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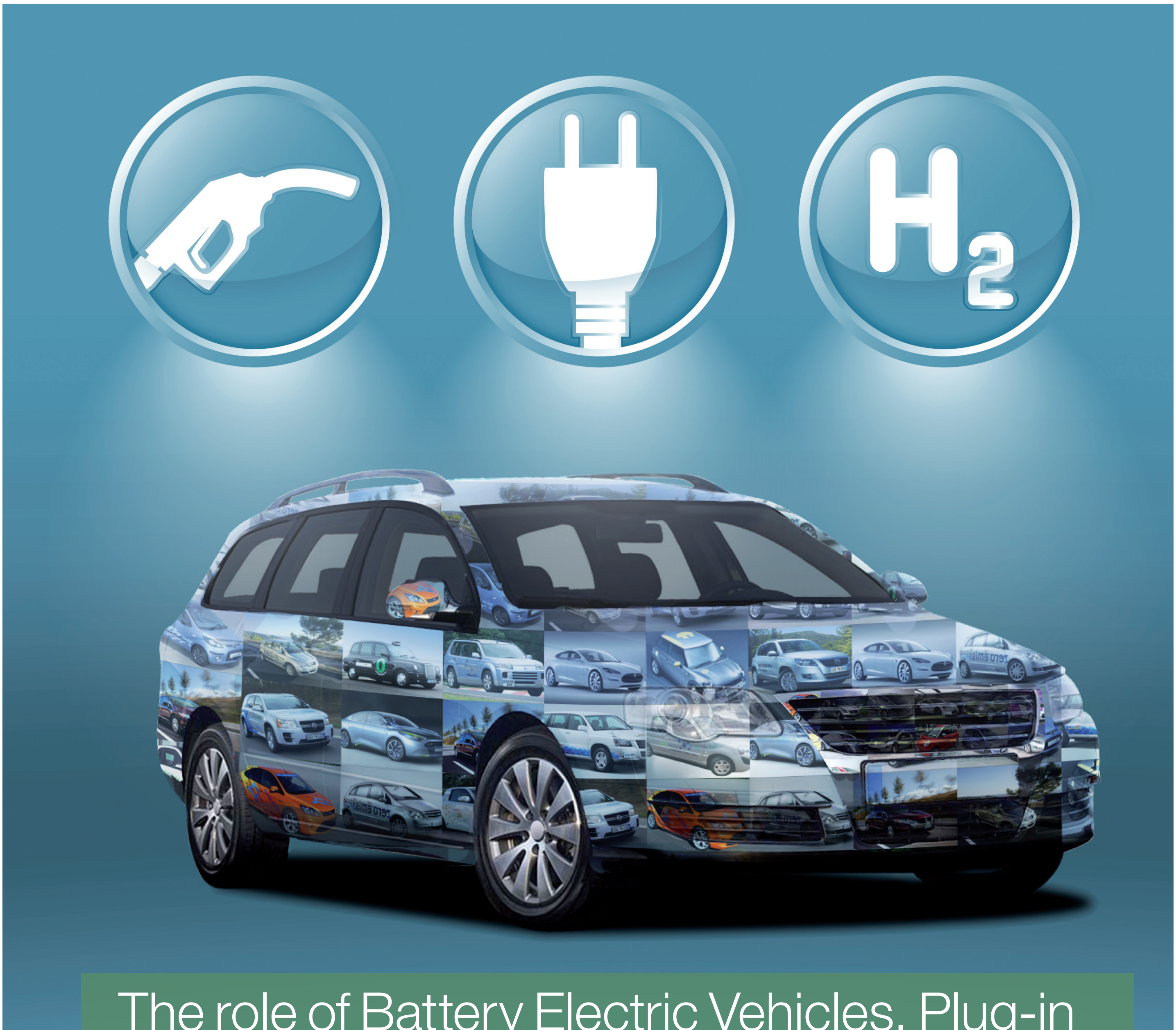
A portfolio of power-trains for Europe: a fact-based analysis



The role of Battery Electric Vehicles, Plug-in Hybrids and Fuel Cell Electric Vehicles

The following companies and organisations participated in this study:

Car manufacturers
BMW AG, Daimler AG, Ford, General Motors LLC, Honda R&D, Hyundai Motor Company, Kia Motors Corporation, Nissan, Renault, Toyota Motor Corporation, Volkswagen

Oil and gas
ENI Refining and Marketing, Galp Energia, OMV Refining and Marketing GmbH, Shell Downstream Services International B.V., Total Raffinage Marketing

Utilities
EnBW Baden-Wuerttemberg AG, Vattenfall

Industrial gas companies
Air Liquide, Air Products, The Linde Group

Equipment car manufacturers
Intelligent Energy Holdings plc, Powertech

Wind
Nordex

Electrolyser companies
ELT Elektrolyse Technik, Hydrogenics, Hydrogen Technologies, Proton Energy Systems

Non-governmental organisations
European Climate Foundation

Governmental organisations
European Fuel Cells and Hydrogen Joint Undertaking, NOW GmbH

McKinsey & Company, the management consultancy, provided analytical support to the study. Any recommendations or positions taken in this report are the responsibility of the authors, not of McKinsey & Company.

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EXECUTIVE SUMMARY

Conventional vehicles alone may not achieve EU CO_2 reduction goal for 2050

In September 2009, both the European Union (EU) and G8[1] leaders agreed that CO_2 emissions must be cut by 80% by 2050 if atmospheric CO_2 is to stabilise at 450 parts per million[2] – and global warming stay below the safe level of 2°C. But 80% decarbonisation overall by 2050 may require 95%[3] decarbonisation of the road transport sector.

With the number of passenger cars set to rise to 273 million[4] in Europe – and to 2.5 billion[5] worldwide – by 2050, this may not be achievable through improvements to the traditional internal combustion engine or alternative fuels: the traditional combustion engine is expected to improve by 30%, so achieving full decarbonisation is not possible through efficiency alone. There is also uncertainty as to whether large amounts of (sustainably produced) biofuels - i.e. more than 50% of demand - will be available for passenger cars, given the potential demand for biofuels[6] from other sectors, such as goods vehicles, aviation, marine, power and heavy industry.

Combined with the increasing scarcity and cost of energy resources, it is therefore vital to develop a range of technologies that will ensure the long-term sustainability of mobility in Europe.

A factual evaluation of BEVs, FCEVs, PHEVs and ICEs based on proprietary industry data

To this end, a group of companies, government organisations and an NGO – the majority with a specific interest in the potential (or the commercialisation) of fuel cell electric vehicles (FCEVs) and hydrogen, but with a product range also spanning battery electric vehicles (BEVs), plug-in hybrids (PHEVs) and conventional vehicles with internal combustion engines (ICEs) including hybridisation – undertook a study on passenger cars in order to assess alternative power-trains most likely to fulfil that need. Medium- or heavy-duty vehicles were not included.

Electric vehicles (BEVs, FCEVs and PHEVs in electric drive) not only have zero tail-pipe emissions[7] while driving – significantly improving local air quality – they can be made close to CO_2-free over time and on a well-to-wheel basis, depending on the primary energy source used. Zero-emission power-trains therefore go hand-in-hand with the decarbonisation of energy supply, with the potential to significantly reduce emissions from central power and hydrogen production by 2050. Electric vehicles have substantially lower pollution from noise, NO_2 and particles.

It was considered particularly important to re-assess the role of FCEVs in the light of recent technological breakthroughs in fuel cell and electric systems that have now increased their efficiency and cost-competitiveness significantly. Given satisfactory testing in a customer environment - with more than 500 cars covering over 15 million kilometres and 90,000 refuellings - the focus has now shifted from demonstration to planning commercial deployment so that FCEVs, like all technologies, may benefit from mass production and the economies of scale.

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1 The Group of Eight industrial powers – Canada, France, Germany, Italy, Japan, Russia, the UK and the United States
2 CO_2-equivalent
3 McKinsey Global GHG Abatement Cost Curve; International Energy Agency World Energy Outlook 2009; US Environmental Protection Agency; European Environment Agency (EEA)
4 Parc Auto Survey 2009, Global Insight 2010; study analysis
5 European Commission, April 2010
6 The study makes the following assumptions: by 2020 biofuels are blended, delivering a 6% well-to-wheel reduction in CO_2 emissions for gasoline- and diesel-engined vehicles, in line with the EU Fuel Quality Directive. By 2050, biofuel blending increases but is limited to 24%, reflecting supply constraints
7 FCEVs emit water vapour only

Over 30 stakeholders therefore came together in order to develop a factual evaluation of the economics, sustainability and performance of BEVs, FCEVs, PHEVs and ICEs across the entire value chain – many with an equal interest in all four power-trains.

It meant providing confidential and proprietary data on an unprecedented scale[8] – including vehicle costs (in this report, purchase price is used to refer to cost plus a standard hypothetical margin, equal for all cars within one segment), operating costs, fuel and infrastructure cost.

In order to ensure a realistic outcome, it was agreed that:

- The study should include a balanced mix of vehicle sizes (or segments) and ensure no bias towards any particular power-train, representing the majority of vehicles on the market[9]
- While it is possible that breakthrough technologies could provide step changes in current pathways to sustainable mobility, the study should only consider vehicle technologies that are proven in R&D today and capable of a) scale-up and commercial deployment and b) meeting the EU's CO_2 reduction goal for 2050
- Average values should be taken, with no "cherry-picking" of the most favourable data
- Input data provided by participating companies would be frozen before results were shared.

A balanced scenario for the electrification of passenger cars in the EU by 2050

A combined forecasting and backcasting approach was then used to calculate the results: from 2010 to 2020, global cost and performance data were forecasted, based on proprietary industry data; after 2020, on projected learning rates (see Annex, Exhibit 42, page 54).

In order to test the sensitivity of these data to a broad range of market outcomes, three European "worlds" for 2050 were defined, assuming various power-train penetrations in 2050:

1. A world skewed towards ICE (5% FCEVs, 10% BEVs, 25% PHEVs, 60% ICEs)
2. A world skewed towards electric power-trains (25% FCEVs, 35% BEVs, 35% PHEVs, 5% ICEs)
3. A world skewed towards FCEVs (50% FCEVs, 25% BEVs, 20% PHEVs, 5% ICEs).

These three "worlds" were then backcasted to 2010, resulting in a development pathway for each power-train. As the impact of the different "worlds" on FCEV costs was found not to be significant (see page 18), this report focuses on results for the second "world" as having a balanced split between the four power-trains (25% FCEVs, 35% BEVs, 35% PHEVs and 5% ICEs).

8 Over 10,000 data points were collected for the study
9 No assumptions have been made on a potential shift in the composition of the car fleet from larger to smaller cars. An average ~30% fuel efficiency gain was included for the entire ICE fleet

Assumptions are robust to significant variations

To test the robustness of results, all assumptions in the study's vehicle and supply models were varied to identify possible "tipping points". However, this showed that the conclusions were robust to significant variations in learning rates for the power-trains and the cost of fossil fuels (see page 24).

The power supply pathway underlying this report is based on the European Climate Foundation's "Roadmap 2050", which was developed in corporation with the industry and describes a pathway to decarbonise the EU power mix by 2050. In 2020, the expected share of renewable (RES) production capacity is approximately 34%. This is the minimum needed to meet the 20% EU renewable energy target, as there is limited RES opportunity outside of the power sector.

For the following results, a conventional hydrogen production mix is assumed to 2020, utilising existing assets – industrially produced hydrogen and centralised steam methane reforming (SMR) – with a growing proportion of distributed units (water electrolysis and SMR). After 2020, a balanced and economically driven scenario is assumed, including CO_2 Capture and Storage (CCS), water electrolysis (increasingly using renewable energy) and avoiding over-dependence on any single primary energy source.

An alternative production mix was also examined (see Exhibit 26, page 38), representing 100% electrolysis, with 80% renewable energy by 2050, which increases the total cost of ownership (TCO) of FCEVs by 5% by 2030 and 3.5% by 2050. However, both production scenarios achieve CO_2-free hydrogen by 2050.

The value of electric vehicles on balancing an (increasingly intermittent) power grid can be significant and could amount to several billions of euros (ref. "Roadmap 2050"). This applies to BEVs (charging when power supply is available) as well as hydrogen cars (using stored hydrogen to produce power when supply is short).

SUMMARY OF RESULTS

1. BEVs, PHEVs and FCEVs have the potential to significantly reduce CO_2 and local emissions

Electric vehicles (BEVs, FCEVs and PHEVs in electric drive) can be fuelled by a wide variety of primary energy sources – reducing oil dependency and enhancing security of energy supply. Well-to-wheel efficiency analysis also shows that electric vehicles are more energy-efficient than ICEs over a broader range of primary energy sources.

Owing to limits in battery capacity and driving range[10] (currently 100-200 km for a medium-sized car[11]) and a current recharging time of several hours, ***BEVs*** are ideally suited to smaller cars and shorter trips, i.e. urban driving (including new transportation models such as car sharing).

With a driving range and performance comparable to ICEs, ***FCEVs*** are the lowest carbon solution for medium/larger cars and longer trips. These car segments account for 50% of all cars and 75% of CO_2 emissions, hence replacing one ICE with one FCEV achieves a relatively high CO_2 reduction.

10 The range chosen in the study for BEVs and PHEVs reflects the car manufacturers' current view on the best compromise between range, cost, and load bearing capacity for the vehicle
11 For C/D segment cars this will increase to 150-250 km in the medium term

With a smaller battery capacity than BEVs, ***PHEVs*** have an electric driving range of 40-60 km. Combined with the additional blending of biofuels, they could show emission reductions for longer trips.

ICEs have the potential to reduce their CO_2 footprint significantly through an average 30% improvement in energy efficiency by 2020 and the additional blending of biofuels. After 2020, however, further engine efficiency improvements are limited and relatively costly, while the amount of biofuels that will be available may be limited.

BEVs, PHEVs and FCEVs have significant potential to reduce CO_2 and local emissions, assuming CO_2 reduction is performed at the production site. They play a complementary role, with BEVs ideally suited to smaller cars and shorter trips and FCEVs to medium/larger cars and longer trips. PHEVs can reduce CO_2 considerably compared to ICEs on short trips or using biofuels, depending on availability. The energy and CO_2 efficiency of ICEs is expected to improve by 30%.

Medium/larger cars with above-average driving distance account for 50% of all cars, and 75% of CO_2 emissions. FCEVs are therefore an effective low-carbon solution for a large proportion of the car fleet. Beyond 2030, they have a TCO advantage over BEVs and PHEVs in the largest car segments (see below).

2. *After 2025, the total cost of ownership (TCO) of all the power-trains converges*

In the study, the economic comparison between power-trains is based on the total cost of ownership (TCO), as it describes the costs associated over their entire lifetime (see page 18). In order to ensure a like-for-like comparison, taxes are not included unless specifically stated.

BEVs and FCEVs are expected to have a higher purchase price than ICEs (battery and fuel cell related) and a lower fuel cost (due to greater efficiency and no use of oil) and a lower maintenance cost (fewer rotating parts).

The cost of fuel cell systems is expected to decrease by 90% and component costs for BEVs by 80% by 2020, due to economies of scale and incremental improvements in technology. Around 30% of technology improvements in BEVs and PHEVs also apply to FCEVs and vice versa. This assumes that FCEVs and BEVs will be mass produced, with infrastructure a key prerequisite to be in place. The cost of hydrogen also reduces by 70% by 2025 due to higher utilisation of the refuelling infrastructure and economies of scale.

PHEVs are more economic than BEVs and FCEVs in the short term. The gap gradually closes and by 2030 PHEVs are cost-competitive with BEVs for smaller cars, with both BEVs and FCEVs for medium cars and less competitive than FCEVs for larger cars.

While the fuel economy of ICEs is expected to improve by an average of 30% by 2020, costs also increase due to full hybridisation and further measures such as the use of lighter weight materials.

The TCOs of all four power-trains is expected to converge after 2025 – or earlier, with tax exemptions and/or incentives during the ramp-up phase.

For larger cars, the TCO of FCEVs is expected to be lower than PHEVs and BEVs as of 2030. By 2050, it is also (significantly) lower than the ICE. For medium-sized cars, the TCOs for all technologies converge by 2050. BEVs have a (small) TCO advantage over FCEVs in the smaller car segments.

PHEVs are more economic than BEVs and FCEVs in the short term. All electric vehicles are viable alternatives to ICEs by 2025, with BEVs suited to smaller cars and shorter trips, FCEVs for medium/larger cars and longer trips. With tax incentives, BEVs and FCEVs could be cost-competitive with ICEs as early as 2020.

3. A portfolio of power-trains can meet the needs of consumers and the environment

BEVs have a shorter range than FCEVs, PHEVs and ICEs: an average, medium-sized BEV with maximum battery loading cannot drive far beyond 150 km at 120 km/hour on the highway, if real driving conditions are assumed (and taking expected improvements until 2020 into account) Charging times are also significantly longer: 6-8 hours using normal charging equipment. Fast charging may become widespread, but the impact on battery performance degradation over time and power grid stability is unclear. Moreover, it takes 15-30 minutes to (partially) recharge the battery. Battery swapping reduces refuelling time; it is expected to be feasible if used once every two months or less and battery standards are adopted by a majority of car manufacturers. BEVs are therefore ideally suited to smaller cars and urban driving, potentially achieving ~80% CO_2 reduction by 2030 compared to today.

FCEVs have a driving performance (similar acceleration), range (around 600 km) and refuelling time (< 5 minutes) comparable to ICEs. They are therefore a feasible low-carbon substitute for ICEs for medium/larger cars and longer trips, potentially achieving 80% CO_2 reduction by 2030 compared to today.

PHEVs have a similar range and performance to ICEs, but electric driving only applies to shorter distances, while the amount of biofuels available for longer trips is uncertain. They represent an attractive solution, reducing CO_2 considerably compared to ICEs.

Over the next 40 years, no single power-train satisfies all key criteria for economics, performance and the environment. The world is therefore likely to move from a single power-train (ICE) to a portfolio of power-trains in which BEVs and FCEVs play a complementary role: BEVs are ideally suited to smaller cars and shorter trips; FCEVs to medium/larger cars and longer trips; with PHEVs an attractive solution for short trips or where sustainably produced biofuels are available.

4. Costs for a hydrogen infrastructure are approximately 5% of the overall cost of FCEVs (€1,000-2,000 per car)

For consumers who prefer larger cars and drive longer distances, FCEVs therefore have clear benefits in a CO_2-constrained world. This segment represents around 50% of cars driven and can therefore justify a dedicated hydrogen infrastructure. The value of the FCEV over alternative power-trains in terms of TCO and emissions (including the cost of the hydrogen infrastructure) is positive beyond 2030. The economic gap prior to 2030 is almost completely determined by the higher purchase price, not by the cost of the hydrogen infrastructure. It can therefore be assumed that if this consumer segment prefers the FCEV, the cost of the infrastructure (5% of the TCO) will not be prohibitive to its roll-out. Having said that, an orchestrated investment plan is required to build up the first critical mass of hydrogen supply.

In order to develop a portfolio of power-trains, several supply infrastructure systems are required – not only for gasoline and diesel, but potentially new infrastructures for CNG, LPG, 100% biofuels, electricity and hydrogen. Early commercial deployment of BEVs and PHEVs is already happening in several European countries: many car manufacturers have announced the introduction of new commercial models between 2010 and 2014. This report therefore focuses on the commercial deployment of FCEVs, which still needs to be addressed.

One could argue that it is inefficient to build an additional vehicle refuelling infrastructure on top of existing infrastructures. However, the additional costs of a hydrogen infrastructure are relatively low compared to the total costs of FCEVs and comparable to other fuels and technologies, such as a charging infrastructure for BEVs and PHEVs. Costs for a hydrogen distribution and retail infrastructure are around 5% of the overall cost of FCEVs – the vast majority lies in the purchase price. The attractiveness of the business case for FCEVs is therefore hardly affected by the additional costs required for distribution and retail. In other words, if FCEVs make commercial sense – as demonstrated by this study – building a dedicated hydrogen infrastructure can be justified.

In the first decade of a typical roll-out scenario, supply infrastructure costs per car – especially those for a retail infrastructure – are initially higher, due to lower utilisation. Nevertheless, sufficient network coverage must be available for consumers and initial investments required could amount to around €3 billion (covering hydrogen production, distribution and retail) for a region such as Germany. Although a single company would struggle to absorb the risk of such an investment, this is not the case at a societal level. This is confirmed by countries which have built up alternative infrastructures, such as LPG and CNG.

The cost per vehicle for rolling out a hydrogen infrastructure compares to rolling out a charging infrastructure for BEVs or PHEVs. The costs for hydrogen retail and distribution are estimated at €1,000-2,000 per vehicle (over its lifetime), including distribution from the production site to the retail station, as well as operational and capital costs for the retail station itself. Building an infrastructure for 25% market share of FCEVs requires infrastructure investments of around €3 billion in the first decade and €2-3 billion per year thereafter. Annual infrastructure investments in oil and gas, telecommunications and road infrastructure each amount to €50-€60 billon.[12] Additional investments required to decarbonise the power sector amount to €20-30 billion per year.[13]

Current costs for an electric charging infrastructure range from €1,500 - €2,500 per vehicle. The higher end of the range assumes 50% home charging (investment of €200 - €400 per charging station) and 50% public charging at €5,000 for a charging station that serves two cars (€10,000 in the first years). Potential additional investment in the power distribution networks are not included, but could be material, depending on the local situation. In contrast, once the territory is covered, no further investment is needed in hydrogen infrastructure – regardless of the number of cars – due to the fast refuelling time. As the number of FCEVs increase, it also benefits from the economies of scale.

12 Global Insight
13 http://www.roadmap2050.eu/attachments/files/Volume1_fullreport_PressPack.pdf

Under the key assumptions of the study (i.e. zero CO_2 from power by 2050[14]), Europe must achieve a significant penetration of electric cars by 2050, if it is to achieve its CO_2 reduction goal. Early commercial deployment of BEVs has already started in several European countries, but infrastructure for FCEVs remains to be addressed.

Over the course of the next decades, costs for a hydrogen distribution and retail infrastructure are 5% of the overall cost of FCEVs (€1,000-2,000 per car) and comparable to rolling out a charging infrastructure for BEVs and PHEVs (excluding potential upgrades in power distribution networks). The attractiveness of the business case for FCEVs is therefore hardly affected by the additional costs required for distribution and retail: if FCEVs make commercial sense – as demonstrated by this study – building a dedicated hydrogen infrastructure can be justified.

5. The deployment of FCEVs will incur a cost to society in the early years

The benefits of lower CO_2 emissions, lower local emissions (NO_2, particles), diversification of primary energy sources and the transition to renewable energy all come at an initial cost. These will ultimately marginalise with the reduction in battery and fuel cell costs, economies of scale and potentially increasing costs for fossil fuels and ICE specifications.

A roll-out scenario that assumes 100,000 FCEVs in 2015, 1 million in 2020 and a 25% share of the total EU passenger car market in 2050 results in a cumulative economic gap of approximately €25 billion by 2020 – mainly due to the cost of the fuel cell system in the next decade, but also including around €3 billion for a hydrogen supply infrastructure. The CO_2 abatement cost is expected to range between €150 and € 200 per tonne in 2030 and becomes negative for larger cars after 2030.

A hydrogen supply infrastructure for around 1 million FCEVs by 2020 requires an investment of €3 billion (production, distribution, retail), of which €1 billion relates to retail infrastructure – concentrated in high-density areas (large cities, highways) and building on existing infrastructure. If only one energy company were to invest in hydrogen retail infrastructure, it faces a first-mover disadvantage due to the initially low utilisation by a small number of FCEVs and the risk of technology delivery failure or delay. In the latter case it would result in a potential write-off in the order of hundreds of millions per annum. The initial investment risk would be somewhat reduced if further companies also invest and even further if the roll-out is supported by adequate policy measures and risk underwriting all one word by governments.

Hydrogen manufacturers have an incentive – as soon as the economics work – to race to beat their rivals. While financial incentives are required to persuade consumers to appreciate FCEVs, there is nothing to hold the hydrogen manufacturers back – as long as the retail infrastructure is in place. Infrastructure providers, on the other hand, bear a first-mover risk, making a heavy upfront outlay to build a retail station network that will not be fully utilised for some years; the unit cost reduces over time simply because the fixed capital expenditure is used by an increasing number of FCEVs.

The cumulative economic gap of around €25 billion for FCEVs up to 2020 is calculated on a global cumulative FCEV production and is mainly due to a higher purchase price. If this is also only met by a few car manufacturers, they will each need to finance around €1 billion per annum. Bridging this gap could be facilitated by adequate government actions and global co-operation. After 2030, it can be reasonably assumed that the majority of the consumers will be financially driven, making their choice of car in response to an established tax and legislative regime.

