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SCENARIOS FOR THE MARKET RAMP-UP OF E-FUELS IN ROAD TRANSPORT

Convenience translation, original in German

A study for UNITI Bundesverband EnergieMittelstand e.V.

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Updated version

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frontier economics

A third-party study, on which this study is partly based has been revised by its authors, resulting in changes to certain cost items used in this study. These changes have been incorporated into the updated version of this study. The key assumptions, methodology, conclusions, and recommended actions remain unchanged from the first version dated 18 September 2024. This update further enhances the relevance and significance of the study.

Study commissioned by:

Bundesverband EnergieMittelstand
UNITI
Kraftstoffe | Brennstoffe | Schmierstoffe

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Summary

The industrial production of e-fuels is just beginning. E-fuels offer an opportunity to defossilise the transport sector, i.e. aviation, shipping and road transport, as well as processes in other sectors such as industry and heating. A key advantage of e-fuels is that they can be used – in pure form or blended with conventional fuels – in existing systems and various modes of transport. In road transport, this applies to vehicles with internal combustion engines, i.e. already built vehicles can also be operated with e-fuels in a climate neutral way. The first demonstration plants for the production of e-fuels are already in operation: a number of companies along the value chain, from plant construction and electrolysis to the refining of fuels, are working worldwide on the market ramp- up of the production of e-fuels.

Currently, production costs for e-fuels are estimated to be high. This is due to the high costs for first of its kind e-fuels production plants that have not yet been scaled up, both in the production of plant components and of e-fuels. However, over time costs of producing e-fuels are expected to fall significantly with increasing experience, technological progress and scaling, similar to prior experience with renewable energies and electricity storage. Experience shows that cost reductions based on "learning rates" happen faster in the first few years than later on. The prerequisite for this development is a gradual ramp-up of production capacities for the production of e-fuels in the coming years.

Against the background of the market ramp-up of e-fuels still being in an initial phase, and the possibility of gradual blending with conventional fuels, we analyse in this study how the price of a fuel mix that contains increasing shares of e-fuels could develop in the long term. Here, we focus on road transport as an example, in particular on the price of petrol and diesel at the filling station. Against this background, several questions arise:

1. What are the key cost components for the provision of e-fuels and what cost trends can be expected for e-fuels in the medium and long term?
2. What volumes can be assumed to be available and what blending ratios of e-fuels to conventional fuels are possible or plausible?
3. With increasing shares of e-fuels, what is the resulting cost path visible at the filling station for fuels? What price changes are to be expected?
4. What conclusions and recommendations for action can be drawn from this?

Current literature shows that considerable cost reductions in the production of e-fuels can be expected in the medium and long term

The perceivably high costs for e-fuels are in line with the market ramp-up still in the initial phase with relatively few initial projects. The essential cost components in the production of e-fuels are the costs for renewable electricity generation, electrolysis, synthesis and CO_2 sourcing. **As the market volume**

increases, significant reductions of production costs can be expected due to learning effects and economies of scale, e.g. in electricity generation and CO_2 sourcing.

To derive a range for the long-term development of production costs for e-fuels, we analyse recently published third-party studies as part of this study. The main studies analysed are from Concawe & Aramco (2024), Öko-Institut, Agora Energiewende & Agora Industry (2024) and Fraunhofer IEE (2021), which are complemented by the study from Agora Verkehrswende, Agora Energiewende and Frontier Economics (2018). The studies show that production costs fall over time and are heavily dependent on the geographic location of production. For example, the costs can vary significantly between production at a location with average solar and wind yields and a top location within a country.

Based on the literature review, we estimate the long-term[1] production costs (including transport to Germany) for e-petrol at 0.99-1.63 € per litre and for e-diesel at 1.09-1.80 € per litre. Therefore, due to falling production costs, the average supply price for pure e-fuels will fall by around 30% in the long term compared to large production plants that will be built within the next few years. The exact production costs within this range depends, among other things, on the selection of production sites for e-fuels and the extent of the learning effects and economies of scale.

Regulatory and political framework conditions affect the availability of e-fuels in Germany

The production potential and capacities will unlikely be a limiting factor in meeting the long-term demand for e-fuels. Pfennig et al. (2023), for example, estimate that the long-term e-fuels production potential at suitable locations outside Europe is higher than the current global final energy consumption of fossil fuels. In fact, the speed and scope of the international ramp-up of capacities and volumes as well as the availability of e-fuels in Germany depend on various factors, with the political and regulatory framework playing a central role.

Due to the numerous influencing factors, predicting the available volumes of e-fuels in Germany is currently highly uncertain. We assume a possible, stylised ramp-up of e-fuel volumes based on literature on product life cycles, following an S-curve, i.e. an initial phase followed by a period of rapid growth, and finally, a plateau where growth slows as the market becomes saturated. We assume that the blending of e-fuels with conventional fuels will progress in line with their market ramp-up and availability[2]. Therefore, the blending share of e-fuels also increases in the same way over time, replacing fossil fuels completely from 2045 onwards.

In the appendix, we also present an alternative blending scenario that only takes technical restrictions into account, assuming ideal legal, political and financial conditions. In this sensitivity, we arrive at a

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1 Until the year 2050, which some studies use as the long-term reference year.

2 In practice, the actual blending share will be influenced by political and regulatory obligations, the physical availability of e-fuels, and the price difference between e-fuels and conventional fuels. Since an exact forecast of the blending share is not the focus of this study, we abstract from these interactions and assume that e-fuels will be blended into the conventional fuel mix to the extent they are available.

faster ramp-up of e-fuels, where e-fuels could completely replace fossil fuels as early as 2037 (e-petrol) or 2043 (e-diesel).

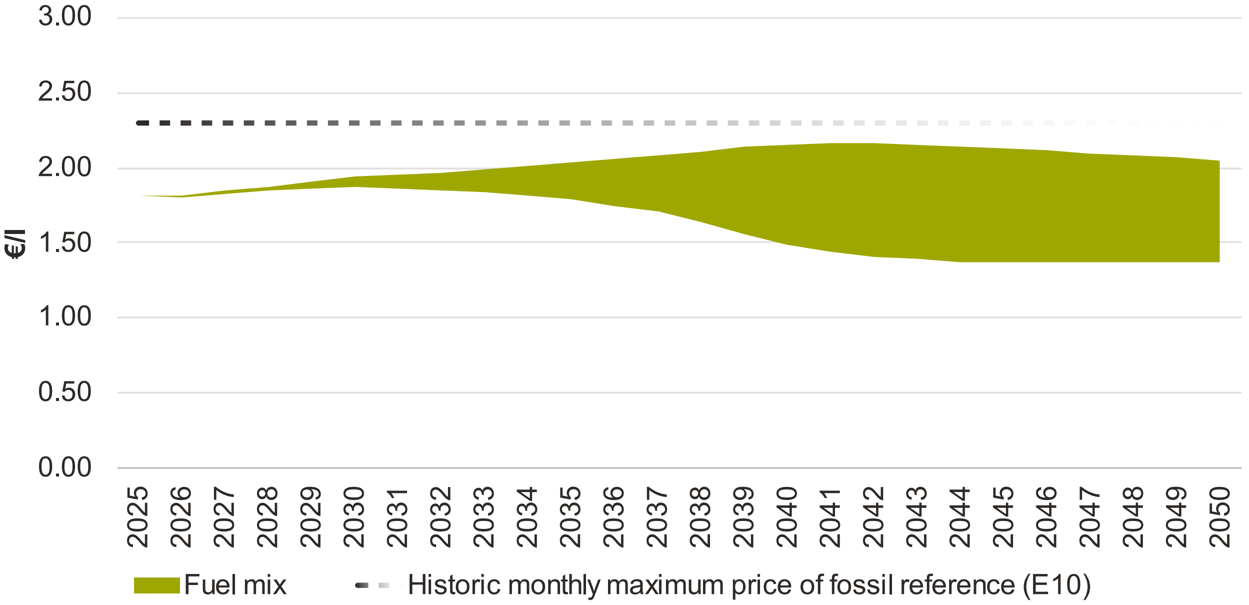
With an increasing share of e-fuels in the fuel mix, price changes at the filling station are expected to me minor

Besides production costs, fuel prices at the filling station also include further cost components such as distribution costs and taxes. Being climate neutral, e-fuels, unlike fossil fuels, are not subject to any levies under the German Brennstoffemissionshandelsgesetz (Fuel Emissions Trading Act) or the EU ETS II (emission trading system for road transport and other sectors) which will replace the national system. We also assume that e-fuels can benefit from a reduced energy tax rate, as provided for as an option in the reform proposal of the Energy Tax Directive published by the European Commission in 2021.

We model price paths for the future fuel mix of e-fuels and reference fuel (for petrol and diesel) assuming the blending scenario and the previously derived cost range. With regard to the price development of the fuel mix, we come to the following conclusions:

- **Negligible price impact in the market ramp-up phase**: In an initial market ramp-up phase, in which e-fuels are foreseeably still significantly more expensive than fossil fuels, only a small proportion of e-fuels are added, so that the higher costs are relatively insignificant.
- **Long-term price advantages due to increasing blend-in of climate-neutral e-fuels**: The future price of the petrol-fuel mix with an increasing share of e-fuels share, will remain within a relatively moderate range similar to current prices, under the assumption of a tax deduction. Even under pessimistic assumptions, the price of the future petrol fuel mix will not rise above the level of (maximum) conventional petrol fuel prices already observed in the past (cf. Figure 1). Similar conclusions also apply to the future average prices of the diesel fuel mix estimated by us (cf. Figure 16), even though the future prices for e-diesel in our calculations are slightly higher than those for e-petrol. In the optimistic scenario, even fuel prices below the current level are achievable in the long term due to the assumed favourable cost developments.
- **The prerequisite for this is tax differentiation for climate-neutral fuels**: A condition for the moderate price development is that the energy tax for fuels is differentiated between fossil and green fuels according to their greenhouse gas intensity. Tax policy therefore has a strong effect on customer prices for e-fuels and thus also on the fuel mix. If e-fuels were taxed with the same energy tax rates as fossil fuels, the prices for the fuel mix at the filling station may be significantly higher in the medium to long term than for fuels today. However, this incentive system would not be effective in terms of climate policy.

Figure 1 Long-term development of petrol prices (fuel mix), base scenario with energy tax reform



Source: Frontier Economics.

Note: E-petrol will completely replace fossil petrol in the fuel mix from 2045 onwards. Retail prices assuming reduced energy tax for e-fuels from 2025. Maximum price for fossil petrol from March 2022. All values in €(2024), i.e. inflation-adjusted.

Further measures can support the market ramp-up of climate-neutral e-fuels

The following policy and regulatory recommendations can be derived from the discussed factors affecting the market ramp-up of e-fuels and the calculations on future fuel prices:

- **Implement the reform of the European Energy Tax Directive:** The Energy Tax Directive 2003/96/EC sets minimum tax rates that apply to all EU member states. Currently, fuels in the EU are taxed purely on a volumetric basis – regardless of whether they are fossil fuels or low-carbon fuels. Instead, fuels should be taxed according to environmental aspects and energy content in order to achieve a desirable steering effect from a climate policy perspective. A reform of the energy tax rates in Germany/the EU would remove considerable obstacles to the substitution of fossil fuels with low-carbon e-fuels and thus make it easier to achieve climate targets in the transport sector. One option for an amendment to the EU Energy Tax Directive is the draft presented by the EU Commission in July 2021, which would make it possible to reduce the German energy tax rate for e-fuels from around 47 ct/l (diesel) or 65 ct/l (petrol) to less than 1 ct/l. This draft for a reform of the Energy Tax Directive should be implemented as soon as possible.
- **Making investments in e-fuels more attractive:** So far, only limited investments have been made in e-fuels projects. The main reason for this is the high investment risks due to an uncertain or insufficiently ambitious regulatory framework. The right policy can help to reduce investment

risks and create more favourable financing conditions, such as the removal of administrative hurdles[3] , the promotion of research and development programmes, market ramp-up support programmes and generally the creation of a reliable regulatory framework that does not impede the broad use of e-fuels in all sectors in an open European fuel market in the long term. Removing administrative barriers includes, for example, implementing business-friendly criteria for the production of green hydrogen and hydrogen-based synthesis products, as well as standardising global certification systems.

- **Expansion of international partnerships for the import and export of e-fuels:** The cost of e-fuels depends largely on the quality of the location for renewable electricity generation. Germany is dependent on the import of hydrogen and hydrogen derivatives such as e-fuels due to its unfavourable renewable electricity generation conditions compared to other countries. To foster the development of a global e-fuels market, it is advantageous in the early market phase to establish strategic partnerships, with Germany acting as both a technology exporter (e.g., for electrolysers or synthesis plants) and as an e-fuels importer. At the same time, the cooperating partners can benefit exporting their energy products.

[3] E.g. the introduction of the Net Zero Industry Act in April 2024 paved the way for simplified authorisation procedures.

2 Background and objectives of the study

Against the backdrop of the German government's climate protection targets of achieving greenhouse gas neutrality by 2045, e-fuels offer an opportunity to defossilise road transport and other sectors. A key advantage of e-fuels is that they can be used in existing vehicles with internal combustion engines ("drop-in fuel"), which means that already built vehicles can be operated in a climate neutral way. E-fuels can be used in pure form or blended with conventional fuels with variable shares.

E-fuels are often criticised for their supposedly high costs compared to conventional fuels, which is due to the fact that the market ramp-up is still in its starting phase with relatively few initial projects. In the coming years and decades, however, a significant reduction in the production costs of e-fuels can be expected as the market ramp-up progresses. At the same time, rising levies on conventional fuels, particularly as a result of CO_2 pricing, can be expected, which will increase the willingness to pay for renewable e-fuels. The use of e-fuels can be facilitated by blending them with conventional fuels in increasing quantities. This would have two effects:

- The financial burden for car drivers could be controlled by the degree of blending. With an initially low degree of blending, today's high costs are hardly noticeable. Increasing blending over time is then accompanied by lower costs for e-fuels, so that there is no noticeable price increase here either.
- A gradual market ramp-up would be made possible, which would avoid a sudden increase in demand for e-fuels.

Against the background of these considerations, in this study commissioned by UNITI Bundesverband EnergieMittelstand e.V., we analyse how consumer prices[4] of a fuel mix in road transport with an increasing share of e-fuels could develop in the long term. Thereby, several questions arise:

1. What cost trends can be expected for e-fuels in the medium and long term and what are the key cost components?
2. How do production costs, together with other factors such as taxes and transport costs, affect the expected market price of e-fuels and how does this compare with fossil fuels?
3. What volumes can be assumed to be available and what blending ratios of e-fuels to conventional fuels are possible or plausible?
4. With increasing shares of e-fuels, what is the resulting cost path visible at the filling station for fuels? What price changes are to be expected?
5. What conclusions and recommendations for action can be drawn from this?

The study is structured as follows:

[4] Frontier Economics endeavours to address all genders equally. If the generic masculine is used in some cases in this document for the sake of readability, this explicitly includes all genders.

- In chapter 3 we analyse the costs of e-fuels in the international market ramp-up ;
- In chapter 4 we outline possible blending paths of e-fuels to fossil fuels over time;
- In chapter 5 we analyse possible long-term development paths for the retail prices of the fuel mix; and
- In chapter 6 we discuss recommendations for policy makers.

3 Costs of e-fuels in the international market ramp-up

In this section, we first present the main components of the costs of e-fuels and the factors affecting the cost trends (Chapter 3.1). On the basis of current studies, we then analyse medium and long-term projections for e-fuels production costs (Chapter 3.2) and derive a plausible cost range on this basis (Chapter 3.3).

3.1 Key cost components of e-fuels and their drivers

Technical background to e-petrol and e-diesel

E-fuels (also known as *power-to-liquids* or *synthetic liquid fuels*) are renewable, liquid fuels that are produced with renewable electricity, water and carbon dioxide (CO_2). Figure 2 shows a simplified illustration of the value chain.

In a first step, renewable electricity, for example produced in PV or wind energy plants[5], is transformed into green hydrogen (H2) through electrolysis using water. Various electrolysis processes exist, which can be sorted into low-temperature (e.g. alkaline electrolysis (AEL) or polymer electrolyte membrane electrolysis (PEM)) and high-temperature electrolysis. Aside from the temperature at which the conversion processes take place, the electrolysis processes differ in terms of technological maturity, efficiency and cost.

Depending on the specific e-fuels product, different synthesis processes can be used after electrolysis. In this study, we are focussing on e-petrol produced by methanol synthesis and e-diesel produced via Fischer-Tropsch synthesis. In methanol synthesis, hydrogen and CO_2 are combined to produce e-methanol, which is then converted into e-petrol. Another synthesis process is the Fischer-Tropsch synthesis, in which synthesis gas is first produced from hydrogen and carbon monoxide (CO), from which a wide variety of hydrocarbons can then be obtained.[6] The CO_2 required for methanol and Fischer-Tropsch synthesis can be obtained from industrial point sources, for example from industrial processes, or captured from the air (Direct Air Capture, DAC). To utilise carbon monoxide in the Fischer-Tropsch process, CO must be extracted from CO_2 in an additional step, e.g. via a Reverse Water Gas Shift (RWGS) process. In order to enable cost-optimised, continuous operation of the conversion plants, upstream buffer storage tanks for hydrogen and CO_2 are suitable.

