEVs (€3,300 for a PHEV-40, €632 for a PHEV-10). Future investment costs are expected to drop with increasing battery ranges (€510 to €2,310 in 2030).

6 The purchaser price is €174, and has been divided by 1.5 (Roland-Holst, 2012; NAS, 2013) to arrive at the manufacturer's price of €116.

7 €4 million have been invested in 155 fast charging points as part of the TEN-T program.

A study from the University of California, Davis (Ogden, Yang, Nicholas & Fulton, 2014) assumes an investment cost of €120–€240 million for 50,000–100,000 HFCEVs served by 100–200 hydrogen refueling stations. Thus, estimated costs on a per-car basis amount to about €2,300. The International Energy Agency (IEA, 2015) estimates costs to range between €700 and €1,500 per HFCEV, depending on world region, including electricity transmission and distribution, and hydrogen retail and generation infrastructure. The National Academy of Sciences (NAS, 2008) assumes that 2,112 hydrogen stations cost €2 billion and can serve 1.8 million cars. Thus, costs per vehicle would be €1,600.

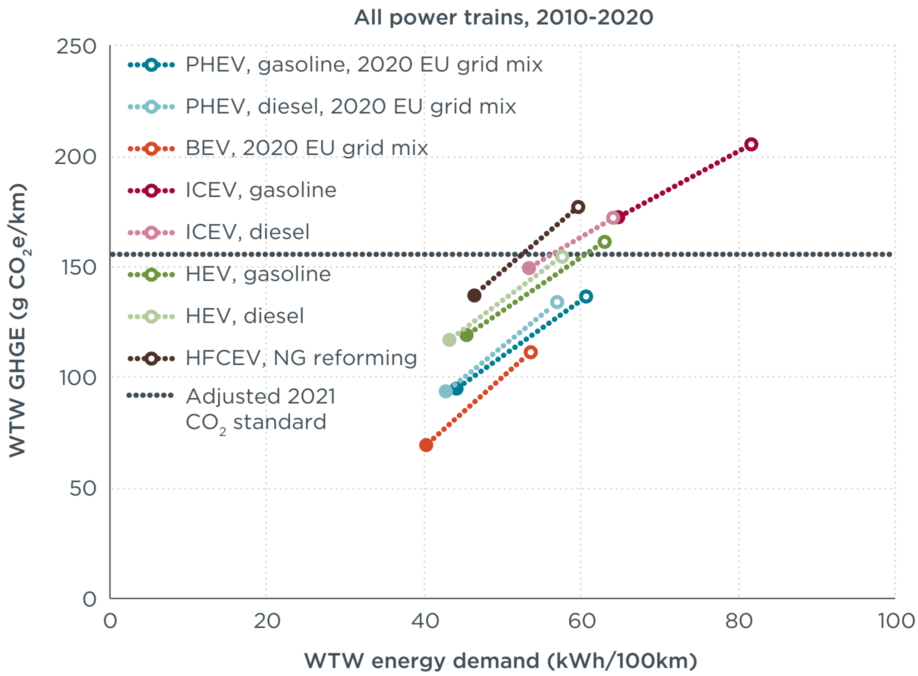

Figure 10. Expected change in WTW GHG emissions and energy demand of different power trains. Hollow dots represent 2010 values, solid dots 2020. The horizontal line represents the 2021 European passenger car CO_2 standard adjusted to WTW and real-world fuel consumption.

11. GHG EMISSIONS AND ENERGY USE REDUCTIONS

As described in section 9, there is a significant discrepancy between type-approval and actual real-world fuel consumption. This discrepancy is assumed to increase from 24% to 45% for ICEVs by 2020, in a business-as-usual scenario where the current NEDC test procedure is kept in place (Tietge, Zacharof, Mock, Franco, German, Bandivadekar, Ligterink & Lambrecht, 2015). Similarly, an increase from 41% to 61% is assumed for hybrid and electric power trains. It should be noted that the anticipated introduction of the new Worldwide Harmonized Light Vehicles Test Procedure (WLTP) in the EU in 2017 is expected to help reduce the discrepancy between official and real-world consumption and emission values—which is not taken into account for the purpose of this study.

Furthermore, the study cited above by the European Commission (Edwards, Hass, Larivé, Lonza, Maas & Rickeard, 2014) assumes that upstream emissions in the energy supply chain will be reduced due to more efficient production processes and thermal power plants. However, the authors assume the same grid electricity GHG intensity in 2010 and 2020 (540 g CO_2e per kWh) due to uncertain penetration rates of low-carbon technologies. In the present study, a growing share of renewable electricity in accordance with IEA's New Policy Scenario (IEA, 2011) is assumed, leading to an estimated grid intensity of about 420 g CO_2e per kWh in 2020, and therefore lower upstream emissions.

