8

FUTURE ENERGY SUPPLY AND THE COMPETITIVENESS OF ELECTRIC VEHICLES

Fredrik Hedenus
Maria Grahn
Department of Energy and Environment, Chalmers University of Technology*

* Division of Physical Resource Theory

Reviewers: Sten Karlsson, Physical Resource Theory, Energy and Environment, and Christoffer Saunders, Electric Power Engineering, Energy and Environment, Chalmers

INTRODUCTION

The future market for electric vehicles (battery electric vehicles and plug-in hybrid vehicles) will likely depend on technological developments (improvements to batteries and charging systems, for instance, see e.g. Chapter 3 and 15); regulatory and institutional settings; public acceptance and customer demands (Chapter 10-14). Academic scholars have examined these factors quite comprehensively. However, it is not sufficient that battery technology improves to a certain level; that charging becomes more efficient; or that regulatory frameworks support electric cars. Electric cars must also compete with other alternative vehicle technologies such as cars fuelled by biofuels or hydrogen fuel cell vehicles. Vehicles are also embedded in larger energy and transport systems. This holds true for all technologies, but may be of greater importance for electromobility, as electric cars are connected to and dependent on the electricity system. The cost and environmental impacts of electric vehicles are influenced by electricity costs and technologies used for producing electricity (see Chapter 5 and 6 on some environmental and energy resource implications of different types of electricity production). In this chapter we examine how the development of the energy sector can influence the competitiveness of electric cars in a carbon-constrained future.[1]

---

[1] This chapter is largely based on Hedenus et al (2010) *Cost-effective energy carriers for transport - the role of the energy supply system in a carbon-constrained world. International Journal of Hydrogen Energy 35 (10) pp. 4638-4651, and Grahn et al (2009) Fuel and vehicle technology choices for passenger vehicles in achieving stringent CO_2 Targets: Connections between transportation and other energy sectors, Environmental Science and Technology (ES&T) 43(9) pp. 3365-3371.*

The cost of producing electricity and transportation fuels will, in the long run, depend on the performance of conversion technologies and availability of resources. Scarce oil resources will increase the price of gasoline, whereas limited areas of productive land will drive up prices of biofuels. The development of technologies such as solar, wind and nuclear energy will be a key determinant of future electricity costs. There is also a potential link between electric cars and intermittent energy sources such as wind and solar, as batteries may temporarily store electric energy to be used in the grid during peak demand (Chapter 9).

This chapter focuses primarily on light duty vehicles for personal transport. We investigate if, and in which ways, the stationary energy system may influence the use of car technologies and fuel options, in a carbon-constrained future. We present data on competing vehicle technologies and explain which overall system effects influence cost-competitiveness. This is illustrated with results from the global long-term energy systems model GET. We conclude by discussing some policy implications of these potential system effects.

FUTURE COSTS OF ELECTRIC CARS AND ITS COMPETITORS

There are several alternative vehicle propulsion technologies and energy carriers that can achieve near-zero emission of greenhouse gases. These may or may not include an electric drivetrain (Chapter 2). In Hybrid Electric Vehicles (HEV), an electric motor is coupled to the internal combustion engine drivetrain (Chapter 3). The battery cannot be charged from the grid but enables the internal combustion engine to run more efficiently and excess energy is stored in the battery. When the engine needs extra power, such as during acceleration, stored electricity supports propulsion. This yields an overall efficiency about 30% higher than that of the conventional internal combustion engine (ICE) vehicle (see e.g. Chapter 6, Figure 6.4). HEVs are presently available on the market where the Toyota Prius is the market leader. At present, hybrid engines can be fuelled with either gasoline or diesel. In the future they may also be compatible with biofuels or gaseous fuels such as methane or hydrogen.

The Plug-In Hybrid Electric Vehicles (PHEVs) are similar to HEVs but with larger batteries that can be charged from the electric grid. PHEVs have a similar driving range to ICE vehicles, since the combustion engine is used when the battery is discharged. Again, fuel used in the internal combustion engine could, in principle, be liquid or gaseous. Today there are few commercially available PHEVs, but markets are expected to grow in years to come.