14 The power supply pathway underlying this report is based on the European Climate Foundation "Roadmap 2050", which was developed in cooperation with the industry and describes a pathway to decarbonise the EU's power mix by 2050 - See page 24

Provided these are stable and clear, car manufacturers, hydrogen manufacturers and infrastructure providers should all be able to make investments on the basis of well-understood risks and projected returns. A global roll-out would further reduce the economic gap for Europe.

A strong case will be required to persuade governments as to the level of explicit subsidy needed. In subsequent steps, it will therefore be important to make proposals that show how industry is taking responsibility for all the risks that they can reasonably analyse, control and mitigate. Discussions with Member State and EU governments are likely to focus on sharing the costs and risks between public and private sectors.

The emerging FCEV market (2010-20) requires close value chain synchronisation and external stimulus in order to overcome the first-mover risk of building hydrogen retail infrastructure. While the initial investment is relatively low, the risk is high and therefore greatly reduced if many companies invest, co-ordinated by governments and supported by dedicated legislation and funding. With the market established, subsequent investment (2020-30) will present a significantly reduced risk and by 2030 any potentially remaining economic gap is expected to be directly passed on to the consumer.

SUMMARY OF NEXT STEPS

Investment cycles in energy infrastructure are long and BEV and FCEV infrastructure and scale-up should be initiated as soon as possible in order to develop these technologies as material transportation options beyond 2020. In the short term, CO_2 emissions will therefore have to be reduced by more efficient ICEs and PHEVs – combined with biofuels – while taking two concrete actions:

1. Study EU market launch plan for FCEVs and hydrogen infrastructure

Car manufacturers have signalled that they are ready to mass-produce FCEVs, as demonstrated by the Letter of Understanding in 2009 (see page 13). This study shows that FCEVs are technologically ready and can be produced at much lower cost for an early commercial market over the next five years. The next logical step is therefore to develop a comprehensive and co-ordinated EU market launch plan study for the deployment of FCEVs and hydrogen infrastructure in Europe (see pages 52-53). This consists of two phases:

- An in-depth business case and implementation plan for a single Member State (i.e. Germany) in order to de-risk the commercialisation of technology and test the supply chain for the rest of Europe, starting in 2015. At the same time, a series of subsidised FCEV demonstration projects in other Member States should start to gain experience with the technology.
- A potential staged roll-out plan – first, a market introduction in Member States that have developed experience through the demonstration projects, followed by other Member States.

The implementation plan should be fit for investment by companies and the public sector. This includes addressing the risks associated with the plan, how hydrogen will be decarbonised and its impact on future CO_2 emissions from the transport sector.

The dynamics of setting up a hydrogen retail infrastructure are such that there is a limited opportunity to gain "early mover" advantage, so the first player will not be able to compensate for any losses. Indeed, they will develop the market for all other infrastructure providers who will then reap the benefits at a later stage. However, if several hydrogen retail infrastructure providers invest – or a market-based mechanism is developed to spread the risk between different infrastructure providers – none will gain a 'free ride'. The market launch plan must therefore go hand-in-hand with appropriate government policies.

After the technology has been de-risked and achieved cost reductions in one Member State – and at the same time gained more experience with a series of demonstration projects in other Member States – a staged roll-out plan for subsequent introductions in other Member States has then to be studied. This will address the supply constraints of car manufacturers and hydrogen infrastructure providers; the primary energy resources of different Member States; and CO_2 reduction goals for the transport sector as a whole.

2. Co-ordinate roll-out of BEVs/PHEVs and battery-charging infrastructure

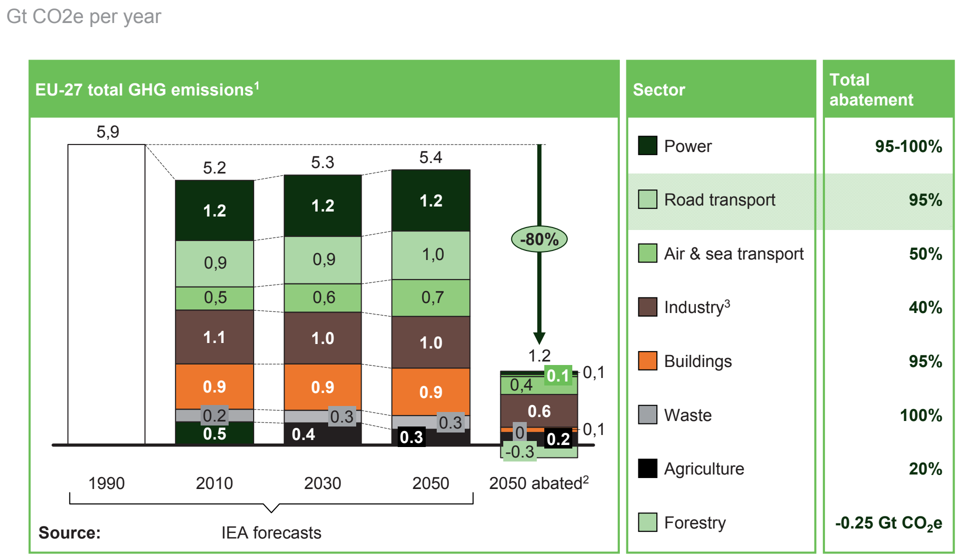
A similar action would be helpful to support the roll-out of BEVs and PHEVs in the EU. Here, too, the risk of market failure exists. Although the investments per electric recharging point are low, the financial risk for infrastructure providers remains. As with hydrogen infrastructure, upfront investment for public charging will be necessary in order to give customers appropriate access to infrastructure from the start.

In order to achieve a sound market introduction, the technology also needs to be commercially de-risked and programmes for BEVs currently exist in several European countries and at EU level, addressing issues such as technology, market introduction, funding schemes and standardisation etc. A coherent approach to these activities would help to optimise development and support early market readiness.

INTRODUCTION

EU CO_2 reduction goal for 2050 requires 95% decarbonisation of road transport

In 2009, both the European Union (EU) and G8 leaders agreed that CO_2 emissions must be cut by 80% by 2050 if atmospheric CO_2 is to stabilise at 450 parts per million[15] – and global warming stay below the safe level of 2°C. But 80% decarbonisation *overall* by 2050 requires 95%[16] decarbonisation of the road transport sector (Exhibit 1).



1 Large efficiency improvements are already included in the baseline based on the International Energy Agency, World Energy Outlook 2009, especially for industry
2 Abatement estimates within sector based on Global GHG Cost Curve
3 CCS applied to 50% of large industry (cement, chemistry, iron and steel, petroleum and gas, not applied to other industries)

SOURCE: www.roadmap2050.eu

Exhibit 1: In order to achieve EU CO_2 reduction goal of 80% by 2050, road transport must achieve 95% decarbonisation

Decarbonisation may be achieved through efficiency, biofuels and electric power-trains (including hydrogen). With the number of passenger cars set to rise to 273 million[17] in Europe – and to 2.5 billion[18] worldwide – by 2050, full decarbonisation may not be achievable through improvements in the traditional internal combustion engine or alternative fuels alone. A comprehensive analysis would be helpful to determine the true global potential of biofuels and for which sectors and regions they may be most effectively used.

Combined with the increasing scarcity and cost of energy resources, it is therefore vital to develop a *range* of technologies to ensure the long-term sustainability of mobility in Europe, with "ultra low-carbon electric power-trains and hydrogen fuel cells the most promising options",[19] according to the European Commission. This study was therefore undertaken in order to compare the performance and costs of alternative power-trains for passenger cars – fuel cell electric vehicles (FCEVs), battery electric vehicles (BEVs) and plug-in hybrids (PHEVs) – with those of conventional vehicles with internal combustion engines (known as ICEs). This included every step of the value chain, or "well-to-wheel".

15 CO_2-equivalent
16 McKinsey Global GHG Abatement Cost Curve; International Energy Agency World Energy Outlook 2009; US Environmental Protection Agency; European Environment Agency (EEA)
17 Parc Auto Survey 2009, Global Insight 2010; study analysis
18 European Commission, April 2010
19 COM(2010)186: A European strategy on clean and energy efficient vehicles, published April 2010

Electric vehicles (BEVs, FCEVs and PHEVs) are necessary to achieve EU CO_2 reduction goal

The benefits of electric vehicles (BEVs, FCEVs and PHEVs in electric drive) over ICEs are:

- Electric vehicles have zero emissions while driving – significantly improving local air quality – and they can be made close to CO_2-free, depending on the primary energy source used[20]. Zero-emission power-trains therefore go hand-in-hand with the decarbonisation of energy supply, with the potential to eradicate emissions from central hydrogen production completely by 2050.

- Electric vehicles can be fuelled by a wide variety of primary energy sources – including gas, coal, oil, biomass, wind, solar and nuclear – reducing oil dependency and enhancing energy security (e.g. through stabilising an increasingly volatile power grid).

- While ICEs have the potential to reduce their CO_2 footprint considerably through improved energy efficiency, this is insufficient to meet the EU's CO_2 reduction goal for 2050. Full decarbonisation through biofuels depends on their availability.

Technologically ready, FCEVs are now focused on commercial deployment

30 stakeholders came together in order to develop a factual evaluation of the four power-trains and their role in decarbonising road transport. It was also considered particularly important to re-assess the role of FCEVs in the light of technological breakthroughs in fuel cell and electric systems that have now increased their efficiency and cost-competitiveness significantly (Exhibit 2). Previous studies[21] predicted that all technological challenges would be addressed simultaneously within a few years. In reality this has happened sequentially, with a steady but significant improvement in all key areas:

- With the implementation of 700 bar storage technology, hydrogen storage capacity has increased – without sacrificing volume – resulting in driving ranges that approach gasoline ICEs. In general, safety concerns have been adequately addressed.

- Cold start is down to -25°C, or even lower, due to the application of purging strategies at shut-down and new materials (e.g. metallic bipolar plates) which have optimised heat management in the stacks.

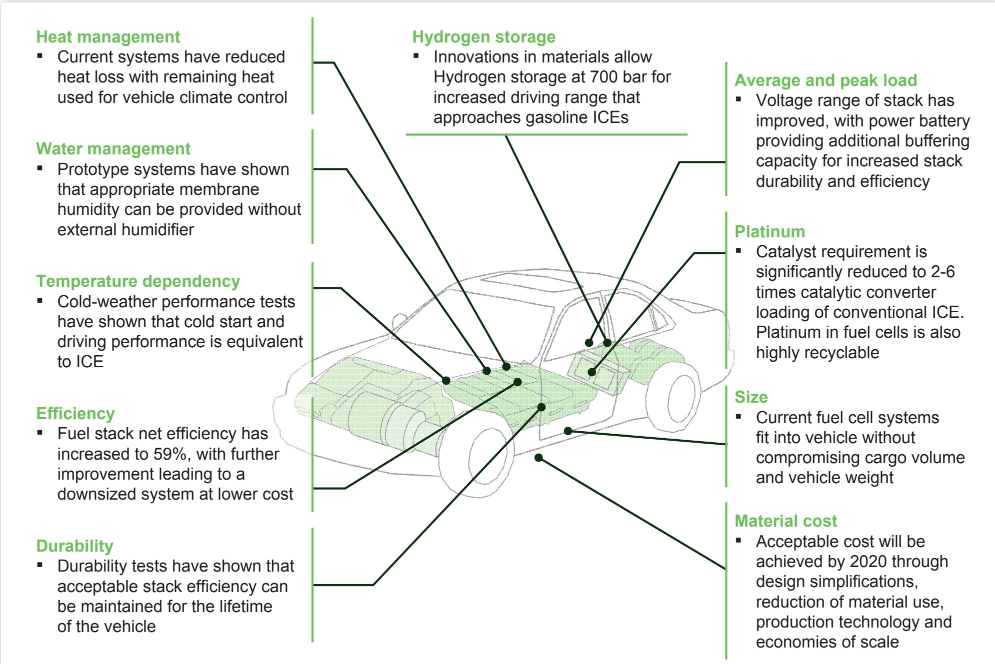
- With better understanding of the mechanisms affecting durability and the implementation of counter measures, such as enhanced materials (e.g. functionalised or nanostructured catalyst supports) and cell voltage management, durability (hence cost) has significantly improved.

- With the development of CCS, an additional low-cost, low CO_2 hydrogen production route would be made available.

Common standards for hydrogen and FCEV equipment have also been agreed, further reducing their complexity and costs: standard connections, safety limits and performance requirements for hydrogen refuelling have been established by several SAE[22] and ISO[22] standards, while the electric system is fully compliant with SAE and ISO safety standards.

20 This is commonly illustrated by well-to-wheel emissions, integrating the CO_2 footprint of fuel production with its transformation by the power-train (see Annex, Exhibit 43, page 54)
21 See Annex, Exhibit 44, page 55
22 SAE International (formerly Society of Automotive Engineers), the recognised authority on standards for commercial vehicles, together with ISO (International Organization for Standardization)

With more than 500 passenger cars – both large and small – covering over 15 million kilometres and undergoing 90,000 refuellings,[23] FCEVs are therefore now considered to have been comprehensively tested in a customer environment. The result: the focus has now shifted from demonstration to commercial deployment so that FCEVs, like all technologies, may benefit from mass production and the economies of scale.



SOURCE: Study analysis

Exhibit 2: With all technological hurdles resolved, the focus for FCEVs has now shifted from demonstration to commercial deployment

This was clearly signalled in a Letter of Understanding issued by leading car manufacturers[24] in September 2009, in which they stated their goal to commercialise FCEVs by 2015, with hundreds of thousands of vehicles being rolled out worldwide shortly thereafter – assuming sufficient hydrogen refuelling infrastructure is in place. This was a catalyst for the in-depth evaluation of the four power-train technologies undertaken in this study.

A public-private partnership called H2 Mobility was also established, which is now developing a business plan for building a hydrogen refuelling infrastructure in a single Member State (i.e. Germany) – complemented by a series of demonstration projects in other Member States – as essential first steps towards a full EU roll-out (see pages 52-53).

The window of opportunity is short. If FCEVs are to achieve economies of scale within the time-frame necessary to meet EU CO_2 reduction goals, action must be taken as a matter of urgency. There is also a danger that Europe will lose its technological leadership as other international markets gain ground. The European Commission has confirmed that “the global trend towards sustainable transport shows that the European automotive industry can only remain competitive by leading in green technologies”.[25]

23 Study data
24 Daimler AG, Ford Motor Company, General Motors Corporation/Opel, Honda Motor Co., Ltd., Hyundai Motor Company, Kia Motors Corporation, the alliance Renault SA and Nissan Motor Co., Ltd. and Toyota Motor Corporation
25 European Commission, April 2010

The reality is that no transportation model can be changed overnight – it requires preparation and ramp-up of production. A "knee-jerk" response to external factors, such as a rise in oil prices, supply constraints and the disastrous consequences of global warming will be too little, too late.

All conclusions are based on proprietary industry data

This study represents the most accurate to date,[26] as conclusions are based not on informed speculation, but on confidential, granular and proprietary data, provided by key industry players. This has allowed a true comparison of the power-trains, with all underlying assumptions clearly stated (see Methodology section, pages 15-25).

In order to present an integrated perspective across the entire value chain, the study addresses five key questions:

1. On a well-to-wheel basis, how do BEVs, FCEVs and PHEVs compare to ICEs over the medium-to-long term on emissions, performance and costs?

2. What are the key drivers by car size, miles driven, supply technology and over time?

3. What are the potential market segments?

4. How do fuels, electricity and hydrogen production, distribution and retail pathways compare?

5. What is required at a high level to deploy electric vehicles (BEVs, FCEVs, PHEVs) at scale so that they can benefit society by significantly reducing CO_2 emissions, enhancing energy security and improving air quality – without compromising its current expectations for mobility?

The positive effect of electric vehicles on public health

The benefits of electric vehicles (BEVs, FCEVs and PHEVs in electric mode) go beyond the decarbonisation of road transport and energy security to address the key issue of air pollution in large, congested cities: the exhaust from ICEs not only emits CO_2, but also local pollutants[27] such as carbon monoxide, hydrocarbons and nitrous oxides. Diesel vehicles also emit particles referred to as particulate emissions or "soots". Although these emissions are mitigated by catalytic converters, all pollutants that cannot be processed are released into the atmosphere, degrading air quality and reducing the ability of large cities to meet air quality targets.

Electric vehicles, on the other hand, release zero emissions in their "tank-to-wheel" process, with emissions limited to the "well-to-tank" process – far removed from the vehicle itself. Emissions also depend on the primary energy source used and can be potentially reduced to zero. Finally, unlike ICEs, electric vehicles are virtually silent, also reducing noise pollution significantly.

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26 Other studies taken into consideration include "Hydrogen Highway": www.hydrogenhighway.com; Roads2HyCom project www.roads2hy.com; "On the road in 2035", published 2008; "The Hydrogen Economy", published 2009; "Hydrogen Production Roadmap: Technology Pathways to the Future", published 2010

27 This would also apply even if using 100% biofuels

METHODOLOGY

This study provides a factual comparison of four different power-trains (Exhibit 3) – BEVs, FCEVs, PHEVs and ICEs – on economics, sustainability and performance across the entire value chain[1] between now and 2050, based on confidential and proprietary industry data. This was possible due to the central role of an independent consultancy and a strict division between the consultancy's "Clean Team" responsible for input gathering and the "Analysis Team" responsible for output generation.

Data was submitted, challenged and, where necessary, benchmarked and validated for every step of the value chain – including purchase price, operating costs, fuel, as well as infrastructure. While it is possible that breakthrough technologies could provide step changes in current pathways to sustainable mobility, the study only considered vehicle technologies that are *proven* in R&D today – and in many cases demonstrated – and therefore capable of a) scale-up and commercial deployment and b) meeting the EU's CO_2 reduction goal for 2050.

To ensure a realistic outcome, it was agreed that all conclusions should be based on average values derived from the range provided, with no "cherry-picking" of the most favourable data.

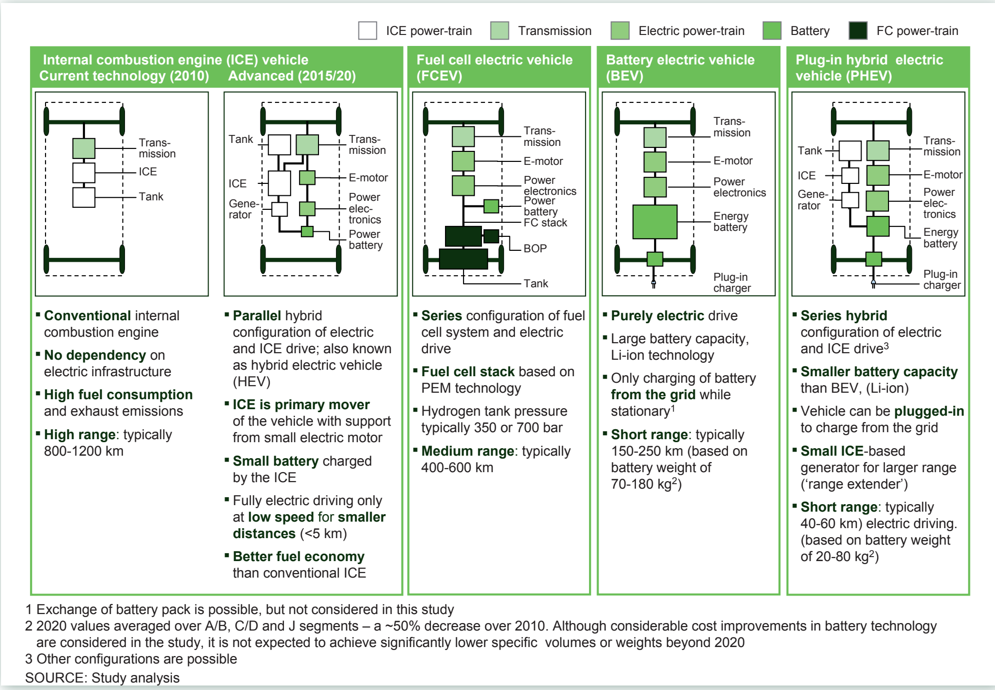


Exhibit 3: The study focused on a portfolio of power-trains: BEVs, FCEVs, PHEVs and ICEs, taking into account significant advances in ICE technology between now and 2020

In order to ensure no bias towards any particular power-train, the study included a balanced mix of car sizes (known as "segments"), representing the majority of vehicles currently on the market and with high data availability among study participants (Exhibit 4). Average values for fleets, as opposed to specific cars, were taken.

1 Commonly referred to as "well-to-wheel"

Defined reference segments

Vehicle segment	Typical characteristics	Example	EU vehicle production 2008, %
A – City	▪ <3,800 mm ▪ 3 door hatchback ▪ €8k-15k	▪ Hyundai i10 ▪ Smart	6
B – Super-mini	▪ 3,700-4,200 mm ▪ 5 door hatchback ▪ €10k-20k	▪ Toyota Yaris ▪ Mercedes A	23
C – Medium	▪ 4,000-4,500 mm ▪ 5 door hatchback ▪ €15k - 25k	▪ Honda Civic ▪ Ford Focus	23
D – Upper medium	▪ 4,400-5,000 mm ▪ 4 door sedan ▪ €25k-45k	▪ Renault Laguna ▪ Honda FCX ▪ Mercedes C	13
E – Large	▪ 4,700-5,100 mm ▪ 4 door sedan ▪ €40k-120k	▪ Mercedes E/S ▪ Lexus GS	5
F – Luxury	▪ 2/4 door sedan ▪ > €100k	▪ Maybach	<1

Vehicle segment	Typical characteristics	Example	EU vehicle production 2008, %
S – Sport	▪ 2 door coupe ▪ >€30k	▪ Mercedes CLK ▪ Nissan 370Z	<1
M1 – Small MPV	▪ 3,900-4,400 mm ▪ 5 door MPV ▪ €10k - 30k	▪ Mercedes B ▪ Renault Scenic	12
M2 – Large MPV	▪ >4,400 mm ▪ 5 door MPV ▪ €25k-50k	▪ Mercedes R	9
J1 – Small SUV	▪ 3,700-4,000 mm ▪ 5 door 4x4 ▪ €10k-30k	▪ Hyundai Tucson ▪ Toyota RAV4	5
J2 – Large SUV	▪ 4,000-5,100 mm ▪ 5 door 4x4 ▪ €25k-75k	▪ Toyota Highlander ▪ Ford Explorer	3

SOURCE: HIS Global Insight 2010; study participants

Exhibit 4: The study focuses on the vehicle segments that represent the majority of the EU car fleet (75%) – selected small (A/B), medium (C/D) and larger (SUV) cars

A balanced scenario for the electrification of passenger cars in the EU by 2050

In order to test the sensitivity of the economics to a broad range of market outcomes, the study envisioned three "worlds" with varying degrees of BEV, FCEV and PHEV penetration (Exhibit 5). These cover:

a. The full spectrum of expected futures for hydrogen, electricity and primary energy sources

b. Market shares and segment penetration rates for the different power-trains

c. Coverage area and availability of hydrogen.

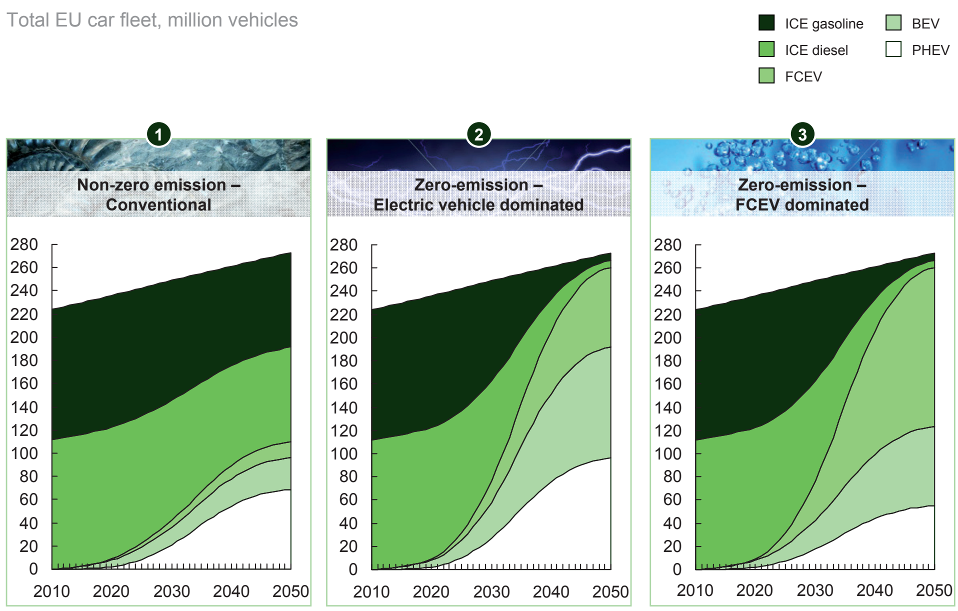
All "worlds" assume 273 million passenger cars in the EU in 2050, with a hydrogen retail network infrastructure starting in the most densely populated areas (i.e. large cities) and growing to meet the needs of expanding vehicle clusters, leading to mass market roll-out. The car fleet is built up by introducing BEVs, FCEVs and PHEVs where they are most competitive with ICEs (Exhibit 6).