Finally, the assumption made by Edwards and colleagues (2014) that power trains increase efficiencies by roughly 30% between 2010 and 2020 is adopted here. In addition, the authors assume an increased electric drive-cycle range from 120 km in 2010, to 200 km in 2020 for the modeled BEV. The PHEV is assumed to have a constant electric range of 20 km.

As shown in Figure 10, electric-drive vehicles offer the potential to greatly reduce carbon emissions, even from advanced 2020 HEVs. Internal combustion engine vehicles in 2020 can achieve emission levels that are in the region of an adjusted 2021 CO_2 emission standard of about 156 g CO_2 per km (see Figure 10). This adjusted standard represents the official CO_2 standard for European passenger vehicles in 2021, which is 95 g CO_2/km, after including upstream petroleum emissions and on-road fuel consumption. To get to the adjusted standard, the official standard is multiplied by a factor of 1.64, which is derived by dividing total WTW emissions by unadjusted tailpipe emissions, resulting in 172 g CO_2e per kWh/105 g CO_2e per kWh = 1.64 (example for a gasoline ICEV).[8]

2020 BEVs and PHEVs would achieve 32%–54% lower emissions than this adjusted 2021 emission standard for conventional vehicles. 2020 BEVs can

8 Using the original unadjusted numbers from Edwards et al. (2014) would result in a factor of 125/105 = 1.19. This factor is lower, as the authors do not take real-world fuel consumption into account.

reduce carbon emissions by another 35% compared with 2010. This results in a total carbon benefit of 65% compared with a 2010 gasoline ICEV. These results are in line with an earlier ICCT report (Lutsey, 2015a), which finds that electric vehicles would go from about a 53% carbon reduction benefit over average EU vehicles in 2013 to a 76% benefit with a shift to a lower carbon grid in 2030 per IEA Policy Cases.

12. CONCLUSIONS AND OUTLOOK

This paper analyzed the role of electric vehicles within a lower carbon 2020–2030 new vehicle fleet in Europe. For this purpose, literature data on cost and emissions has been collected, analyzed, and aggregated. Based on the collected data, the cost of batteries, fuel cells, and charging infrastructure has been estimated. In addition, power train costs of BEVs, PHEVs, and HFCEVs has been approximated using a bottom-up approach. In addition to recent cost declines, power train costs for all three types are expected to decrease further, by 50%–70% between 2015 and 2030. This occurs over the same period as conventional combustion vehicles are having expected cost increases, further narrowing the gap between conventional and electric drivetrains. As a result, BEVs can break even with ICEVs and even fall below the costs of PHEVs by 2030.

Cost reduction in electric drivetrains is largely driven by cost reductions in battery and fuel cell production. This paper estimates 2015 BEV battery pack costs at roughly €250 per kWh for market leaders, which is in agreement with most recent scholarly literature. Further cost reductions down to as low as €130–€180 per kWh are anticipated in the 2020–25 time frame. Fuel cell costs will be highly dependent on the actual production scale.

Li-ion batteries will likely remain the main chemistry for EV batteries in the foreseeable future. Promising new avenues of research may include the further improvement of batteries and fuel cells and the development of new battery concepts beyond Li-ion, such as lithium-air, -metal or -sulfur. Simultaneous deployment of residential, workplace, and public charging will also be important over the same time period.

Estimations of energy demand and carbon emissions of electric and conventional power trains have been made by building on and refining previous work. In doing so, tailpipe emissions and also all upstream emissions from electricity and fuel production were considered. In addition, the real-world fuel consumption of vehicles has been taken into account. It was found that, with some exceptions, electric vehicles provide consistent benefits versus internal combustion vehicles with the mix of power sources widely available. With average European electricity sources, BEVs provide an about 40%–50% GHG benefit compared with average vehicles. With higher power train efficiencies and an increasing share of renewable energy in the European grid mix, carbon emissions from BEVs can be cut by another one-third by 2020.