Battery Electric Vehicles (BEVs) use only a grid charged battery as power source, and are typically around three times more efficient than internal combustion engines (see Chapter 5 for an in depth discussion on efficiency). BEVs also eliminate most local pollutants. From a climate perspective, the electricity supplied to BEVs must be produced from low-emitting power sources such as renewables, nuclear energy or fossil energy using Carbon Capture and Storage (CCS) technology (see Chapter 6). BEVs typically have shorter driving ranges (100-200 km) compared to around 500 km for conventional vehicles. For this reason, BEVs are not directly comparable to other vehicles. There are a few BEVs available today, but batteries (which comprise a large part of vehicle costs) are expensive. To make BEVs commercially competitive, the battery production costs, capacity, and lifetime must be improved. BEVs are best suited to urban commuting due to their limited range (Chapter 10). Unless the overall transport system changes dramatically, BEVs cannot reasonably be expected to out-compete conventional vehicles (see Chapter 11 and 12 for alternative appraisals of customer value).

Fuel cells in vehicles generate electricity to drive an electric motor using hydrogen fuel and oxygen from the air. Fuel cell vehicles (FCVs) are expected to be around 50% more efficient than conventional gasoline vehicles. There are a few FCVs available today, but there is no mass-production. Fuel cells are expensive and improvements to production cost and lifetime are required. Additionally, hydrogen is challenging and costly to distribute and store, and there is a lack of an infrastructure to supply hydrogen to vehicles. FCVs could also be equipped with a reformer so that biofuel or fossil fuel could be converted to hydrogen on board, but this implies both a loss of efficiency and increased cost.

Since this chapter focuses on the climate impacts of transportation, we consider energy carriers such as electricity, hydrogen and biofuels that can lower the CO_2-emissions compared to current fuel use. Fossil fuels considered are gasoline, diesel and natural gas whereas coal-based fuels are assumed to give raise to too large amounts of CO_2-emissions to be considered part of a carbon-constrained future. In principle, the vehicle technologies described here may be combined with all types of fuels, as presented in Table 8.1.

Table 8.1 Examples of combined propulsion technologies and energy carriers for road vehicles that could be consistent with stringent climate targets.

Vehicle technology	Electricity	Hydrogen	Biofuels	Fossil fuels
Battery electric vehicles (BEVs)	X			
Plug-in hybrid electric vehicles (PHEVs)	X	X	X	X
Internal combustion engine vehicles (ICEVs)		X	X	X
Hybrid electric vehicles (HEVs)		X	X	X
Fuel cell vehicles (FCVs)		X	X	X

Hydro and nuclear power are two well-established electricity production technologies with low greenhouse gas emissions. Other alternatives include renewable energy technologies, such as wind power and solar cells (PV), which are currently experiencing rapid growth. Both wind and solar are intermittent energy sources – they generate electricity when the wind is blowing and the sun is shining. The use of wind power and solar PV is thus limited unless temporary storage, enhanced transmission between regions or advanced demand-side management is introduced. Analyses indicate that around 20 % of the electricity supply can be produced from wind power alone in the EU without major systemic changes.[2] There appears to be three possible routes that can achieve significant global reductions of greenhouse gas emissions from electricity production. These are:

---

[2] Gregor Giebel. A Variance Analysis of the Capacity Displaced by Wind Energy in Europe Wind Energy (2007) 10:69–79.

renewable electricity systems with energy storage; fossil fuels with carbon capture and storage; and advanced nuclear technologies with a high level of safety and safeguards against nuclear weapon proliferation.