	1 Non-zero emission – Conventional	2 Zero-emission – Electric vehicle dominated	3 Zero-emission – FCEV dominated
2010-2020	▪ For all worlds, coverage grows to include 10% of Europe's most metropolitan area and 20% of European motorways (>50% of cars)		
FCEV penetration 2050 Percent	FCEV 5%, BEV 10%, PHEV 25%, ICE 60% ▪ FCEV with moderate adoption after 2020 ▪ FCEVs sold in C+ segments, but with limited market shares	FCEV 25%, BEV 35%, PHEV 35%, ICE 5% ▪ BEVs achieve a higher penetration than FCEVs ▪ FCEVs mainly sold in C+ segments with high share in J, M, D	FCEV 50%, BEV 25%, PHEV 20%, ICE 5% ▪ FC is the dominant power-train technology by 2050 so network coverage develops fast ▪ FCEVs sold in all segments with major shares in large segments
Coverage end state 2050	▪ FCEV coverage area increases only to ~1/4 of the EU29 area[1], (75 % cars)	▪ FCEVs are used in all countries with some rural exceptions ▪ Coverage is ~3/4 of the EU29 area[1], (97% cars)	▪ All over Europe, FCEVs are sold and driven. Coverage is equal to the **entire** EU29 area[1] (9 km average distance between stations)
Size of coverage area million km^2	▪ 2020: 0.36 ▪ 2030: 0.60 ▪ 2040: 0.84 ▪ 2050: 1.08	▪ 2020: 0.36 ▪ 2030: 1.3 ▪ 2040: 2.3 ▪ 2050: 3.3	▪ 2020: 0.36 ▪ 2030: 1.7 ▪ 2040: 3.0 ▪ 2050: 4.3

1 EU29 defined to include EU27 + Norway and Switzerland

SOURCE: Study analysis

Exhibit 5: Assumptions for the three "worlds", each showing a different penetration scenario for BEVs, FCEVs, PHEVs and ICEs in the EU in 2050



SOURCE: Study analysis

Exhibit 6: For all three "worlds", the car fleet is built up from 2010 to 2050 by introducing BEVs, FCEVs and PHEVs where they are most competitive with ICEs

A combined forecasting and backcasting approach to maximise accuracy

In order to ensure conclusions were as accurate as possible, both a forecasting and backcasting approach was then used: from 2010 to 2020, all cost and performance projections are based on proprietary industry data; after 2020, on projected learning and annual improvement rates. These forecasted data were then backcasted from the envisioned penetration of power-trains in the EU in 2050, as described above. The results showed that the impact on costs for varying FCEV penetrations is not significant[2] (see Annex, Exhibit 45, page 55):

- 5% penetration of FCEVs might be expected to be uncompetitive, but this is not the case:
  - While a Europe-wide highway infrastructure is deployed, clustering of vehicles in higher population density regions could keep fuel costs from escalating significantly
  - Focusing FCEV deployment on the medium/larger car segments where FCEVs are more competitive helps offset the lower economies of scale and increased vehicle costs
  - Comparing 5% to 25% FCEV penetration in 2050 on a "like-for-like" basis, a C/D segment FCEV has a 6.1% higher purchase price and 17.4% higher fuel costs, resulting in a 7.3% increase in TCO
- No significant improvements in economies of scale exist that improve the economics of FCEVs or hydrogen infrastructure between 25% and 50% penetration.

The study therefore focused on the "world" with a penetration of 25% FCEVs, 35% BEVs, 35% PHEVs and 5% ICEs as a balanced scenario for the penetration of electric vehicles in the EU.

Total cost of ownership (TCO)

In the study, the economic comparison between power-trains is based on the total cost of ownership (TCO), as well as purchase price (see Annex, Exhibit 46, page 56 for a sample TCO calculation for an FCEV).

Consumers buy cars for a wide variety of reasons, including purchase price, new vs. second-hand, depreciation rate, styling, performance and handling, brand preference and social image. The cost of driving the same vehicle when new is also greater than that for the next owner. Calculating the TCO of the power-trains is therefore important because it describes the costs associated over their entire lifetime – on top of which individual customer criteria are applied. TCO includes:

- Purchase price: the sum of all costs to deliver the assembled vehicle to the customer for a specific power-train and segment
- Running costs:
  - Maintenance costs in parts and servicing specific to each vehicle type and power-train combination
  - Fuel costs based on the vehicle fuel economy and mileage, including all costs to deliver the fuel at the pump/charge point and capital repayment charges on investments made for fuel production, distribution and retail; or for BEVs/PHEVs, for charging infrastructure

N.B. There is no discounting of cash flows over the years and no residual value after 15 years. Time value of money has not been taken into account. All taxes on vehicles and fuel (including VAT) are set to zero to ensure that comparisons reflect the true costs of driving and are revenue-neutral to governments.

TCO equation

TCO		Purchase price	+	Running cost
=		=		=
		Parts cost		Maintenance cost
		+		+
		Assembly cost		Fuel cost (incl. infrastructure & fuel costs)
		+		
		SG&A		
		+		
		Margin		

2 The TCO of BEVs and PHEVs is constant over the three worlds due to the fact that their learning rates are defined on a yearly basis, not on an increase in capacity.

A balanced hydrogen production mix including a variety of technologies

N.B. Assumptions on power generation are in line with the European Climate Foundation's "Roadmap 2050", which describes a realistic scenario for all power-trains (see page 24 and Annex, Exhibit 47, page 56).

In this report, well-to-wheel emissions do not incorporate indirect emissions resulting from feedstock exploration and the associated infrastructure build-up (e.g. Exploration platforms, mining activities, power plant build-up), nor so-called CO_2 equivalent green-house gases. If these indirect emissions are taken into account, the well-to-wheel emissions of the different power-trains will change over time, depending on the production and supply pathway. In future analysis, it would be useful to take these into account as well.

The study consists of two business models – the vehicle model (generic for all power-trains) and the supply model (more detailed for hydrogen as the electricity supply chain already largely exists). In each "world" scenario, the demand for each fuel in each year is set by the annual driving and fuel economy of the power-trains on the road.

1. The vehicle model (see Annex, Exhibit 48, page 57) calculates the purchase price, operating cost, TCO and CO_2 emissions based on the cost of electricity and hydrogen and the CO_2 footprint calculated from the supply model. It also includes key assumptions agreed among participating car manufacturers (Exhibit 7).

Parameter	Proposed value
▪ Average vehicle lifetime	▪ 15 years
▪ Average annual distance driven	▪ 12,000 km
▪ Combined fuel economy	▪ Distance weighted average of ECE-15 and EUDC cycles
▪ Sales tax	▪ *Tax-free base model run*
▪ Vehicle assembly cost as % of ICE purchase price[1,2]	▪ 13.5%
▪ SG&A (including distribution) cost as % of ICE purchase price[1,2]	▪ 13.5%
▪ Return on investment as % of ICE purchase price[1,2]	▪ 2% - A/B segment ▪ 7% - C/D segment ▪ 8.5% - J segment

1 Assumed to be similar across reference segments, with the exception of profit assumption, since margins vary significantly between vehicle segments
2 Percentage will be applied to ICE purchase price per reference segment; same absolute cost will then be applied to all power-trains in the segment

SOURCE: Euromonitor, Polk, EU MVEG, Credit Suisse, Goldman Sachs Global Investment Research report, study analysis

Exhibit 7: Key assumptions for the vehicle model were agreed among participating car manufacturers

2. ***The supply model*** (for FCEVs) then calculates the CO_2 footprint, the cost of delivered hydrogen and investment required, based on cost and performance data received for the three components of hydrogen infrastructure – production, distribution and retail.

Key assumptions included:

- Each year, based on hydrogen demand for vehicles, components are added to meet new demand and replace components that are at the end of their life
- With the exception of retail infrastructure and delivery trucks, utilisation is set to 95% (80% for distributed production) due to rapid increase in hydrogen demand, allowing installed equipment to achieve full utilisation within a few years (see Annex, Exhibit 49, page 57).
- Shifting from small to medium to large installation size depends on the annual hydrogen capacity added each year, i.e. small components are built when hydrogen demand is low, large components when demand is high.

a. Production

Nine major production pathways were considered for hydrogen, representing all the main technologies with the potential for rapid, large-scale deployment in Europe (Exhibit 8). Based on these production pathways, many different production mixes are possible.

Among other options, the study examined two hydrogen production mixes: a balanced and economically driven production mix with CCS; the other without CCS, representing 100% electrolysis with 80% renewable energy by 2050. Both, however, lead to CO_2-free hydrogen production by 2050 (Exhibit 9). While the production of hydrogen from SMR with CCS remains the lowest-cost scenario, the 100% electrolysis production mix only increases the TCO of FCEVs (C/D segment) by 5% by 2030 and 3.5% by 2050.

N.B. All the results in this report are based on the first balanced and economically driven production mix described below

Technology	Process	Governing reaction[1]	Variations
SMR Steam Methane Reforming	Methane, Steam → H_2, CO_2	$CH_4 + 2H_2O \rightarrow 4H_2 + CO_2$	▪ On-site SMR ▪ Central SMR ▪ Central SMR + CCS
WE Water Electrolysis	Water, Electricity[3] → H_2, O_2	$2H_2O \rightarrow 2H_2 + O_2$	▪ On-site WE ▪ Central WE
CG/(IGCC) Coal Gasification /Integrated Gasification Combined Cycle	Coal[2], Steam → H_2, CO_2	$C + 2H_2O \rightarrow CO_2 + 2H_2$	▪ CG ▪ CG + CCS ▪ IGCC ▪ IGCC + CCS

1 Simplified reaction
2 Includes co-firing with biomass
3 100% CO2 reduction from power by 2050: www.roadmap2050.eu

SOURCE: Study analysis

Exhibit 8: Nine major production pathways were assessed

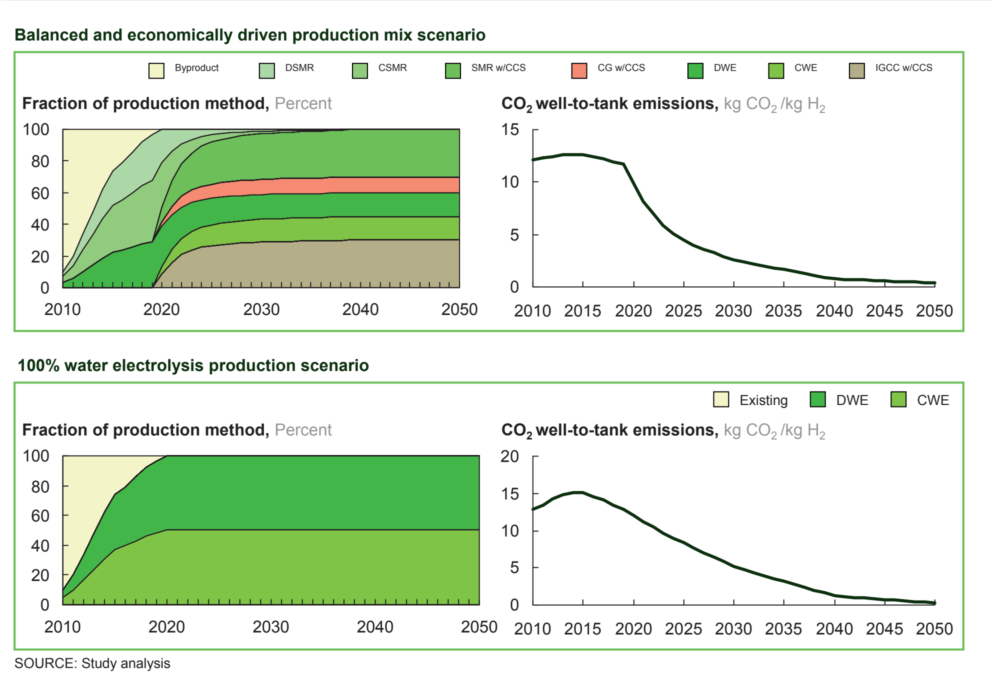


Exhibit 9: The study examined two hydrogen production mixes, both of which lead to CO_2-free hydrogen by 2050

As total hydrogen demand for FCEVs is comparatively low up to 2020, a conventional production mix is assumed, utilising excess hydrogen from existing assets (industrial sites and centralised SMR), with a growing proportion of distributed units (water electrolysis and SMR).

Beyond 2020, when hydrogen demand for FCEVs increases rapidly, a balanced and economically driven scenario is assumed, reflecting the diversity of resources available in different parts of Europe and including new sources of clean and green hydrogen.[3] This scenario avoids over-dependence on any single primary energy source and provides the most cost-effective means of decarbonising hydrogen supply.

In summary:

- Before 2020, utilising existing production assets, Central Steam Methane Reforming (CSMR) has 40% and Distributed Steam Methane Reforming (DSMR) and Distributed Water Electrolysis (DWE) each have 30% share of new production.

- After 2020, CSMR and Integrated Gasification Combined Cycle (IGCC) each have 30%, coal gasification has 10% and Central Water Electrolysis (CWE) and DWE each have 15% share of new production.

- In line with the "Roadmap 2050" study, it is assumed that the share of renewable energy in the power mix increases steadily (important for electrolysis) – see Annex, Exhibit 47, page 56.

- CO_2 Capture and Storage (CCS) is applied to all new CSMR, IGCC and coal gasification capacity starting in 2020 and coal is co-fired with 10% biomass, which costs three times the IEA[4] estimate to account for pre-treatment required prior to gasification.

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3 "Clean hydrogen" refers to the use of CCS; "green hydrogen" to renewable energy
4 International Energy Agency

- Coal, natural gas, clean electricity and biomass are all important for hydrogen production.

Both water electrolysis and IGCC could play a key role in supporting the electricity grid: electrolysis for demand management; IGCC for dispatchable power, i.e. for storage or export. Both technologies are also compatible with providing load balancing services, which will be in high demand in an electricity grid which includes a high percentage of renewable energies.

The role of biofuels

There is still uncertainty as to the amount of (sustainably produced) biofuels that will be available for passenger cars in the medium and long term in Europe. The study takes the following assumptions: by 2020 biofuels are blended, delivering a 6% well-to-wheel reduction in CO_2 emissions for gasoline and diesel engined vehicles, in line with the EU Fuel Quality Directive; by 2050 this increases to 24% to reflect growing supplies.

It also reflects the fact that this market will face increasing competition from other sectors – especially goods vehicles, aviation, marine, electric power and heavy industry to meet the needs of these sectors and a global passenger car fleet of 2.5 billion cars in 2050. A comprehensive analysis on the true global potential of biofuels is needed to determine both their availability and for which sectors and regions they may be most effectively used.

b. Distribution

A range of distribution methods was included in the study (Table 1).

Distribution method	*Tonnes of hydrogen/day*
Liquid trucks	*3.5*
Gaseous trucks	*0.4 (250 bar), 0.8 (500 bar)*
Pipelines	*1, 2.5, 10, 100*

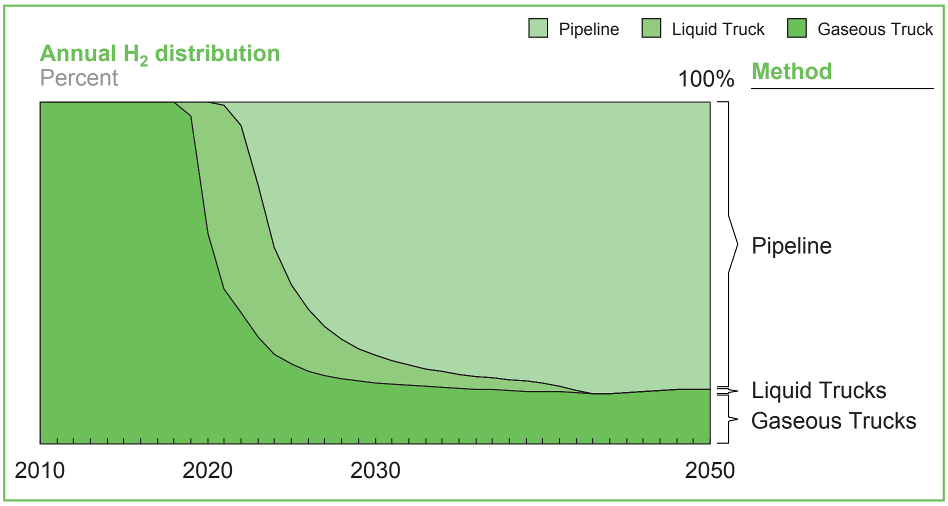
Table 1: An overview of distribution methods included in the study

Industry data were then used to calculate the distribution costs[5] for different volumes and distances, with the least expensive distribution method chosen for the required delivery distance.

A wide variety of distribution infrastructures may be considered, according to hydrogen volumes, distances and local specificities. This study assumes a distribution roadmap where gaseous trucks are initially the most important method, with liquid trucks bridging the gap to pipelines,[6] which will result in a significant reduction in delivery cost and CO_2 emissions (Exhibit 10).

5 Delivered cost = production cost + distribution cost + retail cost (each cost comes from the weighted average cost of all operating components using current feedstock and electricity prices). Components already built are assumed to continue operating for their lifetime until retired

6 Private companies in Europe already own and operate the world's largest hydrogen pipeline network covering ~1600 kilometres in France, Germany and the Benelux countries. Smaller pipelines are also operating in Italy and Sweden.



SOURCE: Study analysis

Exhibit 10: The hydrogen distribution mix assumed for the study

c. Retail stations

Small station (70-100 cars per day)	*2 dispensers, 0.4 tonnes of hydrogen/day*
Medium station (150-250 cars per day)	*4 dispensers, 1 tonne of hydrogen/day*
Large station (450-600 cars per day)	*10 dispensers, 2.5 tonnes of hydrogen/day*

Table 2: An overview of retail stations included in the study

The size of retail stations added was determined by hydrogen demand and coverage area: when coverage expands faster than demand, new retail stations are small; when demand grows faster than the coverage area, larger retail stations are added etc.

In the first decade, utilisation of retail stations is low, resulting in higher costs, but by 2020 it achieves 80% of the designed capacity, based on industry experience in fuels retail (see Annex, Exhibit 49, page 57). As expected, large retail stations have better economics than small and medium stations.

For the simulation in all “worlds” (see pages 16-18), the number of retail stations grows from an initial cluster of four in 2010 to 198 in 2015 and 755 in 2020; for the electric vehicle-dominated “world”, Exhibit 11 shows a breakdown of retail stations from 2020 to 2050.

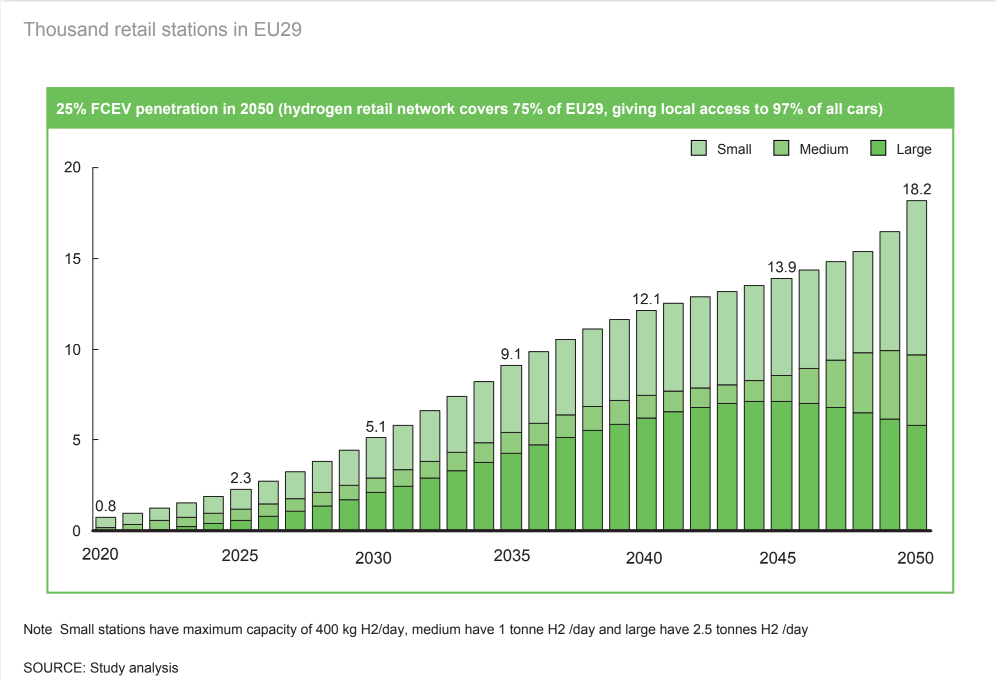


Exhibit 11: The number of hydrogen retail stations from 2020 to 2050 in the electric vehicle-dominated "world"

Key assumptions

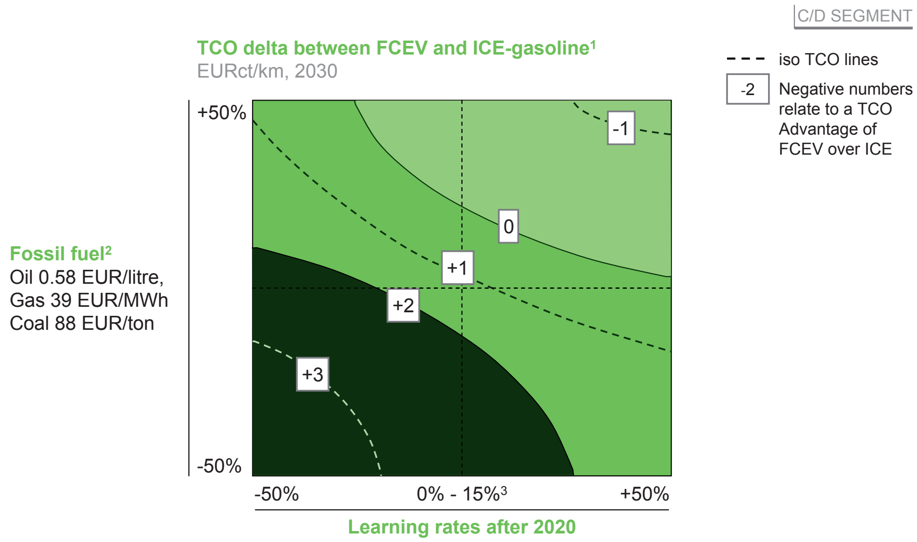
- WACC (Weighted average cost of capital) of 7% in nominal terms (post corporate tax), with no additional margin
- An asset lifetime of 20 years (30 years for pipelines)
- Oil, gas and coal prices are assumed from the IEA (see Annex, Exhibits 50-52, pages 58-59)
- Key raw material prices (e.g. metals) are taken from industry consensus analysis

The power supply pathway underlying this report is based on the European Climate Foundation "Roadmap 2050", which was developed in cooperation with the industry and describes a pathway to decarbonise the EU's power mix by 2050. In 2020, the expected share of renewable production capacity is approximately 34%. This is the minimum needed to meet the 20% EU renewable energy target, as there is limited RES opportunity outside of the power sector (see Annex, Exhibit 47, page 56). This ensures that the treatment of the power sector is consistent with the EU CO_2 reduction goal of 80% by 2050 (i.e. zero CO_2 from power by 2050) and draws a self-consistent set of electricity tariffs for wholesale, industrial and retail use, together with CO_2 emissions from power generation.

Assumptions are robust to significant variations

Projected cost reductions are based on years of experience of conventional vehicles – ICEs – including learning rates, the simplification of systems and economies of scale achieved by scaling up to larger production lines. The introduction of hybrid electric vehicles (HEVs), on the other hand – with millions now on the road – has given a deep insight into the pace of cost reduction for innovative power-trains and components over the last 10 years.

Nevertheless, all conclusions are robust to significant variations in learning rates and the cost of fossil fuels; and by 2030, there is only a small difference of –1 to +3 cents per kilometre (based on a pre-tax cost of 18 cents per kilometre), even with variations of +/– 50% (Exhibit 12).



1 Assuming 15 year lifetime and annual driving distance of 12,000 km
2 No taxes included, e.g. excise tax, CO2 tax, VAT
3 Fuel cell membranes: 15% pdc (per doubling of capacity); non-platinum catalyst: 15% pdc; FC structure: 15% pdc, EV-specific parts: 4.0%/1.5% p.a.; FC periphery 4.0%/1.5% p.a.; glider cost (FCEV & ICE): 0%; ICE basic power-train parts: 0%; technology packages: 1.5% p.a.