However, the expected cost reductions and potential CO_2 emission cuts will not be achieved without targeted policy intervention. As has been shown, the 2021 European passenger car CO_2 standard can be met without notable penetration of electric vehicles. More stringent CO_2 standards, and fiscal and non-fiscal incentives for electric vehicles can help the EV market grow and reduce costs. Also, efforts need to be combined with activities to reduce the carbon intensity of the grid, or the whole potential of electric vehicles to reduce emissions will not be fully exploited. Although the analysis is focused on a European context, similar dynamics with electric vehicle technology, policy, and market development are prevalent across major North American and Asian markets.

13. REFERENCES

Alternative Fuels Data Center, U.S. Department of Energy (AFDC) (2015). *Alternative Fueling Station Counts by State*. Retrieved from http://www.afdc.energy.gov/fuels/stations_counts.html.

Bain & Company (2015). *Eine Million E-Autos in Deutschland bis 2020 nicht zu schaffen.* Retrieved from http://www.bain.de/press/press-archive/bain-analyse-zur-elektromobilitaet.aspx.

Bernhart, W., Riederle, S., & Yoon, M. (2013). *Fuel cells: A realistic alternative for zero emission?* Study for Roland–Berger Strategy Consultants. Retrieved from http://www.rolandberger.com/media/pdf/Roland_Berger_Fuel_cells_20140113.pdf.

Boston Consulting Group (BCG) (2010). *Batteries for Electric Cars: Challenges, Opportunities, and the Outlook to 2020.* Retrieved from http://www.bcg.com/documents/file36615.pdf.

Carbon Trust (2012). *Polymer Fuel Cells – Cost reduction and market potential.* Retrieved from https://www.carbontrust.com/media/195742/pfcc-cost-reduction-and-market-potential.pdf.

Cobb, J. (2015). GM Says Li-ion Battery Cells Down to $145/kWh and Still Falling. *Hybridcars.com.* Retrieved from http://www.hybridcars.com/gm-ev-battery-cells-down-to-145kwh-and-still-falling/.

Cookson, C. (2015, October 30). Cambridge chemists make super-battery breakthrough. *CNBC.com*. Retrieved from http://www.cnbc.com/2015/10/30/hemists-make-super-battery-breakthrough.html.

Deutsches Zentrum für Luft- und Raumfahrt (DLR) and the Wuppertal Institute for Climate, Environment and Energy (2015, March). *Begleitforschung zu Technologien, Perspektiven und Ökobilanzen der Elektromobilität.* Retrieved from the Wuppertal Institute https://epub.wupperinst.org/frontdoor/index/index/docId/5966.

Dunn, J. B., Gaines, L., Kelly, J. C., James, C., & Gallagher, K. G. (2015). The significance of Li-ion batteries in electric vehicle life-cycle energy and emissions and recycling's role in its reduction. *Energy & Environmental Science*, *8*(1), 158–168. Retrieved from http://dx.doi.org/10.1039/c4ee03029j.

Edwards, R., Larivé, J.-F., & Beziat, J.-C. (2011, July). *Well-to-wheels Analysis of Future Automotive Fuels and Power trains in the European Context (Version 3c).* Retrieved from the European Commission Joint Research Centre, Institute for Energy and Transport (IET) website: http://iet.jrc.ec.europa.eu/about-jec/downloads.

Edwards, R., Hass, H., Larivé, J.-F., Lonza, L., Maas, H., & Rickeard, D. (2014, April). *Well-to-Wheels Analysis of Future Automotive Fuels and Power trains in the European Context (Version 4a).* Retrieved from the European Commission Joint Research Centre, Institute for Energy and Transport (IET) website: http://iet.jrc.ec.europa.eu/about-jec/downloads.

U.S. Energy Information Administration (EIA) (2015). *Global EV Outlook 2015.* Retrieved from http://www.cleanenergyministerial.org/Portals/2/pdfs/EVI-GlobalEVOutlook2015-v14-landscape.pdf.

European Commission (EC) (2015). *Infrastructure—TEN-T—Connecting Europe.* Retrieved from http://ec.europa.eu/transport/themes/infrastructure/index_en.htm.

EV Sales (2016). Markets Roundup December 2015 (Special Edition). Retrieved from http://ev-sales.blogspot.de/2016/02/markets-roundup-december-2015-special.html.

Faguy, P. (2015, June 8). *Overview of the DOE Advanced Battery R&D Program.* Retrieved from U.S. Department of Energy website: http://energy.gov/sites/prod/files/2015/06/f23/es000_faguy_2015_o.pdf.

H2 Mobility (2015). *Mission.* Retrieved from http://h2-mobility.de/#mission.