Hydrogen is currently produced commercially from natural gas (via steam reforming) and from electricity (via electrolysis). Hydrogen can be considered a low-emission fuel if the electricity used for electrolysis is produced with low carbon emissions. However, hydrogen produced via electrolysis is more costly than the electricity used to produce it. Other options for producing hydrogen with low emissions include thermo-chemical cycles fuelled by thermal solar or nuclear energy, steam-reforming of methane (natural gas or biogas) or gasification of solid energy sources (coal or biomass) where low or negative emissions can be achieved if carbon capture and storage technologies are applied to the conversion process. Hydrogen production options are less mature (with the exception of electrolysis) than renewable electricity production. Additionally, hydrogen requires a new distribution infrastructure, which is not the case for electricity.

The technological maturity of biofuel production varies for different kinds of fuels. Ethanol production from wheat and sugarcane and FAME production are commercially viable technologies. In contrast, second generation biofuels such as methanol, ethanol or DME produced from cellulosic materials are presently at research or demonstration phases (see Systems Perspectives on Biorefineries 2013, Chapters 2 and 12).

Internal combustion engines that use fossil fuels (gasoline and diesel) are presently the most competitive technology for road transport. This holds true even if there is a CO_2 price of around 100 EUR/ton CO_2, which is the case in many European countries. This is essentially due to the scale and maturity of the industrial system delivering the technology. This may change when the competing technologies benefit from economies of scale and learning. We therefore attempt to make a cost assessment of the various propulsion and energy carrier combinations from a future perspective (year 2030) (see discussion on time perspectives in Systems Perspectives on Biorefineries 2013, Chapter 1).

As a reference, we assume that a gasoline car with an 80 kW mechanical output has a specific price of 11,000 EUR (2010). Incremental costs for more advanced vehicle technologies are estimated for 2030, including an uncertainty range for key components.[3] Vehicle costs depend heavily on component costs. The cost of batteries, fuel cells, and hydrogen storage tanks are the most uncertain. As can be seen in Figure 8.1, the uncertainty of the HEV cost (which is already a relatively mature technology) is low compared to the cost of, e.g., FCVs. Based on our estimates, FCVs and BEVs are likely to be more expensive than alternatives in 2030.

Here we assume that BEVs have a range of 150 km, whereas all other types of cars have a range of 500 km. If we instead assume that the range is more than

---

[3] Battery costs are assumed to vary between 100-330 EUR/kWh compared to current cost around 700 EUR/kWh. Fuel cell stacks presently cost around 520 EUR/kW, and for the future scenario it is assumed that fuel cells are mass-produced in a cost range from 30-200 EUR/kW. Hydrogen and natural gas storage costs are varied over the ranges from 4-13 EUR/kWh and from 3-4 EUR/kWh respectively.

150 km, BEVs would be considerably more expensive as battery costs comprise a substantial part of total costs.

Fuel costs depend largely on how fuel is produced, and for this reason we consider the same types of vehicles in two different scenarios where we either assume that CCS will be large scale available (a CCS scenario) or not where in the latter scenario renewables, first and foremost solar energy, will dominate (a renewable scenario). Comparisons should mainly be made within each scenario. However the costs related to the HEV cars (on the right hand side in Figure 8.1) can be compared to both scenarios since these costs are not directly affected by the stationary energy system. Note that the fuel cost category includes costs of liquid or gaseous fuels alongside the cost of electricity and carbon dioxide emissions (at a price of 300 EUR/ton CO_2). Distribution and handling costs are also included, taking energy losses in different steps into account. The capital costs for producing fuels and electricity are varied by ±50%.

When the total costs are compared in Figure 8.1, hybrid biofuel vehicles are the lowest cost alternative (per km). They are followed by PHEVs run on biofuels, which are the most competitive alternative both in the solar and coal CCS scenarios. Note that the uncertainties are large, and in many cases cost ranges overlap for different vehicles technologies.

