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UTILISING EXCESS POWER: THE CASE OF ELECTROFUELS FOR TRANSPORT

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INTRODUCTION

If the production of electricity at a given moment in time is higher than demand we may talk about excess electricity.[1] It is possible to store excess electricity and storage solutions might be essential for achieving very high renewable energy shares in the energy system. The most common purpose for storing electricity is of course to convert the stored energy back to electricity when needed. Currently there are not many mature alternatives for seasonal energy storage. Pumped hydro, hydrogen and compressed air are facing challenges with geographical distribution and ecological footprint, technical limitations or low density.[2] Another option is to convert electricity into an energy carrier that can be used for other purposes, and not just as a medium for electricity storage. One possibility is to use periods of excess electricity for the production of carbon-based synthetic fuels, so called electrofuels,[3] that can be used for various purposes, e.g. for heating, as a transportation fuel or in the chemical industry for the production of plastics, textiles, medicine and fertilizers.

1 Read more about challenges related to balancing demand and supply of electricity over different time scales in Chapter 9-11
2 See Chapter 4 for an overview of energy storage options.
3 The concept of converting electricity to synthetic methane is sometimes also named “Power-to-Gas” or “carbon recycling” and the product can for example be denoted e-gas, e-methane, synthetic natural gas (SNG) or sun-fuels. In this chapter electrofuels is an umbrella term for carbon-based fuels produced with electricity as the main energy source, following the definition in Nikoleris, A. and Nilsson, L. (2013). *Elektrobränslen en kunskapsöversikt*. Lund, Sweden: Lund University (Report no. 85).

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One challenge, common to all energy storage technologies, is to be economically viable in spite of the fact that excess, or low priced, electricity will likely be available only a fraction of the time. This chapter aims to explore the challenges and opportunities of using electrofuels to utilise excess electricity. Production processes are described and costs are estimated to underpin a discussion on what is required to make electrofuels competitive with gasoline.

USAGE OF ELECTROFUELS

Electrofuels, e-methane and e-methanol, can be stored and then used in various applications in society. They can be converted back to electricity, but with electricity-to-electricity conversion efficiency of only some 35%, other applications could be more attractive. E-methane can be fed directly into the current natural gas infrastructure and used where natural gas is used today, for example as feedstock in the chemical industry, as source of heat in domestic and industrial applications, or as transport fuel. Also e-methanol can be used in the chemical industry and as a transport fuel. A challenge for the transport sector is to find a fuel that can be used in all, or at least many, types of transport modes, that is based on renewable energy, and that do not suffer from the supply constraints and environmental and social issues related to biofuels. Electric vehicles have high energy efficiency (up to 90%) and the electricity use per driven vehicle distance is approximately five times higher for electrofuels compared to electric vehicles. On the other hand electric vehicles are facing difficulties with costly batteries and short driving range. In particular, aviation, shipping and long-distance road transport may have difficulties in relying on fuel cells and batteries (see Figure 12.1).