SOURCE: Study analysis

Exhibit 12: All conclusions are robust to significant variations in learning rates and the cost of fossil fuels

INPUT DATA

The collection, benchmarking and validation of over 10,000 data points

The process of collecting and sanitising data from participating companies was both methodical and rigorous:

1. The independent consultancy and participating companies together defined precisely the data to be collected in order to evaluate the four power-trains on a well-to-wheel basis.

2. The consultancy's "Clean Team" then sent out detailed data requests on economics (Exhibit 13), sustainability and performance for all four power-trains (BEV, FCEVs, PHEVs and ICEs), including the following supply chains: Gasoline and diesel, Electricity, and Hydrogen

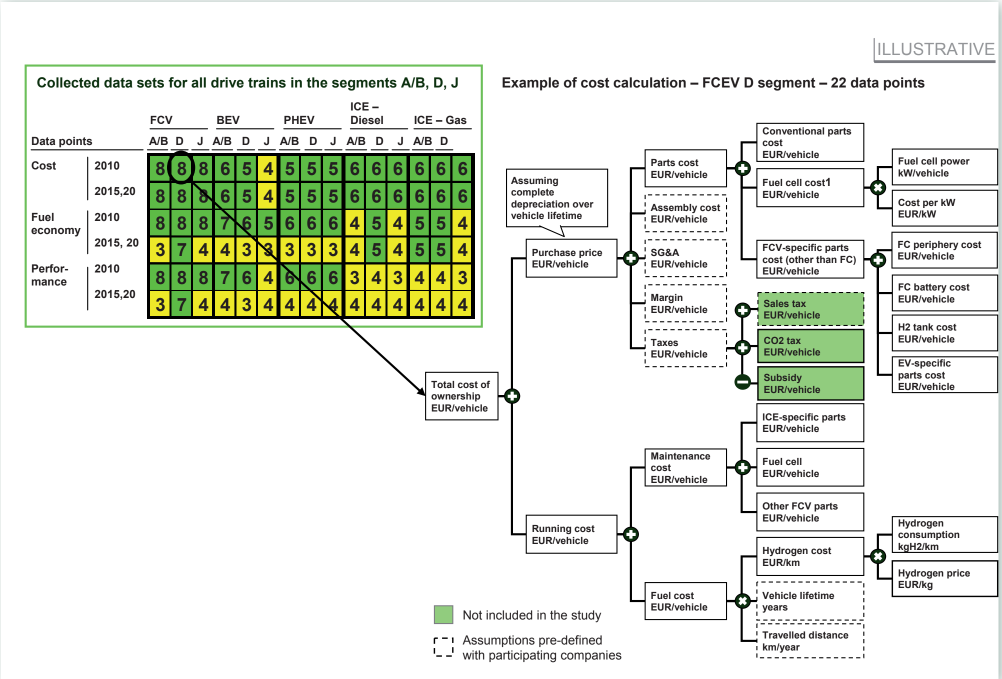


Exhibit 13: An example of cost data collected for a FCEV

3. The Clean Team collected the data and assessed whether they were of the appropriate quality.

4. The Clean Team reviewed the submitted data in order to understand the differences between the data sets of the various companies, asking them to preside correct data, where necessary.

5. Individual output data were submitted to relevant companies for sign-off (Exhibit 14)

Exhibit 14: An example of cost output data for water electrolysis

After all the output data had been signed off, it was then considered frozen and the analysis of the power-trains began.

RESULTS

The following conclusions are not forecasts, but one possible outcome – the result of a backcasting exercise based on a penetration of 25% FCEVs, 35% BEVs, 35% PHEVs and 5% ICEs in the EU by 2050 (see pages 16-18).

1. *BEVs and FCEVs have the potential to significantly reduce CO_2 and local emissions*

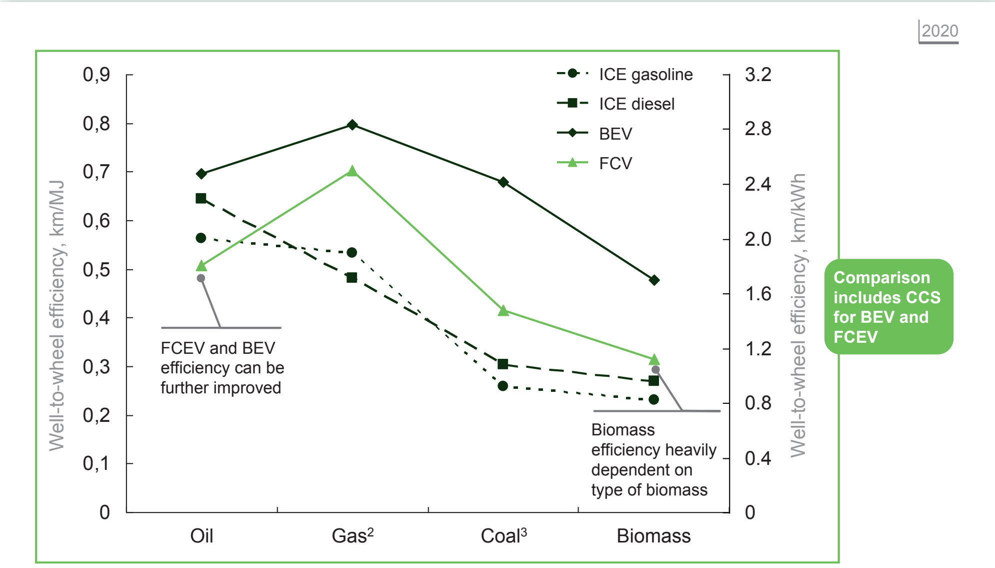
BEVs: given their limited energy storage capacity and driving range (150-250 km[1]) – and a current recharging time of several hours – BEVs are ideally suited to smaller cars and shorter trips, i.e. urban driving.

FCEVs: with a driving range and performance comparable to ICEs, FCEVs are the lowest-carbon solution for medium/larger cars and longer trips.

PHEVs: with a smaller battery capacity than BEVs, electric driving for PHEVs is restricted to short trips (40-60 km). Combined with the additional blending of biofuels (see page 2), they also show emission reductions for longer trips, but uncertainty remains as to the amount of sustainably produced biofuels that will be available for this market. Nevertheless, they are an attractive solution, reducing emissions considerably compared to ICEs.

ICEs: ICEs also have the potential to reduce their CO_2 footprint significantly through improved energy efficiency and biofuels. After 2020, however, further engine efficiency improvements are limited and relatively costly, while the availability of biofuels may also be limited.

a. Electric vehicles are more energy efficient than ICEs over a broader range of feedstocks



1 All power-trains have different performance criteria and therefore different driving missions
2 CNG used in gasoline ICE; diesel production from natural gas through Fischer-Tropsch process
3 Gasoline and diesel production from coal-to-liquids transformation through Fischer-Tropsch process

SOURCE: CONCAWE-EUCAR JEC-WTW study; study analysis

Exhibit 15: The well-to-wheel efficiency of FCEVs is comparable to ICEs, while BEV remains the most efficient power-train

1 For C/D segment cars in the medium term

In the energy- and carbon-constrained world in which we now live, the efficient use of primary energy resources is essential.

Exhibit 15 shows the well-to-wheel efficiency of the different power-trains using different types of primary energy sources. BEVs are the most efficient solution. FCEVs are more efficient than ICE on gas and coal. On oil and biofuels, the difference between ICE and FCEVs is small (see Annex, Exhibit 43, page 54, for a more detailed analysis).

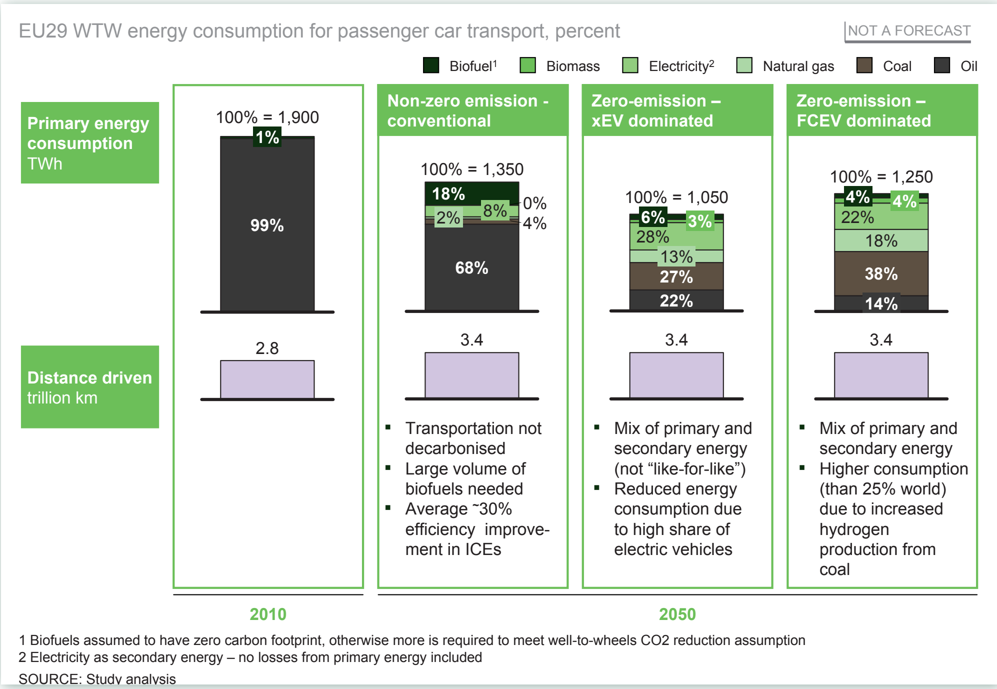
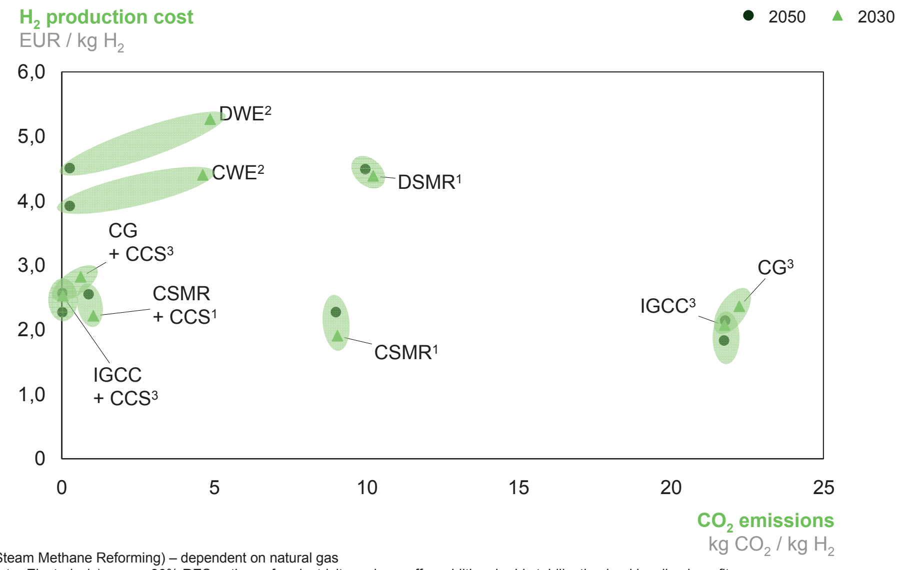


Exhibit 16: On a net-distance-travelled basis, electric vehicles could potentially drive more kilometres than ICEs using less energy

The data in this exhibit are the result of a backcasting exercise based on FCEVs achieving a range of penetrations in the EU by 2050 (see pages 16-18) and the scenario for power generation outlined in the European Climate Foundation's report, "Roadmap 2050" (see page 24).

While oil will remain the main source of energy for passenger cars in the short-to-medium term, switching to a high percentage of electric vehicles will increase flexibility and security of energy supply as they can be fuelled by a variety of primary energy sources.

For all future scenarios – and on a total global vehicle travel basis – BEVs, FCEVs, PHEVs and future ICEs can drive more total kilometres than today's ICEs using less primary energy due to increased efficiency.



1 SMR (Steam Methane Reforming) – dependent on natural gas
2 WE (Water Electrolysis) – uses 80% RES pathway for electricity and can offer additional grid stabilisation load leveling benefits
3 CG (Coal Gasification) – relies on domestic coal and when combined with CCS is assumed to be co-fired with 10% biomass

SOURCE: Study analysis

Exhibit 17: A variety of technologies are available to produce CO_2-free hydrogen (future cost levels)

A variety of technologies and feedstocks will be able to produce CO_2-free hydrogen, including fossil fuels, renewable electricity, nuclear and biomass.

The most cost-effective future production methods use existing technologies – steam reforming and coal gasification.

Costs of existing technologies such as SMR and coal gasification, will increase due to increasing fuel prices and costs of CCS (partly offset by technology advancements).

Cost of water electrolysers reduces due to efficiency improvements. The assumed power price reflects that these units can be run intermittently, providing a balancing solution for the power grid.

Hydrogen can be produced cost-effectively on both a small and large scale – from 0.4 to 1000 tonnes per day – from centralised or decentralised production.

CO_2 Capture and Storage (CCS)

CO_2 Capture and Storage (CCS) has been identified as an important solution for reducing CO_2 emissions, with the potential to provide 20% of the cuts required in the EU by 2030 and 20% of global cuts required by 2050

While the technology is being developed to reduce the CO_2 footprint of power generation, an additional benefit is that pre-combustion CO_2 capture technology also allows the production of large volumes of CO_2-free hydrogen. This is important to the economic assumptions of the study, as in the balanced and economically driven hydrogen production scenario (see pages 20-22), 70% of hydrogen is assumed to be produced using CCS.

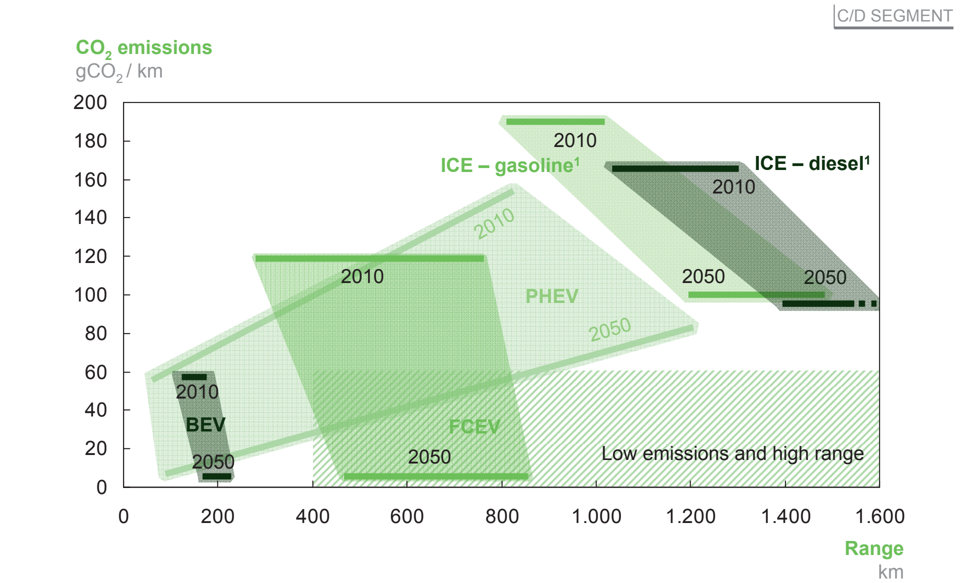
CO_2 capture has already been practised on a small scale, while the technology for CO_2 storage is similar to that used by the oil and gas industry for decades – to store natural gas or for enhanced oil recovery (EOR). CO_2 storage technology combined with EOR is therefore very advanced, providing ample data for storage in depleted oil and gas fields, while pure storage has been demonstrated for over a decade in a limited range of deep saline aquifers. However, the inherent risks associated with scale up and deployment are recognised.

The next step is therefore to scale-up the technology, with demonstration projects of a size large enough to allow subsequent projects to be at commercial scale. This will also build public confidence, as it is seen that CO_2 storage is safe and reliable.

The EU has already made significant progress in advancing CCS, establishing a legal framework for the geological storage of CO_2 and public funding to support an EU programme of up to 12 CCS demonstration projects. The goal: to enable the commercial availability of CCS by 2020. This has been echoed by many similar initiatives worldwide.

For more information, please refer to the European Technology Platform for Zero Emissions Fossil Fuel Power Plants (ZEP), otherwise known as the Zero Emissions Platform: www.zeroemissionsplatform.eu.

b. BEVs are ideally suited to smaller cars and shorter trips



1 ICE range for 2050 based on fuel economy improvement and assuming tank size stays constant. Assuming 6% CO2 reduction due to biofuels by 2020; 24% by 2050

SOURCE: Study analysis

Exhibit 18: BEVs and FCEVs can achieve significantly low CO_2 emissions, with BEVs showing limitations in range

Despite improvements in fuel economy, the capacity of ICEs to reduce CO_2 is significantly less than that of BEVs and FCEVs, which can achieve close to zero CO_2 emissions (well-to-wheel). As the range of BEVs is limited for medium sized cars, they are ideally suited to smaller cars and shorter trips.

See Annex (Exhibit 53, page 59) for a graphical analysis of how BEVs, FCEVs and PHEVs can reduce CO_2 emissions over time.

c. FCEVs are the lowest-carbon solution for medium/larger cars and longer trips

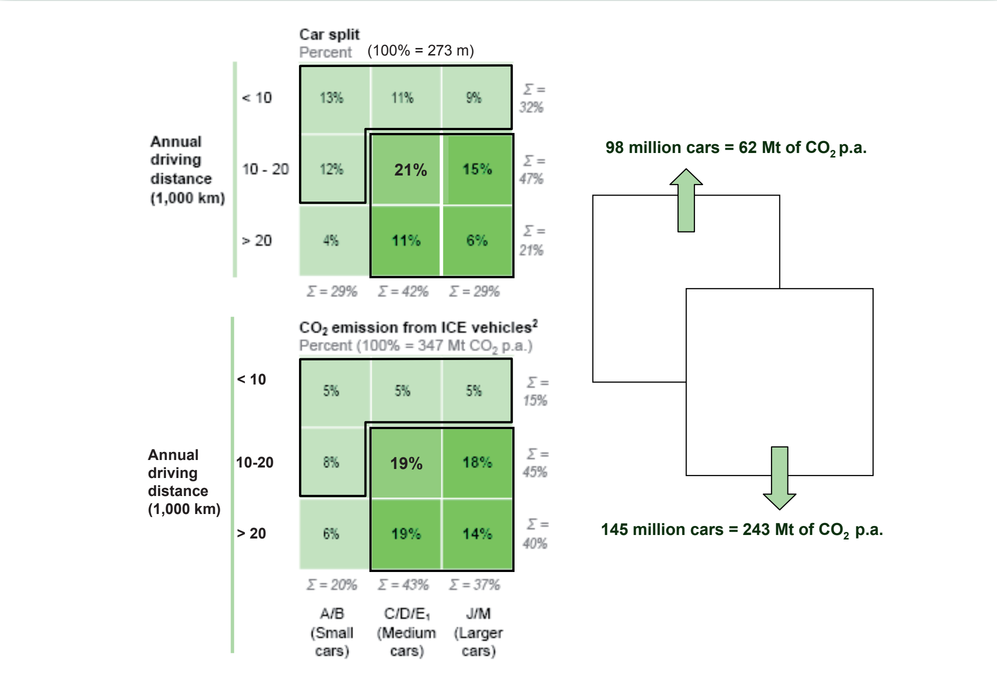


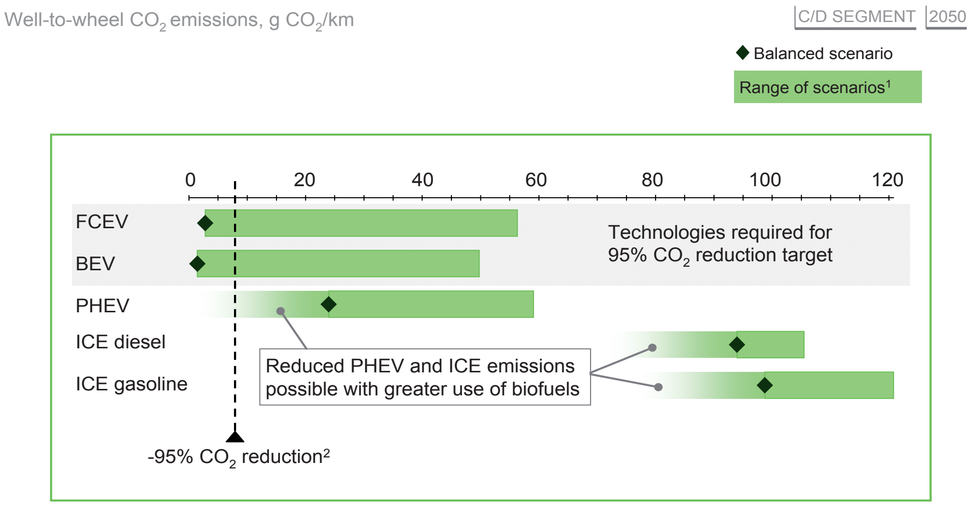
Exhibit 19: Medium/larger vehicles with above average driving distance account for 50% of all cars and 75% of CO_2 emissions

Medium/larger cars are responsible for a disproportionately greater share of CO_2 emissions due to the fact that they generally cover longer distances, as well as emit more CO_2. Replacing one ICE in these segments with one FCEV therefore achieves a relatively higher CO_2 reduction.

As FCEVs also have a clear TCO advantage over BEVs and PHEVs for medium/larger cars and longer trips (see Exhibit 32, page 42), FCEVs represent the lowest-carbon solution for a large proportion of the car fleet, based on current mobility patterns.

BEVs and FCEVs have the potential to significantly reduce CO_2 and local emissions.

d. PHEVs are an attractive solution for short trips or using biofuels



1 Scenarios refer to a range of potential futures of varying electricity decarbonisation and biofuel implementation:
Balanced – decarbonised electricity sector via renewables, CCS and nuclear, and 24% well-to-wheel reduction in diesel and gasoline CO2 footprint
High CO2 – central SMR for H2 production, EU 2010 electricity mix and 6% well-to-wheel reduction in diesel and gasoline CO2 footprint
2 C/D segment emission limit set to 4% of current 2010 vehicle emissions to achieve 95% CO2 reduction allows 20% more vehicles in 2050

SOURCE: Study analysis

Exhibit 20: BEVs and FCEVs can achieve 95% decarbonisation of road transport by 2050

In order to achieve the EU's goal to reduce CO_2 emissions by 80% by 2050, CO_2 emissions in the road transport sector must be reduced by 95%.

PHEVs can reduce CO_2 emissions when using the electric drive, but only for short trips (40-60 km). Combined with the additional blending of biofuels, they also show emission reductions for longer trips, but uncertainty remains as to the amount that will be available for this market (see page 2).

2. After 2025, the total cost of ownership of all the power-trains converge

In the study, the economic comparison between power-trains is based on the total cost of ownership (TCO), as well as purchase price, as it describes the costs associated over their entire lifetime (see page 18). All costs are "clean" of tax effects, including carbon prices.

BEVs and FCEVs are expected to have a higher purchase price than ICEs (battery and fuel cell related) lower fuel cost (due to greater efficiency and no use of oil) and a lower maintenance cost (fewer rotating parts).

The cost of fuel cell systems is expected to decrease by 90% and component costs for BEVs by 80% by 2020, due to economies of scale and incremental improvements in technology. Around 30% of technology improvements in BEVs and PHEVs also apply to FCEVs and vice versa. This assumes that FCEVs and BEVs will be mass produced, with infrastructure as a key prerequisite to be in place. The cost of hydrogen also reduces by 70% by 2025 due to higher utilisation of the refuelling infrastructure and economies of scale, e.g. the capital cost of hydrogen refuelling stations is expected to reduce by 50% between 2010 and 2020.

PHEVs are more economic than BEVs and FCEVs in the short term. The gap gradually closes and by 2030 PHEVs are cost-competitive with BEVs for smaller cars, with both BEVs and FCEVs for medium cars and less competitive than FCEVs for larger cars.

While the fuel economy of ICEs is expected to improve by an average of 30% by 2020, costs also increase due to full hybridisation and further measures such as the use of lighter weight materials. The TCOs of all four power-trains are expected to converge after 2025 – or earlier, with tax exemptions and/or incentives during the ramp-up phase.

For larger cars, the TCO of FCEVs is expected to be lower than PHEVs and BEVs as of 2030. By 2050, it is also (significantly) lower than the ICE. For medium-sized cars, the TCOs for all technologies converge by 2050. BEVs have a (small) TCO advantage over FCEVs in the smaller car segments.