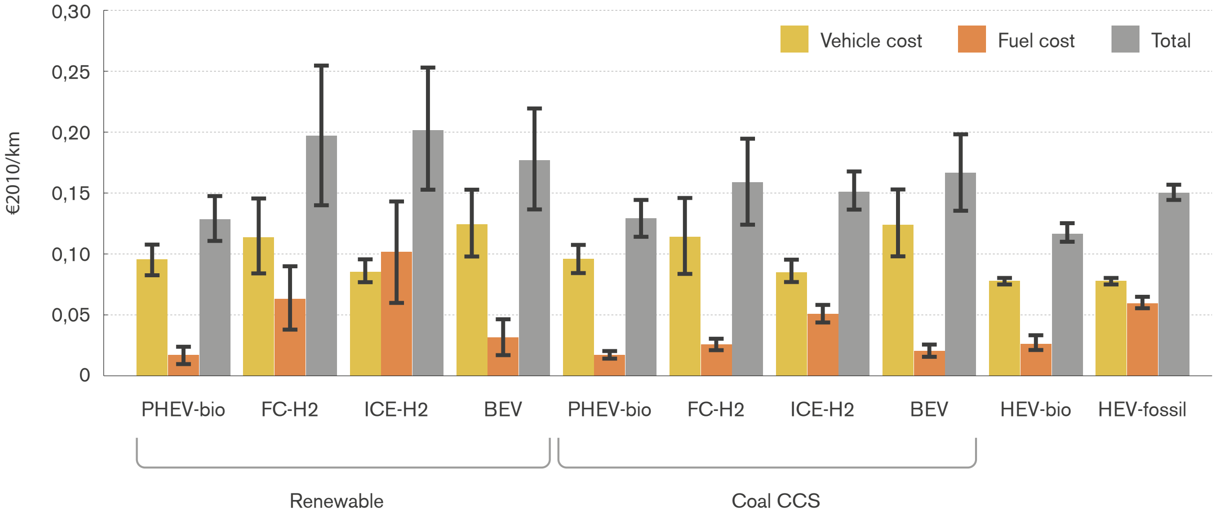

Figure 8.1 Costs per km for different propulsion and energy carrier combinations with uncertainty bars. Two different supply production scenarios are showed: one assuming that CCS will be large scale available and one without CCS where instead renewables dominate. A carbon dioxide cost of 300 EUR/ton CO_2 is applied to all fossil-based options. Vehicle costs are based on a theoretical standard car with an 80 kW engine and a driving range of 500 km. BEVs are assumed to have a driving range of 150 km.

IMPACT OF RESOURCE SCARCITY AND THE FUTURE EVOLUTION OF THE ENERGY SUPPLY SYSTEM

The costs in Figure 8.1 are basically estimates of production costs for vehicles and fuels. However, consumer prices are not only related to production costs. One critical issue is how the scarcity of different energy sources will affect the price of electricity and fuels.

If the demand for a product increases at a higher rate than production, there emerges a scarcity of that good and the price increases. For example, the high prices of apartments in city centres are related to a high demand and limited supply. It does not cost more to build an apartment in the centre compared to in the country side. But as demand for apartments in the centre grows, prices increase, and since there is not adequate space for more apartments supply cannot increase. A permanently higher price of apartments in attractive areas compared to less attractive areas is the result.

If there is a limited supply capacity for crude oil, for instance, the price of oil may increase rapidly if demand increases. A temporary scarcity rent may thus emerge. However, as new investments are made, supply increases and the price drops. However, if there is a physical scarcity of oil because of natural resource depletion, prices will continue to increase unless substitutes are available. To evaluate the relative competitiveness between different vehicle types it is thus important to evaluate scarcities that may emerge in the future. To this end one must assess geological resources; developments in extraction technologies; and demand projections. Oil is mainly used for transport and coal is mainly used for producing electricity and heat for industrial processes. Since the geological resources of oil are smaller than those of coal, it is likely that the oil price will rise at a faster pace than the coal price. This could favour a transition to electric cars because gasoline prices will increase faster than electricity prices – assuming that coal continues to be the primary fuel for electricity production.