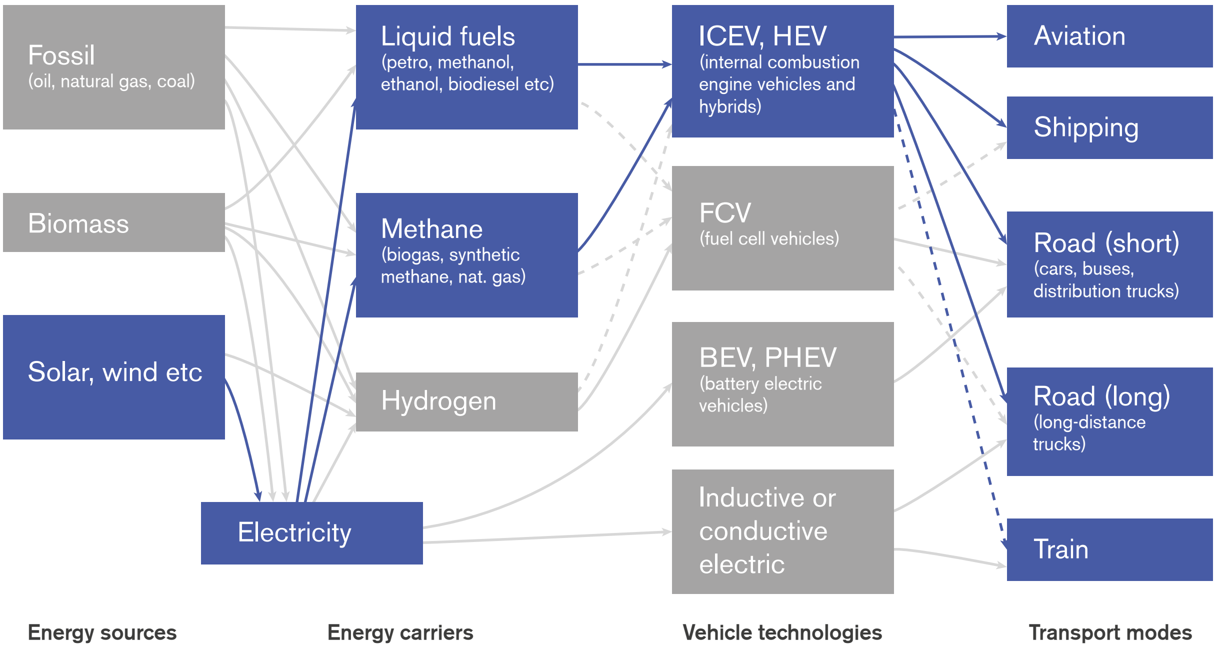

Figure 12.1. Possible energy flows and engine technology options for different transport modes. Blue boxes and arrows mark the electrofuel options utilising renewable power.

Hydrogen, produced from splitting water with renewable electricity,[4] is less costly to produce per energy unit compared to electrofuels but is by many considered to

4 The energy for water splitting can also be supplied from solar radiation directly or from high temperature heat generated from concentrated solar radiation, without an intermediate step of electricity production.

be unpractical in transport applications, e.g. due to the low volumetric energy density, safety issues and the need for a new infrastructure in the distribution chain. Electrofuels may then be an attractive option since there is no need for advanced vehicle technologies or major changes of infrastructure and they are suitable also for aviation and shipping. Although, compared to electric or hydrogen vehicles, combustion of hydrocarbons releases other emissions than CO_2, e.g. particles, NO_x and CO, which contributes to air pollution and the formation of ground-level ozone.

Current interest in electrofuels from the vehicle industry is demonstrated by Audi that has invested in a 6 MW electrofuel plant in Germany that uses solar electricity to produce e-methane.[5] Volkswagen recently highlighted e-methane as an important future complement to conventional natural gas and biomass based methane.[6] Also in the shipping sector, the company Stena Line sees methanol as a possible replacer of oil and has converted the auxiliary engine at Stena Scanrail to DME (converted on-board from methanol) and is planning to convert 25 of 34 ferries to run on methanol during the next few years.[7] In a long-term scenario they see e-methanol as a possible replacement of current fossil based methanol.

Another example of current electrofuel production is the Icelandic renewable e-methanol company, Carbon Recycling International, that built their first commercial plant in 2012 with a capacity to produce more than 5 million litres of e-methanol per year for the purpose of blending 3% methanol in gasoline. The CO_2 feedstock and the power for producing electrofuels are both supplied by a geothermal power plant and the electricity prices are very low.[8] If larger volumes are produced, the excess e-methanol will be exported to Europe.

PRODUCTION OPTIONS AND COST ESTIMATES

Several steps are needed to produce electrofuels (Figure 12.2): (i) producing hydrogen from water (electrolysis), (ii) capturing CO_2, and (iii) mixing hydrogen and CO_2 to form different types of electrofuels (the Sabatier reaction).

Producing hydrogen through electrolysis is a commercially available technology used in e.g. the chemical industry. In an electrolyser, electricity is used to split water into oxygen and hydrogen. Hydrogen production via electrolysis can instantaneously increase, decrease, and stop production rates, and thereby efficiently meet rapid variations of electricity supply. There are three main types of electrolysers: alkaline (AEC), proton exchange membrane (PEM) and solid oxide (SOEC) electrolysers. Commercial AEC electrolysers have conversion efficiencies of 60-70%. High-temperature SOECs, which are expected to enter the market in 2015-2020, are expected to reach conversion efficiencies of 80-90%. PEM electrolysers have similar conversion efficiency as AEC, use more expensive materials, and will most probably not be as cost-effective as SOEC.

5 Audi e-gas project. (2014) *Energy turnaround in the tank.* [accessed 2014-06-30].

6 Volkswagen Group Strategies. (2012) *0% Emission, 100% emotions, The road to Electromobility.* Wolfsburg, Germany: Volkswagen Aktiengesellschaft, Global Government Affairs.