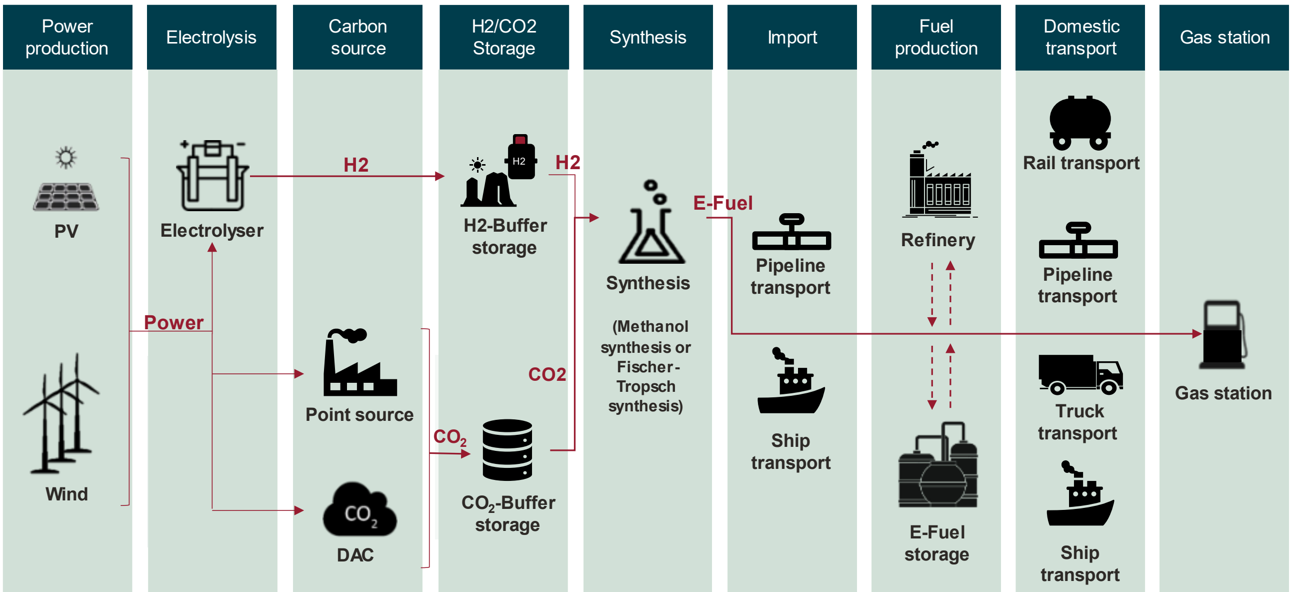
The existing infrastructure for fossil fuels can be used to transport e-petrol and e-diesel. Transport over long distances usually takes place over the ocean via tankers. Alternatively, import by pipeline is possible. Fuel transport from the port to the filling station is done by lorry, pipeline or (inland) ship. Existing storage facilities can also be used due to the chemical equivalent for e-fuels.

5 A combination of PV and wind systems is referred to as a "hybrid" PV/wind system.

6 There is the option of refining in an integrated plant at the production site or in the country of consumption (here: Germany) after exporting the intermediate product (methanol or synthesis gas). The impact on costs is negligible.

In cars, e-petrol can be used as drop-in fuel to fossil petrol or as a 100% alternative (pure fuel) in vehicles with petrol engines. Similarly, no technical modifications in diesel engines are necessary when using e-diesel.

Figure 2 The e-fuels value chain



Source: *Frontier Economics*
Note: *Refining in the exporting country is also possible.*

Electricity generation costs account for the largest share of production costs; the greatest learning curve effects are to be expected in CO_2 sourcing

In recent years, a large number of studies have analysed the costs of e-fuels along their value chain. In most cases, the studies estimate production costs plus transport costs to Germany or Europe. In this study, we go one step further and look at prices in Germany, which also take into account local transport costs (to the filling station) as well as taxes and duties. An evaluation of current cost estimates follows in chapter 3.2.

Based on the literature review, it can be deduced

1. that the production of e-fuels on an industrial scale is in the starting blocks; and
2. which are the key drivers for cost savings potential.

The industrial production of e-fuels is currently in its starting phase. The first demonstration plants are already in operation and many companies around the world are working on the market launch and are scaling up the production of e-fuels.[7] As the market volume increases, significant cost savings can be expected in the medium to long term compared to today's demonstration plants due to learning curves and economies of scale, as it has also been observed in the past with other renewable energy technologies (see *Excursus: Cost degression in renewable technologies* below).

In particular, the following fundamental drivers for the costs of e-fuels were identified (cf. Figure 3):

- **Electricity:** Electricity generation costs are the largest component of the total costs of e-fuels, even in very favourable locations for electricity production (e.g. with high solar radiation and/or strong winds). Due to the relevance of this cost factor, the choice of location plays a key role in the economic viability of e-fuel production. Electricity production costs also depend on the technology used to generate electricity (e.g. PV, wind, hybrid system). From an economic perspective, locations with outstanding conditions for wind power generation (e.g. in Patagonia) or with simultaneously good PV and wind conditions (e.g. in the MENA region[8]) are particularly suitable because more electricity can be generated for the same installing cost. Hybrid plants, in which electricity from both PV and wind is used for hydrogen production, can be advantageous, as solar radiation and wind are partly complementary, which means that higher utilisation of the electrolysers and the plants for further hydrogen processing can be achieved. In recent years, significant cost reductions have already been realised for PV and wind systems due to the development of the technologies and the associated economies of scale. Further cost savings can be expected in the future.
- **CO_2 sourcing**: Costs for CO_2 sourcing account for a large proportion of the production costs of e-fuels if CO_2 is sourced from the atmosphere using direct-air-capture (DAC) technology. In general, DAC costs are still subject to major uncertainties, as only demonstration plants currently exist. However, significant learning effects and cost savings are expected as the technology is scaled up to industrial production scale in the future. In the short term, the costs for CO_2 can be reduced if CO_2 from point sources such as biogas plants or from industrial processes is used. Although the latter will no longer be recognised for the production of green fuels at EU level from 2041 at the latest.[9]
- **Electrolysis:** In recent years, there have been significant technological developments in the field of electrolysis and several electrolysis technologies are commercially available.[10] The first industrial-scale projects are currently in planning or under construction.[11] As this is still a young market for the plants, in which substantial investments are being made, further significant cost

7 An overview of announced and planned production is provided by eFuel Alliance (2024).

8 MENA = Middle East and North Africa.

9 See Delegated Act (EU) 2023/1185 - Methodology for determining greenhouse gas emissions of RFNBOs. In addition, the CO_2 must be taken into account in an upstream step in an effective CO_2 pricing system, which makes the use of CO_2 from industrial processes generated outside the EU more difficult (for example, there is currently no CO_2 pricing in the MENA region).

10 IEA (2024).

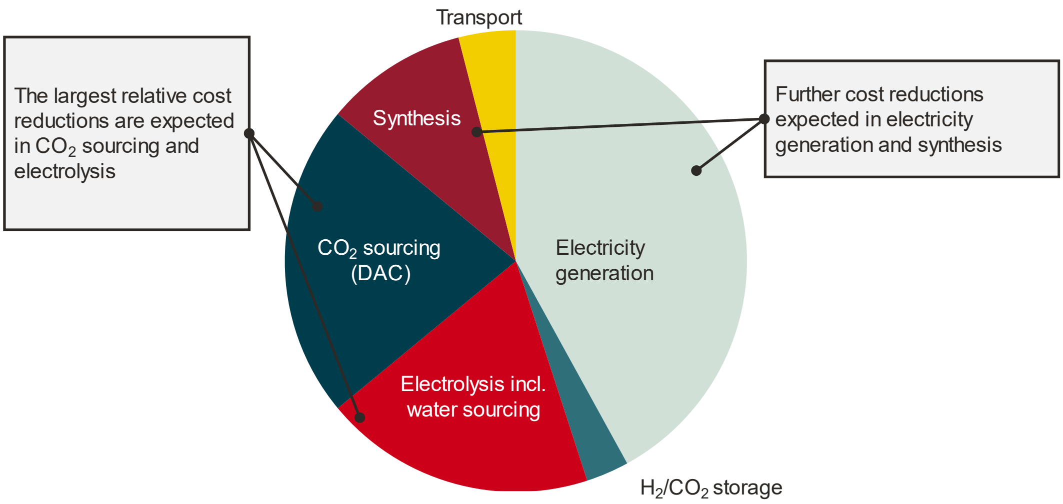
11 See IEA (2023a).

savings can be expected in the medium term – particularly with the imminent upscaling of production capacity for plant manufacture into the gigawatt range.

- **Synthesis:** Compared to the other technologies, synthesis costs play a lesser role.

The costs for the provision of water, H_2 / CO_2 storage and transport are of secondary importance. VAT and energy tax also have a major influence on the retail price of fuels, including e-fuels, in Germany. These price components are not taken into account in most studies.

Figure 3 Key cost components of e-fuels – illustration



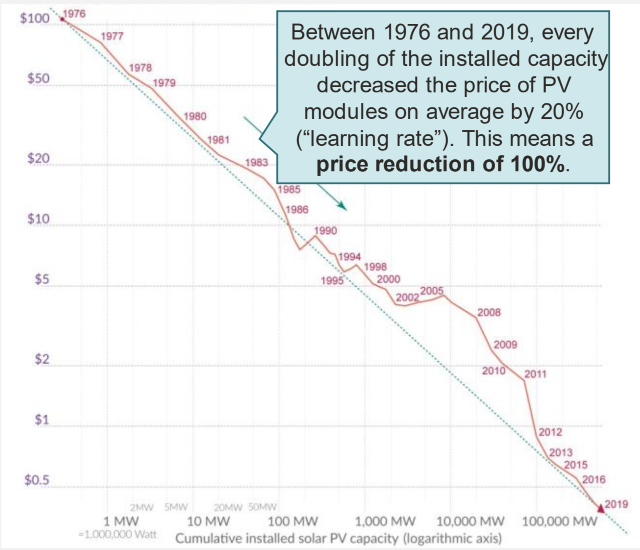
Source: Own presentation.
Note: Example: Today's production in North Africa, DAC, import to Germany.

Excursus: Cost degression for renewable technologies

Renewable technologies, for which a market ramp-up has been observed in recent years, provide an indication of the cost degression that can be expected during the market ramp-up of e-fuels technologies. Electrolysis, synthesis and DAC are currently in the start-up phase, in which the first pioneering projects are being commercialised. The technologies are already well developed, but are not yet being used on a large scale.

As production volumes increase, the unit costs are expected to fall ("learning curve"). The reasons for this include economies of scale, research and development and the standardisation of production processes for the systems. Possible cost degression for the system components of e-fuels technologies not yet used on a large scale can potentially be derived from the example of PV modules. Since the 1970s, prices have fallen by an average of 20 % with a doubling of installed capacity (see figure). A similar learning rate (with an average price-reducing effect of 19 % when global production capacity doubles) has been observed for batteries since the 1990s.[12] If a learning rate of 20 % were also to materialise for e-fuels, costs would fall by 20 % for every doubling of capacity.

Price of PV modules, in $/watt (logarithmic scale, adjusted for inflation)



Source: Our World in Data, https://ourworldindata.org/learning-curve

12 RMI (2023).

3.2 Evaluation and assessment of current projections for production costs for e-fuels

The development of production costs for e-fuels has been estimated in numerous studies in recent years. In this study, we analyse widely received and recent studies and use them to derive a range for the costs of e-fuels. The main studies analysed are from Concawe & Aramco (2024), Öko-Institut, Agora Energiewende & Agora Industry (2024) and Fraunhofer IEE (2021) with cost estimates for the years 2020, 2030, 2040 and 2050 (cf. Table 1).[13] In addition, Agora Verkehrswende, Agora Energiewende and Frontier Economics (2018) complements the selection albeit we do not consider the results in the further analyses.

The studies analyse different reference years, production sites, electricity sources, CO_2 sources and electrolysis technologies. In order to achieve the best possible comparability between the studies, we select the scenarios that make assumptions that are as comparable and realistic as possible.[14] We consider the region of Patagonia (in southern Chile and Argentina), the MENA region and southern Europe as representative production locations.[15] Moreover, there are numerous other production locations worldwide that are also suitable for the production of e-fuels, such as locations in Australia, the USA and South/East Africa. As the costs at these locations are likely to be within the range of Patagonia, the MENA region and Southern Europe, they are already included in the derived cost range.

From 2030 onwards, we show cost estimates based on DAC as a source of CO_2 where available in the studies. This is not the case for Concawe & Aramco (2024), as DAC is only assumed as a source of CO_2 from 2050. We believe it is likely that during the early market ramp-up, CO_2 extraction via point sources (e.g. from industrial processes or biomass) will be favoured over the DAC process. Although DAC will be needed in the long term, it is more cost-intensive and requires further technical developments.

If several power sources have been modelled for a site, we consider the most cost-effective technology, as this would be used first from an economic perspective. We also show the results for the cheaper low-temperature electrolyser, which has already reached the commercialisation phase in

13 The first version of this study (dated 18 September 2024) was based on the cost estimates from the then current version 2.0 of the PTX Business Opportunity Analyser from Öko-Institut, Agora Energiewende and Agora Industry. This update of our study is based on version 2.1.1 of the PTX Business Opportunity Analyser, in which the estimates of production costs were corrected downwards compared to version 2.0.

14 When different scenarios are modelled, we always refer to the reference or the average scenario.

15 If a large number of suitable locations within a country are modelled (as in Fraunhofer IEE (2021)), we use the results for the location with the highest and lowest production costs in the respective region to derive a range.

contrast to high-temperature electrolysis.[16] If high-temperature electrolysis also reaches market maturity, even higher efficiencies and thus lower costs for electrolysis could be achieved.

For production outside of Europe, all studies take into account not only production costs but also transport costs to a European port. Furthermore, all studies consider production facilities on an industrial scale.[17]

Table 1 Overview of the analysed studies

Study	Time frame	Production sites	Power source	CO_2-source
Concawe & Aramco (2024): E-Fuels: A technoeconomic assessment of European domestic production and imports towards 2050 - Update	2020, 2030, 2050	Norway, Germany, Spain, Saudi Arabia	Renewable mix from respective countries	Point source for 2020 and 2030, DAC for 2050
Öko-Institut, Agora Energiewende & Agora Industry (2024): PtX Business Opportunity Analyser, Version 2.1.1	2030, 2040	Large number of selected countries and locations worldwide	PV, wind (onshore, offshore), wind-PV hybrid	DAC and point source
Fraunhofer IEE (2021): Global potential for the production of green hydrogen and climate-neutral synthetic fuels ("Global PtX Atlas")	2050	Large number of selected locations outside Europe	PV, wind, wind-PV hybrid (mix of the respective location)	DAC
Agora Verkehrswende, Agora Energiewende and Frontier Economics (2018): The Future Cost of Electricity-Based Synthetic Fuels	2020, 2030, 2050	North Africa, Middle East, Iceland, North Sea	MENA: PV, wind-PV hybrid; North Sea: wind-offshore; Iceland: geothermal hydropower	DAC and point source

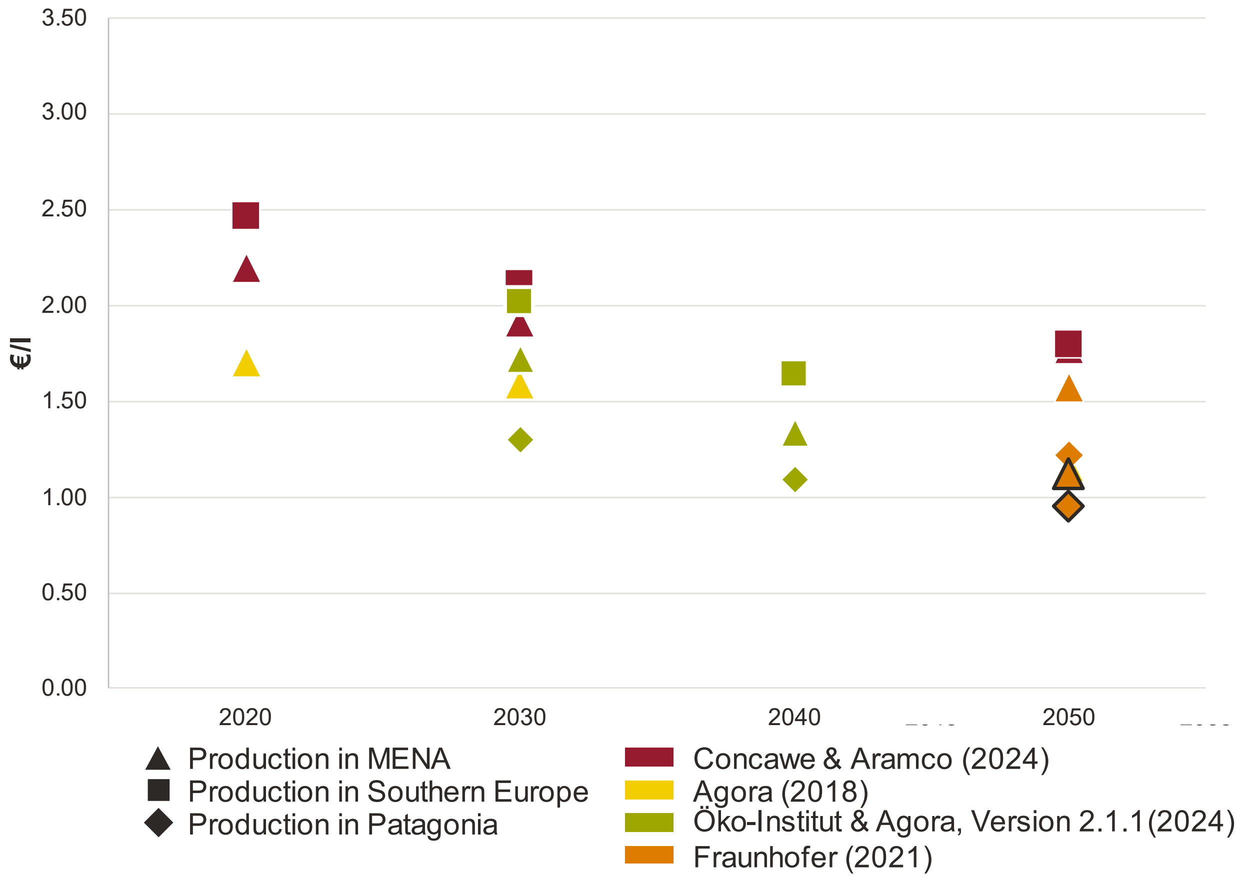
16 PEM and alkaline electrolysis have a technology readiness level (TRL) of 9 on a scale of 1-11. See IEA (2023b): ETP Clean Energy Technology Guide, https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide. The costs between PEM and AEL electrolysis differ only slightly.