By 2020, the cost of a fuel cell system falls by 90%, BEV components by 80%

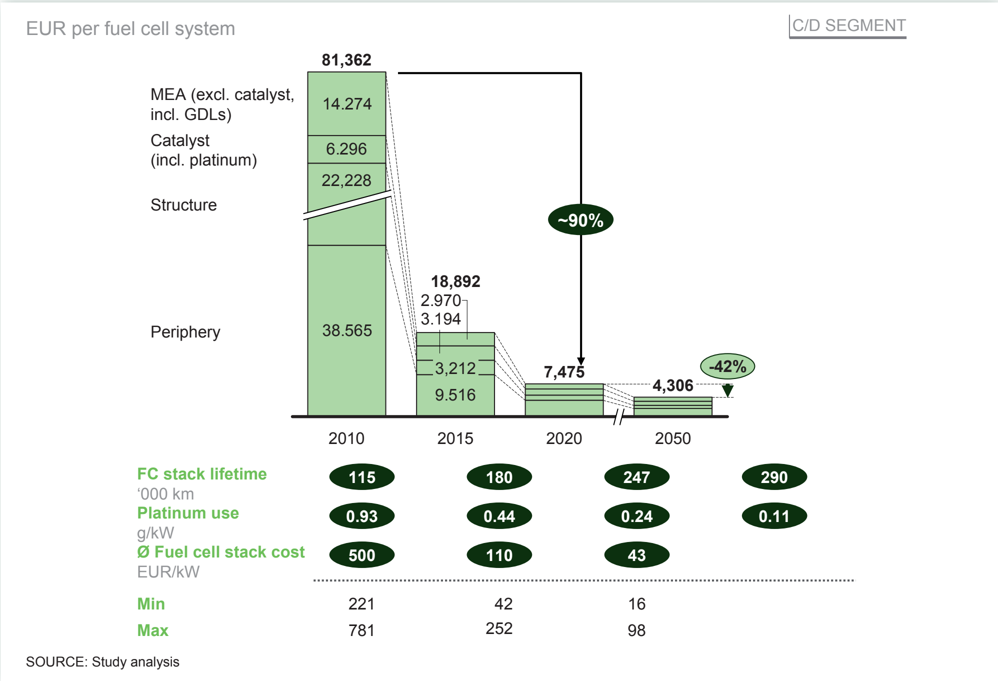


Exhibit 21: The cost of a fuel cell system falls by 90% by 2020

Exhibit 21 is based on a set of data provided by the participating companies. As discussed in the Methodology section, the average value for the fuel cell system cost is used for further calculations. The data set in 2010, 2015 and 2020 forms a broad range (see Annex, Exhibit 54, page 60), which is normal for an industry planning on mass production. The difference between the best and the worst cost data points can vary by a factor of 5, depending on the different technologies and processes used by car manufacturers.

The fuel cell system is the most significant cost component in an FCEV (other cost elements include the electric power-train and hydrogen tank). With all critical technological hurdles resolved, all projected cost reductions for FCEVs are based on engineering improvements and manufacturing efficiencies for commercial production. These include:

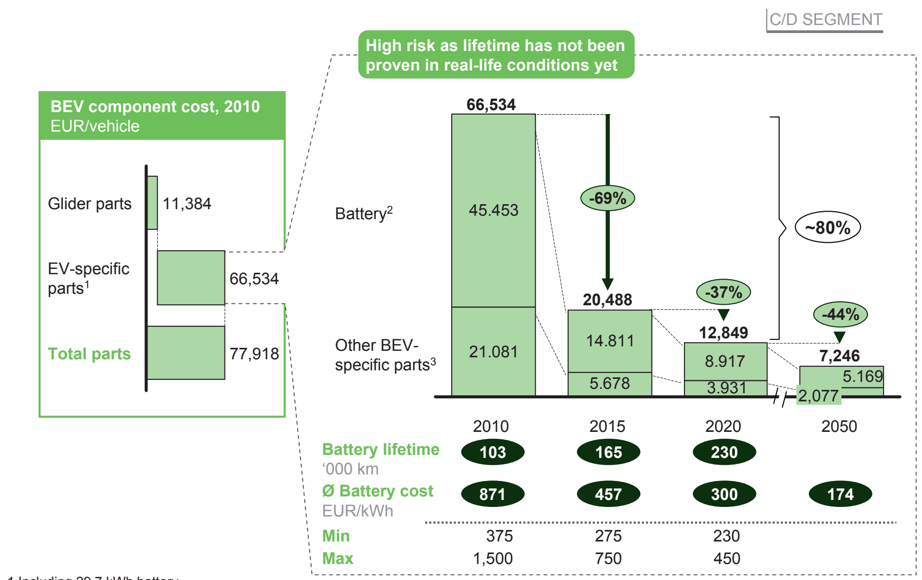
- Improvements in design, e.g. removing components; operating at a higher temperature in order to simplify the units

- Different use of materials, e.g. reduced platinum use; using alloys and smart catalyst structure; mitigation of fuel cell degradation

- Improvements in production technology – moving from batch to continuous production patterns; solvent-free (dry processes) with high throughput

- Economies of scale (1 million FCEVs in the EU by 2020).

All projected cost reductions for FCEVs and hydrogen supply until 2020 are based on proprietary data. In order to ensure a realistic outcome, learning rates after 2020 are conservative and considerably lower than historical improvements of comparable technologies, such as Wind, Solar PV or LNG (see Annex, Exhibit 42, page 54).



1 Including 29.7 kWh battery
2 ~1.75 batteries required over BEV lifetime in 2010; ~1.1 required in 2015; only cost of utilized battery lifetime is included
3 E.g., electric motor, transmission, inverter, wiring, controls, etc.

SOURCE: Study analysis

Exhibit 22: The cost of BEV components falls by 80% by 2020

Exhibit 22 is based on a set of data provided by the participating companies. As discussed in the Methodology section, the average value for the BEV component cost is used for further calculations. The data set in 2010, 2015 and 2020 forms a broad range (see Annex, Exhibit 55, page 60), which is normal for an industry that has just started mass production. The difference between the best and the worst cost data point can vary by a factor of 3.

All projected cost reductions for BEV components are based on proprietary data and include:

- Improvements in production engineering: operations such as electrode cutting, forming, stacking and contacting of the collectors will gradually grow more efficient through the introduction of advanced laser technologies and a shift from “batch to continuous” production modes. The automatisation and rationalisation of quality testing along the production line will also generate efficiency gains.

- Economies of scale from larger production plants (3 million BEVs in the EU by 2020).

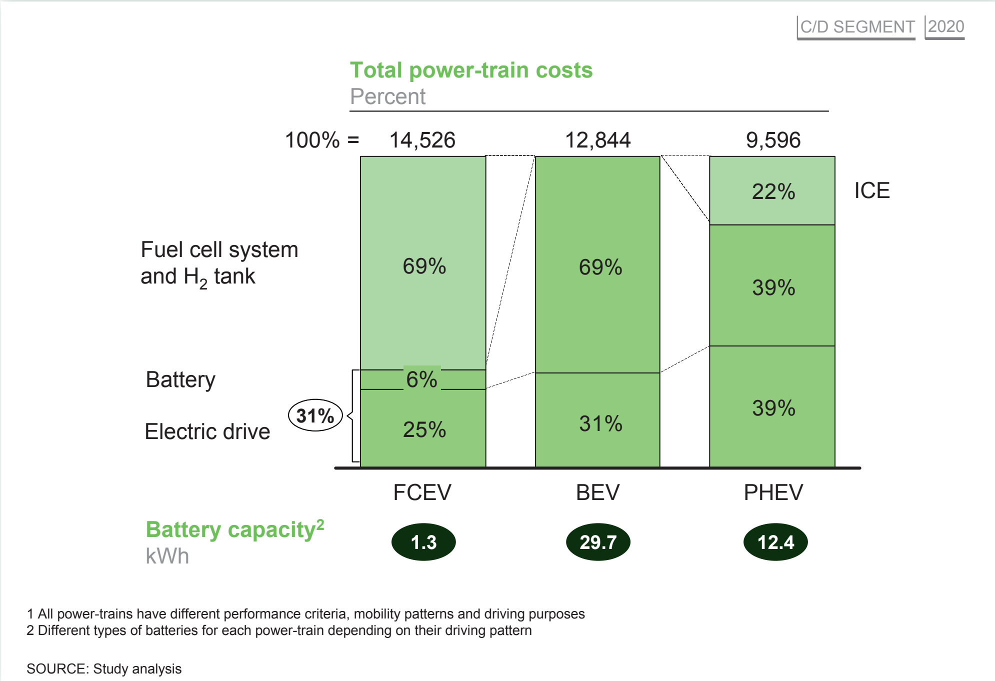


Exhibit 23: In 2020, 31% of technology improvements in BEVs and PHEVs also apply to FCEVs

- BEVs, FCEVs and PHEVs are complementary technologies as they share many similar electrical drive-train components, i.e. battery and electric drive. Investments in BEVs and PHEVs therefore also benefit FCEVs and vice versa.

2010 – Increasing hybridization

- Fuel economy mainly improved by ICE power-train and non-power-train packages
- In addition, all OEMs have hybrid vehicles in development or already on the market
- Level of hybridization varies

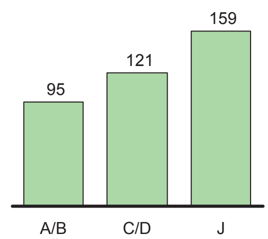
Typical hybridization measures

- Power-train improvements
  - ICE downsizing
  - Variable valve control
  - Engine friction reduction
  - Electric drive efficiency
  - Battery improvements, e.g., Li-ion
- Non-power-train improvements
  - Regenerative braking
  - Start-stop system
  - Low rolling resistance tyres
  - Strong weight reduction
  - Electrification of auxiliaries
  - Improved aerodynamics

2020 – Significant hybridization

- OEMs expect that 80% of ICE vehicles in the C/D segment will be hybridized
- Optimized hybridization of C/D segment vehicle (with both power-train and non-power-train measures) increases component cost by EUR 3,100
- Fuel economy is assumed to increase by an average of ~30%[1]

2020 CO_2 emissions ICE gasoline
gCO_2/km, WtW



1 Maximum fuel reduction potential from hybrid package, including non-power-train improvements

SOURCE: Study analysis

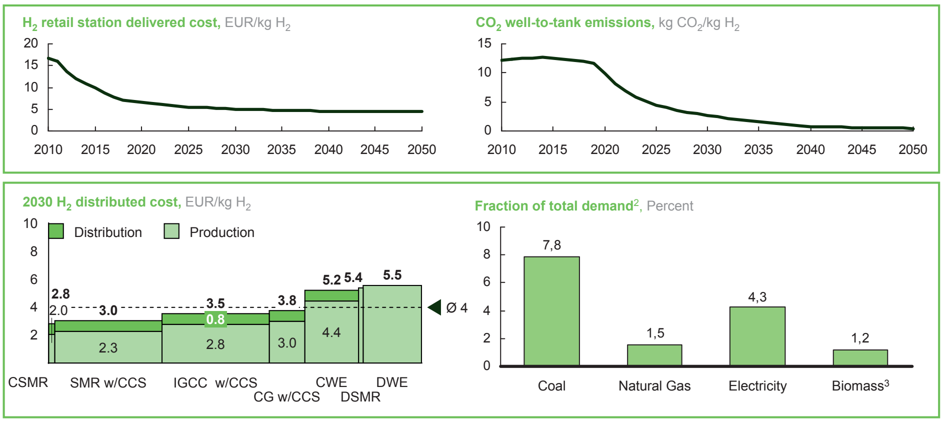
Exhibit 24: ICE fuel economy is assumed to increase by an average of 30% by 2020

The results of the study take into account significant improvements in fuel economy in ICEs by 2020.

a. The cost of hydrogen reduces by 70% by 2025

Description

- Before 2020, CSMR has 40% and DSMR & DWE each have 30% share of new production
- After 2020, CSMR & IGCC each have 30%, CG has 10% and CWE & DWE each have 15% share of new production
- CCS is applied to all new CSMR, IGCC and CG capacity starting in 2020
- Coal is co-fired with 10% biomass, which costs 3x IEA estimate to account for pre-treatment required prior to gasification[1]
- Coal, natural gas, electricity and biomass are all important for Hydrogen production



1 Co-firing more than 10% biomass with coal in IGCC and CG with CCS can allow negative CO2 emissions
2 Fraction is the amount of primary energy source consumed in 2050 divided by total EU-29 wide consumption in 2008
3 Fraction of biomass is that assumed available to the power generation sector (1,600 TWh/year)

SOURCE: Study analysis

Exhibit 25: The production mix assumed in the study is robust to energy shocks

Of the nine hydrogen production mixes studied, two were considered the most relevant for this study: the first (Exhibit 25) is more economically driven and based on a mix of fossil fuels and renewable energy; the second is based entirely on renewable energy (see Exhibit 26). Both production mixes reduce CO_2 emissions (well-to-tank) to near-zero.

Before 2020, the first production mix assumes that the limited volume of hydrogen required will be produced using centralised SMR (40%), distributed SMR (30%) and distributed water electrolysis (30%). After 2020, when the costs of FCEVs have come down and hydrogen demand rapidly increases, it assumes centralised SMR + CCS (30%); IGCC + CCS (30%); coal gasification + CCS (10%); centralised water electrolysis (15%); and decentralised water electrolysis (15%). Between 2010 and 2050, the study assumes an increasing share of renewable energy in the power mix (see Annex, Exhibit 47, page 56).

The exhibit shows results for the first hydrogen production mix on which the study is based: the lower left hand chart indicates the costs of the chosen production mix. In the upper left hand chart, hydrogen retail delivered costs rapidly approach €4.50/kg, while in the upper right hand chart, the CO_2 well-to-tank emissions first increase, then reduce rapidly after 2020.

As can be seen in the lower right hand chart, hydrogen can be produced, distributed and retailed cost-effectively by 2020 from a variety of feedstocks to suit local and market conditions.

N.B. All the results in this report are based on the balanced and economically driven production mix described in Exhibit 25.

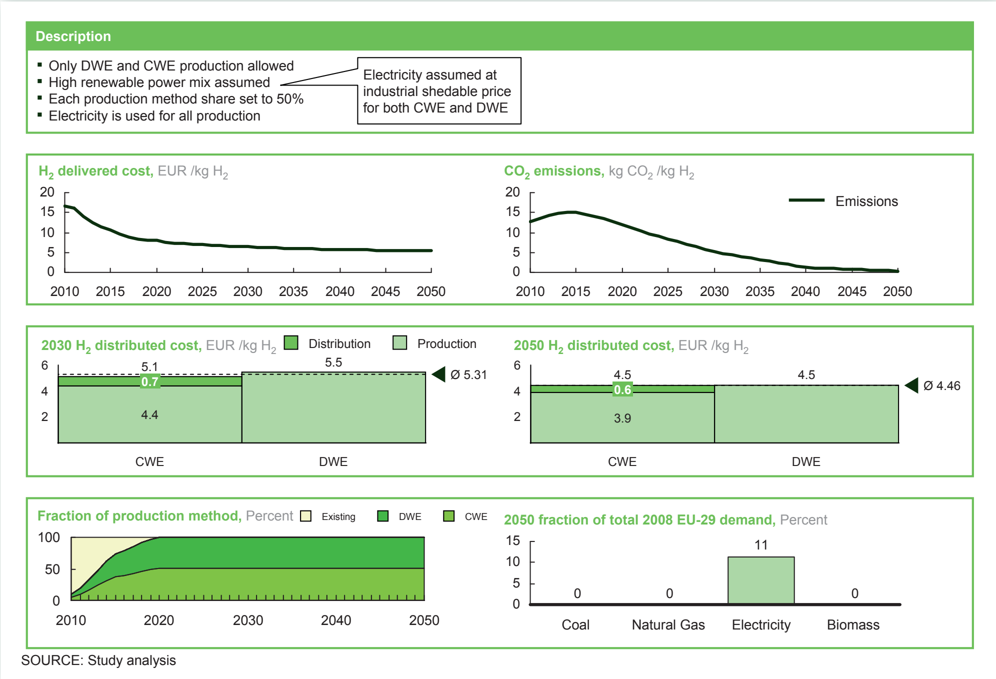


Exhibit 26: An alternative production mix representing 100% electrolysis, with 80% renewable production by 2050

The alternative production mix – representing 100% electrolysis, with 80% renewable production by 2050 – increases the TCO of FCEVs by 5% by 2030 and 3.5% by 2050.

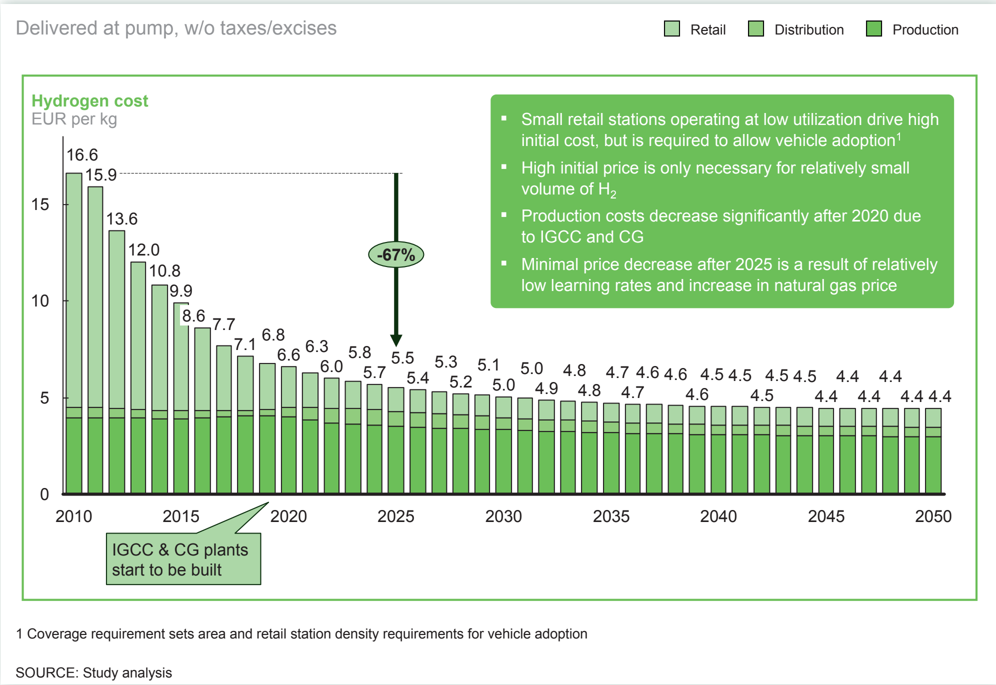


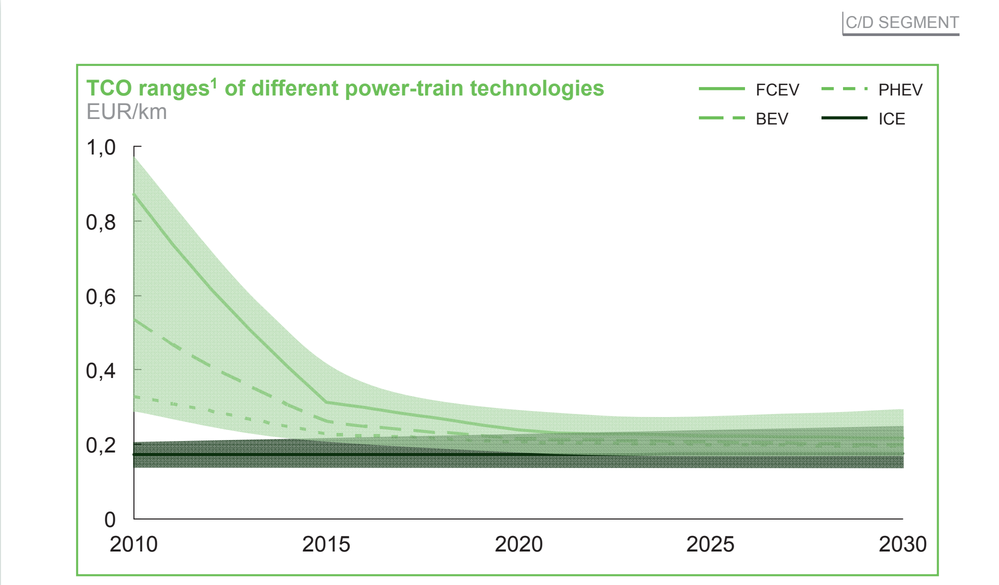
Exhibit 27: The cost of hydrogen reduces by 70% by 2025, then stays relatively flat (excluding taxes and incentives)

The cost of hydrogen will be high in the first five years (2010-2015), as a result of the under-utilisation of retail stations and the fact that very small stations will be built to reduce capital costs. This is still a pre-commercial market, so these stations will have very low economies of scale. For example, in order to persuade current gasoline and diesel station owners (dealers) to start providing hydrogen, hydrogen will need to be untaxed and dealers will require subsidy.

In the next five years – in the early commercial phase, when stations become larger and utilisation grows as more FCEVs come on the road – hydrogen (assuming it is untaxed) could become cost-competitive with gasoline ICEs (assuming gasoline is taxed).

By 2020, retail costs will have significantly reduced, as more FCEVs come on the road and large stations, with multiple pumps and a higher utilisation, are built. New large-scale IGCC and CG plants will also start to be built, further reducing the cost of hydrogen.

b. By 2030, BEVs, FCEVs, PHEVs are all cost-competitive with ICEs in relevant segments



1 Ranges based on data variance and sensitivities (fossil fuel prices varied by +/- 50%; learning rates varied by +/- 50%)

SOURCE: Study analysis

Exhibit 28: After 2025, the TCOs of all the power-trains converge

Due to the initial steep decrease in the cost of fuel cell systems, BEV components and hydrogen as a result of higher utilisation and economies of scale, the TCOs of all the power-trains converge after 2025.

EUR thousands — EXCLUDING ALL TAXES | 2020

Segment	Vehicle	Purchase price (+)	Maintenance (+)	Fuel cost[1] (+)	Infrastructure[2] (=)	TCO
A/B Segment	FCEV	20.0	2.8	4.6	2.2	29.6
	BEV	16.9	2.3	2.8	2.5	24.5
	PHEV	14.7	2.9	3.3	1.4	22.3
	ICE - gasoline	11.3	3.0	3.7	0.5	18.5
	ICE - diesel	11.3	3.0	3.7	0.4	18.4
C/D Segment	FCEV	30.9	4.5	5.6	2.7	43.8
	BEV	28.9	3.7	3.4	2.5	38.5
	PHEV	26.8	4.9	3.8	1.4	36.9
	ICE - gasoline	21.4	5.5	4.7	0.6	32.3
	ICE - diesel	21.9	5.7	4.7	0.5	32.8
J Segment	FCEV	38.9	5.6	6.9	3.3	54.8
	BEV	41.0	5.4	4.2	2.5	53.1
	PHEV	37.0	6.7	5.1	1.4	50.2
	ICE - gasoline	28.5	7.1	6.2	0.8	42.5
	ICE - diesel	29.5	7.5	6.5	0.7	44.1

1 Includes production and distribution cost
2 Includes retail cost
NOTE: Assuming 15 year lifetime, annual driving distance of 12,000 km, no tax (e.g., fuel excise, VAT)

SOURCE: Study analysis

Exhibit 29: By 2020, the purchase price of BEVs, FCEVs and PHEVs is several thousand more euros than ICEs, which could be offset by tax exemptions

By 2020, the purchase price of electric vehicles is still several thousand euros more than that of ICEs, but reasonable public incentives on vehicle, fuel and an attractive customer value proposition could be sufficient to bridge this cost gap (see page 43). The purchase price of BEVs is lower than FCEVs.

The purchase prices of electric vehicles may vary widely according to market conditions and car manufacturers who may either be further advanced in achieving cost reductions and/or choose to limit the premium. They also depend on branding strategies, with a whole range of purchase prices within any car segment – from lowest cost to premium vehicles.

EUR thousands — EXCLUDING ALL TAXES | 2030

Segment	Vehicle	Purchase price (+)	Maintenance (+)	Fuel cost[1] (+)	Infrastructure[2] (=)	TCO
A/B Segment	FCEV	16.0	2.5	4.4	1.2	24.0
	BEV	15.2	2.2	2.7	2.5	22.6
	PHEV	13.7	2.8	3.4	1.4	21.3
	ICE - gasoline	11.1	3.0	4.1	0.5	18.7
	ICE - diesel	11.2	3.0	4.1	0.4	18.7
C/D Segment	FCEV	25.7	4.2	5.2	1.4	36.5
	BEV	26.3	3.6	3.2	2.5	35.6
	PHEV	25.0	4.9	3.7	1.4	35.0
	ICE - gasoline	21.1	5.4	5.3	0.6	32.3
	ICE - diesel	21.6	5.6	5.2	0.5	32.9
J Segment	FCEV	32.7	5.3	6.2	1.7	45.9
	BEV	37.3	5.2	3.9	2.5	48.9
	PHEV	34.7	6.7	5.1	1.4	47.9
	ICE - gasoline	28.3	7.0	6.9	0.8	42.9
	ICE - diesel	29.1	7.4	7.2	0.7	44.4

1 Includes production and distribution cost
2 Includes retail cost
NOTE: Assuming 15 year lifetime, annual driving distance of 12,000 km, no tax (e.g., fuel excise, VAT)

SOURCE: Study analysis

Exhibit 30: By 2030, all electric vehicles are viable alternatives to ICEs, with running costs that are comparable and a purchase price that is close to comparable for larger cars

By 2030, the advantages of lower running costs almost outweigh the higher purchase price of electric vehicles, which start to close the gap with ICEs on both purchase price and TCO. Typically, electric vehicles (BEVs, FCEVs, PHEVs) cost 2-6 cents more per kilometre than ICEs.