7 Nohrstedt. L. (2013) Stena Line satsar på metanol, *Ny Teknik,* Apr. 4, [accessed 2013-12-03]

8 Carbon Recycling International (CRI). [accessed 2013-12-03].

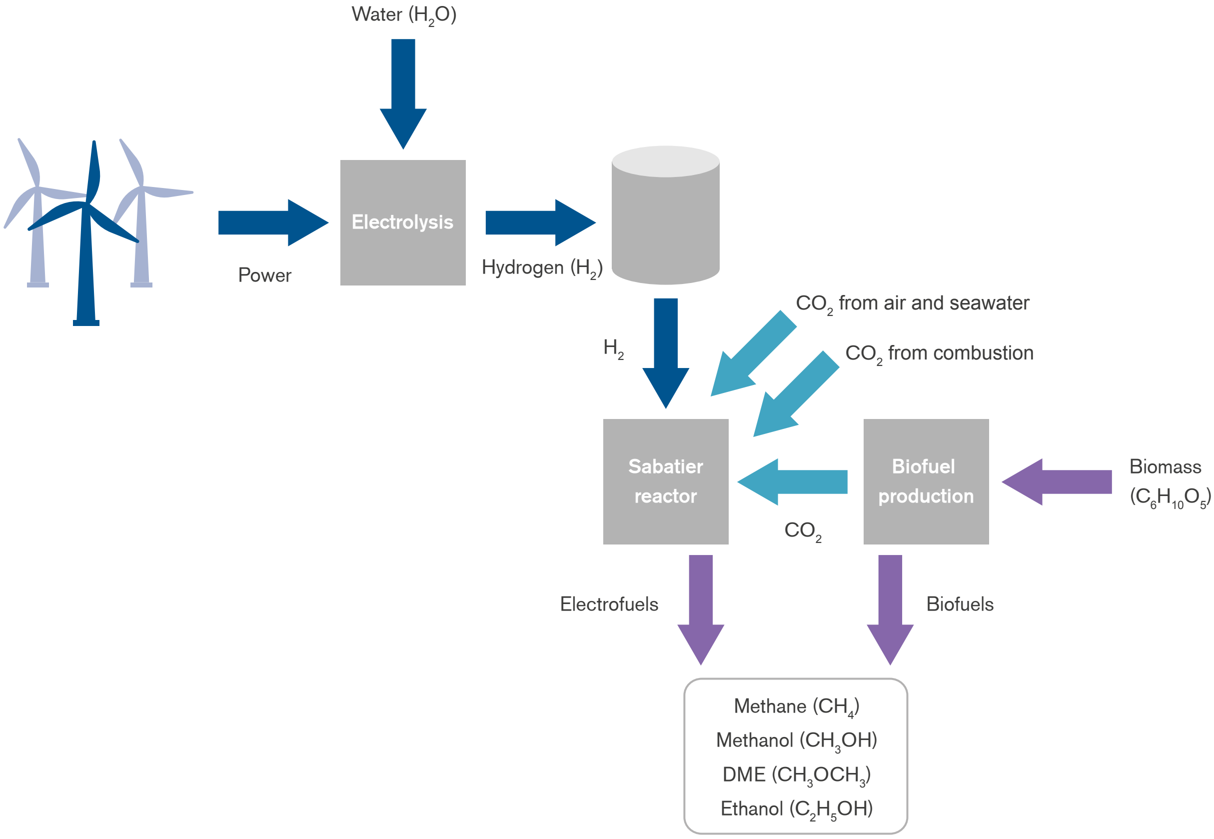

Figure 12.2. Process steps in the production of electrofuels where the main reaction occurs in the Sabatier reactor where CO_2 and H_2 form different types of electrofuels. The CO_2 can be derived from different carbon sources.

While the cost of electrolysers currently lies in the range of 600-1500 EUR/kW, it is estimated to drop to 250-500 EUR/kW in coming years.[9] In Figure 12.3, a cost estimate of hydrogen production is presented for different electricity prices and capacity factors (the ratio of the annual production and the maximum production capacity). We assume an energy efficiency of 80%, and an electrolyser investment cost of 400 EUR/kW. It can be noted that at capacity factors above approximately 15% the hydrogen production cost is rather similar for a given electricity price.