17 For example, Concawe & Aramco (2024) assumes in the base scenario that the Fischer-Tropsch plant produces 1 million tonnes of diesel annually. The effect of the size of the production plant on costs is analysed in Annex B.

The analysed studies estimate that the production costs of e-diesel (including transport to Germany) will fall to 0.96-1.80 € per litre in the long term

Figure 4 illustrates the results of the four studies for the costs of Fischer-Tropsch e-diesel[18] and allows comparisons between the studies (represented by different colours) and between production sites (represented by different symbols) over time.

Figure 4 Literature review: Production costs (incl. transport) of e-diesel in 2020, 2030, 2040 and 2050



Source: Frontier Economics based on study results from Concawe & Aramco (2024): E-Fuels: A technoeconomic assessment of European domestic production and imports towards 2050 - Update, Öko-Institut, Agora Energiewende & Agora Industry (2024): PTX Business Opportunity Analyser, Version 2.1.1, Fraunhofer IEE (2021): Global potential for the production of green hydrogen and climate-neutral synthetic fuels ("Global PtX Atlas") and Frontier Economics (2018): The Future Cost of Electricity-Based Synthetic Fuels.

Note: Fischer-Tropsch synthesis is applied in all studies. Values from Fraunhofer IEE (2021) outlined in black show the most cost-effective locations worldwide. Relevant cost estimates are converted to €/l e-diesel and adjusted for 2024 prices.

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[18] In contrast to cost estimates for Fischer-Tropsch e-diesel, not all studies include cost estimates for e-petrol, which is why the costs for e-petrol, are derived using a simplified approach, as described in Chapter 3.3.

The results of the four studies show some similarities:

- **Production costs fall over time**: All studies that model several years come to the conclusion that production costs will fall in the future. For example, the costs in Concawe & Aramco (2024) for Southern Europe fall by 27% between 2020 and 2050. This cost degression can be explained by technological progress and efficiency gains in the relevant processes of e-fuels production. In Concawe & Aramco (2024), for example, the expected efficiency of the electrolysers increases from 66.5 % in 2020 to 75 % in 2050, while the electricity generation costs decrease by 19 % over the same period.[19] The range of cost estimates in the four studies analysed is 1.30-2.11 €/l for the year 2030 and falls to 0.96-1.80 €/l by 2050.
- **Production costs are highly dependent on the location of production**: All studies consider e-fuels production at different locations. It becomes clear that the choice of the location of production has a significant effect on the projected costs, even among the selected regions with high location quality.

Despite these common trends, the production costs for e-fuels in the studies analysed differ considerably in some cases, even within a single country. There are significant differences in the assumptions regarding the production location and the CO_2 source, as we show below. Furthermore, in Fraunhofer IEE (2021) and Öko-Institut (2024)[20], a cost-minimising system design of the plant capacities is carried out on the basis of hourly profiles for electricity generation.

The cost difference between production at an average and a top location within a country can be considerable

The location of production affects the choice for the technology used to generate renewable electricity and the achieved full load hours, which determine the levelised cost of electricity. Site quality differs not only between regions[21] , but also within a country. The analysed studies differ in terms of whether they examine particularly suitable sites (e.g. in coastal regions) or average sites. The latter may be less essential for actual investment projects. While Fraunhofer IEE (2021) analyses representative, suitable locations, the other studies do not explicitly name any locations within the respective countries or regions under consideration.

The main indicator for a site's quality is the full load hours (FLH) of renewable electricity generation. In the best locations enable more FLH than average locations and therefore also lower electricity generation costs. However, prime locations and their production potential are ultimately

---

[19] In the selected example for Southern Europe, the electricity generation costs fall from 5.8 ct/kWh in 2020 to 4.7 ct/kWh in 2050. Costs for the expansion of the electricity distribution grid are included in these figures. Significantly lower electricity costs can be achieved for other locations or if there are no costs for connecting to infrastructure.

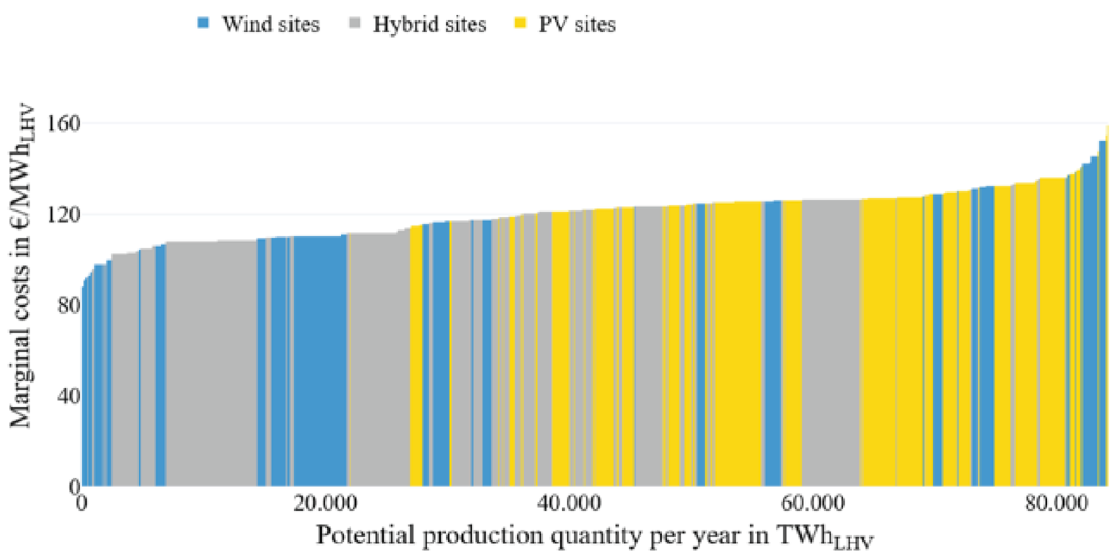
[20] Öko-Institut (2024) models the optimisation for eight sample weeks.

[21] Cf. Figure 18 in Annex B.

geographically limited. If the demand for e-fuels exceeds the production potential of these locations, other locations with (slightly) poorer site conditions must be considered.

Figure 5 shows the relationship between the e-fuels production costs modelled by Fraunhofer IEE (2021) at various global sites in 2050 and the possible production potential in 2050. Prime locations are on the left-hand side of the figure with production costs of around 80 €/MWh (approx. 0.72 €/l e-diesel). As the required production volume increases, additional locations must be exploited and production costs rise. With production volumes of around 40,000 TWh per year, locations with e-fuels production costs of around 120 €/MWh (approx. 1.08 €/l e-diesel) would have to be exploited. Production potential of more than 80,000 TWh per year could be tapped at production costs of just under 160 €/MWh (approx. 1.44 €/l e-diesel).[22] To put this into perspective: Current global mineral oil consumption stands at around 55,000 TWh.[23] In the long term, increased efficiency and electrification (i.e. increased use of electricity appliances) in certain areas will tend to reduce the demand for liquid fuels (see chapter 4.2).

Figure 5 Marginal costs and production potential for Fischer-Tropsch diesel in 2050



Source: Pfenning et al (2023).

Note: Production costs of 80 €/MWh correspond to approx. 0.72 €/l e-diesel, 120 €/MWh correspond to approx. 1.08 €/l and 160 €/MWh correspond to approx. 1.44 €/l. Production costs only without transport to Germany. Costs in €(2021) (not adjusted for inflation).

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22 The lowest estimated production costs are around 87 €/MWh (0.78 €/l). With an annual production capacity of 20,000 TWh, the costs are around 120 €/MWh (1.08 €/l). With an annual production capacity of 60,000 TWh, the costs are around 126 €/MWh (1.14 €/l). All values are pure production costs without transport to Germany. The costs are given in 2021 values and are not adjusted for inflation.

23 Our World in Data (2024).

Source for CO_2 as a driver for production costs

As shown in Table 1 most studies distinguish between different types of CO_2 sourcing when modelling e-fuels costs. As explained above Figure 4 illustrates the costs for 2020 assuming that CO_2 point sources (e.g. from industrial processes or biomass) are used. For a transitional period, CO_2 from these sources will be available at comparatively low cost. In the longer term, dependence on the combustion of fossil fuels in industrial processes should be avoided.[24] We therefore refer to cost estimates that rely on the direct-air-capture technology (DAC) from 2030 onwards (with the exception of Concawe & Aramco (2024), which does not include modelling with DAC for 2030). As this is the more expensive option compared to point sources,[25] the values shown tend to overestimate the e-fuels costs for the period up to 2041, in which point sources for the production of CO_2-neutral fuels are still permitted in accordance with EU regulations under certain conditions (in particular the existence of an effective CO_2 pricing system).

Further differences between the studies result from different assumptions regarding other parameters

The effect of electricity generation costs and costs for CO_2 on production costs is also illustrated in Figure 6 for production at different locations. Where available, we show exemplary locations from the three main studies for the years 2030 and 2050 (Concawe & Aramco: 2030 and 2050, Öko-Institut: 2030, Fraunhofer: 2050). For 2030, for example, the total costs of production for production in Spain estimated by Öko-Institut are similar to those for production in the MENA region estimated by Concawe & Aramco. Although Öko-Institut assumes lower electricity generation costs[26], the massively higher CO_2 costs due to the DAC technology compensate for this effect.[27] The comparison with the results for 2050 suggests that substantial cost savings are possible over time and over the choice of location.

Other differences between the studies are

- **Electricity transmission**: Öko-Institut (2024) does not include costs for electricity transmission between the renewable electricity plants and the e-fuels production sites. However, Concawe & Aramco (2024) assume that the geographical distance between the renewable plants and e-fuels

[24] See Agora Verkehrswende, Agora Energiewende and Frontier Economics (2018).

[25] Agora Verkehrswende, Agora Energiewende and Frontier Economics (2018), for example, assumes costs of 145 €/tCO_2 for DAC compared to 33 €/tCO_2 for CO_2 from the cement industry in Germany for 2020 (not inflation-adjusted values from 2017). The effect of the CO_2 source on production costs is also shown in Figure 19 in Annex B.

[26] In contrast to Öko-Institut (2024), the LCOE in Concawe & Aramco (2024) also include the construction of distribution grids, see below. In both studies, PV-wind hybrid plants are used for electricity generation, but the FLH assumed by Concawe & Aramco for the MENA region are significantly higher than those assumed by Öko-Institut for Spain (5,227 h/year vs. 4,135 h/year). Even within the MENA region, Concawe & Aramco assume around 26 % higher FLH (5,227 h/year vs. 3,704 h/year).

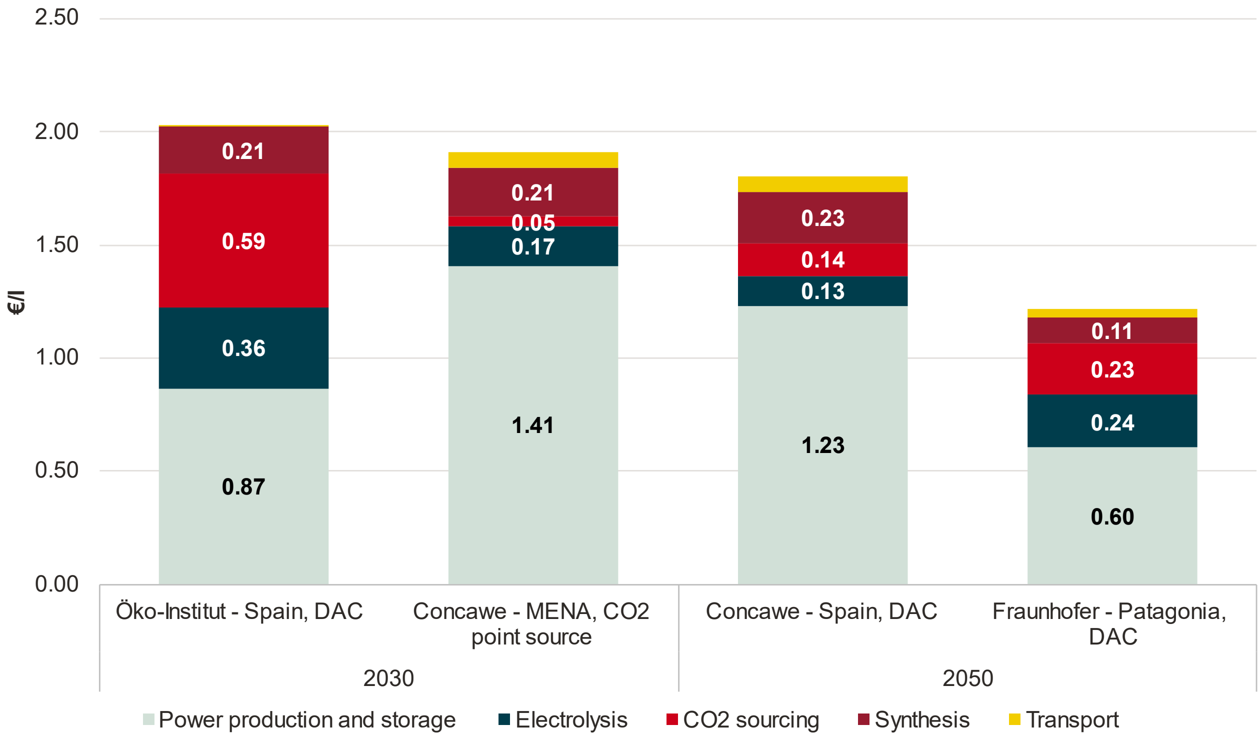
[27] In the reference year 2030, Concawe & Aramco (2024) assumes CO_2 extraction from point sources, while Öko-Institut (2024) models CO_2 sourcing using the more cost-intensive direct air capture process in the reference scenario. In a sensitivity analysis assuming CO_2 from point sources, the CO_2 costs in Öko-Institut (2024) fall to around 0.10 € per litre.

production is 200 km on average. It is assumed that the transmission grids will be newly built, which will increase the costs for conversion and transmission by around 27 %.

- **Capital costs**: Capital costs are another significant driver of production costs. The relevant capital costs (expressed as weighted average cost of capital, WACC) differ significantly between the studies. Concawe & Aramco (2024) works with comparatively high capital costs for MENA (WACC at 8%), while Öko-Institut (2024) assumes lower capital costs for Spain (WACC at 6.94%). The higher capital costs have an impact on all investments along the value chain, resulting in higher overall production costs.

  - The cost of capital is not "fixed", but is largely driven by the creditworthiness of the developers and the respective projects. In the case of international projects, creditworthiness is also affected by specific country risks. Political and economic stability as well as a stable legal framework and effective regulation can have a positive impact on the cost of capital. An increased exchange rate risk or high interest rates in the project country, on the other hand, can have a negative impact on the cost of capital. Political recommendations for action that can lead to a reduction in the cost of capital are discussed further in chapter 6.