EUR thousands — EXCLUDING ALL TAXES | 2050

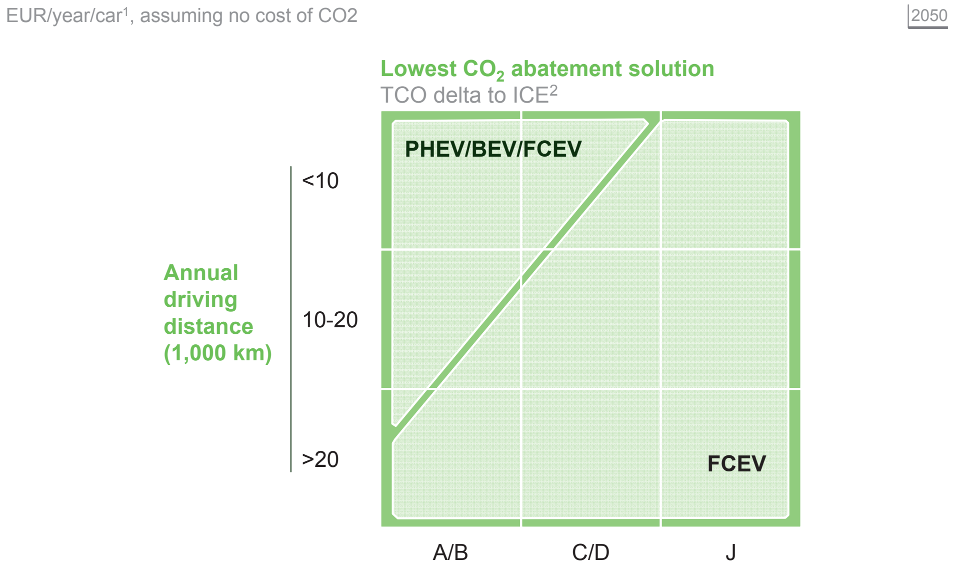
Segment	Vehicle	Purchase price (+)	Maintenance (+)	Fuel cost[1] (+)	Infrastructure[2] (=)	TCO
A/B Segment	FCEV	14.3	2.3	3.7	1.0	21.4
	BEV	13.4	2.2	2.4	2.5	20.5
	PHEV	12.8	2.8	3.5	1.4	20.5
	ICE - gasoline	10.8	2.9	4.6	0.5	18.8
	ICE - diesel	11.0	2.9	4.6	0.4	18.9
C/D Segment	FCEV	23.7	4.0	4.0	1.1	32.8
	BEV	23.5	3.5	2.8	2.5	32.3
	PHEV	23.5	4.8	3.6	1.4	33.3
	ICE - gasoline	20.5	5.1	5.8	0.6	32.0
	ICE - diesel	21.2	5.4	5.8	0.5	32.9
J Segment	FCEV	30.4	5.0	4.6	1.3	41.4
	BEV	33.3	5.1	3.4	2.5	44.3
	PHEV	32.6	6.6	5.1	1.4	45.7
	ICE - gasoline	27.9	6.9	7.7	0.8	43.2
	ICE - diesel	28.7	7.2	8.0	0.7	44.6

1 Includes production and distribution cost
2 Includes retail cost
NOTE: Assuming 15 year lifetime, annual driving distance of 12,000 km, no tax (e.g., fuel excise, VAT)

SOURCE: Study analysis

Exhibit 31: By 2050, FCEVs are more economic than ICEs for larger cars and fully competitive for medium-sized cars

By 2050, all electric vehicles are cost-competitive with ICEs, FCEVs are the lowest-cost solution for larger cars (J segment).



1 Constant lifetime, but different total driving distances (90,000 km; 180,000 km; 360,000 km)
2 Calculated as ICE TCO minus lowest FCEV/BEV/PHEV TCO. Negative numbers indicate a TCO advantage over the ICE

SOURCE: Study analysis

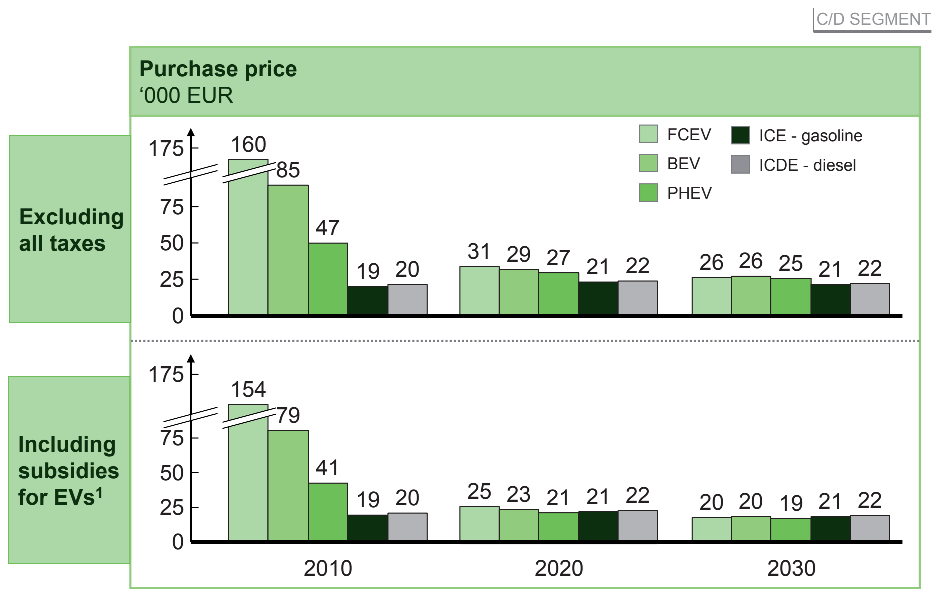
Exhibit 32: The FCEV has a TCO advantage over BEVs and PHEVs in the heavy/long-distance car segments

In terms of car size and annual driving distance, BEVs are economic for smaller cars and shorter trips while FCEVs perform best for C/D and J segments (medium and larger cars) and longer trips.

FCEVs score almost as well as BEVs on annual driving distances of 10,000-20,000+ km in the A/B (small car) segments.

As medium/larger vehicles with above average driving distance account for 50% of all cars, but 75% of CO_2 emissions, FCEVs are therefore an attractive abatement option for a large proportion of the car fleet.

c. **Incentives could make BEVs and FCEVs cost-competitive with ICEs by 2020**

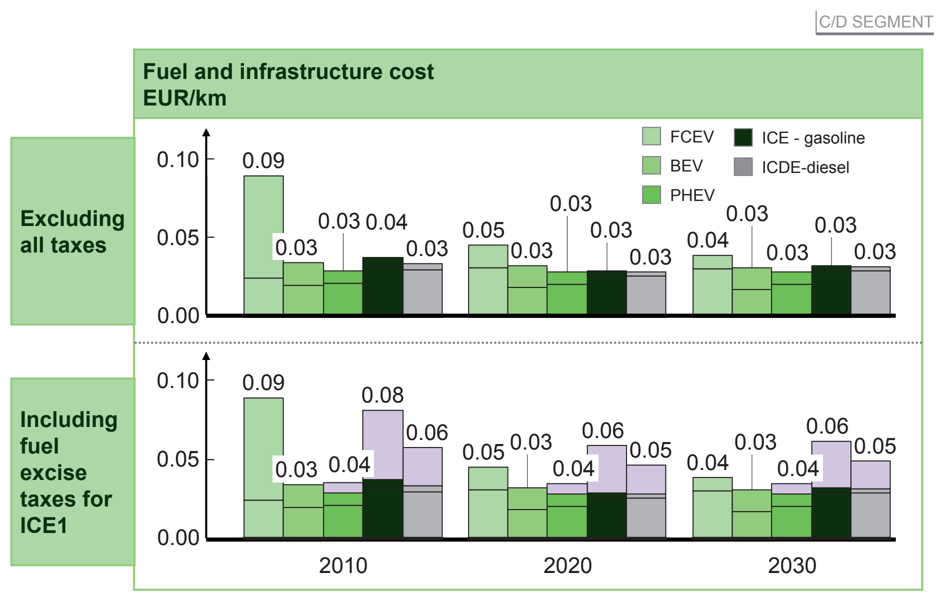


1 Assuming a EUR 6,000 subsidy on electric vehicles (either passively through foregoing excise taxes or actively through support)

SOURCE: Study analysis

Exhibit 33: The higher purchase price of BEVs, FCEVs and PHEVs could be partially offset by tax exemptions

With an average vehicle subsidy of nearly €6,000 for FECVs as currently provided for BEVs in several Member States , the purchase price of FCEVs could start to close with ICEs by 2020 and be lower in 2030.



1 Excluding VAT, but including fuel tax of EUR 0.655/litre gasoline (~EUR 5,500 over 180,000 km) and EUR 0,470/litre diesel (~EUR 3,300 over 180,000 km), corresponding to 2010 legislation in Germany

SOURCE: Study analysis

Exhibit 34: Temporarily forgoing fuel taxes on hydrogen or electricity will level fuel costs for all power-trains over the next 10 to 20 years

If hydrogen is not taxed like gasoline and diesel in the ramp-up phase, infrastructure and fuel costs for FCEVs could become cost-competitive with ICEs as early as 2020.

3. A portfolio of power-trains can satisfy the needs of consumers and the environment

Over the next 40 years, no single power-train satisfies all key criteria for economics, performance and the environment. As different power-trains meet the needs of different consumers, the world is therefore likely to move from a single power-train (ICE) to a portfolio of power-trains in which BEVs and FCEVs play a complementary role.

The results show that BEVs are ideally suited to smaller cars and shorter trips, FCEVs to medium/larger cars and longer trips, with PHEVs providing an intermediate solution to a zero-emission world.

a. FCEVs and PHEVs are comparable to ICEs on driving performance and range

1 Bars represent range of performance across reference segments
2 Fast charging; implies higher infrastructure costs, reduced battery lifetime and lower battery load
3 The gas tank of a PHEV has the same refueling time as a conventional vehicle

SOURCE: Study analysis

Exhibit 35: FCEVs and PHEVs have a driving performance and range comparable to ICEs

With limited energy storage capacity, BEVs are in a different category to FCEVs, PHEVs and ICEs with regard to speed, range or refuelling times:

- For example, an average, medium-sized BEV with maximum battery loading e.g. 30 kWh, around 220 kg in 2020) will not be able to drive far beyond 150 km at 120 km/hour, if real driving conditions are assumed (taking expected improvements until 2020 into account).
- Charging times are longer, even at maximum proven battery technology potential: 6-8 hours using normal charging equipment. Using more sophisticated and expensive technologies can reduce charging time. Fast charging may become widespread, but the impact on battery

performance degradation over time and power grid stability is unclear. Moreover, it takes 15-30 minutes to (partially) recharge the battery. Battery swapping reduces refuelling time; it is expected to be feasible if used once every two months or less and battery standards are adopted by a majority of car manufacturers.

FCEVs have a driving performance and range comparable to ICEs: an average driving range of 500-600 km, similar acceleration and a refuelling time of less than 5 minutes, similar to ICE fuelling which is a proven business model.

The driving range and performance of PHEVs is similar to ICEs when in ICE drive.

See Annex, Exhibit 56, page 61, for a graphical analysis of the impact of cruising speed on range.

b. Snapshot of 2030: different power-trains meet different needs

Excellent | Good | Moderate | Challenged | C/D SEGMENT | 2030

	FCEV	BEV	PHEV	ICE
Performance	▪ Driving performance in similar range to ICE ▪ ~600 km average driving range ▪ Refueling only takes a couple of minutes ▪ Fewer services needed	▪ Limited energy storage capacity and driving range (150-250 km) ▪ Refueling time in the order of hours[2] ▪ Ideally suited to smaller cars and urban driving	▪ Driving range equal to ICE in ICE drive (>800km); 40-60 km in electric drive ▪ Similar top speed, gasoline refueling time & service intervals ▪ Battery recharging takes some hours	▪ Highest driving range ▪ Best top speed and refueling time ▪ Only service intervals shorter
Environment	▪ High CO_2 reduction (~80%) compared to today with CCS & water electrolysis ▪ No local vehicle emissions ▪ Lowest carbon solution for medium/larger cars & longer trips	▪ High CO_2 reduction (~80%) if CCS or renewable energy is used ▪ Depends on electricity footprint ▪ No local vehicle emissions	▪ Considerable CO_2 reduction (~70%) ▪ Some local emissions in ICE drive ▪ Low CO_2 if 100% biofuels	▪ Highest CO_2 and local vehicle emissions ▪ Unlikely to meet EU CO_2 reduction goal for 2050 ▪ Low CO_2 if 100% biofuels
Economics[1]	▪ Purchase price is ~€4,000 higher than ICE ▪ TCO comparable to ICE for larger, but not smaller cars ▪ Infrastructure cost comparable cost to BEVs	▪ Economic for smaller cars ▪ Purchase price higher than ICE ▪ TCO ~€3,000 higher than ICE TCO ▪ Fuel costs comparable to ICE due to high infrastructure cost	▪ Higher purchase price and TCO than ICE ▪ Better fuel economy than ICE for larger cars ▪ Low infrastructure cost	▪ Most economic vehicle ▪ Lowest purchase price ▪ Higher fuel or maintenance costs ▪ Existing infrastructure

1 Consumer economics can be different, dependent on tax region
2 Fast charging for BEVs implies reduced battery lifetime, lower battery load and higher infrastructure costs than included in this study
SOURCE: Study analysis

Exhibit 36: Snapshot of 2030 – only a portfolio of power-trains can satisfy key criteria for performance and the environment

With a driving performance comparable to ICEs and a TCO comparable in the J segment, FCEVs are the lowest-carbon solution for medium/larger cars and longer trips.

With limited driving range, BEVs are ideally suited to smaller cars and urban mobility. Although considerable cost improvements in battery technology are considered in this study, it is not expected to achieve significantly lower specific volumes or weights beyond 2020.

PHEVs demonstrate a considerable CO_2 reduction. This applies either when using biofuels or driving short distances. The smaller installed battery depletes quickly when driving at a higher speed, with a heavier load or over a longer distance. Although fuel economy is better than ICEs for larger cars (especially in stop/start city driving), the purchase price and TCO is higher and from 2030, PHEVs no longer have a cost advantage compared to FCEVs.

4. Costs for a hydrogen infrastructure are around 5% of the overall cost of FCEVs (€1,000-2,000 per vehicle)

In order to develop a portfolio of drive-trains, several supply infrastructure systems are required – not only for gasoline and diesel, but potentially new infrastructures for CNG, LPG, 100% biofuels, electricity and hydrogen. Early commercial deployment of BEVs and PHEVs is already happening in several European countries: many car manufacturers have announced production and the first commercial models are expected between 2011 and 2014. This report therefore focuses on the commercial deployment of FCEVs, which still needs to be addressed.

One could argue that it is inefficient to build an additional vehicle refuelling infrastructure on top of existing infrastructures. However, the additional costs of a hydrogen infrastructure are relatively low compared to the total costs of FCEVs and comparable to other fuels and technologies, such as a charging infrastructure for BEVs and PHEVs.

Costs for a hydrogen distribution and retail infrastructure represent 5% of the overall cost of FCEVs – the vast majority lies in the purchase price. The attractiveness of the business case for FCEVs is therefore hardly affected by the additional costs required for distribution and retail. In other words, if FCEVs make commercial sense – as demonstrated by this study – building a dedicated hydrogen infrastructure can be justified.

In the first decade of a typical roll-out scenario, supply infrastructure costs – especially those for a retail infrastructure – are initially higher, due to lower utilisation. Nevertheless, sufficient network coverage must be available for consumers and initial investments required could amount to €3 billion (covering hydrogen production, distribution and retail). Although a single company would struggle to absorb the risk of such an investment, this is not the case at a societal level. This is confirmed by countries which have built up alternative infrastructures, such as CNG and LPG.

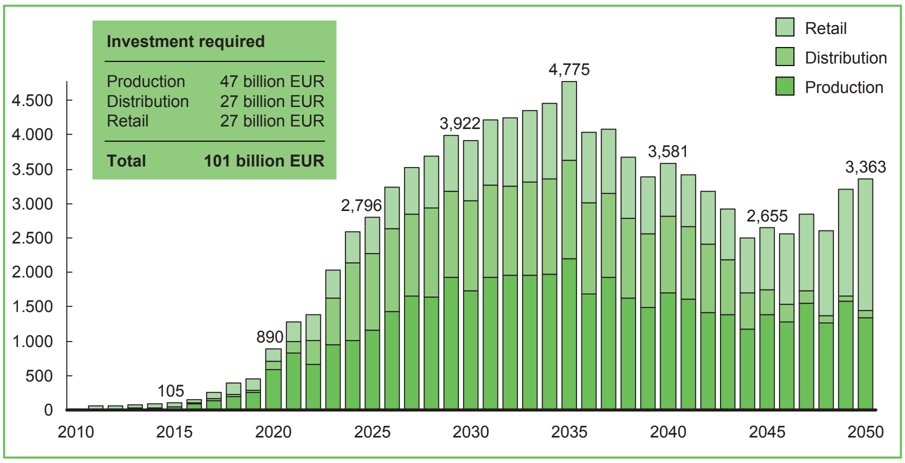
The cost per vehicle for rolling out a hydrogen infrastructure compares to rolling out a charging infrastructure for BEVs or PHEVs (excluding potential upgrades in power distribution networks) – see Exhibit 38 below. The costs for hydrogen retail and distribution are estimated at €1,000-2,000 per vehicle (over the lifetime), including distribution from the production site to the retail station, as well as operational and capital costs for the retail station itself. The average annual investment of €2.5 billion compares to that for other industries, such as oil and gas, telecommunications and road infrastructure, which each amount to €50-€60 billion[2]. It is also significantly less than additional investments required to decarbonise power (€1.3 trillion[3] over 40 years).

Costs for an electric charging infrastructure range from €1,500 to €2,500 per vehicle. The higher end of the range assumes 50% home charging (investment of €200-€400 per charging station) and 50% public charging (investment of €5,000-€10,000 for a charging station that serves two cars. Potential additional investment in the power distribution networks are not included, but could be material, depending on the local situation. In contrast, once the territory is covered, no further investment is needed in hydrogen infrastructure – regardless of the number of cars – due to the fast refuelling time. As the number of FCEVs increase, it also benefits from economies of scale.

2 Global Insight
3 www.roadmap2050.eu

a. Up to 2020, FCEVs require €3 billion supply infrastructure investment for 1 million cars

EUR millions



1 Current annual capex requirement for the EU

SOURCE: WIS Global Insight; OVUM; OECD / International Transport Forum; study analysis

Exhibit 37: Total capital investment for a large-scale roll-out of hydrogen supply infrastructure in Europe is estimated at €100 billion over 40 years

Initial investment before 2020 is relatively low, as it will be concentrated in areas of high density, such as large cities. Investment in retail stations is required in order to reach sufficient coverage of the territory, while being initially under-utilised. Retail cost then decreases as more vehicles are deployed, with a higher utilisation of the retail station.

The conclusions in this study are based on 25% penetration of FCEVs in Europe by 2050 (see pages 16-18). To achieve a 50% penetration, the cost of infrastructure would rise by another €75 billion, but there would be no significant difference in TCO per vehicle.

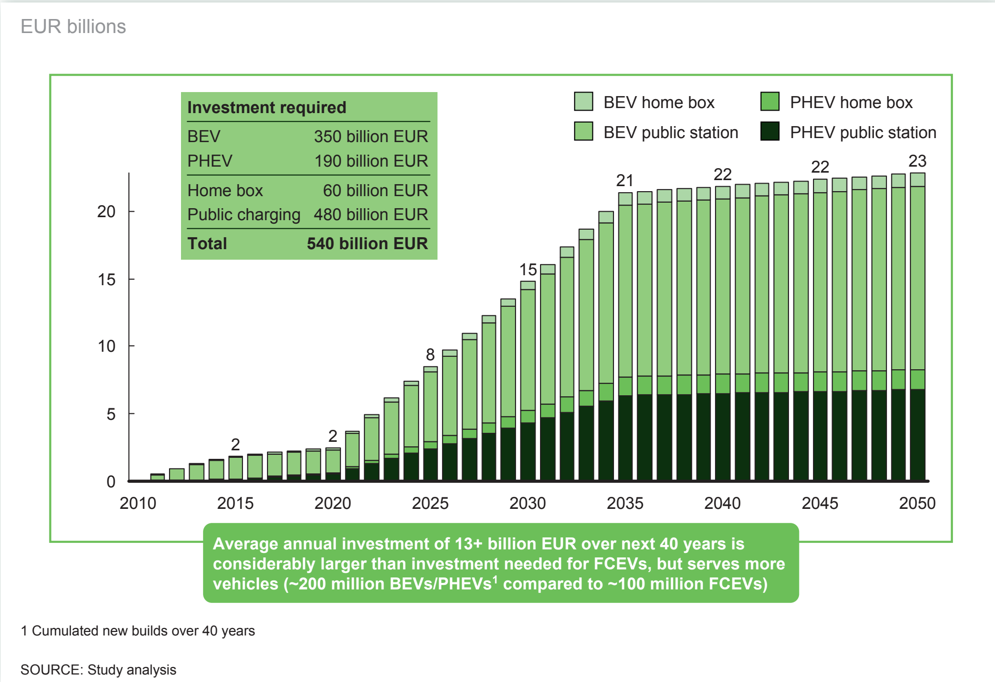


Exhibit 38: A large-scale roll-out of BEVs and PHEVs in Europe could require up to €500+ billion over the next 40 years

Electrical infrastructures could require an average annual investment of €13+ billion until 2050 in order to serve 200 million BEVs/PHEVs. Two thirds of this relates to BEV infrastructure, as they could require a higher share of public charging stations than PHEVs.

5. The deployment of FCEVs will incur a cost to society in the early years

The benefits of lower CO_2 emissions, lower local emissions (NO_2, particles), diversification of primary energy sources and the transition to renewable energy all require an initial investment. However, these will ultimately disappear with the reduction in battery and fuel cell costs, higher economies of scale and potentially increasing costs for fossil fuels and ICE specifications.

A roll-out scenario that assumes 100,000 FCEVs in 2015, 1 million in 2020 and a 25% share of the total EU passenger car market in 2050 results in a cumulative economic gap[4] of €25 billion by 2020. Almost 90% of this relates to the relatively higher cost of the FCEV in the next decade. The CO_2 abatement cost is expected to range between €150 and €200 per tonne in 2030 and becomes negative for larger cars after 2030.

A strong case will be required to persuade governments as to the level of explicit subsidy needed. In subsequent steps, it will therefore be important to make proposals that show how industry is taking responsibility for all the risks that they can reasonably analyse, control and mitigate. Discussions with Member State and EU governments are likely to focus on sharing the costs and risks between public and private sectors.

4 Economic gap is the delta between the TCO of the power-train under consideration and the ICE TCO, multiplied by the number of vehicles in the respective year.

Up to 2020: a cumulative economic gap of €25 billion

Around €3 billion investment is required for a hydrogen supply infrastructure (production, distribution, retail) for 1 million FCEVs by 2020. Of this investment, around €1 billion relates to retail infrastructure. This will be concentrated in high-density areas (large cities, highways) and build on existing infrastructure. If only one energy company made the investment in retail, it would face a first-mover disadvantage due to the initially low utilisation by a small number of FCEVs. This could lead to a potential write-off of around €0.5 billion per annum if roll-out is terminated or delayed. The initial investment risk would be somewhat reduced if further companies also invest and even further if the roll-out is co-ordinated by government and supported by dedicated legislation and funding.

The remaining €2 billion required for production and distribution presents a different investment risk: hydrogen producers do not expect a shortfall and can meet hydrogen demand as it arises, being paid-for product at rates that would cover their costs. In the first couple of years, in particular, hydrogen producers can respond with existing production capacity without large speculative upfront expenditures. Incremental capacity could then be added in small units at reasonable cost. The same applies to the distribution of hydrogen envisaged during this period.