The carbon dioxide can come from many sources including various industrial processes giving rise to excess CO_2, e.g. biofuel production facilities, natural gas processing, flue gases from fossil and biomass combustion plants, steel plants, oil refineries and other chemical plants, geothermal activity, air and seawater. The concentration of CO_2 in the source is of great importance for costs and present commercial facilities use sources with high CO_2 concentrations.

In biofuel production, e.g. by fermentation of sugar into ethanol, anaerobic digestion of household waste into biogas or gasification of biomass into methane, considerable amounts of CO_2 are produced as a by-product. The off-gases from biofuel plants, as well as from ammonia plants, are more or less pure streams of

9 The cost and efficiency numbers for hydrogen production are taken from estimations by Fusch et al. (2012) *Technology overview on electricity Storage.* Berlin, Germany: Smart Energy For Europe Platform GmbH (SEFEP); Parfomak et al. (2012) *Energy Storage for Power Grids and Transportation.* Washington, DC, USA: U.S. Congressional Research Service (CRS). (R42455).; International Energy Agency (IEA). (2007) *IEA Energy Technology Essentials -Hydrogen Production and Distribution* IEA/OECD (ETE05); U.S. Department of Energy Hydrogen Program (2009) *Current State-of-the-Art Hydrogen Production Cost Estimate Using Water Electrolysis.* Golden. Golden, CO, USA: NREL. (NREL/BK-6A1-46676)

CO_2. One study claims that methane production from biomass can more than double if the CO_2 released in the process is allowed to react with hydrogen.[10] Other studies confirm that 26-80% of the carbon in the feedstock of biofuel plants is released as pure CO_2.[11] The CO_2 capturing cost with a pure CO_2 stream can be low and in most cases depends on transport distances. The capture technology does not have to be much more than a pipe into the Sabatier reaction process and the capturing cost is estimated to lie in a range from a negligible cost up to approximately 7 EUR/ton CO_2.

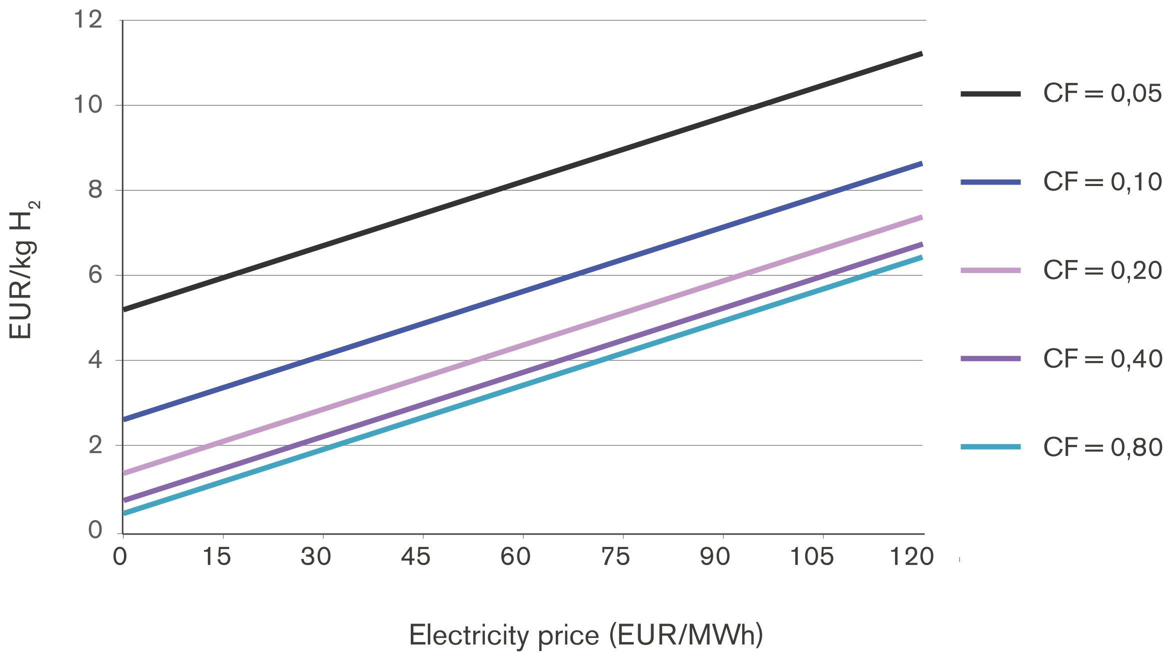

Figure 12.3 Hydrogen production costs depending on the electricity price and the share of maximum conversion capacity that the electrolyser runs per year, i.e. its capacity factor (CF). The conversion efficiency is assumed to be 80% and the electrolyser investment cost is set to 400 EUR/kW.