Figure 6 Cost components of e-diesel for production at different locations and CO_2 sources, 2030 and 2050



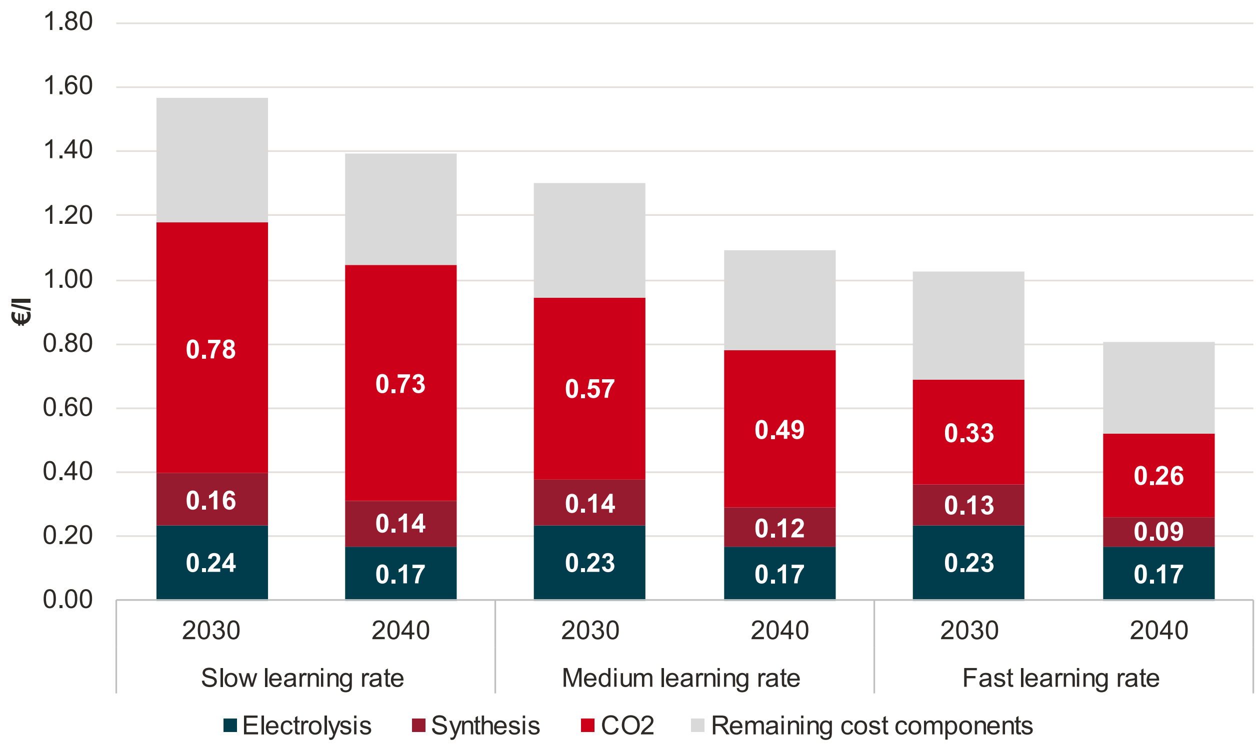
Source: *Frontier Economics based on Concawe & Aramco (2024): E-Fuels: A technoeconomic assessment of European domestic production and imports towards 2050 - Update, Öko-Institut, Agora Energiewende & Agora Industry (2024): PTX Business Opportunity Analyser, Version 2.1.1 and Fraunhofer IEE (2021): Global potential for the production of green hydrogen and climate-neutral synthetic fuels ("Global PtX Atlas"). "Storage" includes electricity storage and H2 storage, which cannot be shown separately due to the granularity of the data. Production costs incl. transport to Germany.*

The learning rate determines how much the costs fall over time

The assumed learning rates in the studies are usually not shown explicitly, but are primarily reflected implicitly in the respective cost assumptions for the individual technologies over time. The capital costs of the plants decrease over time across all studies, whereby the cost reductions vary depending on the study and technology. In addition, it is generally assumed that the technologies become more efficient (illustrated by the efficiency), which means that a higher production volume can be achieved from a given input volume. This is based on the assumption that technological progress and the expansion of production will generate a learning effect.

With a higher learning rate (e.g. as a result of extensive R&D efforts and thus faster market ramp-up of e-fuels), significantly lower e-fuel costs could be realised by 2030 and 2040, cf. Figure 7, based on an analysis by the Öko-Institut (2024). As described in chapter 3.1, learning effects are expected above all for the DAC processes, as this is currently the technology with the lowest level of technological maturity along the value chain. In the specific example, the costs for DAC (incl. heat supply) account for 50% of the total costs in 2030 in the high cost path, and only 32% in the low cost path. In comparison, the expected cost savings for electrolysis and synthesis are lower.

Figure 7 E-fuels production costs with different learning rates



Note: "Remaining cost components" includes all those for which no significant learning rate is expected.

Source: Frontier Economics based on Öko-Institut, Agora Energiewende & Agora Industry (2024): PTX Business Opportunity Analyser, Version 2.1.1. Costs here are based on production in Chile using onshore wind as the source for electricity. The costs in the average cost path correspond to the costs shown by the Öko-Institut in Figure 4.

3.3 Long-term cost range of e-fuels

The costs for e-diesel are derived directly from the literature review

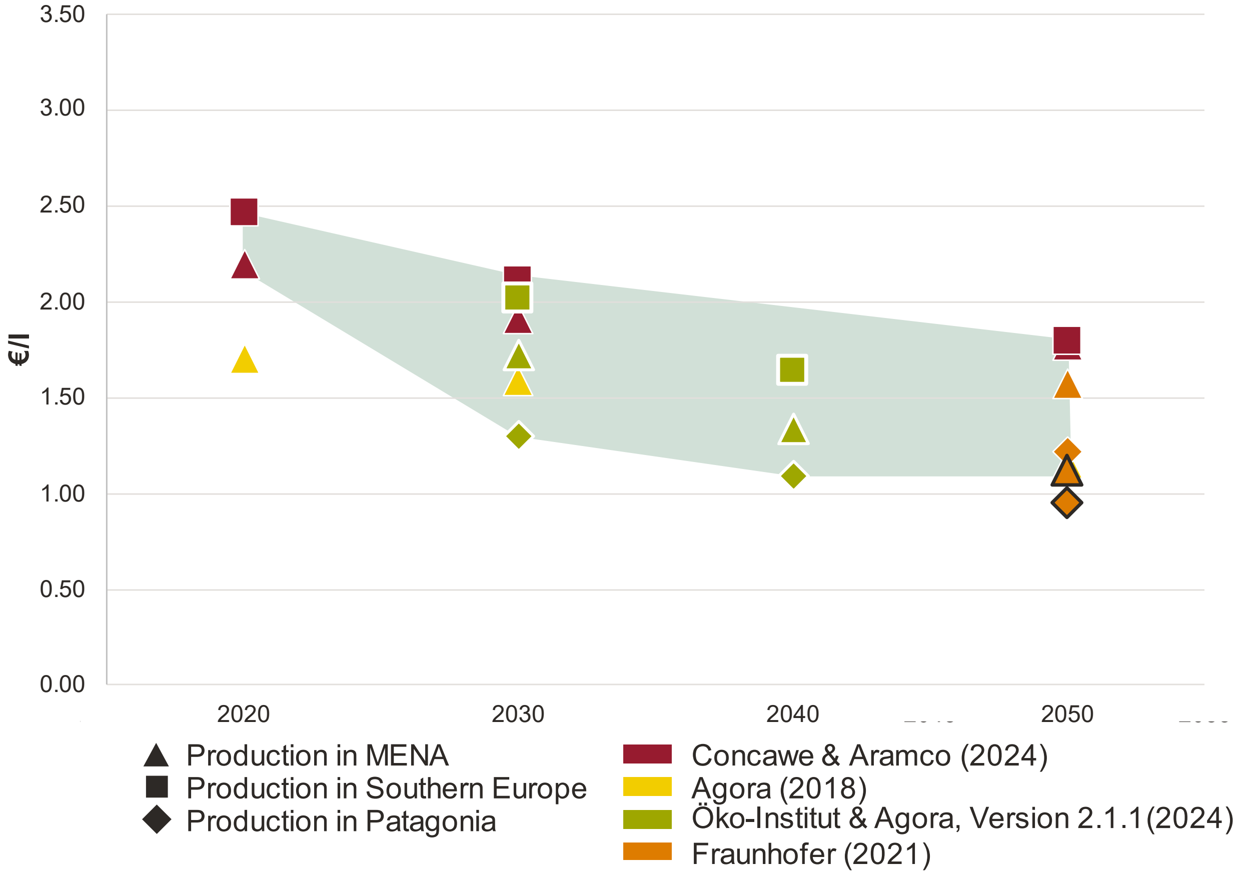
Based on our literature review, we derive a plausible range for the production costs of **e-diesel**, which is shown in Figure 8 in grey colour. The range is based on the representative locations in the MENA region, Southern Europe and Patagonia, but covers a large number of other suitable production locations worldwide where the costs of e-fuels production are likely to be within the derived range.

The **lower end of the range** is formed by cost estimates for the most favourable production location from Öko-Institut (2024) for the years 2030 and 2040. For 2020 we use the estimate from Concawe & Aramco (2024) for production in the MENA region. We do not include the most optimistic results from Fraunhofer IEE (2021) for the year 2050 in the cost range, as they relate to the best locations in Patagonia and MENA, which refer to a production potential that is unlikely to be sufficient to meet global demand in the long term. We therefore keep the lower range constant from 2040 onwards, even if further cost savings could also be possible after 2040 due to economies of scale.

The **upper end of the range** of cost estimates for the reference years 2020, 2030 and 2050 is formed by the highest costs of the studies analysed. These are the cost estimates from Concawe & Aramco for production in South Europe. We regard these values to be conservative, partly because this study assumes high cost for electricity production and does not optimise system capacities. These cost estimates are even higher than the costs for the most expensive location modelled by Fraunhofer, at whose costs a global production potential of over 80,000 TWh/year can be developed (cf. Figure 5). For the year 2040, we take a conservative approach and linearly interpolate Concawe & Aramco's cost estimates for 2030 and 2050.

The estimates for they years 2020, 2030, 2040 and 2050 are then used to interpolate estimates for the remaining years. The interpolation results in the grey area shown below.

Figure 8 Literature review: Production costs of e-diesel incl. transport, 2020-2050, and resulting range



Source: *Frontier Economics based on study results from Concawe & Aramco (2024): E-Fuels: A technoeconomic assessment of European domestic production and imports towards 2050 - Update, Öko-Institut, Agora Energiewende & Agora Industry (2024): PTX Business Opportunity Analyser, Version 2.1.1, Fraunhofer IEE (2021): Global Potential for the Production of Green Hydrogen and Climate-Neutral Synthetic Fuels ("Global PtX Atlas") and Agora Verkehrswende, Agora Energiewende and Frontier Economics (2018): The Future Cost of Electricity-Based Synthetic Fuels.*

Note: *Fischer-Tropsch synthesis is applied in all studies. Values from Fraunhofer IEE (2021) outlined in black show the most cost-effective locations worldwide. Relevant cost estimates are converted to €/l e-diesel and adjusted for 2024 prices.*

The costs for e-petrol are derived on the basis of adjusted costs

In addition to e-diesel, we also consider e-petrol produced via methanol synthesis. The production costs of e-petrol are only explicitly analysed in two of the four selected studies. In Concawe & Aramco (2024), the cost of e-petrol per unit of energy (MWh) is 11-19% lower than the cost of e-diesel produced via Fischer-Tropsch synthesis.[28] The other study, Agora (2018), estimates the production

[28] In this study, e-petrol is produced via the methanol-to-gasoline process. The comparison is based on the production costs in the MENA region. The cost differences vary between the sample years due to different learning effects in the respective technologies. The significant cost difference between e-diesel and e-petrol in Concawe & Aramco (2024) could also be due to the fact that the production costs of e-diesel are comparatively high, cf. Figure 5.

costs per unit of energy for e-petrol and e-diesel to be equal. Öko-Institut (2024) and Fraunhofer IEE (2021) do not model production costs for e-petrol, but they do so for the intermediate product methanol. Both studies estimate the production costs (per MWh) of methanol to be 3%-9% lower than those for FT diesel. The costs for converting methanol into e-petrol, which are not modelled in either study, could offset the cost advantage over e-diesel. For example, based on Concawe's calculations, the conversion of methanol into e-petrol increases total production costs by 3-9% (per MWh of the end product).

Based on these available cost estimates, we assume as a conservative estimate that the production costs per unit of energy for e-petrol are as high as for e-diesel.

When converting production costs from €/MWh to €/l, the different calorific values (energy content per volume, expressed here in litres) of e-diesel and e-petrol must be taken into account. E-diesel has a higher calorific value than e-petrol; when 1 litre of e-diesel is burned, more energy is released and is therefore available for the mechanical overcoming of distances than when 1 litre of e-petrol is burned. With the same production costs per unit of energy and a higher energy content per litre, this results in higher production costs per litre of e-diesel compared to e-petrol. This difference is 9.6%[29] , which is why we derive the cost range per litre of e-petrol by applying a discount of 9.6% to the cost range of e-diesel.

The derived production costs for e-fuels are between around 0.99 € and 1.80 € per litre in the long term

The following ranges result for the production costs (incl. transport to Germany) of e-fuels (cf. Figure 9):

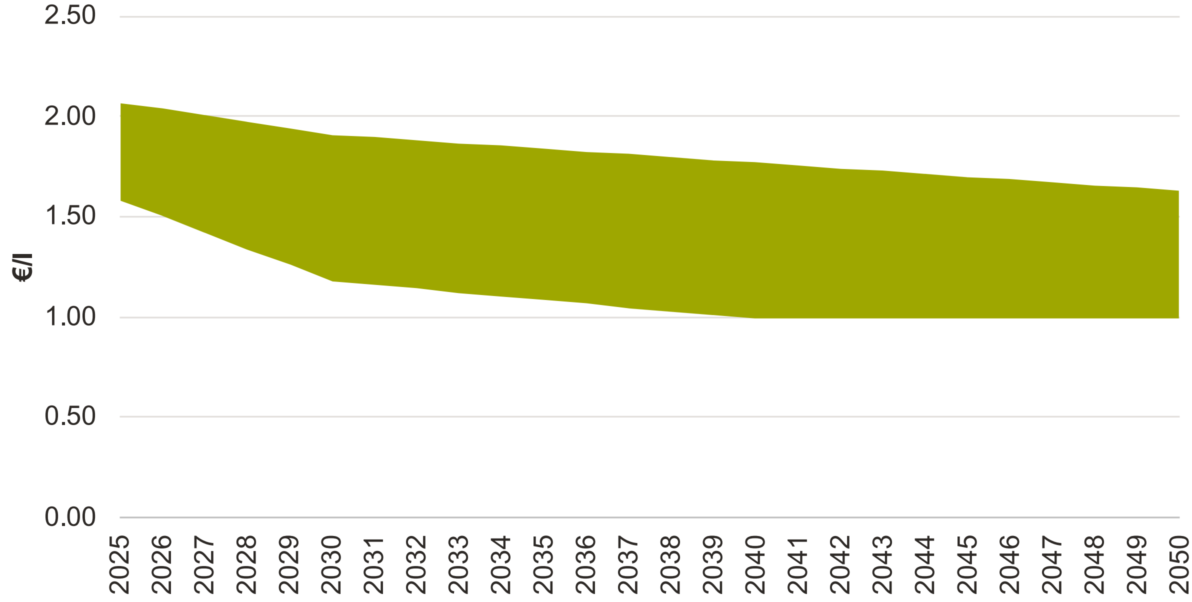
- The cost of **e-petrol** are projected to be 1.58-2.07 €/l in 2025 and fall to 0.99-1.63 €/l by 2050.
- The cost of **e-diesel** are projected to be 1.75-2.29 €/l in 2025 and will fall to 1.09-1.80 €/l by 2050.[30]

[29] The calorific value of e-diesel is 34.3 MJ/l, while the calorific value of e-petrol is 31.0 MJ/l, which is 9.6 % lower, see Concawe (2019).

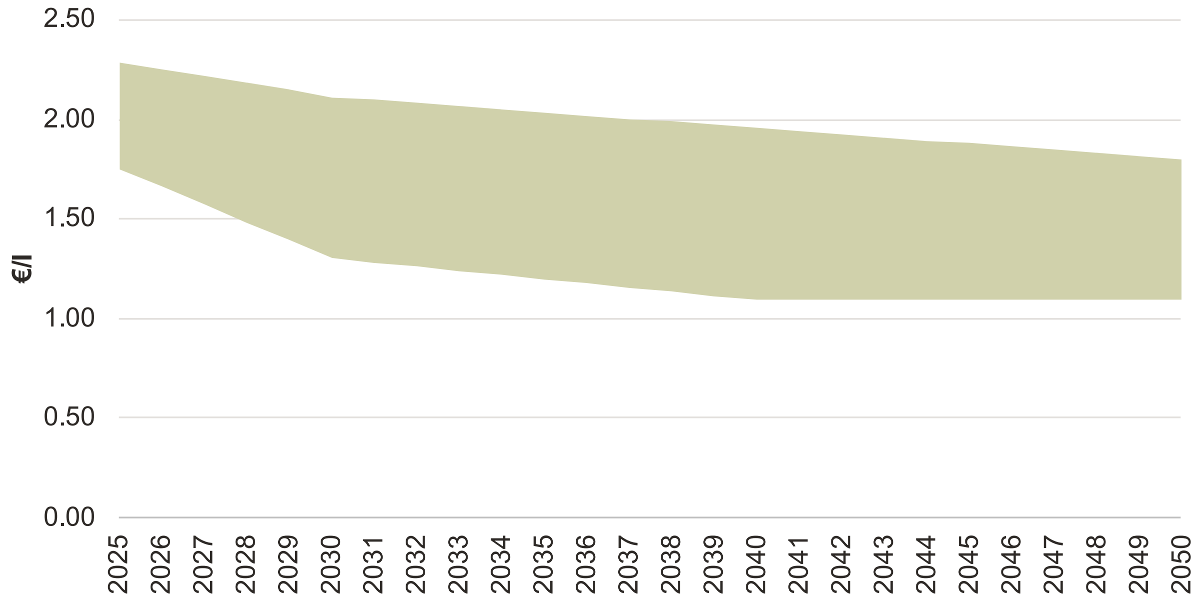
[30] The higher litre-related production costs of e-diesel compared to e-petrol are relativised by its higher energy density, which is actually available to the vehicle user as final energy for driving. However, in order to better compare the cost scenarios, we consider the cost per litre to be a useful benchmark for this study.