While hydrogen producers may enjoy a first-mover advantage, retail investors face a first-mover disadvantage. Hydrogen manufacturers have an incentive – as soon as the economics work – to race to beat their rivals. While financial incentives are required to persuade consumers to appreciate FCEVs, there is nothing to hold the hydrogen manufacturers back – as long as the retail infrastructure is in place. They may also gain a marketing advantage. Infrastructure providers, on the other hand, bear a first-mover risk, making a heavy upfront outlay to build a retail station network that will not be fully utilised for some years; the unit cost reduces over time simply because the fixed capital expenditure is used by an increasing number of FCEVs.

To reap the benefits of lower emissions, energy diversification and technology development, a cumulative economic gap for FCEVs of €25 billion may develop up to 2020, mainly due to a higher purchase price. If this is met by only a few car manufacturers, they will each need to finance €1 billion per year. An incentive to ramp up production therefore only exists if most car manufacturers commit and co-ordinate, and government provides temporary funding support.

This report assumes complete tax neutrality among the four power-trains, which allows clean comparison of technologies, but may not be realistic where practical policy is concerned. Gasoline is heavily taxed throughout the EU and various green incentives are in place (see page 43).

Financial support for car manufacturers could be provided through tuning the tax regime. For the period to 2020, more explicit per-vehicle subsidies could also be applied. In the case of infrastructure support, some form of underwriting or sharing by government of investment risk may be more appropriate – the issue being not so much the cost of building the infrastructure as the risk that the market does not develop, leaving the infrastructure a stranded asset.

It is possible that governments could elect not only to provide the “carrot” of support to both cars manufacturers and infrastructure providers, but also the “stick” of legislation. Legislation would need to be credible and may present the risk of unstable outcomes that could leave the first-mover problem only partly resolved; however, it could have a role.

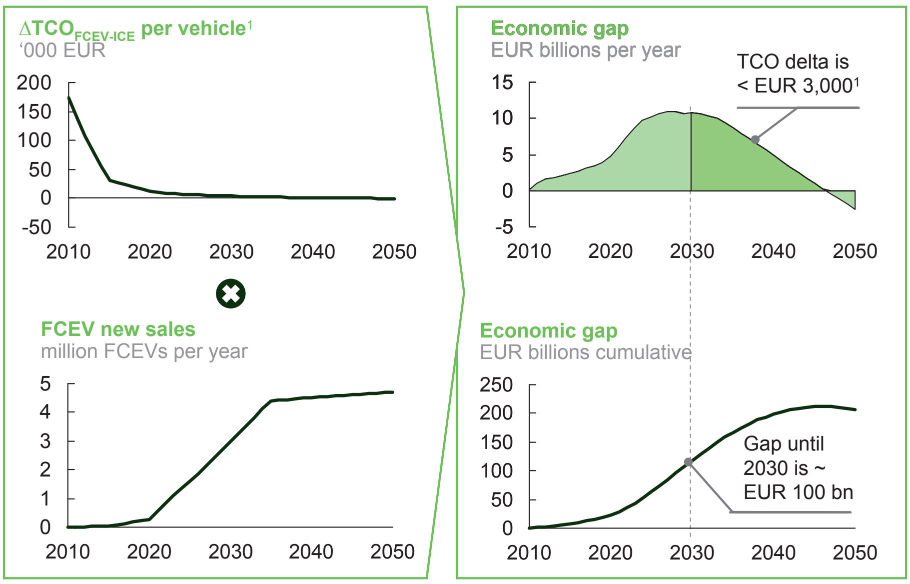
2020-2030: a cumulative economic gap in the order of €75 billion due to increasing car volumes

If a core infrastructure is in place by 2020, even if it were regional, with a critical mass of FCEVs on the road, there could be a much greater willingness to invest and more scope for finely tuned legislative measures and tax incentives. However, as 2020 approaches, it will become clearer whether target numbers and costs are being reached – and whether 1 million vehicles is indeed the critical number to achieve momentum. At this stage, it seems possible that any government support needed during this period could be provided through tax and regulatory systems, without special measures or subsidies.

Beyond 2030: any potential remaining economic gap per vehicle is expected to be small and carried by the consumer

After 2030, it can be assumed that the majority of the consumers will be financially driven, making their choice of car in response to an established tax and legislative regime. Provided these are stable and clear, car manufacturers, hydrogen manufacturers and infrastructure providers should all be able to make investments on the basis of well-understood risks and projected returns.

a. FCEVs face a cumulative economic gap of €25 billion (cars + infrastructure) up to 2020



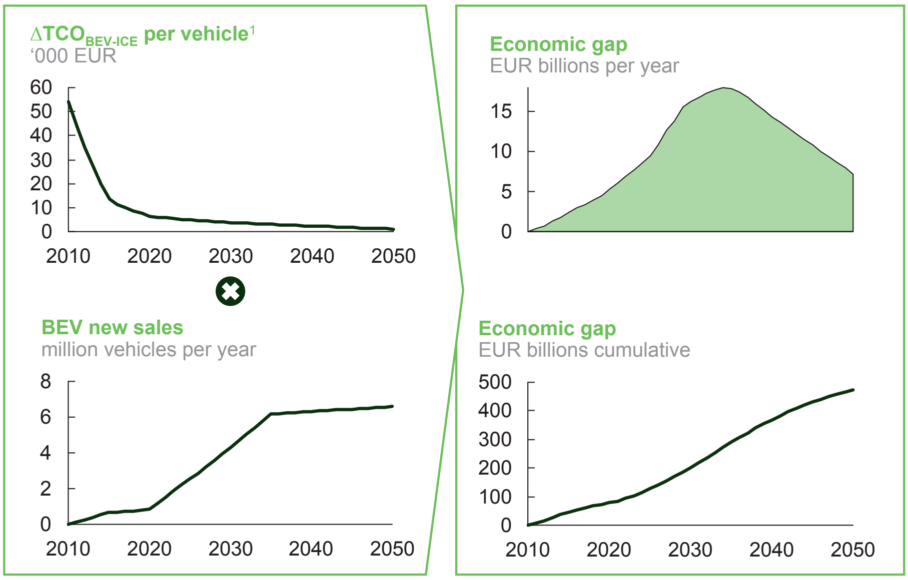
1 Weighted by segments (7% in A/B segments, 39% in C/D/E segments and 54% in J/M segments)

SOURCE: Study analysis

Exhibit 39: The cost of shifting from ICEs to FCEVs may amount to €4-5 billion per year for Europe (€500 per new car), with the economic gap beginning to close after 2030

Up to 2020, FCEVs face a cumulative economic gap (cars + infrastructure) of €25 billion (mainly due to a higher purchase price) and an additional €75 billion up to 2030.

The TCO of FCEVs vs. ICEs falls dramatically by 2020 and is competitive with ICEs by 2030 for medium/larger cars, at which point it is anticipated that the economic gap per vehicle may be passed on to the consumer. However, the economic gap continues to rise due to increased sales.



1 Weighted by segments (53% in A/B segments, 43% in C/D/E segments, and 5% in J/M segments)

SOURCE: Study analysis

Exhibit 40: BEVs could face a cumulative economic gap of €80 billion by 2020, €500 billion by 2050

In total, a cumulative economic gap of €80 billion exists for BEVs by 2020 and €500 billion by 2050. (For an analysis of the economic gap for PHEVs, see Annex, Exhibit 57, page 61.)

Owing to their modular nature,[5] electrical infrastructures are easier to build up, but after 2020, infrastructure costs for FCEVs are less than those for BEVs as the number of public charging stations remains commensurate with the number of cars, due to the lengthy recharging time. In contrast, once the territory is covered, no further investment is needed in hydrogen infrastructure – regardless of the number of cars – due to the fast refuelling time. By 2030, infrastructure for BEVs therefore costs 1.5 - 2.5 cents per kilometre, compared to 1.5 cents per kilometre for FCEVs.

5 The study assumes 50% home charging (75% for PHEVs), 50% public charging, with two sockets serving two cars per public charging station, i.e. four cars

NEXT STEPS

In April 2010, the European Commission confirmed that "Green vehicles, including those capable of using electricity, hydrogen, biogas and liquid biofuels in high blends, are likely to contribute significantly to the Europe 2020 priorities of...promoting a more resource efficient, greener and more competitive economy".[1] This echoed the call of the European Parliament in 2007 to "institute hydrogen fuel cell storage technology, and other storage technologies, for portable, stationary and transport uses and establish a decentralised bottom-up hydrogen infrastructure by 2025 in all EU Member States".

Urgent action is required for passenger cars to achieve EU CO_2 reduction goal

Plans for the market launch of electric vehicles should therefore be initiated jointly by car manufacturers, equipment manufacturers and infrastructure providers. In the short term, CO_2 emissions will have to be reduced by more efficient ICEs and PHEVs, combined with biofuels.

But investment cycles in energy infrastructure are long and for BEVs and FCEVs to achieve the economies of scale necessary to meet the EU's CO_2 reduction goal, action must be taken as a priority. Implementation plans for BEVs and PHEVs are described in other reports, therefore this report focuses on FCEVs.

a. Prepare EU market launch plan study for FCEVs and hydrogen infrastructure

This study presents a first step towards a wider, co-ordinated EU roll-out plan study for FCEVs and hydrogen infrastructure. With all technological hurdles resolved and thousands of hours of testing in a customer environment, industry is clearly ready – as demonstrated by the Letter of understanding issued by car manufacturers in 2009 (see page 13) and the global consortium of stakeholders who have been prepared to share confidential data for the express purposes of this study. The next logical step is to develop a comprehensive and co-ordinated EU market launch plan study (Exhibit 41). This consists of two phases:

1. An in-depth business case and implementation plan for a single Member State (i.e. Germany), starting in 2015. At the same time, a series of FCEV demonstration projects should also start in other Member States in order to gain experience with the technology.

2. A staged roll-out plan study – first, a market introduction in Member States that have developed experience through the demonstration projects above, followed by other Member States.

The above single Member State implementation plan should be fit for investment by companies and the public sector. This includes addressing the risks associated with the plan, how hydrogen will be decarbonised and its impact on future CO_2 emissions from the transport sector.

As this study indicates, there is a first-mover disadvantage for retail investors. ***However, if several hydrogen retail infrastructure providers invest (e.g. via a consortium), or a market-based mechanism is developed to spread the risk between different infrastructure providers, none will gain a "free ride". The market launch plan must therefore go hand-in-hand with clear government incentive mechanisms to offset this risk, or the launch will not happen.***

After the technology has been de-risked and achieved cost reductions in one Member State – with a series of small, subsidised demonstration projects taking place in parallel in other Member States – a staged EU roll-out plan study is required, with market introductions in those Member States that have gained experience through the earlier demonstrations.

1 COM(2010)186: A European strategy on clean and energy efficient vehicles

(Staging the roll-out will address the supply limitations of car manufacturers and hydrogen infrastructure providers who cannot undertake market introductions in all Member States at the same time.) Market introductions and hydrogen supply infrastructure build-up should also take into account the preferred primary energy resources of different Member States and CO_2 reduction goals for the transport sector as a whole.

FCEV demonstration projects in other Member States are likely to start in 2015. These should ideally benefit from the learnings in Germany. Starting too early could result in a 50% higher investment for the same volume of cars, e.g. for a country such as Belgium a FCEV demonstration project comprising 100 vehicles and four stations in 2011 would cost €30 million now, versus €12-13 million if implemented after the German launch (the cost of FCEVs will have reduced by a factor of four to five and retail stations by a factor of two).

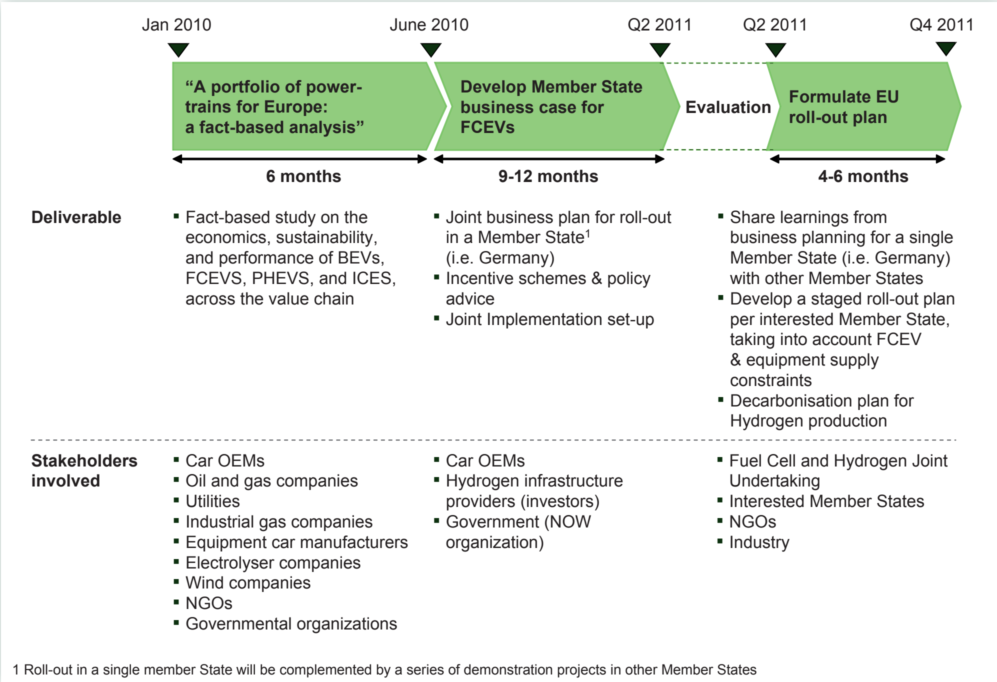


Exhibit 41: Market launch plan for FCEVs in Europe

b. Co-ordinate roll-out of BEVs/PHEVs and battery charging infrastructure

A similar action would be helpful to support the roll-out of BEVs and PHEVs in the EU. Here, too, the risk of market failure exists, but as investment per electric recharging point is low in non-public applications, so is the financial risk for infrastructure providers in such cases. However, as with hydrogen infrastructure, upfront investment for public charging will be necessary in order to give customers appropriate access to infrastructure from the start.

In order to achieve a sound market introduction, the technology also needs to be commercially de-risked and several programmes for BEVs already exist in various European countries and at EU level,[2] addressing issues such as technology, market introduction, funding schemes and standardisation etc. A coherent approach to all these activities would help to optimise development and support early market readiness.

2 European Green Car Initiative

ANNEX

Value set by study participants

Value chain		Learning Rate[1] Percent	Annual Improve[2] Percent
Vehicle	FC stack	15	2.2[3]
	H_2 tank	15	2.2[3]
	FC periphery	15	2.2[7]
	EV-specific parts[4]	10	2.3[7]
	Battery	7	1.5
	ICE related parts[5]	N/A	1.5
	Tech. packages[6]	N/A	1.5
	ICE parts	N/A	0
	"Glider"	N/A	0
Supply[3]	DSMR	6	0.0[8]
	CSMR	5	0.1
	WE	7	0.4
	IGCC/CG	3	0.1
	CCS	7	0.7
	Delivery Trucks	1	0.1
	Pipeline	1	0.2
	Liq./Comp.	1	0.1
	Retail stations	3	0.6

Example Technologies	Learning Rate[1] Percent	Annual Improve[2] Percent
Solar PV	22	10
Wind	15	7
Solar Thermal	9	7
Ethanol	15	6
LNG	13	4

Higher learning rates are observed in other new technologies

1 Percent cost reduction with every doubling of accumulated installed capacity
2 Annual reduction in cost
3 Annual improvement from 2020-2050 from applied learning rate
4 electric motor, transmission, inverter, wiring, controls
5 ICE, generator, fuel tank, exhaust
6 Includes power-train and non-power-train efficiency packages
7 Annual improvement rate is 4% and 1.5% from 2020-2030 and after 2030 respectively
8 No capacity added after 2020, resulting in no annual improvement

SOURCE: Worldwatch Institute; IEA; BTM Consult; ABS; NREL; IIIEE; ABI; Drewry 2007; UC Berkeley ERG

Exhibit 42: Projected cost reductions of FCEVs and hydrogen supply are lower than historical improvements for comparable technologies

Efficiency, Percent

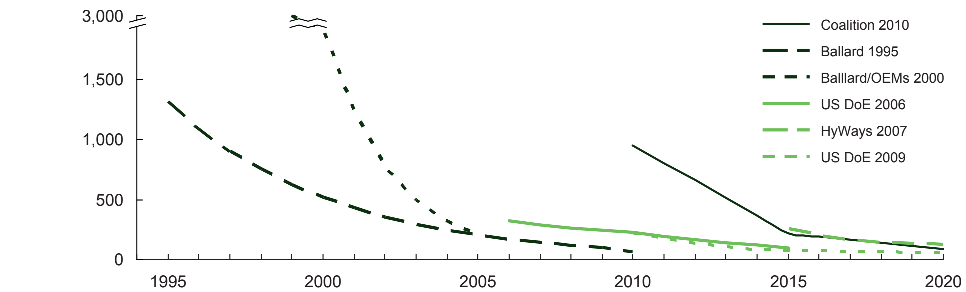
Common production pathways | 2020

	Primary energy carrier	Fuel production		Distribution		Retail		Vehicle		Well-to-wheel efficiency
Primary sources	Oil	Gasoline	86%	Distribution	98%	Retail	99%	ICE	30%	25%
		Diesel	84%	Distribution	98%	Retail	99%	ICE	35%	29%
		Power	51%	Distribution	90%			BEV	68%	31%
		Power → H_2	34%	Distribution	89%	Retail	90%	FCEV	56%	15%
		H_2	51%	Distribution	89%	Retail	90%	FCEV	56%	23%
	Gas	CNG	94%	Distribution	93%	Retail	90%	ICE	30%	24%
		Diesel[1]	63%	Distribution	98%	Retail	99%	ICE	35%	21%
		Power	58%	Distribution	90%			BEV	68%	35%
		Power → H_2	39%	Distribution	89%	Retail	90%	FCEV	56%	18%
		H_2	70%	Distribution	89%	Retail	90%	FCEV	56%	31%
	Coal	Gasoline[1]	40%	Distribution	98%	Retail	99%	ICE	30%	12%
		Diesel[1]	40%	Distribution	98%	Retail	99%	ICE	35%	14%
		Power	50%	Distribution	90%			BEV	68%	30%
		Power → H_2	34%	Distribution	89%	Retail	90%	FCEV	56%	15%
		H_2	41%	Distribution	89%	Retail	90%	FCEV	56%	18%
	Biomass	Ethanol	35%	Distribution	98%	Retail	99%	ICE	30%	10%
		Biodiesel	35%	Distribution	98%	Retail	99%	ICE	35%	12%
		Power	35%	Distribution	90%			BEV	68%	21%
		Power → H_2	24%	Distribution	89%	Retail	90%	FCEV	56%	11%
		H_2	31%	Distribution	89%	Retail	90%	FCEV	56%	14%
Power	Renewable power	Power	100%	Distribution	90%			BEV	68%	61%
		Power → H_2	68%	Distribution	89%	Retail	90%	FCEV	56%	30%
	Uranium	Power	28%	Distribution	90%			BEV	68%	17%
		Power → H_2	19%	Distribution	89%	Retail	90%	FCEV	56%	8%

1 Gasoline and diesel production through Fischer-Tropsch process

SOURCE: CONCAWE-EUCAR JEC-WTW study; study analysis

Exhibit 43: FCEV well-to-wheel efficiency is competitive with ICE, with a flexible use of feedstocks, while BEV remains the most efficient power-train



	Ballard, 1995	Ballard/OEMs, 2000	US DoE, 2006
Basis of promise	▪ Technical advancements, mass production	▪ Mass production, catalyst reduction	▪ Higher yields, mass production, reduced BOP
Size/timing of FC market	▪ USD 4 billion in 2000, ▪ 10-50 billion in 2010	▪ 100,000 vehicles by 2005	▪ Mass FCEV production by 2020
Data sources	▪ Ballard Power Systems, Daimler	▪ Ballard Power Systems, Daimler, Ford	▪ US Department of Energy
Share of car OEMs committing[1]	▪ ~40%	▪ ~70%	▪ ~75%
"Showstoppers" resolved and major breakthroughs	▪ Sufficient fuel cell power density for automotive use	▪ Advances in materials technology (including platinum reduction), improved manufacturability	▪ Catalyst loading reduction, standardized modular design, improved MEA fabrication

Study fuel cell cost estimates are more conservative than previous estimates and are in line with most recent reports

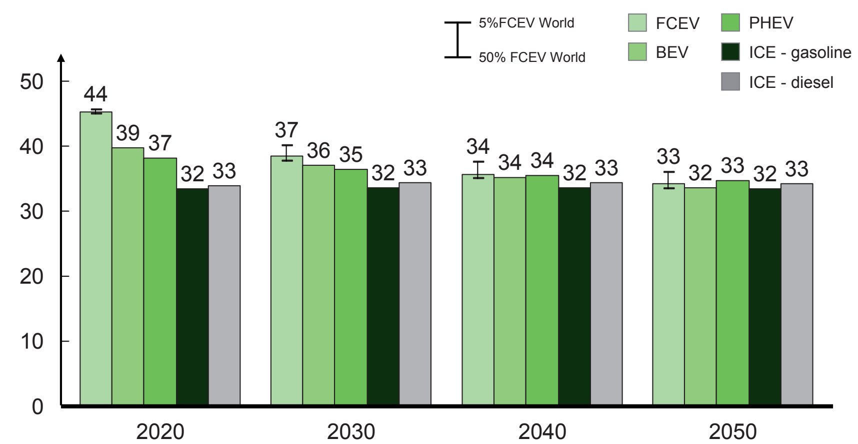
1 Combined light duty passenger vehicle market share of OEMs committing to fuel cell and/or FCEV research

SOURCE: Press search, OICA, US Department of Energy, study analysis

Exhibit 44: Summary of previous studies which were not based on proprietary industry data

C/D SEGMENT

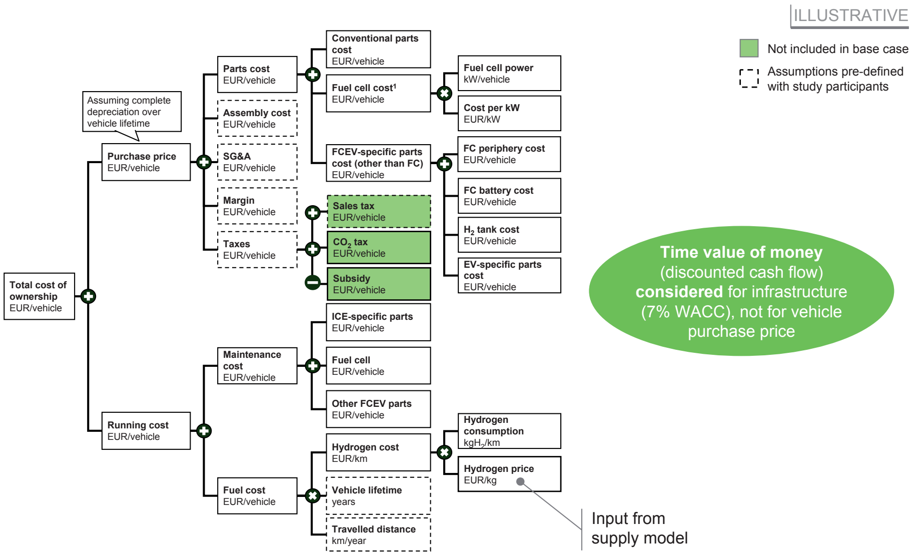
Total Cost of Ownership (TCO[1])
'000 EUR



1 Based on 15 years vehicle lifetime, 12,000 km annual driving distance, no tax (e.g., fuel excise, VAT)

SOURCE: Study analysis

Exhibit 45: The different "world" scenarios for the penetration of FCEVs in the EU – 5%, 25% and 50% – do not alter the business case dramatically

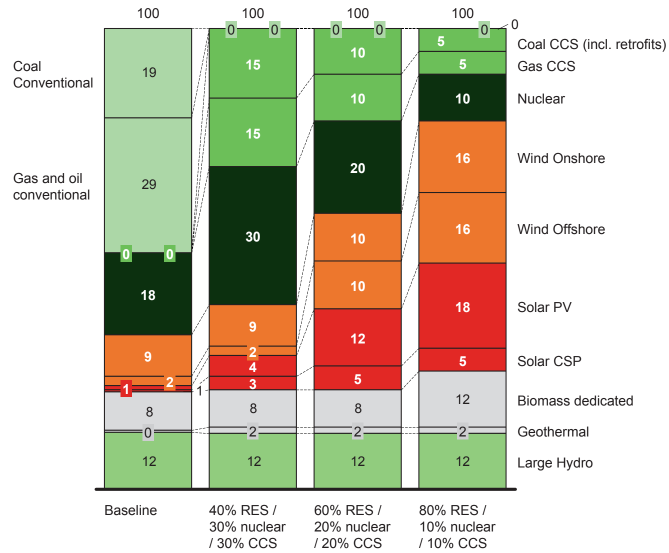


1 If fuel cell lifetime is less than average vehicle lifetime (mileage), a replacement fuel cell(s) will be required. The cost of the replacement fuel cell(s) will be included in the vehicle purchase price.
2 TCO based on 15 years lifetime and 12,000 km annual driving distance