Flue gases from fossil or biomass combustion plants have a CO_2 concentration of 3-15%. Therefore, an extra purification step is needed before the gas can be mixed with hydrogen in the Sabatier reactor. Capturing CO_2 from flue gases can be done by three different technologies: post-combustion, pre-combustion and oxy-fuel combustion. By looking at 50 engineering studies of CO_2 capture installations at power plants, the International Energy Agency has estimated that the capturing cost at power plants ranges from 15 to 60 EUR/ton CO_2 depending on capturing technology and type of fossil fuel.[12] The capturing cost might be slightly higher for biomass power plants due to their smaller size.

The CO_2 concentration in air is approximately 400 ppm and it would require 2-4 times more energy to extract the CO_2 from air compared to flue gases. Strong bases such as NaOH, KOH and $Ca(OH)_2$ can effectively scrub CO_2 out of the atmosphere, but the regeneration of the bases is an energy intensive process, and

10 Mohseni ,F. (2012) *Power to Gas- Bridging Renewable Electricity to the Transport Sector.* Lic. thesis, KTH Royal Institute of Technology.

11 Luckow, P. et al. (2010) *Biomass Energy for Transport and Electricity: Large Scale Utilization Under Low CO_2 Concentration Scenarios*. Richland, Washington: Pacific Northwest National Laboratory for the U.S. Department of Energy. (PNNL-19124)

12 Finkenrath, M. (2011) *Cost and Performance of Carbon dioxide Capture from Power Generation*. Paris, France: IEA/OECD.

other alternative materials that might be more energy efficient are under development. Different techniques and materials have been proposed and many designs are technically feasible. However, all are still in a very early development phase, and more research and pilot plants are needed to optimise the technology. The cost estimations are uncertain but fall in the range of 150-1250 EUR/ton CO_2.[13] A couple of start-up companies have provided prototypes of carbon capture plants from air. The company Air Fuel Synthesis built a demonstration plant in 2012 and produces 5-10 litres per day of synthetic fuels from air-captured CO_2 and hydrogen.[14]

Carbon capture from seawater might also be an option. The concentration of dissolved CO_2 in seawater is approximately 140 times higher than in air, but only 2-3% of the CO_2 in seawater can efficiently be used for fuel production.[15] The US Navy has shown interest in developing technology for extracting CO_2 from seawater with the purpose of producing synthetic aviation fuel at sea using electricity generated from nuclear energy. The capturing costs are expected to be in the same order of magnitude as for air capture technologies.

Electrofuels, e.g. e-methanol or e-methane, is produced by feeding hydrogen and CO_2 into a Sabatier reactor, see Figure 12.1. The Sabatier reactions for e-methane (CH_4) and e-methanol (CH_3OH) are:

$$CO_2 + 4\,H_2 \longrightarrow CH_4 + 2\,H_2O + \text{energy}$$

$$CO_2 + 3\,H_2 \longrightarrow CH_3OH + H_2O + \text{energy}$$

Small molecules, like methanol and methane, are preferable since more complex molecules require additional process steps, which lead to efficiency losses. The technique of synthesising e-methane from CO_2 and water has been known since the beginning of the twentieth century, and is currently commercially used in many industrial applications, like ammonia production. It would therefore be relatively easy to implement the technology for fuel production at a commercial scale. In the process, 90% of the carbon in the CO_2 stream form e-methane. For e-methanol the conversion efficiency is lower and the reaction requires high pressure and a recycling of non-reacted CO_2. Catalysts are needed in the production and a variety of commercial catalysts are available. The process equipment costs are estimated at 140 EUR/kW for the Sabatier reactor, 2 EUR/kW for the catalyst and 4 EUR/GJ for the synthetic methane storage (the methanol storage cost is approximately a third of this).[16] Thus, the Sabatier reactor accounts for approximately a fifth of the capital cost (compare the electrolyser cost above). In Table 12.1 one can find an overview of the cost and availability of the technology for the different steps in the electrofuel production process just described.

13 Goeppert and colleagues have summarized and evaluated different articles estimating air capture costs in: Goeppert et al. (2012) Air as the renewable carbon source of the future: an overview of CO_2 capture from the atmosphere. *Energy and Environmental Science*, 5(7):7833-7853.