Hacker, F., Harthan, R., Matthes, F., & Zimmer, W. (2009). Environmental impacts and impact on the electricity market of a large scale introduction of electric cars in Europe—Critical Review of Literature. European Topic Centre on Air and Climate Change. Retrieved from acm.eionet.europa.eu/docs/ETCACC_TP_2009_4_electromobility.pdf

Hawkins, T. R., Singh, B., Majeau-Bettez, G., & Strømman, A. H. (2012). Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles. *Journal of Industrial Ecology, 17*(1), 53–64. Retrieved from http://dx.doi.org/10.1111/j.1530-9290.2012.00532.x.

Hegmann, G. (2015, October 28). So soll der Traum vom Wasserstoff-Auto wahrwerden. *Die Welt*. Retrieved from http://www.welt.de/wirtschaft/article148150274/So-soll-der-Traum-vom-Wasserstoff-Auto-wahrwerden.html.

HomeAdvisor (2016). How Much Does It Cost to Install an Electric Vehicle Charging Station? Retrieved from http://www.homeadvisor.com/cost/garages/install-an-electric-vehicle-charging-station/.

Hydrogen Cars Now (2016a). *European Union Hydrogen Highway.* Retrieved from http://www.hydrogencarsnow.com/index.php/european-union-hydrogen-highway/.

Hydrogen Cars Now (2016b). *Hyundai Tucson FCEV.* Retrieved from http://www.hydrogen-carsnow.com/index.php/hyundai-tucson-fcev/.

Hydrogen Cars Now (2016c). *Toyota Mirai.* Retrieved from http://www.hydrogencarsnow.com/index.php/toyota-mirai/.

Idaho National Laboratory (INL) (2015, September). *Plug-in Electric Vehicle and Infrastructure Analysis.* Report prepared for the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy. Retrieved from https://avt.inl.gov/sites/default/files/pdf/arra/ARRAPEVnInfrastructureFinalReportHqltySept2015.pdf

International Energy Agency (IEA) (2011, November 9). *World Energy Outlook 2011.* Retrieved from http://www.worldenergyoutlook.org/weo2011/.

International Energy Agency (IEA) (2015). *Technology Roadmap: Hydrogen and Fuel Cells.* Retrieved from http://www.iea.org/publications/freepublications/publication/technology-roadmap-hydrogen-and-fuel-cells.html.

Imanishi, N., & Yamamoto, O. (2014). Rechargeable lithium-air batteries: characteristics and prospects. *Materials Today, 17*(1), 24–30. Retrieved from http://www.sciencedirect.com/science/article/pii/S1369702113004586.

International Renewable Energy Agency (IRENA) (2013). *Plug-in hybrid electric vehicles (PHEVs)*. Retrieved from http://costing.irena.org/charts/plug-in-hybrid-electric-vehicles-%28phevs%29.aspx.

James, B. D., Kalinoski, J. A., & Baum, K.N. (2010). *Mass Production Cost Estimation of Direct H2 PEM Fuel Cell Systems for Transportation Applications: 2010 Update*. Retrieved from the U.S. Department of Energy website: http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/dti_80kwW_fc_system_cost_analysis_report_2010.pdf.

James, B. D., Moton, J. M., & Colella, W. G. (2014). *Mass Production Cost Estimation of Direct H2 PEM Fuel Cell Systems for Transportation Applications: 2013 Update.* Retrieved from the U.S. Department of Energy website: http://energy.gov/eere/fuelcells/downloads/mass-production-cost-estimation-direct-h2-pem-fuel-cell-systems.

Kromer, M. A., & Heywood, J. B. (2007*). Electric Power trains: Opportunities and Challenges in the U.S. Light-Duty Vehicle Fleet* (Publication No. LFEE 2007-03 RP) Cambridge, Mass.: Massachusetts Institute for Technology (MIT). Retrieved from http://web.mit.edu/sloan-auto-lab/research/beforeh2/files/kromer_electric_powertrains.pdf.

Ludwig-Bölkow Systemtechnik (LBS) (2016). *Hydrogen Filling Stations Worldwide.* Retrieved from http://www.netinform.net/H2/H2Stations/H2Stations.aspx?Continent=NA&StationID=-1.

Lutsey, N. (2012). A technical analysis of model year 2011 US automobile efficiency. *Transportation Research Part D: Transport and Environment, 17*(5), 361–369. Retrieved from http://dx.doi.org/10.1016/j.trd.2012.03.002.