Figure 9 Cost range for e-petrol and e-diesel in pure form

E-petrol



E-diesel



Source: Frontier Economics based on study results from Concawe & Aramco (2024): E-Fuels: A technoeconomic assessment of European domestic production and imports towards 2050 - Update, Öko-Institut, Agora Energiewende & Agora Industry (2024): PTX Business Opportunity Analyser, Version 2.1.1, Fraunhofer IEE (2021): Global potential for the production of green hydrogen and climate-neutral synthetic fuels ("Global PtX Atlas") and Agora Verkehrswende, Agora Energiewende and Frontier Economics (2018): The Future Cost of Electricity-Based Synthetic Fuels.

Note: All values in €(2024).

4 Possible future blending paths for e-fuels during market ramp-up

In this chapter, we derive how the blending ratio of e-fuels with fossil fuels could develop up to 2045, the year in which climate neutrality is to be achieved at the latest. Firstly, we discuss which factors have a fundamental effect on the availability and market ramp-up of e-fuels (Chapter 4.1). In chapter 4.2 we show that the theoretical supply potential of e-fuels generally exceeds demand. We derive possible blending paths in chapter 4.3.

4.1 Factors affecting the ramp-up of e-fuels volumes

The speed and extent to which the international market ramp-up of e-fuels can take place depends on various factors. Some of the more relevant supply- and demand-side factors are listed below.

Supply-side factors affecting the availability of e-fuels on the market:

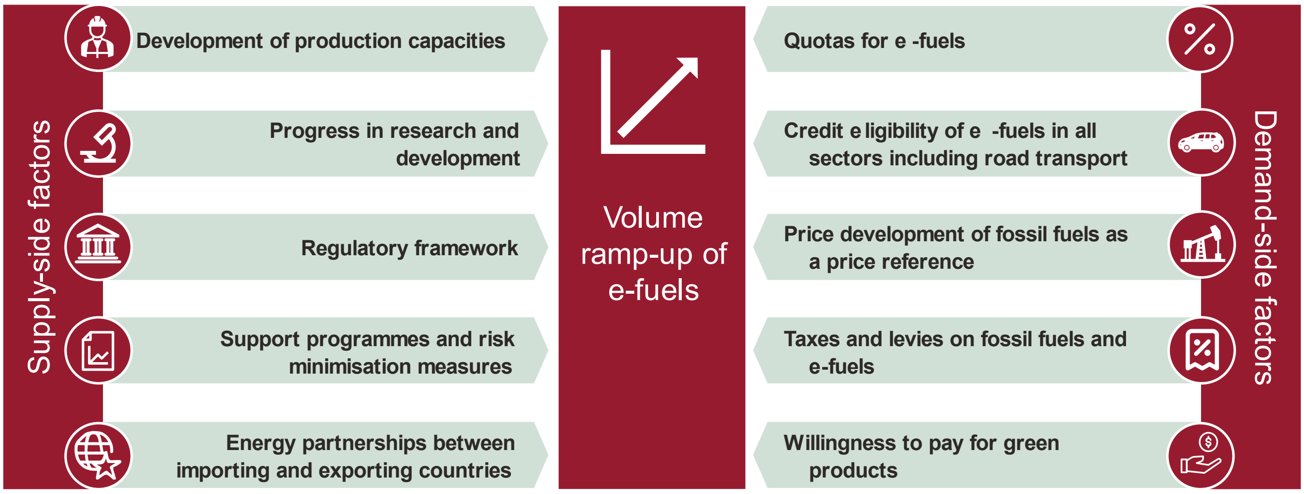
- Advances in research and development affect how quickly technologies reach market maturity. The processes along the e-fuels value chain (see chapter 3.1) already have a high degree of technological maturity. One exception is currently the reverse water gas shift process (RWGS), which is required for the production of carbon monoxide for Fischer-Tropsch synthesis.
- The speed at which production capacity is built up and the associated reduction in production costs (particularly for electrolysers and synthesis plants) depends, among other things, on technological developments, the availability of raw materials and primary products, personnel and technical restrictions.
- The regulatory framework and its long-term reliability affect investors' willingness to invest. Specific aspects here are legal and political regulations such as the design of authorisation procedures, the legal definition of renewable fuels (including the permitted CO_2 sources as input), the eligibility of fuels for quotas such as the GHG quota and the strictness of the requirements compared to other renewable energy sources. Simplicity and reliability are particularly important here, as they have a positive effect on the planning security of investors.
- Support programmes (such as H2 Global or the European Hydrogen Bank) reduce the risks investors are exposed to, particularly at the beginning of the market ramp-up phase. Such programmes can promote early investments and initiate the market ramp-up.
- Due to the relatively unfavourable conditions for renewable energies in Germany in a global comparison, Germany will foreseeably be able to obtain its energy supply for e-fuels much more cheaply through imports and thus remain an energy net importer even in a renewable energy system. Bilateral cooperation between importing and exporting countries is necessary for imports from other regions of the world to Germany, e.g. in order to support and involve local players. Programmes that specifically establish strategic partnerships between Germany/the EU and third

countries can pave the way for exporting technologies (e.g. electrolysers) from Germany while importing e-fuels.

Demand-side factors affect the ramp-up of e-fuels production volumes by affecting the demand for e-fuels from downstream stages of the value chain such as petrol stations or end consumers**:**

- The regulatory framework is powerful lever for e-fuels demand, particularly
  - quotas for e-fuels in Germany and the EU;
  - the eligibility of e-fuels in all sectors, including road transport, e.g. for CO_2 emission performance standards for cars and vans (CO_2 fleet targets).
- Furthermore, the price difference between e-fuels and fossil fuels also affects demand. This difference depends on
  - the price of fossil fuel (which is influenced by the CO_2 price, among other things);
  - Taxes and levies on fossil fuels and e-fuels (e.g. energy tax); and
  - the consumer's willingness to pay for the green product.

Figure 10 Factors affecting the ramp-up of e-fuels



Source: Frontier Economics

Ultimately, there are various interdependencies between supply-side and demand-side factors, making is difficult to separate their effects in practice: For instance, higher or more predictable demand reduces investment risk, enabling faster growth in supply. Conversely, supply can also stimulate demand, as buyers gain confidence in product availability. Favourable conditions tend to have systemic rather than strictly defined effects. In an investment-friendly environment, economies of scale and learning effects can be achieved more quickly, reducing the costs of e-fuels and accelerating market growth.

4.2 Analysing the availability of e-fuels

A decisive factor for the market ramp-up of e-fuels is the extent to which production capacities will be available. This raises the question of whether sufficient suitable locations are available for economical e-fuels production to meet global demand.

A study by Pfennig et al. (2023) based on Fraunhofer IEE (2021) provides valuable insights in the form of a model of production capacities and production costs for potential locations outside of Europe, taking into account exclusion criteria (e.g. land use, protected areas, slope inclination, high electricity generation costs). The analysis of 600 representative locations worldwide shows that the production capacity of e-fuels at long-term production costs of less than 1.50 €/l (FT diesel) amounts to approx. 87,000 TWh/year (cf. Figure 5). Around half of the production potential is located in countries with a large availability of land, such as the USA, Australia and Argentina. There is also production potential within Europe that was not modelled in Pfennig et al. (2023).

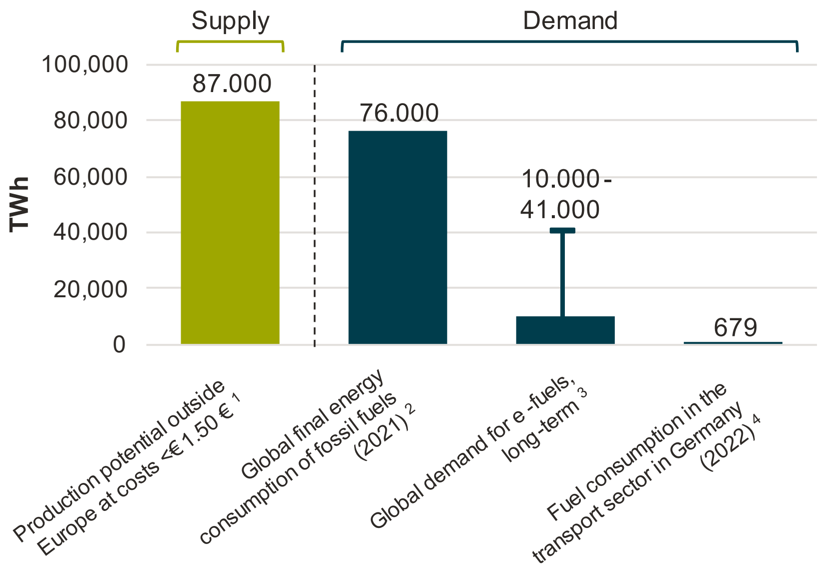
The non-European production potential for e-fuels of 87,000 TWh/year already exceeds the total global final energy consumption of fossil fuels (coal, oil, natural gas), which totalled 76,000 TWh in 2021.[31] In the long term, demand for liquid fuels is expected to decrease due to electrification. For example, Frontier Economics (2018a) estimates in a study for the World Energy Council Germany that the global demand for e-fuels could amount to 10,000-41,000 TWh/year in the long term. Although the rough global demand estimates are likely to be minimum quantities, the (conservatively estimated) production potential of 87,000 TWh/year significantly exceeds the demand estimates. In Germany, the current consumption of fuels in the transport sector is around 679 TWh/year.[32] Figure 11 illustrates the orders of magnitude.

Based on these results, it can be assumed that the production potential of e-fuels should not represent a limitation for the global supply of e-fuels in the long term, but rather that the capacity and volume ramp-up and the availability of e-fuels in Germany will depend on the regulatory and political framework (see Chapter 4.1).

[31] IEA (2024), Energy Statistics Data Browser. Global primary energy demand for coal, oil and natural gas totalled at around 138,000 TWh in 2021, see IEA World Energy Balances, total energy supply.

[32] German Environment Agency (2024), Development of final energy consumption by fuel in the transport sector, excluding electricity.

Figure 11 Supply and demand potential of e-fuels



Source: Frontier Economics based on 1: Pfennig et al. (2023), 2: IEA (2023c), 3: Frontier Economics (2018a), 4: German Environment Agency (2024), in which 679 TWh corresponds to 2,446 PJ.

4.3 Blending path of e-fuels with fossil fuels

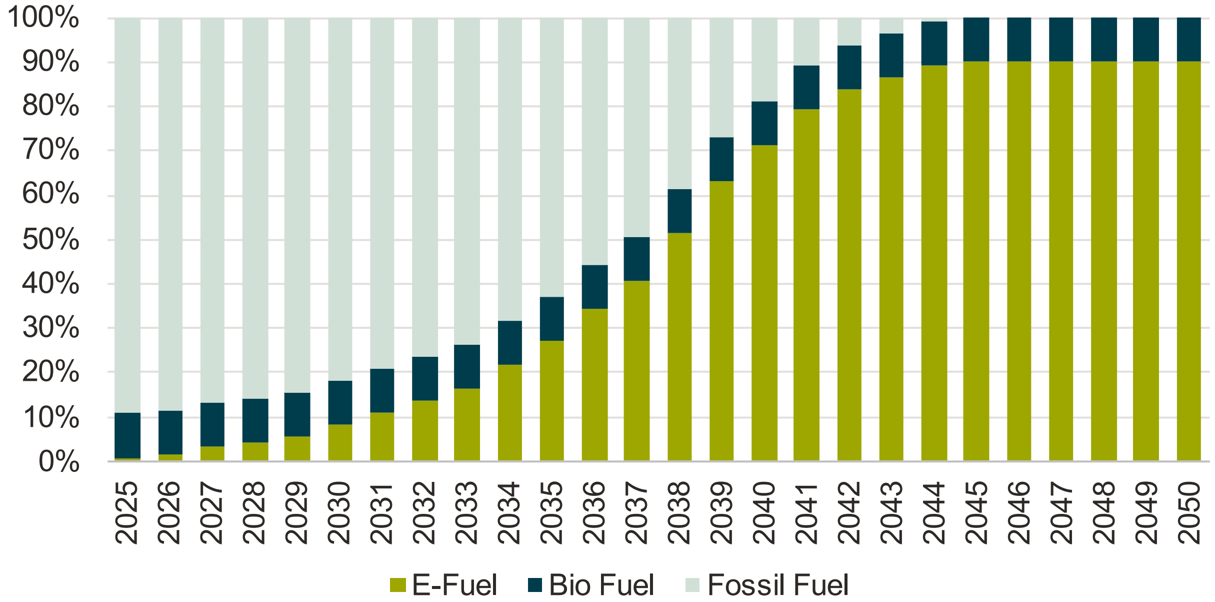
As described in chapter 4.1, the market ramp-up of e-fuels is affected by a variety of factors, which makes the prediction for the development of e-fuels volumes in Germany highly uncertain. In order to derive a possible ramp-up of volumes, we primarily use a possible, stylised ramp-up of e-fuel volumes based on literature on product life cycles, following an S-curve, i.e. showing a gradual early production and adoption, followed by a significant increase as e-fuels become more widely available, before eventually stabilising as the market matures. A similar curve was assumed for the market ramp-up of e-fuels in Prognos AG, Fraunhofer UMSICHT and DBFZ (2018), for example. We assume that the blending of e-fuels with conventional fuels will progress in line with their market ramp-up and availability[33]. Therefore, the blending share of e-fuels also increases in the same way over time, replacing fossil fuels completely from 2045 onwards. The disadvantage of this approach is that it does not take into account any factors that are specifically relevant to the production of e-fuels.

We also assume that the blended fuel mix contains a constant share of biofuel of 7% (diesel) and 10% (petrol). Following an S-curve, e-petrol and e-diesel completely replace fossil fuels in the fuel mix from 2045 onwards. The composition of the fuel mix over time is shown in Figure 12 for petrol.

[33] In practice, the actual blending share will be influenced by political and regulatory obligations, the physical availability of e-fuels, and the price difference between e-fuels and conventional fuels. Since an exact forecast of the blending share is not the focus of this study, we abstract from these interactions and assume that e-fuels will be blended into the conventional fuel mix to the extent they are available – approximated by the stylised S-curve.

The composition of the diesel fuel mix is almost identical and differs only in the biofuel share (7% instead of 10%).

Figure 12 Composition of the petrol fuel mix



Source: Frontier Economics.

In appendix B.4 we also pursue an alternative approach that takes purely technical restrictions into account for a blending scenario, i.e. ideal political conditions are assumed. In this sensitivity, a faster e-fuels ramp-up is possible, in which e-fuels could completely replace fossil fuels as early as 2037 (e-petrol) or 2043 (e-diesel).

5 Future prices for fuels during the e-fuels market ramp-up

In this chapter, we combine the results of the development of production costs (Chapter 3) and of the blending pathways (Chapter 4) in order to derive a possible development of prices for the fuel mix in Germany. In chapter 5.1, we show the consumer price components at the filling station. Chapter 5.2 presents the resulting development of consumer prices. Finally, in chapter 5.3 we discuss the effect of taxation on fuel prices.

5.1 Assumptions for the components of consumer prices

In chapter 3.3 we analysed production costs of e-fuels plus costs for transport to Europe. Prices for consumers at the filling station also include distribution costs, taxes and levies.[34] Thus, the following cost components must also be added to the costs of e-fuels analysed in chapter 3.3:

- **Energy tax:** We introduce two scenarios ("energy tax reform" and "no tax reform") that differ in terms of how energy taxation evolves. The key issue is that under German law, e-fuels are taxed the same as fossil fuels. Both the European Commission and the German government would like to change that. In the "energy tax reform" scenario, we envision that the tax rates for e-fuels in Germany from 2025 onwards follow the minimum requirements of the reform proposal of the Energy Tax Directive published by the European Commission in 2021.[35]
  - **Base scenario "energy tax reform"**: 15 ct/GJ for e-fuels from 2025 onwards, equivalent to around 0.54 ct/l for e-diesel and around 0.47 ct/l for e-petrol.
  - **Scenario "No tax reform"**: 47.04 ct/l for e-diesel, 65.45 ct/l for e-petrol

- **Distribution costs:** Based on estimates from Prognos (2018), we assume that the costs and margins for transport and distribution amount to 0.19 €/l for petrol and 0.24 €/l for diesel.[36]

- **Value added tax (VAT)**: 19 % on the value of goods incl. energy tax.