14 Air fuel synthesis [accessed 2013-12-03].

15 Willauer et al. (2011) Development of an electrochemical acidification cell for the recovery of CO_2 and H_2O from seawater. *Industrial & Engineering Chemistry Research,* 50:9876–9882.

16 Mohseni, F. (2012) *Power to Gas- Bridging Renewable Electricity to the Transport Sector.* Lic. thesis. KTH Royal Institute of Technology.

The geographical localisation of the Sabatier reactor may also be of interest. Electricity, hydrogen and the final fuels are all transportable with high efficiency indicating that localisation of the Sabatier process may be determined by current infrastructure to avoid expensive infrastructure extensions. Since hydrogen is more costly to transport than carbon dioxide and electricity, the optimum localisation of a Sabatier process most likely is close to the electrolyser. Preferable locations for electrofuel production could be geographically isolated and relatively small systems (e.g. islands such as Iceland or Ireland) with a lot of renewable power production and difficulties with transmissions cables to the main land.

Table 12.1. Overview of cost estimates and availability of the technology for different steps in the electrofuel production process. All costs are recalculated to EUR values of 2010 (1.37 USD/EUR).

Technology	Cost estimate	Availability
Electrolysis (conv.eff 50-90%)	600-1500 EUR/kW 250-600 EUR/kW in near future	Alkaline (AEC), proton exchange membrane (PEM) are commercial, (<70%) but more efficient (80-90%) high-temperature solid oxide electrolyser cells (SOEC) are under development.
Pure CO_2 from biofuel plants	Up to 7 EUR/ton CO_2	Mature technology but few in use.
CO_2 from combustion	15-60 EUR/ton CO_2	Demonstration phase
CO_2 from air capture	150-1250 EUR/ton CO_2	Early development phase
Sabatier reactor	140 EUR/kW	Known for a long time, but few fuel production facilities
Storage e-methane	4 EUR/GJ	Mature technology
Storage e-methanol	1.5 EUR/GJ	Mature technology
Catalyst costs	2 EUR/kW	Mature technology

COST COMPETITIVENESS OF ELECTROFUELS

Under what circumstances can electrofuels compete with gasoline as transport fuel? Would it be cost-effective to run a production process only part of the year and with a low capacity factor? In the following, we try to estimate the cost of electrofuels and compare the costs of e-methanol to gasoline.

The unit cost of the electrofuel (EUR/GJ) is given by the cost of electricity and CO_2, the annuity of the investment cost, the operation and maintenance cost and the capacity factor. The investment cost is the sum of the costs of the electrolyser, Sabatier reactor and storage of synthetic fuel (see Table 12.1 for cost details).[17]

In 2013, the average electricity price for a three-year contract for a small-sized industry in Sweden was 45 EUR/MWh.[18] It is difficult to estimate how a higher penetration of wind and solar will affect the electricity price. Probably it will result

17 The annuity is calculated from the investment cost, using a discount rate of 5% and a lifetime of 25 years. It is, further, assumed that the stack has to be replaced every 7th year, i.e. three times, at 33% of the original purchase cost. The operation and maintenance cost is estimated at 4% of the total investment cost.
18 Statistics Sweden (2013) Prices on electricity and transmission of electricity [accessed 2014-06-12].

in more rapid price variations including more frequent periods with low electricity prices, due to variation in weather conditions (Chapter 9 and 11). With electro-fuels produced at large-scale, high wind and solar penetrations in the vicinity of 40-50%, will however most likely be needed in order to get repeatable periods of low electricity prices. We have chosen to make calculations based on an electricity price of 0, 30 and 50 EUR/MWh. The zero case corresponds to a situation with a major electricity surplus part time of the year.

The cost of the electrolyser and its conversion efficiency are assumed to be 400 EUR/kW and 80%, respectively. The total investment cost over a 25 year lifetime including the electrolyser, three stack replacements, the Sabatier reactor and the fuel storage, is assumed to be 950 EUR/kW. In our baseline case we assume that the carbon needed in the electrofuel production comes from pure streams of CO_2 that easily can be connected to the Sabatier process and thus available at low cost. As a baseline, the cost of capturing CO_2 is assumed to be 7 EUR/ton CO_2.