Lutsey, N. (2015a*). Global climate change mitigation potential from a transition to electric vehicles.* Retrieved from The International Council on Clean Transportation website: http://www.theicct.org/global-ev-2050-ghg-mitigation-potential.

Lutsey, N. (2015b). *Transition to a Global Zero-Emission Vehicle Fleet: A Collaborative Agenda for Governments.* Retrieved from The International Council on Clean Transportation website: http://www.theicct.org/sites/default/files/publications/ICCT_GlobalZEVAlliance_201509.pdf.

Mayer, T., Kreyenberg, D., Wind, J., & Braun, F. (2012). Feasibility study of 2020 target costs for PEM fuel cells and lithium-ion batteries: A two-factor experience curve approach. *International Journal of Hydrogen Energy, 37*(19), 14463–14474. Retrieved from http://dx.doi.org/10.1016/j.ijhydene.2012.07.022.

Mock, P. (2010). *Entwicklung eines Szenariomodells zur Simulation der zukünftigen Marktanteile und CO2-Emissionen von Kraftfahrzeugen (VECTOR21)* (Doctoral dissertation). Retrieved from http://elib.uni-stuttgart.de/handle/11682/6777.

Mock, P. (2013). *Reducing CO2 and fuel consumption from new cars: Assessing the near-term technology potential in the EU.* Retrieved from The International Council on Clean Transportation website: http://www.theicct.org/sites/default/files/Briefing%20Technology%20Potential%20Short%20EN%20v2.pdf.

Mock, P., ed. (2015). *European Vehicle Market Statistics, Pocketbook 2015/1.* Retrieved from The International Council on Clean Transportation website: http://www.theicct.org/sites/default/files/publications/ICCT_EU-pocketbook_2015.pdf.

Mock, P., Schmid, S. A. (2009). Fuel cells for automotive powertrains—A techno-economic assessment. *Journal of Power Sources, 190*(1), 133–140. Retrieved from http://dx.doi.org/10.1016/j.jpowsour.2008.10.123.

National Academy of Sciences (NAS) (2008). *Transitions to Alternative Transportation Technologies—A Focus on Hydrogen.* doi: 10.17226/12222. Retrieved from http://www.nap.edu/catalog/12222/transitions-to-alternative-transportation-technologies-a-focus-on-hydrogen.

National Academy of Sciences (NAS) (2013). *Transitions to Alternative Vehicles and Fuels. National Academy of Sciences*. doi: 10.17226/18264. Retrieved from http://www.nap.edu/catalog/18264/transitions-to-alternative-vehicles-and-fuels.

National Academy of Sciences (NAS) (2015). *Overcoming Barriers to Deployment of Plug-in Electric Vehicles.* doi: 10.17226/21725. Retrieved from http://www.nap.edu/catalog/21725/overcoming-barriers-to-deployment-of-plug-in-electric-vehicles.

Nationale Plattform Elektromobilität (NPE) (2015). *Ladeinfrastruktur für Elektrofahrzeuge in Deutschland - Statusbericht und Handlungsempfehlungen 2015.* Retrieved from http://nationale-plattform-elektromobilitaet.de/fileadmin/user_upload/Redaktion/NPE_AG3_Statusbericht_LIS_2015_barr_bf.pdf.

Nelson, P. A., Ahmed, S., Gallagher, K. G., & Dees, D. W. (2015). Cost savings for manufacturing lithium batteries in a flexible plant. *Journal of Power Sources, 283*, 506–516. Retrieved from http://dx.doi.org/10.1016/j.jpowsour.2015.02.142.

Notter, D. A., Gauch, M., Widmer, R., Wäger, P., Stamp, A., Zah, R., & Althaus, H.-J. (2010). Contribution of Li-ion Batteries to the Environmental Impact of Electric Vehicles. *Environmental Science & Technology, 44*(17), 6550–6556. Retrieved from http://dx.doi.org/10.1021/es903729a.

Nykvist, B., & Nilsson, M. (2015). Rapidly falling costs of battery packs for electric vehicles. *Nature Climate Change, 5*(4), 329–332. Retrieved from http://dx.doi.org/10.1038/NCLIMATE2564.

Ogden, J., Yang, C., Nicholas, M., & Fulton, L. (2014). *The Hydrogen Transition*. Retrieved from the Institute of Transportation Studies at UC Davis website: http://steps.ucdavis.edu/files/08-13-2014-08-13-2014-NextSTEPS-White-Paper-Hydrogen-Transition-7.29.2014.pdf.