In addition to the e-fuels supply price, the price of the reference fuel is the other component of the fuel mix price. Besides a certain share of fossil fuel (which is successively replaced by e-fuels in our modelling), we also take into account a constant share of 10 % (petrol) or 7 % (diesel) biofuel, which corresponds to the maximum blending ratios currently in use at filling stations. The prices for fossil fuels and biofuel consist of production costs, costs for CO_2 pricing, energy tax and VAT. We make the following assumptions regarding their future development:

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34 In reality, the price formation mechanism is complicated and depends, among other things, on whether a global spot market for e-fuels will be established (analogous to the current market for fossil fuels). As the market development is uncertain, we make the simplifying assumption that the prices are made up of the price components described and use the production costs derived from the third-party studies as a basis.

35 See https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52021PC0563

36 Agora (2018) estimates distribution costs at around 13 ct/l (adjusted for inflation). Agora estimates the margins at 1-3 ct/l.

- **Development of wholesale prices for petrol and diesel**: We use current wholesale prices and model future price developments in line with price expectation for crude oil in the IEA's "Announced Pledges Scenario", which is based on the successful implementation of announced climate protection measures. In this scenario, crude oil prices decrease by around 24% until 2030. By 2050, prices will even fall by 39 %. The reason for this is that the expectation of the future crude oil price is significantly affected by the expected CO_2 prices. Higher CO_2 prices increase the prices of crude oil and oil products, which in turn reduces the demand for these products if more favourable alternatives are available.[37] In order to construct a consistent future scenario, we adopt both the CO_2 prices from IEA's "Announced Pledges Scenario" (see below) and price expectations for crude oil.

  The relative changes in the price of crude oil are interpolated linearly between the reference years and applied to today's wholesale prices for diesel and petrol. The prices (before CO_2 pricing and taxes) for fossil diesel fall from 0.57 €/l in 2025 to 0.39 €/l in 2045. The costs for fossil petrol are 0.62 €/l in 2025 and 0.42 €/l in 2045. Figure 22 in Appendix B.2 shows the resulting price development over time. It should be noted that, despite the existing price forecasts, the use of fossil fuels will practically no longer be possible by 2045 at the latest, as the German government's climate targets aim to reduce greenhouse gas emissions to net zero by 2045.[38]

- **Development of wholesale prices for bioethanol and biodiesel:** Bioethanol and biodiesel[39] are currently the most widely used biofuels for blending with petrol or diesel. The current wholesale prices for bioethanol stand at around 0.53 €/l and 0.92 €/l for biodiesel, which we keep constant over time for the sake of simplicity.

- **Development of the CO_2 price:** As of 2027, a European emissions trading system (EU ETS 2) is to be introduced for road transport (and heating in buildings); a similar system already exists in Germany (Brennstoffemissionshandel, BEHG).

  The CO_2 prices for fossil fuels were modelled on the basis of the IEA's "Announced Pledges Scenario".[40] This scenario forecasts CO_2 prices of 147 €/t CO_2 in 2030, 190 €/t CO_2 in 2040 and 217 €/t CO_2 in 2050. [41] The German CO_2 prices for the transport sector are applied for the years 2025 and 2026 (2025: 55 €/t CO_2, 2026: 65 €/t CO_2).[42] This results in CO_2 costs per litre of fuel of 0.11 €/l for petrol and 0.12 €/l for diesel in 2025, which rise to 0.54 €/l for diesel and 0.48 €/l for petrol by 2045. The annually modelled CO_2 prices are presented in Figure 23 in Appendix B.2.

37 There are therefore lower quantities of crude oil available at lower prices (before CO_2 pricing).

38 As a result, no more replaceable fossil fuels are used or the non-replaceable ones have to be compensated for by negative emissions.

39 For the purpose of this study we are analysing FAME (fatty acid methyl ester) as the representative biodiesel.

40 IEA (2023d), Table B.2. CO_2 prices for industrialised countries with net zero pledges.

41 CO_2 prices are converted to Euro and adjusted for inflation.

42 BMWK (2024a).

From 2040 in particular, there is great uncertainty at European level regarding the development of the CO_2 price, as the EU ETS I is currently due to expire around 2040 ("ETS endgame"). For example, it is unclear whether and, if so, when there will be a merger with the EU ETS II and whether a regulated market for negative emissions will emerge.

Biofuels are usually per definition climate-neutral, so we do not apply a CO_2 price.

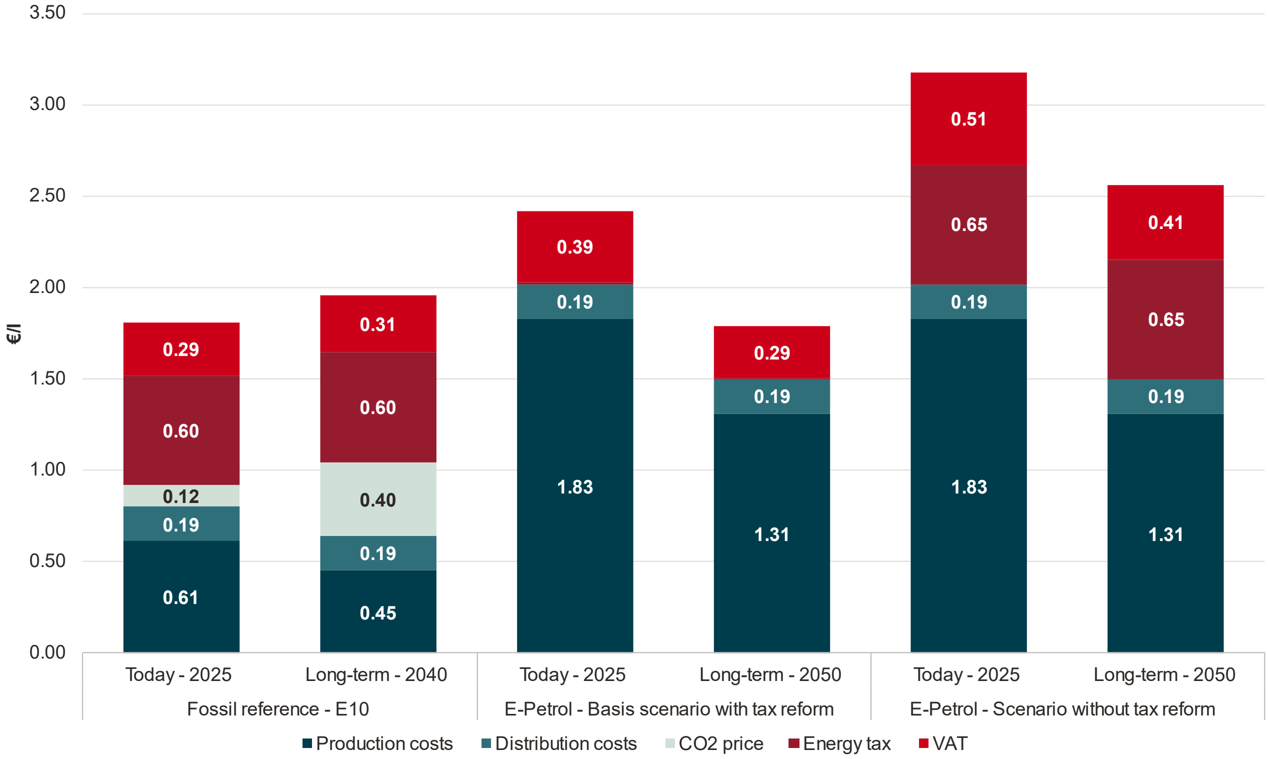
- **Energy tax**: We assume that the current energy tax for fossil fuels remains unchanged until 2045 (47.04 ct/l for diesel, 65.45 ct/l for petrol). As with e-fuels, we assume that a reduced energy tax will be applied to biofuels in the base scenario. The tax level for bioethanol and FAME in the EU Commission's proposal is 5.38 €/GJ, which corresponds to 0.11 €/l for bioethanol and 0.18 €/l for biodiesel.[43] In the "no tax reform" scenario, the same tax rates apply as for fossil fuels.

Figure 13 shows the development of the price components of the reference fuel petrol E10 and the average of the derived cost range for e-petrol as an example.[44] The total price for the petrol reference fuel remains roughly constant over time, with production and supply costs falling while CO_2 costs rise. In the base scenario with an energy tax reform, the average price for e-petrol will fall by 19% by 2050 compared to today. Although the pure production costs of e-petrol are higher than those of fossil petrol, with appropriate tax regulations there are no costs for CO_2 and in the base scenario only marginal energy taxes to be added to e-petrol due to its climate neutrality. That means that the total price can fall below the E10 price in the long term.

43 In reality, there is a maximum quota for conventional biofuels and a minimum quota for advanced biofuels, which will increase to 2.6 % by 2030. It is therefore to be expected that the share of advanced biofuels will increase over time and lead to higher prices for the biofuel share due to the higher production costs of advanced biofuels. To some extent, the higher costs of advanced biofuels could be offset by a favourable tax treatment. As this is not the focus of the study, we abstract from this.

44 The difference between the price components of e-diesel and fossil diesel is similar (cf. Figure 21 in Annex B).

Figure 13 **Price components of e-petrol (average of the range) and petrol reference fuel (E10), today (2025) and in the long term**



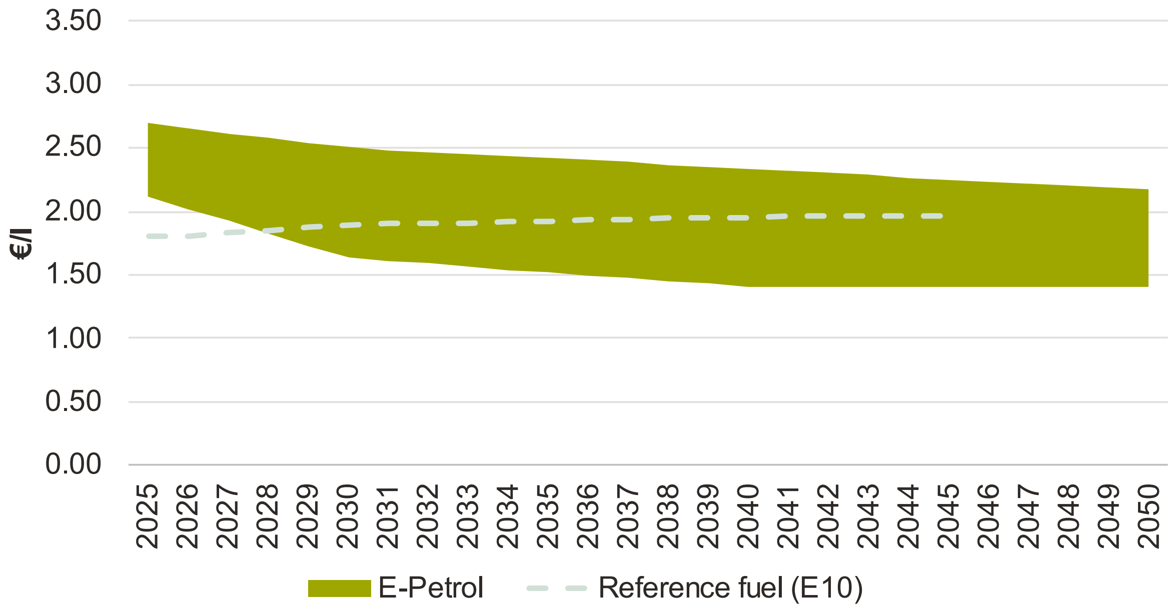
Source: *Frontier Economics*

Note: *All values in €(2024). The price components for e-petrol (in pure form) are shown for the average of the upper and lower end of the range.*

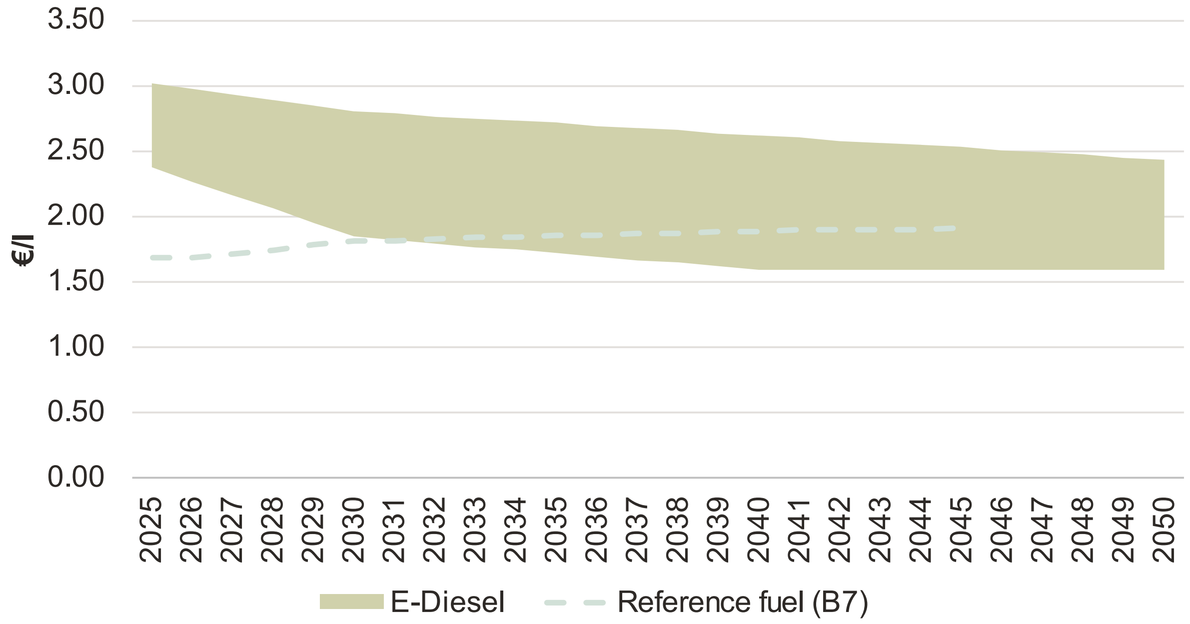
The results show a range for the potential development of the supply price of e-petrol and e-diesel and are depicted in Figure 14. It is expected that the price of e-petrol (in pure form, without blending with fossil fuel) will fall to 1.41-2.17 €/l in the long term, while the supply price per litre of e-diesel will be around 13% higher. The higher supply costs per litre for e-diesel are relativised by its higher energy density, which is actually available to the vehicle user as final energy for driving (see section 3.3). On average, e-petrol in pure form would already reach the price of the reference fuel E10 from the mid-2030s. While e-petrol will become cheaper over time, the price of fossil petrol will rise due to higher costs for CO2 certificates.

Figure 14 Range for the supply price of e-fuels (in pure form) and price of the reference fuel, with energy tax reform

Petrol



Diesel



Source: *Own presentation.*

Note: *The reference fuels include a share of 10% bioethanol for petrol and 7% FAME for diesel; the prices shown for e-fuels do not include blending with biofuels. All values in €(2024).*

5.2 Development path of consumer prices under increasing e-fuels blending volumes

The supply price of e-fuels and the prices of the reference fuels are combined by applying the methods described in Chapter 4.3 to calculate the price of a fuel mix. The resulting prices of the fuel mix are shown in Figure 15 and Figure 16.

The blending of e-petrol can have a price-reducing effect on petrol prices

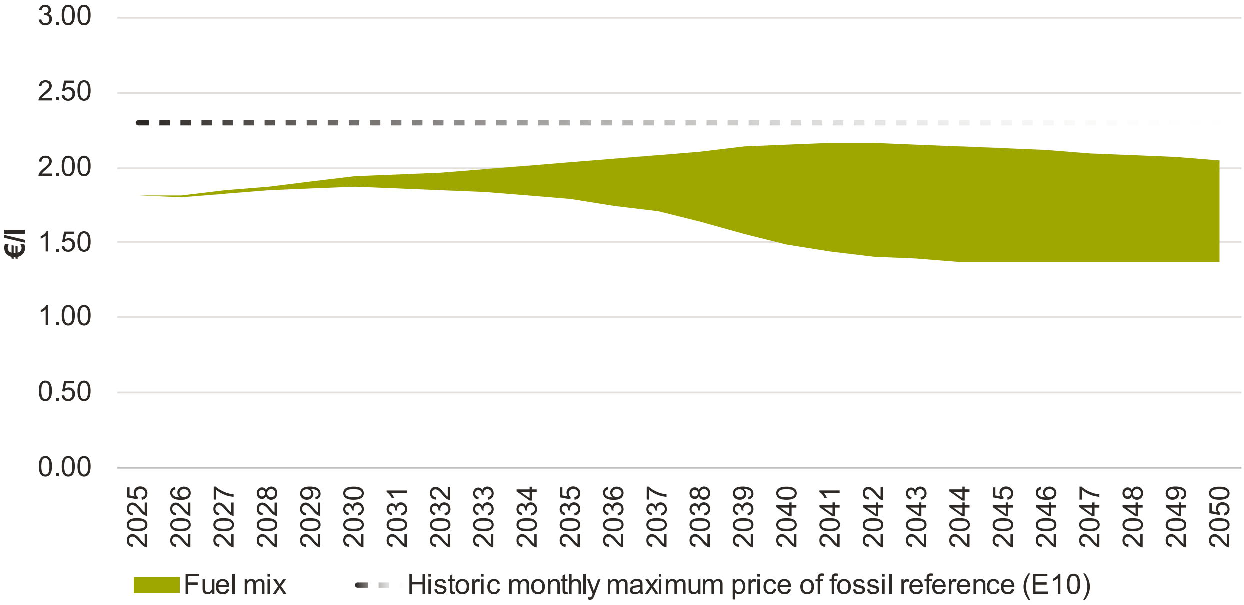
The gradual blending of the initially more cost-intensive e-petrol has only a minor impact on the consumer prices of the petrol fuel mix until the beginning of the 2030s. Accordingly, the expected difference between the price of the reference fuel and the price of the fuel mix is initially marginal. During market ramp-up, blending could even result in price advantages in the consumption of e-fuels, assuming a reduced energy tax. In the long term (by 2050), customer prices for the fuel mix could fall to below 1.50 €/l in the optimistic case due to decreasing e-fuel production costs and the tax effect and thus below the current price level of petrol. Without blending, on the other hand, fossil petrol (E10) would become continuously more expensive over time if the price of CO_2 certificates rises. Even the higher price range of the petrol fuel mix would not exceed the maximum E10 prices already observed in the past[45] at the filling station (line in Figure 15).[46]

At what exact level the price will settle depends, among other things, on the production sites at which e-fuels are manufactured (see Chapter 3.2 and 3.3) and how strong the learning effects and economies of scale are.