In Figure 12.4 the resulting production cost of e-methanol in EUR per litre gasoline equivalents is shown for different capacity factors and different electricity prices. The crude oil price has increased drastically during the last decade, except from a drop in 2009. In 2013, the oil price fluctuated between 96 and 110 USD/barrel. Here we compare to crude oil prices of 50, 100 and 150 USD/barrel.

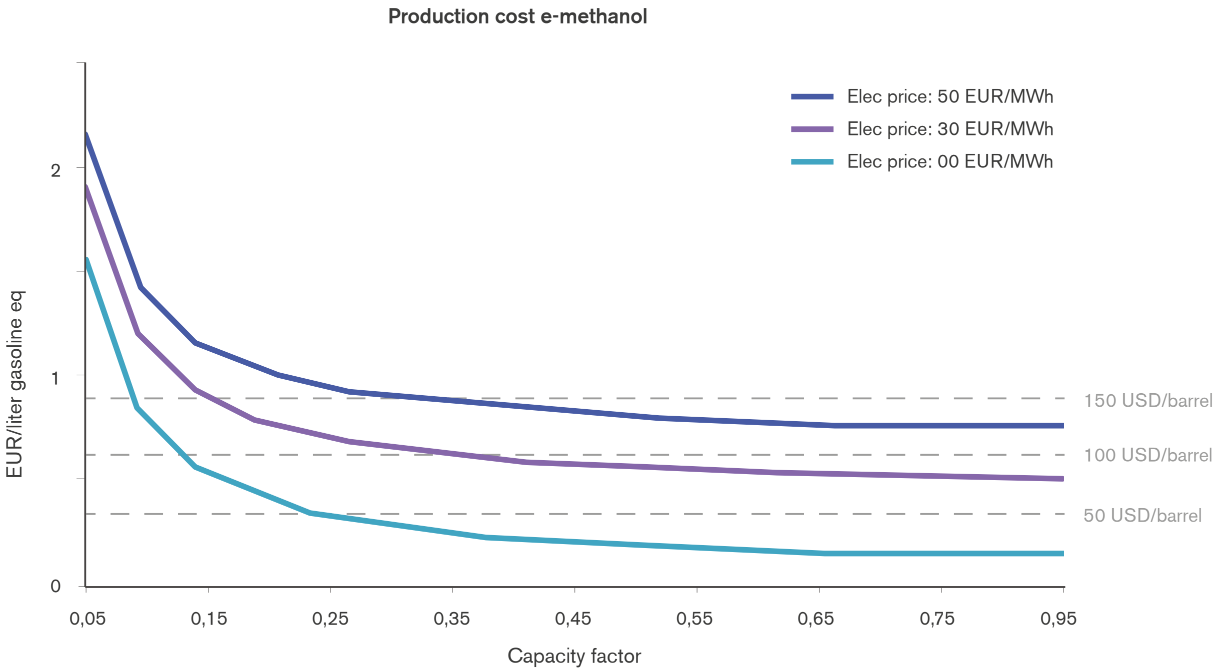

Figure 12.4 Production cost of electrofuels in the form of methanol when assuming that CO_2 is available at 7 EUR/ton, and that electrolysers, with 80% conversion efficiency, are available at 400 EUR/kW (with stack replacements every 7th year). The dotted horizontal lines show the production cost of gasoline, at a crude oil price of 50, 100 and 150 USD/barrel.

With an oil price of 100 USD/barrel and electricity available free of charge, the production of e-methanol is profitable at a capacity factor of 0.15 or higher, which corresponds to a situation that the electrolyser runs at full capacity 15% of the year on excess electricity (and without producing anything 85% of the year). If the electricity price is increased to 30 EUR/MWh, the e-methanol will be profitable if the production process is running, at full capacity, 45% of the year or more. E-methanol will however not be profitable at an electricity price of 50 EUR/MWh and an oil price of 100 USD/barrel or lower. At an oil price of 150 USD/barrel, production of e-methanol can be profitable compared to gasoline for all three electricity price scenarios at relatively low capacity factors, 10%, 17% and 40%, respectively. The cost is more sensitive to the electricity price than to the capacity factor; there is a large increase in cost only at very low capacity factors. This makes the technology suitable for electricity storage.