SOURCE: Study analysis

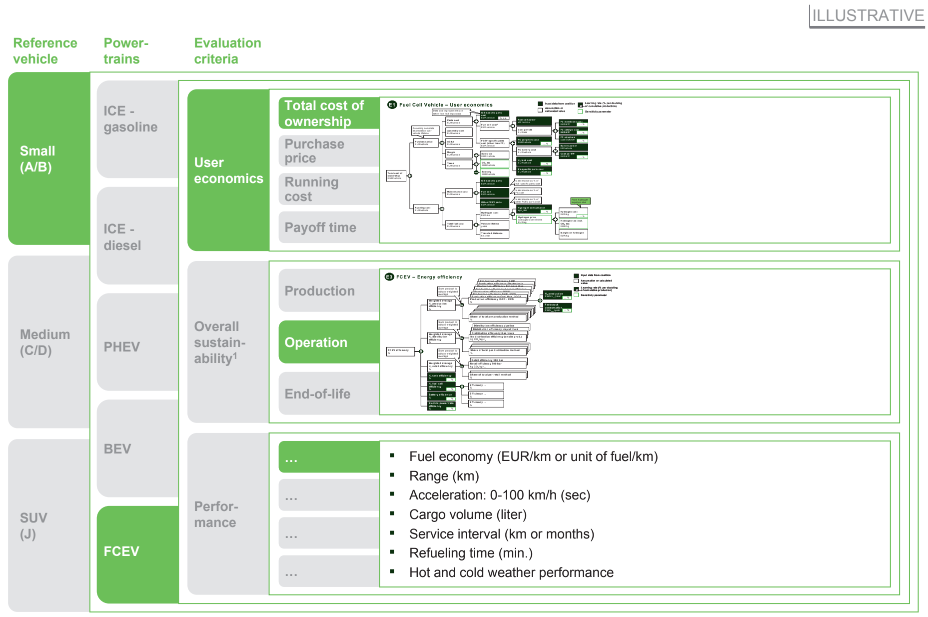
Exhibit 46: An example of a TCO calculation for FCEVs

In percentage of production



SOURCE: Imperial College; KEMA analysis; study analysis

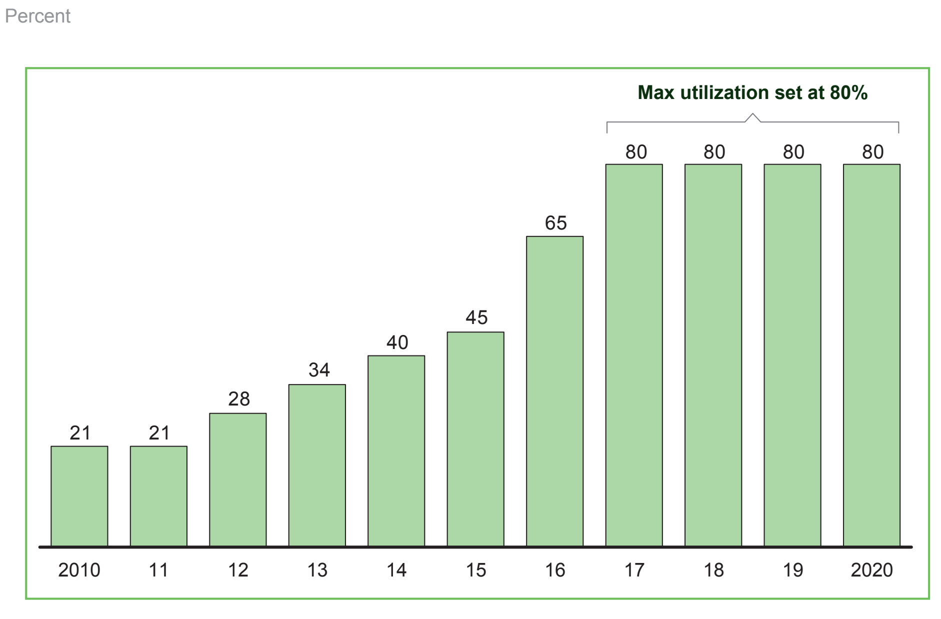
Exhibit 47: An EU 2050 production mix of 60% RES was assumed



1 Sustainability focuses on the operation (running period) of the vehicle, not emissions for vehicle production or end-of-life

SOURCE: Study analysis

Exhibit 48: The basic structure of the vehicle model used for the study



SOURCE: Study analysis

Exhibit 49: Average utilisation rate of hydrogen refuelling stations

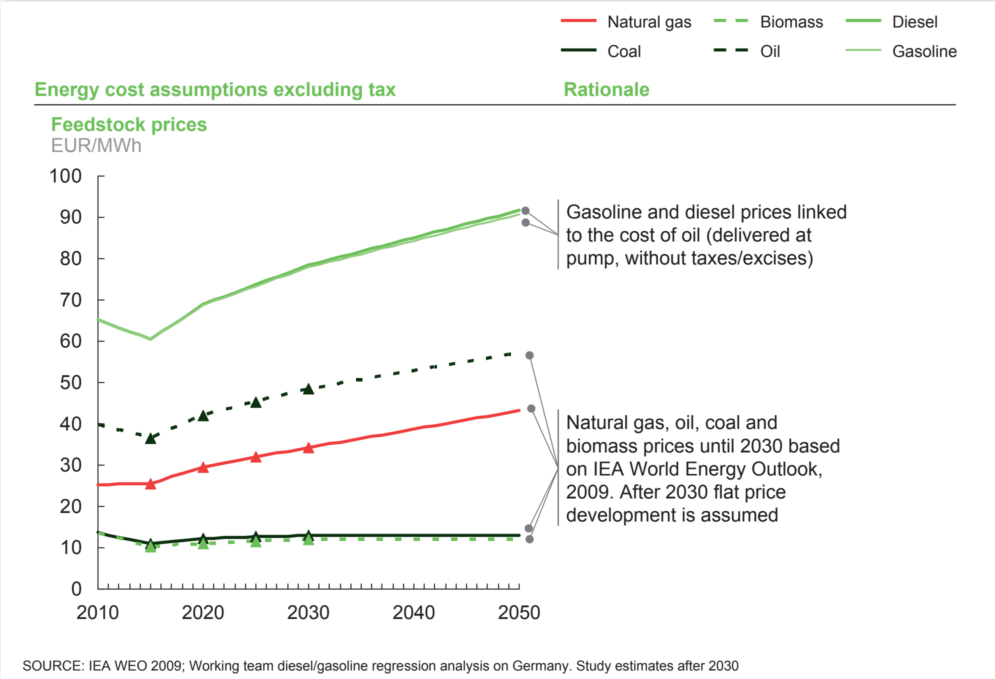


Exhibit 50: Feedstock price assumptions up to 2050 and corresponding gasoline and diesel prices (version 1)

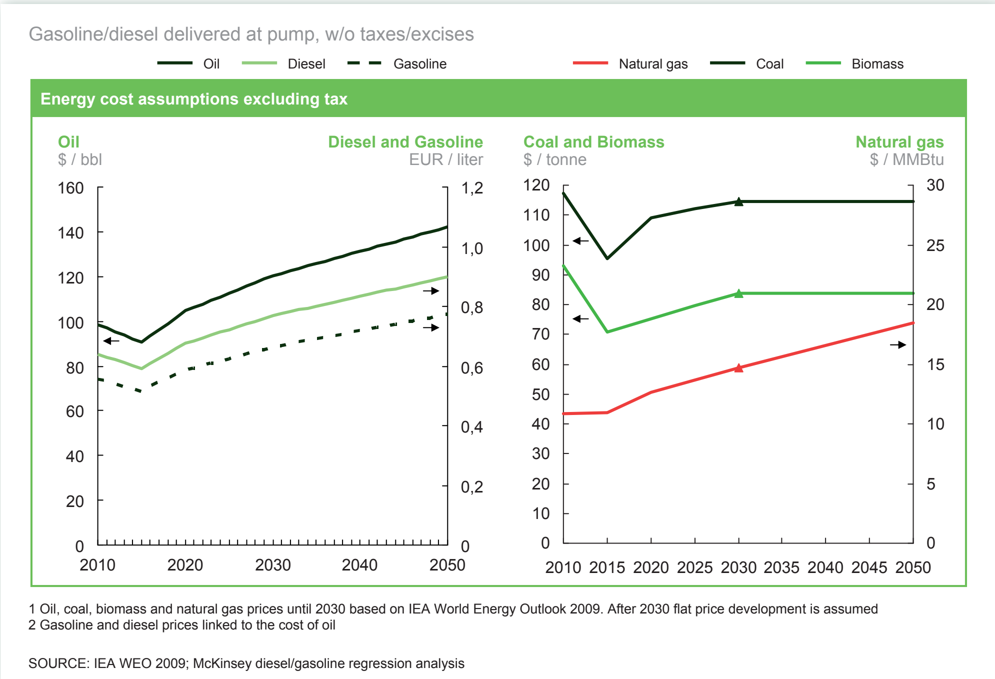
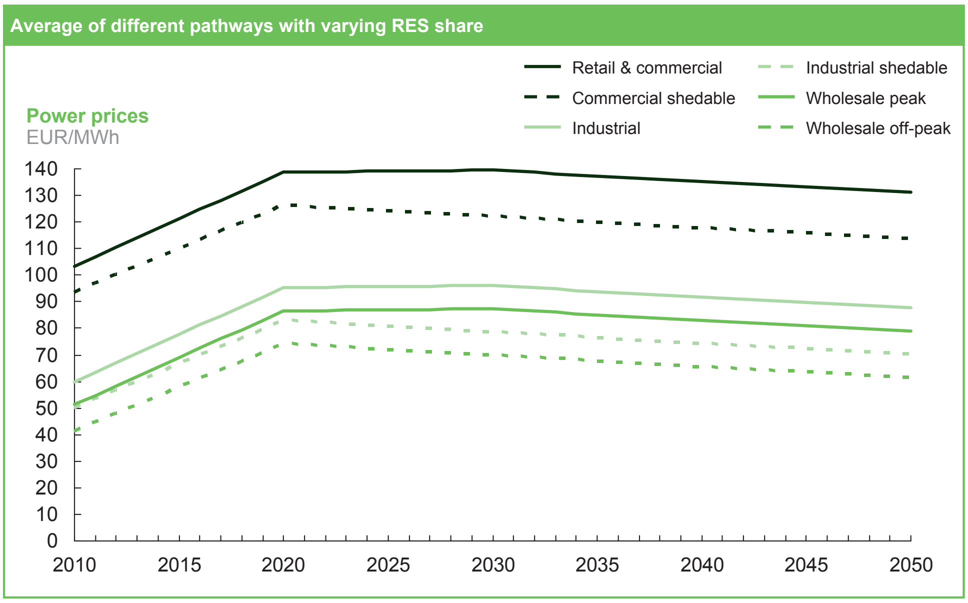
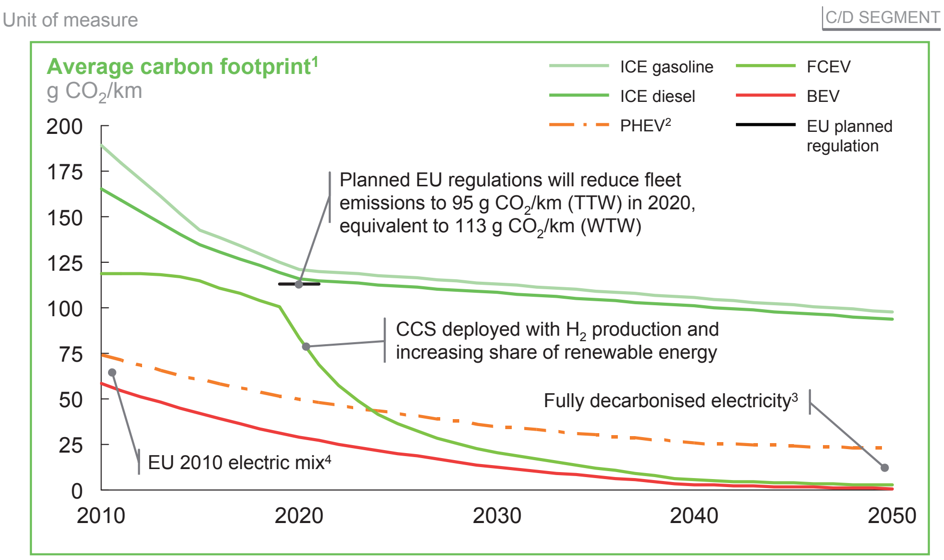


Exhibit 51: Feedstock price assumptions up to 2050 and corresponding gasoline and diesel prices (version 2)



SOURCE: EEX power spot price; "Roadmap 2050" study by the European Climate Foundation; Global Insight; study data

Exhibit 52: Power price assumptions for electrolysis production scenario



1 NEDC efficiency assumed
2 PHEV assumed to drive all electric for 77.5% of its total driving distance
3 EU2050 electricity assumes 80% renewable, 10% nuclear and 10% fossil with CCS generation
4 EU mix in 2010 contains 22% gas, 29% coal, 27% nuclear, 4% biomass, 16% renewable and 2% oil

SOURCE: Study analysis

Exhibit 53: In the long run, BEVs and FCEVs have the greatest potential to reduce CO_2 emissions

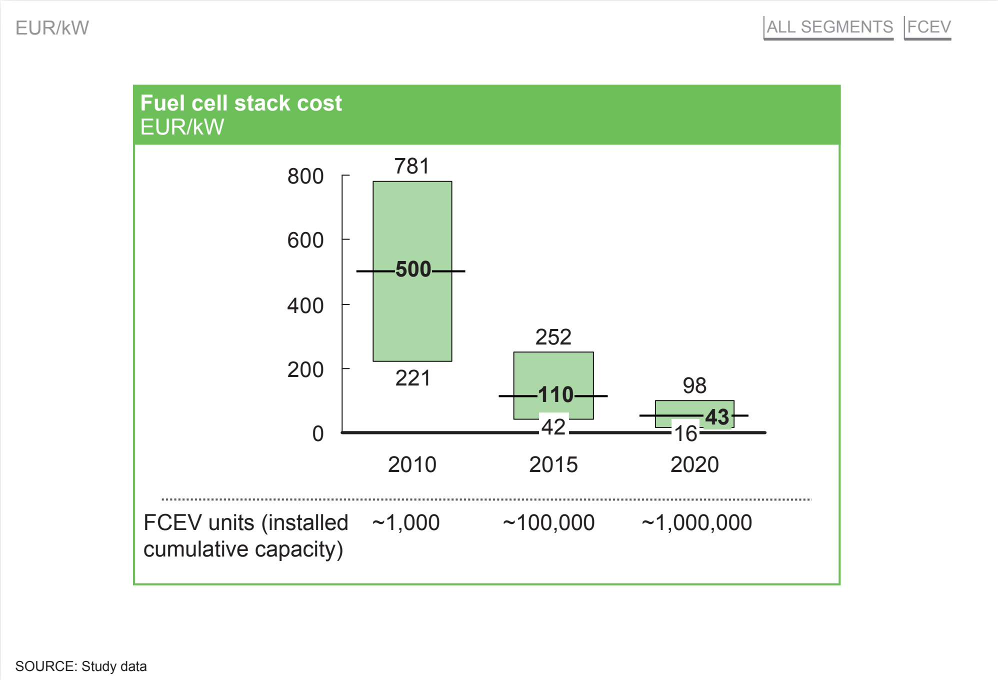


Exhibit 54: The cost of the fuel cell stack, based on data submitted by participating car manufacturers and suppliers

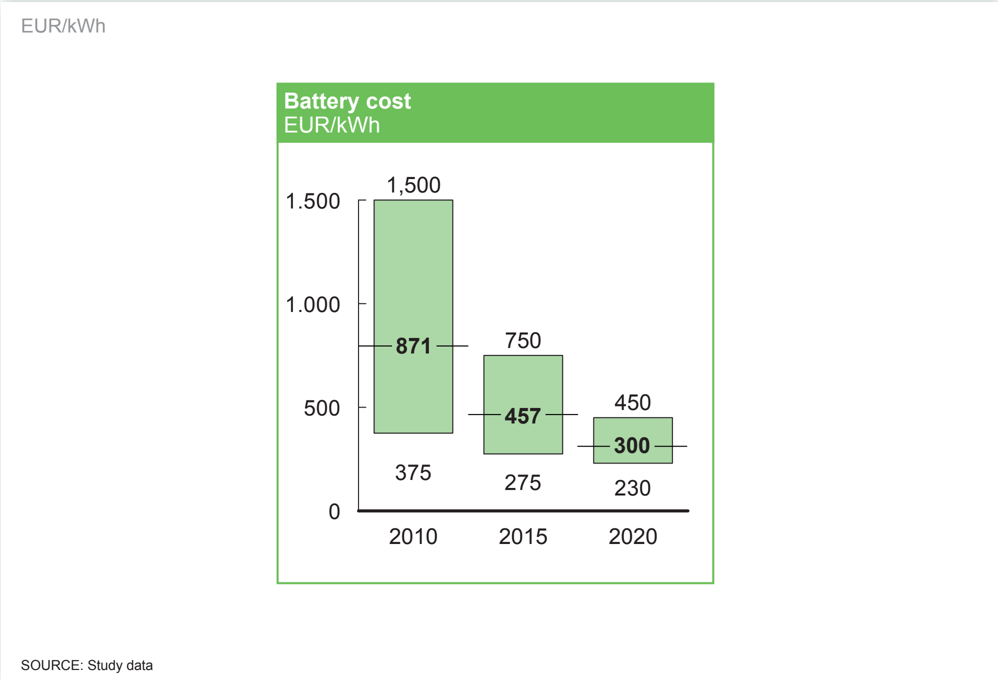
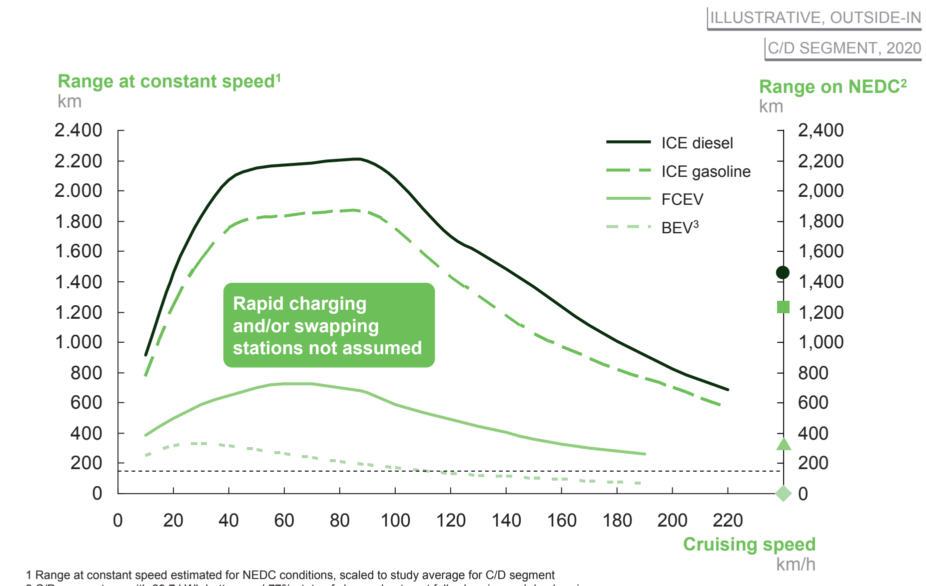


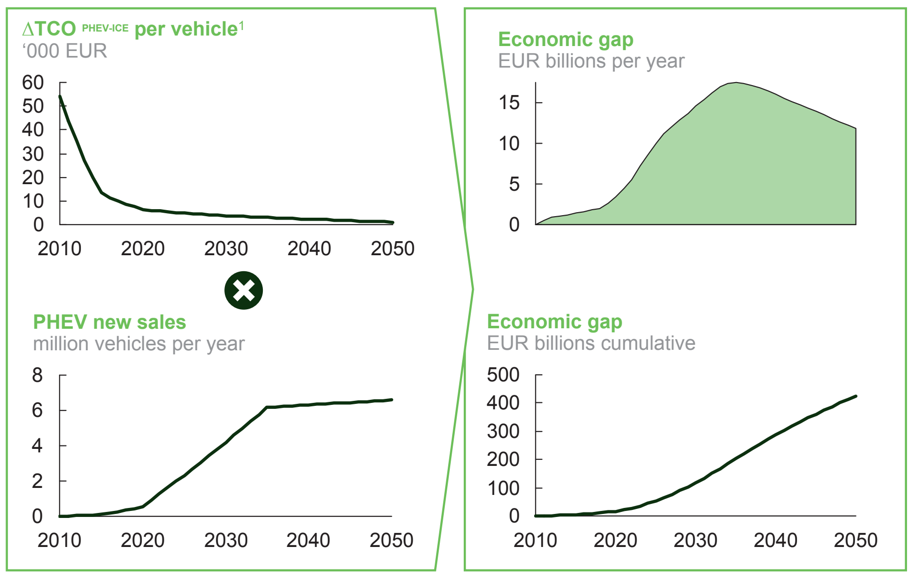
Exhibit 55: The cost of the battery, based on data submitted by participating car manufacturers and suppliers



1 Range at constant speed estimated for NEDC conditions, scaled to study average for C/D segment
2 C/D segment car with 29.7 kWh battery and 77% state of charge due to not fully charging and de-charging the battery for lifetime and performance reasons. Range on NEDC based on study data, assuming tank size and battery capacity stay constant ; range on NEDC is relatively better for FCEV and BEV, due to higher efficiency in transient driving
3 C/D segment BEV only allows 150 km trip at 120 km/hr

SOURCE: Study analysis

Exhibit 56: FCEVs have sufficient range at higher cruising speed, while BEVs are restricted on range



1 Weighted by segments (25% in A/B segments, 42% in C/D/E segments, and 33% in J/M segments)

SOURCE: Study analysis

Exhibit 57: PHEVs face an economic gap of €420 billion by 2050

GLOSSARY

350/750 bar	Pressure levels for hydrogen storage tanks
4 x 4	Four-wheel drive
BBL	Barrels of oil
BEV	Battery Electric Vehicle
CCS	CO_2 Capture and Storage
CG	Coal Gasification
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalents
CSMR	Central Steam Methane Reforming
CWE	Central Water Electrolysis
DSMR	Distributed Steam Methane Reforming
DWE	Distributed Water Electrolysis
ECE-15	The United Nations Economic Commission for Europe specification for urban driving cycle simulation
EU	European Union
EU27	European Union Member States
EU29	European Union Member States + Norway and Switzerland
ECE-15	The United Nations Economic Commission for Europe specification for urban driving cycle simulation
EUDC	Extra Urban Driving Cycle – specification for European urban driving cycle simulation
EV	Electric Vehicle
FC	Fuel Cell
FCEV	Fuel Cell Electric Vehicle
GDL	Gas Diffusion Layer
GHG	Greenhouse Gas
Gt	Giga (billion) tonnes
H2	Hydrogen
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
IEA	International Energy Agency
IGCC	Integrated Gasification Combined Cycle
ISO	International Organization for Standardization

kg	Kilogramme
km	Kilometre
m	Million
MEA	Membrane Electrode Assembly
MWh	Megawatt Hour
MPV	Multi-purpose vehicle
MJ	Megajoule
Mt	Mega (million) tonne
NEDC	New European Driving Cycle
NGO	Non-governmental organisation
OEM	Original equipment manufacturer
p.a.	Per annum
PEM	Proton Exchange Membrane
PDC	Per doubling of capacity
PHEV	Plug-in Hybrid Electric Vehicle
PPM	Parts per million
R&D	Research and Development
RES	Renewable energy sources
RTD	Research and Technology Development
SAE	Society of Automotive Engineers (SAE International)
Segment (A/B)	Small-size cars (see page 16)
Segment (C/D)	Medium-size cars (see page 16)
Segment (J)	Larger 4 x 4 SUV-type cars (see page 16)
SG&A	Selling, General and Administrative Expenses
SMR	Steam Methane Reforming
SUV	Sports Utility Vehicle
TCO	Total cost of ownership
TWh	Terawatt Hour
VAT	Value Added Tax
WACC	Weighted Average Cost of Capital
WE	Water Electrolysis
WTW	Well-to-wheel

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