However, resources such as biomass may also be subject to scarcity effects. Productive land and water is needed to produce biomass. Land is a limited resource that is subject to competition between food and fibre production. There is approximately 1.5 Gha of arable land and 3.5 Gha of pastoral land in the world. With rather optimistic assumptions we could dedicate 0.5 Gha to bioenergy production, which could produce around 100 EJs of raw biomass and perhaps an additional 100 EJ of bioenergy could be produced from residues in agriculture and forestry (see also Chapter 4 on bioenergy resources in Systems perspectives on Biorefineries). Energy demand for global road transport by 2050 is expected to be around 100 EJ of fuel, which is approximately the amount of fuel that can be produced from 200 EJ of raw biomass. However, other sectors may also demand biomass for industrial process heat, feedstock for chemicals, or electricity production. If demand is higher than the potential supply, a scarcity problem emerges and the price of land increases. This means that the price of both food and bioenergy will increase.[4] It is thus not sufficient only to assess production cost of biomass today. It must be assessed from a long-term perspective that includes scarcities.

Hydrogen and electricity are energy carriers that must be produced from other energy sources. The relative price between electricity and hydrogen will influence the competitiveness of electric cars or hydrogen fuel cell cars in the future. Furthermore, the efficiency of the drive train is roughly 50% higher in an electric car than in a hydrogen fuel cell car. If hydrogen is produced from electricity with electrolysis, the price of hydrogen will be higher than electricity. Given the lower

---

[4] D. J. Johansson and C. Azar. A scenario based analysis of land competition between food and bioenergy production in the US. Climatic Change (2007) 82: 267–291.

efficiency of hydrogen cars, there must be a considerable difference between fuel cell and battery costs in order for fuel cell vehicles to become cost-effective in a scenario where hydrogen is produced with electrolysis. However, it should be noted that hydrogen can be produced at times when intermittent electricity is abundant and therefore electricity price is low. Hydrogen produced with electrolysis at low electricity prices can thus be cheaper than electricity produced when supply is scarce (i.e. when electricity prices are high).

Hydrogen can also be produced directly from high temperature heat with a thermo-chemical cycle. Hydrogen can thus be produced from concentrating solar collectors or nuclear energy at about the same cost and efficiency as electricity.

Coal with CCS can be used to produce both hydrogen and electricity with low carbon emissions. If hydrogen is produced from coal with gasification, a rather pure CO_2 stream is produced and can be captured and stored. If integrated gasified combined cycle (IGCC) with CCS becomes the preferred technology to produce coal-based electricity in the future, the price of producing hydrogen can be expected to be around half that of electricity. This would make hydrogen cars more competitive than PHEVs and BEVs.

From this we can conclude that the future electricity system will have an important impact on the competitiveness of future vehicle types. For this reason it is important not only to explore different future scenarios that assess different costs for batteries, biomass, etc. as is often done, but also overall developments of energy systems.

MODELLING RESULTS

In order to explore the potential effects of changing production costs and scarcity rents; we include them in an energy system model. The GET (Global Energy Transition) model is a linearly programmed cost-minimising model that describes the global energy system in a 100-year perspective. The model generates the fuel and technology mix scenario that meets energy demands at lowest global energy system cost. The model includes demand scenarios for different end-use sectors; estimates of primary energy resources; and the costs and efficiencies of energy conversion and vehicle technologies.

Primary energy sources in GET include fossil fuels (crude oil, natural gas, and coal); non-renewable non-fossil sources (nuclear); and renewable sources (hydroelectric, wind, solar, and biomass). These energy sources can be converted to transportation fuels or used for heat generation, electricity, or both (cogeneration). The use of nuclear energy has been limited to the present level, as the model represents a future influenced by political concerns for nuclear proliferation and safety.

Capture and storage of CO_2 from combustion of fossil fuels is an energy technology that can facilitate the production of low-CO_2 electricity, industrial process heat and hydrogen. Its potential to mitigate climate change is substantial given that it can be applied to several different types of energy conversion. Furthermore, if biomass is equipped with CCS, electricity or hydrogen can be produced with net negative CO_2 emissions (see also Chapter 7 in Systems Perspectives on Biorefineries 2013).