OICA (2016). *World vehicles in use: By country and type 2005–2013.* Retrieved from the International Organization of Motor Vehicle Manufacturers (OICA) website: http://www.oica.net/category/vehicles-in-use/.

Oak Ridge National Laboratory (ORNL) (2013, July). *Status and Prospects of the Global Automotive Fuel Cell Industry and Plans for Deployment of Fuel Cell Vehicles and Hydrogen Refueling Infrastructure.* Retrieved from http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/fcev_status_prospects_july2013.pdf.

Ricardo-AEA (2015). *Improving understanding of technology and costs for CO_2 reductions from cars and LCVs in the period to 2030 and development of cost curves.* Final Report for the Directorate-General for Climate Action. [Forthcoming].

Roland-Holst, D. (2012). *Plug-in Electric Vehicle Deployment in California: An Economic Assessment.* Retrieved from the University of California, Berkeley, Department of Agricultural and Resource Economics website: http://are.berkeley.edu/ dwrh/CERES_Web/Docs/ETC_PEV_RH_Final120920.pdf.

Singh, B., Strømman, A. H., & Hertwich, E. G. (2011). Comparative life-cycle environmental assessment of CCS technologies. *International Journal of Greenhouse Gas Control, 5*(4), 911–921. doi: 10.1016/j.ijggc.2011.03.012.

Stewart, A., Hope-Morley, A., Mock, P., & Tietge, U. (2015). *Quantifying the impact of real-world driving on total CO_2 emissions from UK cars and vans.* Final report for The Committee on Climate Change prepared by The International Council on Clean Transportation. Retrieved from https://www.theccc.org.uk/wp-content/uploads/2015/09/Impact-of-real-world-driving-emissions-for-UK-cars-and-vans.pdf.

Tesla Motors (2014). *Tesla Gigafactory*. Retrieved from https://www.teslamotors.com/de_DE/gigafactory.

Tietge, U., Zacharof, N., Mock, P., Franco, V., German, J., Bandivadekar, A., Ligterink, N., & Lambrecht, U. (2015). *From Laboratory to Road: A 2015 Update of Official and "Real-World" Fuel Consumption and CO_2 Values for Passenger Cars*. Retrieved from The International Council on Clean Transportation website: http://theicct.org/sites/default/files/publications/ICCT_LaboratoryToRoad_2015_Report_English.pdf.

Toyota (2015, January 22). *Toyota Mirai production to be increased*. Retrieved from http://blog.toyota.co.uk/toyota-mirai-production-increased.

UBS (2014). *Q-Series® Global Utilities, Autos \& Chemicals: Will solar, batteries and electric cars re-shape the electricity system?* Retrieved from http://www.qualenergia.it/sites/default/files/articolo-doc/ues45625.pdf.

Union of Concerned Scientists (UCS) (2015). *Cleaner Cars from Cradle to Grave: How Electric Cars Beat Gasoline Cars on Lifetime Global Warming Emissions.* Retrieved from http://www.ucsusa.org/clean-vehicles/electric-vehicles/life-cycle-ev-emissions#.V1XEFBQrIWo.

U.S. Department of Energy (DOE) (2014). *Fuel Cell System Cost 2013.* Washington D.C.: United States Department of Energy. Retrieved from https://www.hydrogen.energy.gov/pdfs/14012_fuel_cell_system_cost_2013.pdf.

U.S. Department of Energy (DOE) (2015). *Revolution…Now: The Future Arrives for Five Clean Energy Technologies – 2015 Update.* Washington D.C.: United States Department of Energy. Retrieved from http://energy.gov/eere/downloads/revolution-now-future-arrives-five-clean-energy-technologies-2015-update.

U.S. Department of Energy (DOE) (2016). *Hydrogen Production: Natural Gas Reforming*. Washington, D.C.: United States Department of Energy. Retrieved from http://energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming.

U.S. Environmental Protection Agency (EPA) (2012). *Regulatory Impact Analysis: Final Rulemaking for 2017–2025 Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards.* Washington, D.C.: U.S. Environmental Protection Agency. Retrieved from https://www3.epa.gov/otaq/climate/documents/420r12016.pdf.

U.S. Geological Survey (USGS) (2015). *Lithium Statistics and Information.* Washington, D.C.: U.S. Geological Survey. Retrieved from http://minerals.usgs.gov/minerals/pubs/commodity/lithium/index.html#mcs.