45 Inflation-adjusted, monthly average values from January 2020 to July 2024 from ADAC (2024). The highest average prices were observed in March 2022.

46 Appendix B.4 contains a corresponding illustration for the alternative blending scenario.

Figure 15 Long-term development of petrol prices (fuel mix), base scenario with energy tax reform



Source: Frontier Economics. Historic monthly maximum price since 2022 for E10 from ADAC (2024).

Note: The composition of the fuel mix is shown in Figure 12. E-petrol completely replaces fossil petrol in the fuel mix from 2045 onwards. Prices based on the assumption of reduced energy tax rates for e-fuels from 2025. Maximum price for petrol from March 2022. All values in €(2024).

In the long term, the average price of the diesel fuel mix is in a range that has also been observed for diesel in the past

In the same way, the diesel fuel mix would not bring any significant price changes for consumers compared to today: While the blending share of e-diesel gradually increases, production costs fall continuously. In our blending scenario with a gradual market ramp-up of e-fuels, the price of the diesel fuel mix would initially be about 1.70 €/l. In the long term, prices of 1.59-2.37 €/l for the fuel mix could arise as a result of lower production costs and tax breaks for e-diesel. These prices are also within a range that has been observed for diesel in the recent past (cf. Figure 16).[47] The price increase up to the beginning of the 2040s is not exclusively due to the higher share of e-diesel in the fuel mix, but also to the fact that rising prices for CO_2 certificates and thus for fossil diesel are to be expected. As discussed for petrol, the price that occurs within the range depends, among other things, on the quality of the production sites, the achievable cost reductions and the tax treatment of e-fuels.

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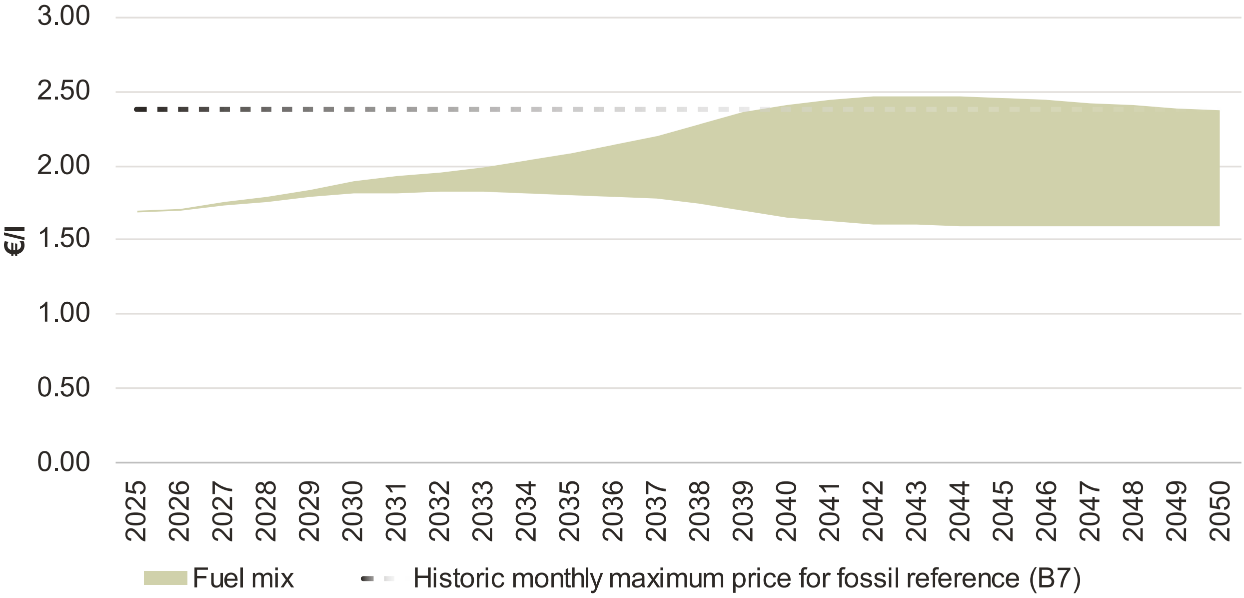
47 The fuel mix price range is based on the stylised blending scenario. Appendix B.4 contains an illustration of the resulting price range assuming the alternative blending scenario.

Figure 16 Development of long-term diesel prices (fuel mix), base scenario with energy tax reform



Source: Frontier Economics. Historic monthly maximum price since 2022 for diesel from ADAC (2024).

Note: E-diesel will completely replace fossil diesel in the fuel mix from 2045 onwards. Prices based on the assumption of reduced energy tax rates for e-fuels from 2025. All values in €(2024).

5.3 Effect of taxation on fuel prices

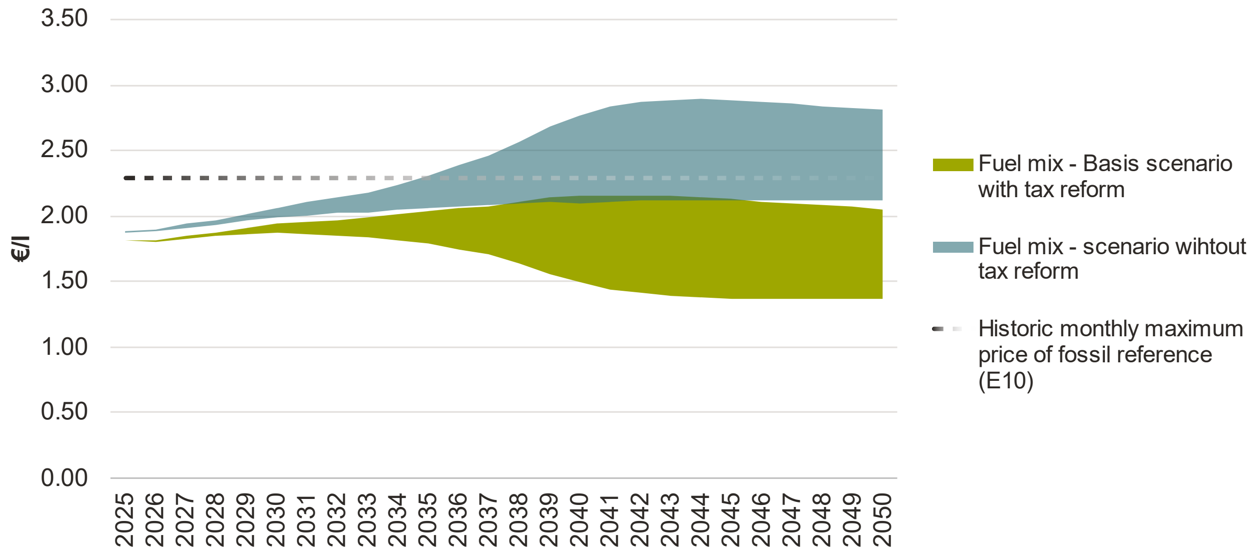
The design of the energy tax for e-fuels has a significant impact on consumer prices for e-fuels and the fuel mix. In the base scenario, under the assumption of an energy tax reform in line with the EU Commission's proposal, the energy tax on e-fuels is reduced by around 65 ct/l (petrol) and 47 ct/l (diesel) by 2025. The German government is also considering to reduce the energy tax for e-fuels,[48] so we believe that a reform of the energy tax law is likely.

As a sensitivity analysis, we consider a scenario in which the energy tax reform does not materialise and e-fuels are taxed at the same rates as fossil fuels until 2050. Under pessimistic assumptions and in in the absence of an energy tax reform, the prices for the fuel mix could rise to around 3 €/l, which would be significantly higher than today’s prices for diesel and petrol (cf. Figure 17). The effect would intensify over time as the blending rate of e-fuels increases so that prices rise by around 76 ct/l (petrol) or 54 ct/l (diesel). Such taxation of e-fuels would therefore be counterproductive in terms of climate policy.

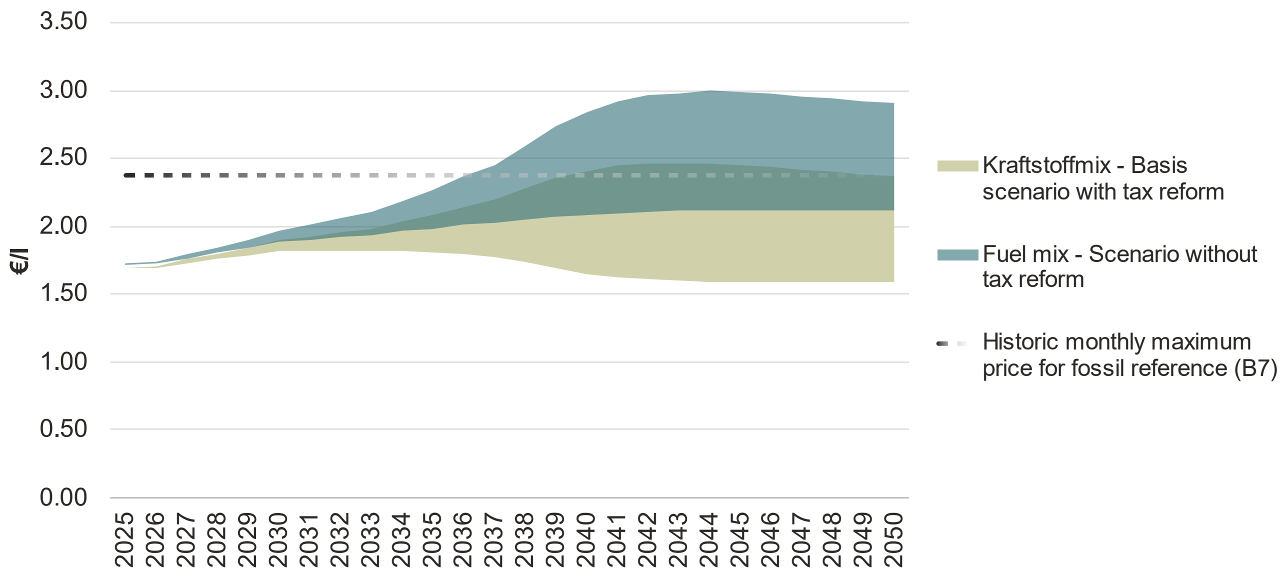
[48] See Tagesschau (2023).

Figure 17 Development of long-term fuel prices, "No energy tax reform" scenario

Petrol (fuel mix)



Diesel (fuel mix)



Source: Frontier Economics. Historic monthly maximum prices since 2022 for petrol (E10) and diesel from ADAC (2024).
Note: All values in €(2024).

6 Conclusions and recommendations for the market ramp-up of e-fuels

Our analysis has shown that, under a revised regulatory framework, the gradual blending of e-fuels to fossil fuels would result in relatively minor changes to the consumer price: Temporarily, during the market ramp-up phase in which e-fuels are foreseeably still significantly more expensive than fossil fuels, the higher price is of little consequence, as e-fuels would only be blended in to a small extent. In the long term, under the assumption of lower energy tax rates for e-fuels suggested by the European Commission’s proposal, consumers could even benefit from an increasing share in the petrol fuel mix if costs develop favourably: On average, by the mid-2030s the price is lower than the price of the reference fuel E10 (without e-petrol blending). Even the average price of e-diesel is similar to the reference fuel (E10) price in the long run. Furthermore, if more reductions in production costs can be realized, for example in electricity generation, then even lower prices at the filling station would be possible.

Based on the drivers for the market ramp-up of e-fuels discussed in chapter 4.1 and the development of fuel prices in chapter 5, recommendations for political and regulatory actions can be derived to ensure that a market ramp-up of climate-neutral e-fuels is supported. These recommendations can also ensure that price signals incentivise the increasing use of e-fuels as a climate-neutral energy source so that greenhouse gases are minimised.

Recommendation 1: Reform of the European Energy Tax Directive

The Energy Tax Directive 2003/96/EC sets minimum tax rates that apply to all EU member states. Currently, fuels in the EU are taxed purely on a volumetric basis – regardless of whether they are fossil fuels or low-carbon fuels. Instead, fuels should be taxed according to their effect on climate in order to achieve a desirable directional impulse from a climate policy perspective. Our analysis has shown that reforming the energy tax rates in Germany would remove significant barriers for low-carbon e-fuels and thus make it easier to achieve the climate targets in the transport sector. One promising amendment to the EU Energy Tax Directive is the draft presented by the EU Commission in July 2021, which would allow to reduce the German energy tax rate for e-fuels from around 47 ct/l (diesel) or 65 ct/l (petrol) to less than 1 ct/l. This draft should lead to a reform of the Energy Tax Directive as soon as possible.

Recommendation 2: Make investments in e-fuels more attractive

Technically, there are no substantial barriers to ramping up the expansion of production capacities for e-fuels within a few years. Nevertheless, only minor investments have been made in e-fuels projects to date. The main reason for this is the high investment risks due to uncertain or insufficiently ambitious regulatory framework, particularly in relation to meeting climate targets. In addition to newly registered cars with combustion engines, which as of 2035 will only be possible in the EU if they use e-fuels, a large number of existing vehicles remain. The defossilisation of the existing car stock is possible by refuelling with e-fuels, which is why a corresponding availability of e-fuels should be sought. Further, the EU is aiming for the use of renewable fuels in heavy goods transport. Focusing solely on aviation and shipping transport would require significantly smaller volumes of e-fuels to be made available. However, as production volumes increase, learning and economies of scale come into play. Therefore, if the market ramp-up does not exceed these limited quantities, there is a risk that the cost reductions identified in this study, driven by learning and scale effects, will not be realised.

Various measures can help to reduce investment risks and create more favourable investment conditions, such as removing administrative barriers[49], promoting research and development programs, supporting market ramp-up initiatives, and, importantly, establishing a reliable regulatory framework. This framework should not hinder the long-term, widespread use of e-fuels across all sectors in an open European fuel market.