In the road transportation sectors, cars, trucks, and buses are represented. The GET model includes five fuel options: petroleum, natural gas, synthetic fuels (produced from coal, natural gas or biomass) electricity and hydrogen. The model also includes five vehicle powertrain technologies: internal combustion engine vehicles, hybrid-electric vehicles, plug-in hybrid electric vehicles, battery-electric vehicles and fuel cell vehicles.

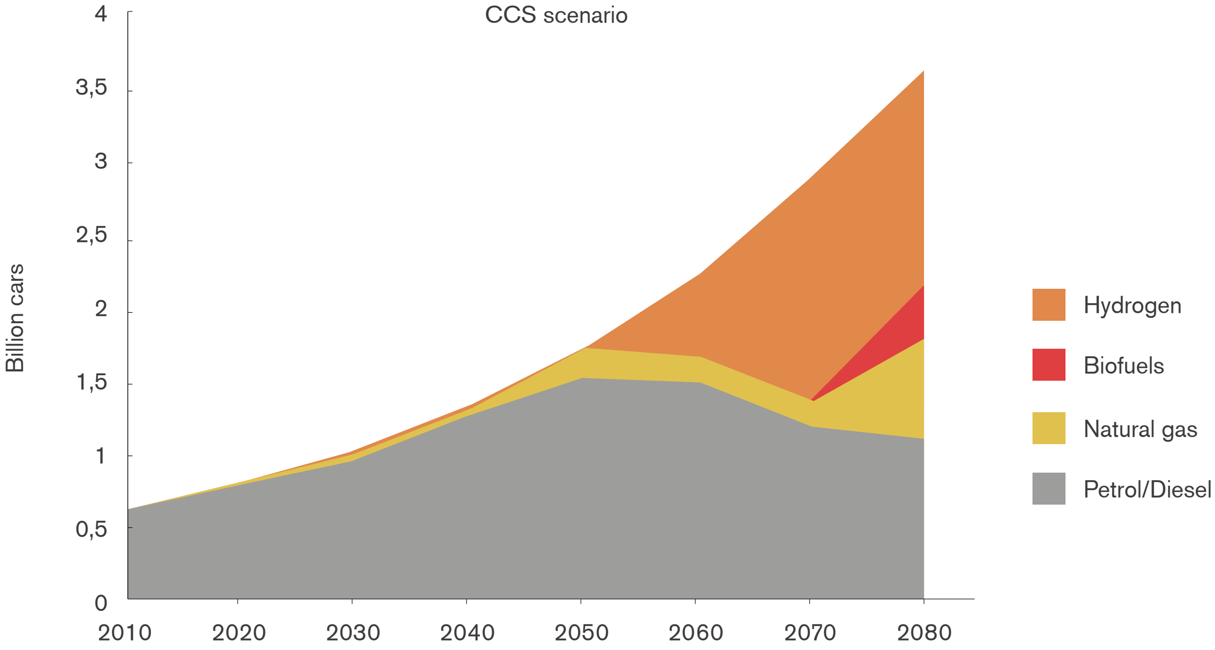

Figure 8.2 Cost-effective fuel choices for the global car fleet in a scenario where atmospheric CO_2 concentration are stabilised at 400 ppm. CCS technology is assumed to be available on a large scale.

This modelling framework is useful for studying how the development of different aspects of the energy sector can affect cost-effective choices of transportation fuels and propulsion technologies that can meet stringent climate targets. To illustrate this, we run the model twice, both towards a CO_2 concentration stabilization target of 400 ppm. In one run CCS technology is assumed to be available on a large scale and in the other it is not. CCS technology is currently under development, and there are presently no full-scale facilities in the world. CCS has also been subject to public resistance in Germany and there are uncertainties regarding legislative frameworks. Even though CCS has the potential to be an important mitigation technology, there remain technical and social barriers to its widespread deployment. Results in terms of lowest cost fuel choices for the world's car fleet are presented for the two model runs in Figure 8.2 and 8.3.