Weinert, J., Shajoun, L., Ogden, J., & Jianxin, M. (2007). Hydrogen refueling station costs in Shanghai. *International Journal of Hydrogen Energy, 32*(16), 4089–4100. Retrieved from http://dx.doi.org/10.1016/j.ijhydene.2007.05.010.

Wiedmann, T. O., Suh, S., Feng, K., Lenzen, M., Acquaye, A., Scott, K., & Barrett, J. R. (2011). Application of Hybrid Life Cycle Approaches to Emerging Energy Technologies—The Case of Wind Power in the UK. *Environmental Science & Technology, 45*(13), 5900–5907. Retrieved from http://dx.doi.org/10.1021/es2007287.

A. ANNEX

A.1. DETAILED VALUES AND ASSUMPTIONS FOR THE WTW META-ANALYSIS

Table A 1. ICEV and HEV, 2010

Fuel	kWh/100km	CO_2e g/km	Assumptions and details
Diesel	65	174	Diesel fuel, DICI, 300 g CO_2e/kWh
Diesel, hybrid	57	155	Diesel fuel, DICI, 300 g CO_2e/kWh
Gasoline	81	204	Gasoline fuel, DISI, 290 g CO_2e/kWh
Gasoline, hybrid	63	161	Gasoline fuel, DISI, 290 g CO_2e/kWh

DISI = direct injection spark ignited engine, DICI = direct injection compression ignited

Table A 2. BEV, 2010

Electricity source	kWh/100km	CO_2e g/km	
EU grid mix, 2009	53	110	EU grid mix electricity, 540 g CO_2e/kWh
Hard coal	47	243	Hard coal electricity, conventional, 1,190 g CO_2e/kWh
Hard coal, IGCC	43	209	Hard coal, IGCC, 1,025 g CO_2e/kWh
Hard coal, IGCC+CCS	49	63	Hard coal, IGCC+CCS, 308 g CO_2e/kWh[(a)]
Natural gas, CCGT	38	90	Natural gas, CCGT, pipe transportation 4,000 km, 440 g CO_2e/kWh
Natural gas, CCGT+CCS	45	32	Natural gas, CCGT+CCS, pipe transportation 4,000 km, 158 g CO_2e/kWh[(a)]
Wind	22	6	Wind, 29 g CO_2e/kWh[(b)]

IGCC = integrated gasification combined cycle, CCGT = combined-cycle gas turbine, CCS = carbon capture and storage
(a) Assuming that CCS can cut carbon emissions from natural gas by 64% and from coal by 70% (Singh, Strømman, & Hertwich, 2011)
(b) Assumed zero in Edwards et al. (2014) and updated with results from a life cycle assessment on wind power in the UK (Wiedmann, Suh, Feng, Lenzen, Acquaye, Scott, & Barrett, 2011).

Table A 3. PHEV, 2010

Electricity source	kWh/100km	CO_2e g/km	Assumptions and details
EU grid mix, 2009	60	136	EU grid mix electricity and gasoline, DISI
	56	133	EU grid mix electricity and diesel, DICI
Hard coal	56	202	Hard coal electricity and gasoline, DISI
	53	199	Hard coal electricity and diesel, DICI
Hard coal, IGCC	54	185	Hard coal (IGCC) electricity and gasoline, DISI
	51	182	Hard coal (IGCC) electricity and diesel, DICI
Hard coal, IGCC+CCS	58	112	Hard coal (IGCC+CCS) electricity and gasoline, DISI
	54	109	Hard coal (IGCC+CCS) electricity and diesel, DICI
Natural gas, CCGT	52	125	Natural gas (combined-cycle gas turbine, CCGT) and gasoline, pipe transportation 4,000 km, DISI
	48	122	Natural gas (CCGT) and diesel, pipe transportation 4,000 km, DICI
Natural gas, CCGT+CCS	56	97	Natural gas (CCGT+CCS) and gasoline, pipe transportation 4000 km, DISI
	52	94	Natural gas (CCGT+CCS) and diesel, pipe transportation 4,000 km, DICI
Wind	44	82	Wind electricity and gasoline, DISI
	41	79	Wind electricity and diesel, DICI

Note: Same fuel and electricity GHG intensities used as in Table A 1 and Table A 2.