When the production cost of an electrofuel is lower than the gasoline production cost, the difference indicates the amount that can be paid for CO_2. The availability of CO_2 at low cost will be limited and if one wants to use captured CO_2, e.g. from flue gases, the cost of CO_2 will be higher (see Table 12.1). In this case, a higher oil price or a carbon tax on fossil fuels (see below) is needed to make electrofuels competitive with gasoline. Alternatively, very high capacity factors are required, indicating that the technology will not be a cost-effective option to store excess electricity. Capturing CO_2 from air or seawater will require a very high oil price or carbon tax before they can become profitable (Table 12.1).

A cost for emitting CO_2, for instance, in the form of a carbon tax, will increase the price of gasoline. A carbon tax of 100 EUR/ton CO_2 corresponds to 0.25 EUR/litre of gasoline. Such a tax would increase the competitiveness of electrofuels based on a renewable CO_2 source. When the CO_2 comes from a fossil source, the electrofuel would also have to pay for the emission. The cost would be roughly the same as for gasoline per litre gasoline equivalent, varying slightly with the carbon content per energy unit of the electrofuel and the carbon efficiency of the Sabatier reactor. However, the electrofuel could get credits for recycling CO_2 and thus benefit from a reduced carbon emission penalty. For the CO_2 supplier and the electrofuel producer taken together the net change in emission penalty costs should be zero. How costs and revenues are distributed between the electrofuel producer and the CO_2 supplier ultimately depends on the negotiating power of the parties. The net effect of a CO_2 emission penalty on the competitiveness of electrofuels is therefore not clear, especially as a cost for CO_2 emissions probably also will affect the electricity market.

Costs for CO_2 emissions can possibly be mitigated by Carbon Capture and Storage (CCS). The CO_2 supplier may then have a cheaper alternative to pay for emitting CO_2. This will be unfavourable for the electrofuel producer in a bid for the CO_2.

FUTURE CARBON MANAGEMENT: RECYCLING OR TERMINAL STORAGE OF CO_2

Apart from the economic aspect, one may discuss if it is preferable from a climate change perspective to store captured CO_2 underground or recycle the CO_2 into electrofuels.

From one perspective it is preferable to capture and store CO_2 underground, using CCS technology, and not convert CO_2 into a fuel that after combustion will be released to the atmosphere. If the CO_2 has been captured from burning fossil fuels, CCS will avoid increased CO_2 concentration; if the CO_2 is captured from burning biomass (or from air), CCS will decrease the CO_2 concentration. Today, however, there are several obstacles that have to be overcome before CCS could be available at a large scale, including public acceptance.

If even if CCS is available, should CO_2 always be pumped underground? An argument for converting CO_2 into electrofuels, instead of using CCS, has to do with the lack of long-term fuel options in the transportation sector. If no other major long-term alternative transportation fuels are available or technically possible, e.g. if bioenergy has been expanded to its maximum and batteries as well as fuel cells face difficulties with up-scaling, maybe only synthetic carbon based fuels, electrofuels, remain as an alternative to oil or coal based fuels. Electrofuels produced from non-fossil CO_2 with the help of renewable electricity has the potential to be a large-scale fuel option in a world with ambitious climate targets.

Finally, there might be other advantages of recycling CO_2 into electrofuels and using it instead of producing gasoline and diesel from fossil sources including (i) rural development (if electrofuel production is placed outside cities), (ii) energy security, i.e. less dependency on imported oil, and (iii) reduced environmental impact, e.g., from avoiding the extraction and transportation of oil.

CONCLUSIONS

We conclude that electrofuels for transport is an interesting option of utilising excess electricity, although further research is needed to better understand the potential. We have shown that if the electricity price is not higher than 30 EUR/MWh, and the oil price is not lower than 100 USD/barrel, e-methanol could be profitable if the production process is running at full capacity at least 45% of the year. E-methanol might also be profitable at an electricity price of 50 EUR/MWh if there is a carbon tax on gasoline. One important finding is that the technology is suitable for electricity storage since the production cost of electrofuels is more sensitive to the electricity price than to the amount of hours per year that the production runs at full capacity. Production costs increase significantly only when the process runs less than approximately 15% of the year. Nevertheless, to increase competitiveness, improvements of electrolysers are required, in terms of production cost, conversion efficiency and response time.

The development of an electrofuel production industry may also be determined by other factors apart from the production cost. Electrofuels are, for example, not likely to enter the market as a storage option of excess electricity if alternative low cost electricity storage technologies or other low-emitting alternative transport fuels are developed and produced on a large scale at low cost. Finally, with widespread deployment of CCS, CO_2 might be stored, instead of recycled into electrofuels.