Figures 8.2 and 8.3 show that an energy system based on CCS vs. renewables has an important effect on the cost-effective choice of transportation technologies. Note that fossil fuels remain in the global car fleet until 2080 in both scenarios. This is because the cost of reducing emissions in other sectors, such as electricity production and residential heat, is typically lower than reducing emissions in the transportation sectors. Here it is assumed that the climate target is reached at lowest possible cost, which also implies that more expensive investments are delayed. This is related to the assumption that GDP will increase over the coming century and that society (according to standard economic theory) prefers to burden more wealthy future generations. Interestingly, fossil fuels are more prominent in the CCS scenario compared to the renewable scenario. The reason is that the cost of reducing emissions in the energy and industrial sector is lower when CCS is available. In this scenario less mitigation efforts are required within the transportation sector, which explains the larger use of fossil fuels.

Although biofuels have gleaned a relatively high level of public support, they are used to a limited extent in our transport scenarios. Biofuels are rarely used in internal combustion engines in our scenarios, but emerge in plug-in hybrids in the model run where CCS is not available on a large scale. However, electricity is used for around 65 % of the distance travelled by plug-in hybrids. Around 10 EJ biofuel is thus used for cars in 2070 in our renewable scenario, which could be compared to around 170 EJ crude oil produced, and around 30 EJ used in global car fleet, annually today. The limited use of biofuel in the transport sector is related to the fact that there are alternative uses for biomass (residential and industrial process heat) where the same amount of biomass can reduce CO_2 emissions at a lower cost.

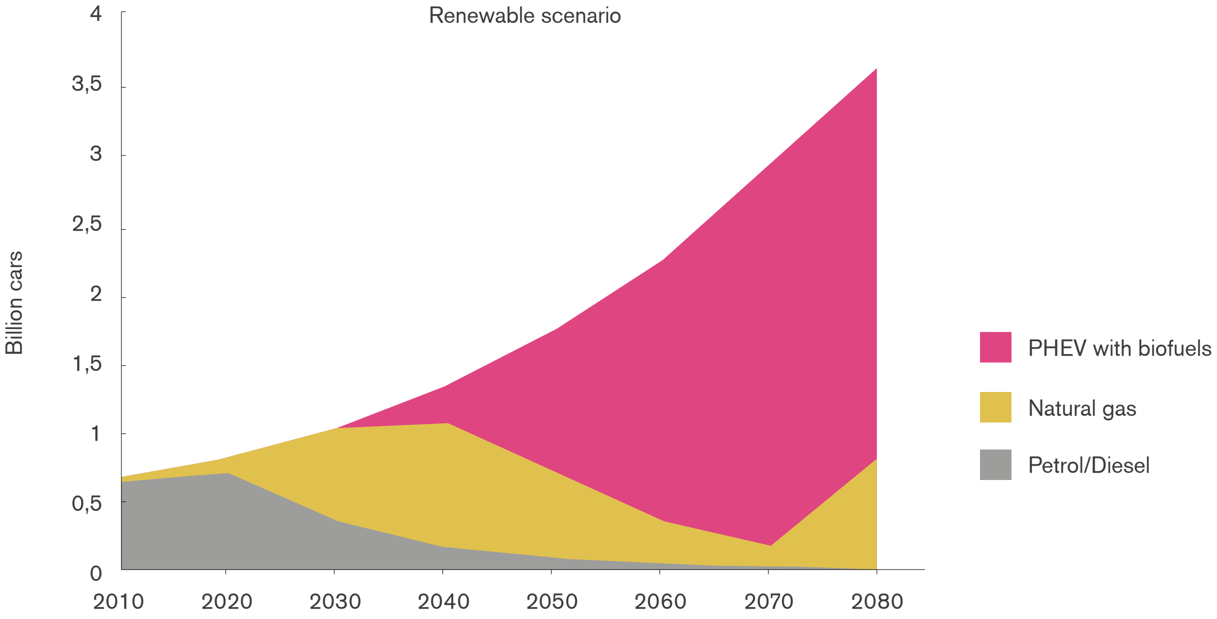

Figure 8.3 Cost-effective fuel choices for the global car fleet in a scenario where atmospheric CO_2 concentration are stabilised at 400 ppm. CCS technology is assumed *not* to be available on a large scale.