Table A 4. HFCEV, 2010

Electricity source	kWh/100km	CO_2e g/km	
Natural gas reforming	55	177	C-H_2, natural gas, central reforming, pipe transp. 7,000km, 480 g CO_2e/kWh
Natural gas reforming, CCS	57	64	C-H_2, natural gas, central reforming, pipe transp. 4,000 km, CCS, 170 g CO_2e/kWh
Coal gasification	73	284	C-H_2, coal EU-mix, central reforming, pipe transp., 770 g CO_2e/kWh
Coal gasification, CCS	81	85	C-H_2, coal EU-mix, central reforming, pipe transp., CCS, 230 g CO_2e/kWh
Wind, electrolysis	57	15	C-H_2, wind power, central electrolysis, pipe transp., 41 g CO_2e/kWh

C-H_2 = compressed gaseous hydrogen

Table A 5. All power trains, 2020

Electricity/fuel type	kWh/100km	CO_2e g/km	Assumptions and details
HFCEV, natural gas reforming	47	115	C-H2, natural gas, central reforming, pipe transp. 7,000 km, 460 g CO_2e/kWh
ICEV, gasoline	65	172	Gasoline fuel, DISI, 290 g CO_2e/kWh
ICEV, diesel	54	153	Diesel fuel, DICI, 300 g CO_2e/kWh
HEV, gasoline	47	126	Gasoline fuel, DISI, 290 g CO_2e/kWh
HEV, diesel	44	120	Diesel fuel, DICI, 300 g CO_2e/kWh
PHEV, gasoline, 2020 EU grid mix	45	97	EU grid mix electricity (420 g CO_2e/kWh) and gasoline (300 g CO_2e/kWh), DISI
PHEV, diesel, 2020 EU grid mix	43	96	EU grid mix electricity (420 g CO_2e/kWh) and diesel (320 g CO_2e/kWh), DICI
BEV, 2020 EU grid mix	41	72	EU grid mix electricity, 420 g CO_2e/kWh

A.2. COST BREAKDOWN OF DIFFERENT ELECTRIC POWER TRAINS

Table A 6. Assumed specifications for the 2015 power trains

	BEV				PHEV					HFCEV
Fuel cell (kW)	-	-	-	-	-	-	-	-	-	91
Motor (kW)	80	80	80	80	60	60	60	60	60	90
Battery (kWh)	24	36	48	72	2.7	5.4	8.2	10.9	16.0	1.0
Electric drive-cycle range (NEDC) (km)	160	240	320	480	16	32	48	64	96	380*
Electric drive-cycle range (NEDC) (mi)	100	150	200	300	10	20	30	40	60	240*

* Drive-cycle range on hydrogen fuel

Table A 7. Cost breakdown of EV power train cost in €, 2015

	Fuel cell system	H_2 storage	EV transmission	Other EV systems[(a)]	Electric motor system[(b)]	Battery pack	ICE credits[(c)]	Total
BEV								
Unit cost	-	-	280	740	110+21 kW^{-1}	250 kWh^{-1} [(d)]	- 3,160	-
BEV-100	-	-	280	740	1,790	6,000	- 3,160	5,560
BEV-150	-	-	280	740	1,790	9,000	- 3,160	8,650
BEV-200	-	-	280	740	1,790	12,000	- 3,160	11,650
BEV-300	-	-	280	740	1,790	18,000	- 3,160	17,650
PHEV								
Unit cost	-	-	-	740	110+21 kW^{-1}	330 kWh^{-1} [(e)]	-	-
PHEV-10	-	-	-	740	1,370	891	-	3,001
PHEV-20	-	-	-	740	1,370	1,782	-	3,892
PHEV-30	-	-	-	740	1,370	2,706	-	4,816
PHEV-40	-	-	-	740	1,370	3,597	-	5,707
PHEV-60	-	-	-	740	1,370	5,280	-	7,390
HFCEV								
Unit cost	225 kW^{-1}	2,600	280	390	110+21 kW^{-1}	630 kWh^{-1} [(f)]	- 3,160	-
HFCEV	20,520	2,600	280	390	2,008	630	- 3,160	23,193

(a) Includes control unit (€150), regenerative braking system (€240), and for BEVs and PHEVs only: onboard charger (€350).
(b) Includes fixed and variable (per kW) cost for electric motor, boost converter, and inverter.
(c) Includes cost subtractions for non-existing combustion engine, exhaust pipe, and conventional transmission.
(d) Central cost estimate at an assumed production volume in the mid-ten thousands; see section 10.1.
(e) According to NAS (2013) PHEV batteries have a cost surcharge of roughly €80 per kWh over BEV batteries.
(f) Assumes the HFCEV battery price from NAS (2013) for 2020 (mid-range scenario) as battery prices declined faster than previously assumed; see section 10.1.