In the renewable scenario the cost of producing hydrogen and electricity from solar energy is roughly the same. Here PHEVs are expected to be more cost-effective than hydrogen cars. However, when CCS is applied, hydrogen can be produced at almost half the cost of electricity. This is because CCS can be applied to plants that produce hydrogen from fossil fuels with steam reforming or gasification. In the renewable scenario we assume that 80 % of electricity could be supplied by wind and solar energy using a combination of low cost storage technologies, demand side management, and extended grid expansion. For this reason, hydrogen is not utilised as an electricity storage option in the renewable scenario. However, if we are less optimistic about the potential of introducing large-scale renewables without using hydrogen as an energy storage option, we expect that electricity prices are around 50% higher than hydrogen prices. Notwithstanding, PHEVs are projected to be the long-term dominant vehicle technology in this scenario.

IMPLICATIONS FOR POLICYMAKERS

In the modelling exercise above we assume that the climate target is met in the most cost-effective way from a global perspective. In reality, this is not the most likely development for several reasons. It seems very unlikely that developing countries, having lower levels of GDP, will adopt similar emissions restrictions as OECD. However, our global results would probably hold in qualitative terms for smaller regions such as the European Union. Yet it is unlikely even in this case that internal EU targets will be met in a cost-effective manner. Current policy incentives for emissions reduction are generally much stronger in the road transportation sector compared to the stationary energy sector. Some sectors such as agriculture and shipping are still unregulated as regards to greenhouse gas emissions. There are several reasons for this. First, there is a long tradition of environmental regulation in the transport sector. Second, agricultural lobbyists have an interest in promoting biofuels and governments strive to become less dependent on imported fuels for energy security reasons. Third, road transport is not exposed to international competition in the same way as some industries. For these reasons policymakers tend to impose weaker regulations on globally competitive industries in order to protect jobs and to avoid carbon leakage (where industries relocate to other countries and continue to pollute). In conclusion, we can expect that the emission reductions in the transportation sector will be larger than what could be expected from a pure cost-efficiency perspective.

The way this affects the relative competitiveness of different vehicle technologies depends on which policy instruments are introduced. A biofuel mandate would promote further use of biofuels. Energy taxation, where the energy carrier is taxed based on its energy content (common in Europe today) would promote electricity and hydrogen as they have higher drivetrain efficiencies (see Chapter 5).

CONCLUSIONS

Many factors affect the competition between BEVs, PHEVs, FCVs and ICEVs and the relative roles of electricity, hydrogen, biofuels and fossil fuels. In this chapter we examined the influence of factors such as vehicle cost and efficiency, discussed the importance of policy design and briefly mentioned institutional and behavioural aspects. We focused mainly on how developments in the electricity supply sector affect the cost-efficiency of fuel and propulsion technologies in the transportation sector. Out of many possible model runs, we displayed a renewable scenario and a CCS scenario. There are two main mechanisms that we would like to highlight. First, the relative cost of producing electricity and hydrogen (which is mainly determined by technological factors) is a major component in the development of the transportation sector. Second, technologies available to mitigate climate change in other sectors affect the urgency with which one need to reduce the use of fossil fuels in the transportation sector. Uncertainties remain regarding how technologies will perform in the future and related to their application in different industrial contexts. However, our main conclusion is that connections between the energy sector and the transportation sector are important to understand for the long-term development of electromobility and use of biofuels for transport.