Recommendation 3: Expand international partnerships

The costs of e-fuels depend largely on the quality of the location for renewable electricity generation. Due to its comparably unfavourable conditions and therefore relatively high renewable electricity costs, Germany is dependent on the import of hydrogen and hydrogen derivatives such as e-fuels. The import of e-fuels is made easier by their relatively simple transport as a liquid energy carrier at room temperature and pressure, either before or after the refining process. This allows for low-cost transportation using existing infrastructure. In its import strategy for hydrogen and hydrogen derivatives published in July 2024, the German government first described the potential and the opportunities of global trade in hydrogen derivatives in detail.[50] Germany has been largely dependent on energy imports, mainly in the form of oil and natural gas. Until a global market for e-fuels emerges, or to develop one, it is beneficial for investment to enter into strategic partnerships in which Germany acts as a technology exporter (e.g. for electrolysers or synthesis plants) and e-fuels importer. At the same time, the cooperation partners can financially benefit from exporting energy products.[51]

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49 The adoption of the Net Zero Industry Act in April 2024 paved the way for simplified authorisation procedures, which was a welcome step. Further removing administrative hurdles includes, for example, the creation of business-friendly criteria for the production of green hydrogen and thus hydrogen-based synthesis products, as well as standardised global certification systems wherever possible

50 See BMWK (2024b).

51 See Uniti (2021) and Frontier Economics (2018b).

Annex A Literature

ADAC (2024): Spritpreis-Entwicklung: Benzin- und Dieselpreise seit 1950, https://www.adac.de/verkehr/tanken-kraftstoff-antrieb/deutschland/kraftstoffpreisentwicklung/

Agora Verkehrswende, Agora Energiewende and Frontier Economics (2018): The Future Cost of Electricity-Based Synthetic Fuels

boerse.de: Spot prices for Diesel, https://www.boerse.de/rohstoffe/Dieselpreis/XC0009677813

BMWK (2024a): Der CO_2-Preis: Wichtiger Beitrag zum Klimaschutz, https://www.energiewechsel.de/KAENEF/Redaktion/DE/Dossier/co2-preis.html

BMWK (2024b): Importstrategie für Wasserstoff und Wasserstoffderivate, https://www.bmwk.de/Redaktion/DE/Publikationen/Energie/importstrategie-wasserstoff.pdf?__blob=publicationFile&v=18

Concawe (2019): A look into the role of e-fuels in the transport system in Europe (2030–2050)

Concawe & Aramco (2024): E-Fuels: A technoeconomic assessment of European domestic production and imports towards 2050 – Update

CME Group: Futures Prices for FAME, https://www.cmegroup.com/markets/energy/biofuels/fame-0-argus-biodiesel-fob-rdam-red-compliant-swap-futures.html

eFuel Alliance (2024): Selection of announced or already existing production sites, https://www.efuel-alliance.eu/efuels/efuels-production-map

European Comission (2021): Proposal for a Council Directive restructuring the Union framework for the taxation of energy products and electricity (recast), https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52021PC0563

finanzen.net: Spot prices for ethanol, https://www.finanzen.net/rohstoffe/ethanolpreis

Fraunhofer IEE (2021): Global potential for the production of green hydrogen and climate-neutral synthetic fuels („Global PtX atlas“), https://maps.iee.fraunhofer.de/ptx-atlas/

Frontier Economics (2018a): International Aspects of a Power-to-X Roadmap

Frontier Economics (2018b): Synthetische Energieträger – Perspektiven für die deutsche Wirtschaft und den internationalen Handel

Frontier Economics (2022): Zukünftige Kraftstoffe: FVV Kraftstoffstudie IVb

IEA (2023a): Hydrogen Production and Infrastructure Projects Database, https://www.iea.org/data-and-statistics/data-product/hydrogen-production-and-infrastructure-projects-database

IEA (2023b): ETP Clean Energy Technology Guide, https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide

IEA (2023c): Energy Statistics Data Browser, https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser?country=WORLD&fuel=Energy%20supply&indicator=TESbySource

IEA (2023d): World Energy Outlook 2023

IEA (2024): Electrolysers, https://www.iea.org/energy-system/low-emission-fuels/electrolysers

Öko-Institut, Agora Energiewende & Agora Industry (2024): PTX Business Opportunity Analyser, Version 2.1.1

Our World in Data (2024): Fossil fuels, https://ourworldindata.org/fossil-fuels

Pfennig et al. (2023): Global GIS-based potential analysis and cost assessment of Power-to-X fuels in 2050, Applied Energy Volume 347

Prognos AG, Fraunhofer UMSICHT and DBFZ (2018): Status und Perspektiven flüssiger Energieträger in der Energiewende

RMI (2023): X-Change: Batteries. The Battery Domino Effect

Tagesschau (2023): Lindner will E-Fuel-Fahrzeuge entlasten, https://www.tagesschau.de/wirtschaft/verbraucher/lindner-will-kfz-steuerreform-101.html

German Environment Agency (2024): Energieverbrauch und Kraftstoffe, https://www.umweltbundesamt.de/daten/verkehr/endenergieverbrauch-energieeffizienz-des-verkehrs#verkehr-braucht-energie

Uniti (2021): IW-Gutachten – Synthetische Kraftstoffe: Potenziale für Europa, https://www.uniti.de/fileadmin/publikationen/Studien/Studie%20Synthetische%20Kraftstoffe%20-Potenzial%20f%C3%BCr%20Europa.pdf

Wallstreet Online: Spot prices for petrol, https://www.wallstreet-online.de/rohstoffe/benzinpreis

Annex B Further results and assumptions

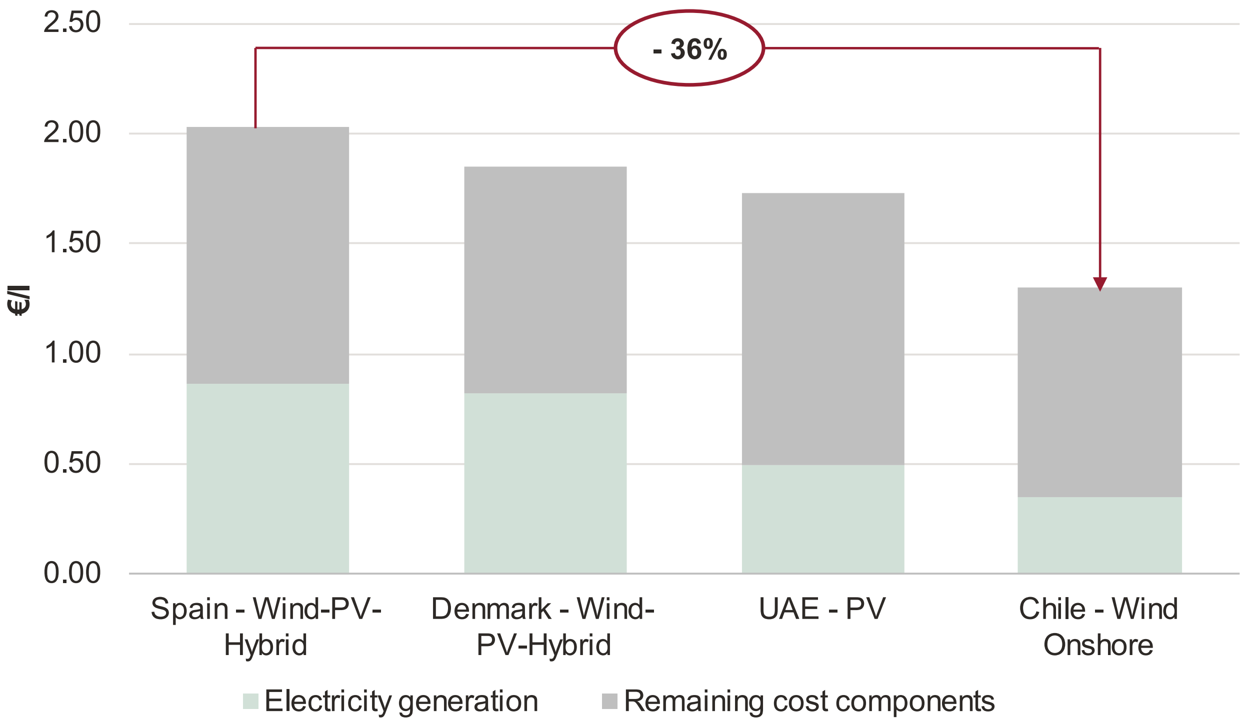
B.1 Drivers for the production costs of e-fuels

The following figures illustrate the effect of the three drivers production location, CO_2 source and size of the production plant on e-fuel production costs.

Driver 1: Location of production

Figure 18 shows the e-fuels production costs in 2030 at various production sites. The production sites and their renewable potential determine and electricity generation costs and thus the e-fuels production costs. The most cost-effective technology can vary depending on the location. For the location and technology combinations shown below the cost difference within the Öko-Institut study is 36%.

Figure 18 E-fuels production costs at different locations and renewable power generation technologies



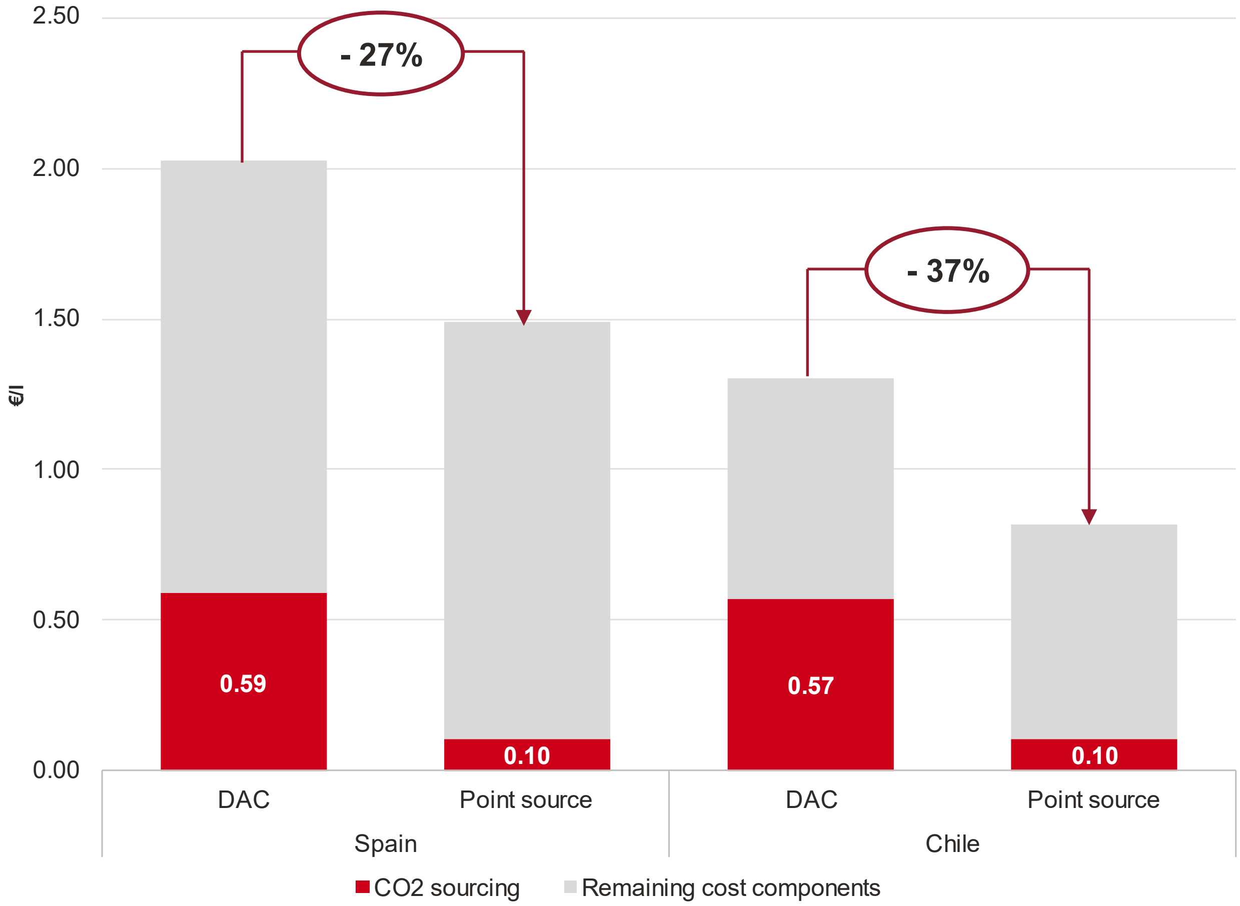
Source: Frontier Economics based on Öko-Institut, Agora Energiewende & Agora Industry (2024): PTX Business Opportunity Analyser, Version 2.1.1.

Note: UAE = United Arab Emirates.

Driver 2: CO_2 source

Two different CO_2 sources are modelled within the studies: Direct air capture (DAC) and point sources (e.g. from industrial processes or biogas plants). The DAC technology is significantly more cost-intensive than point sources. In the Öko-Institut study, the cost difference between the use of DAC and point sources is between 27% and 37% depending on the location of the production facilities.

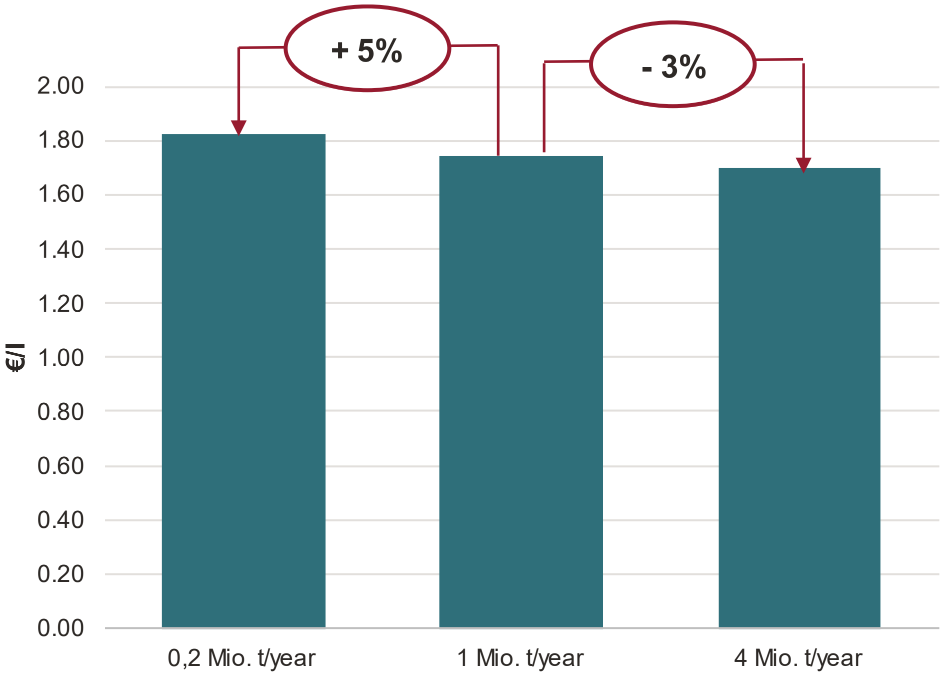
Figure 19 E-fuels production costs with different CO_2 sources



Source: *Frontier Economics based on Öko-Institut, Agora Energiewende & Agora Industry (2024): PTX Business Opportunity Analyser, Version 2.1.1.*

Driver 3: Size of the production plants

Figure 20 E-fuels production costs by production capacity



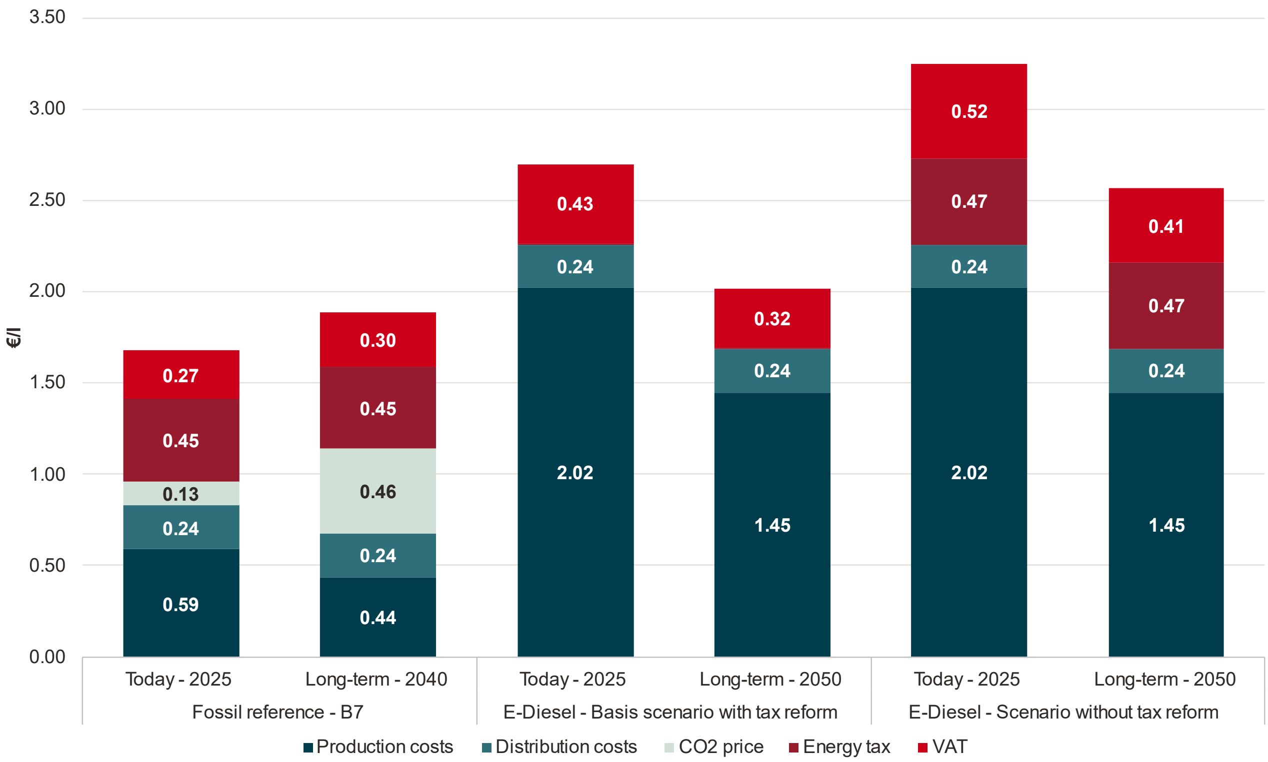
Source: *Frontier Economics based on Concawe & Aramco (2024): E-Fuels: A technoeconomic assessment of European domestic production and imports towards 2050 - Update.*

Note: *Production costs of FT jet fuel, production in MENA, 2050.*

As production capacities increase, the specific CAPEX (i.e. investment costs per unit of output) decreases due to economies of scale. Even the smallest plant shown in Figure 20 is already a very large plant: With an output of 0.2 million tonnes of diesel per year, an electrolysis capacity of 550-1080 MW (electricity input) is required. None of the four studies analysed considers the costs of smaller production plants.

B.2 Further results

Figure 21 Price components of e-diesel (average of the range) and fossil diesel (B7), 2025 and in the long term

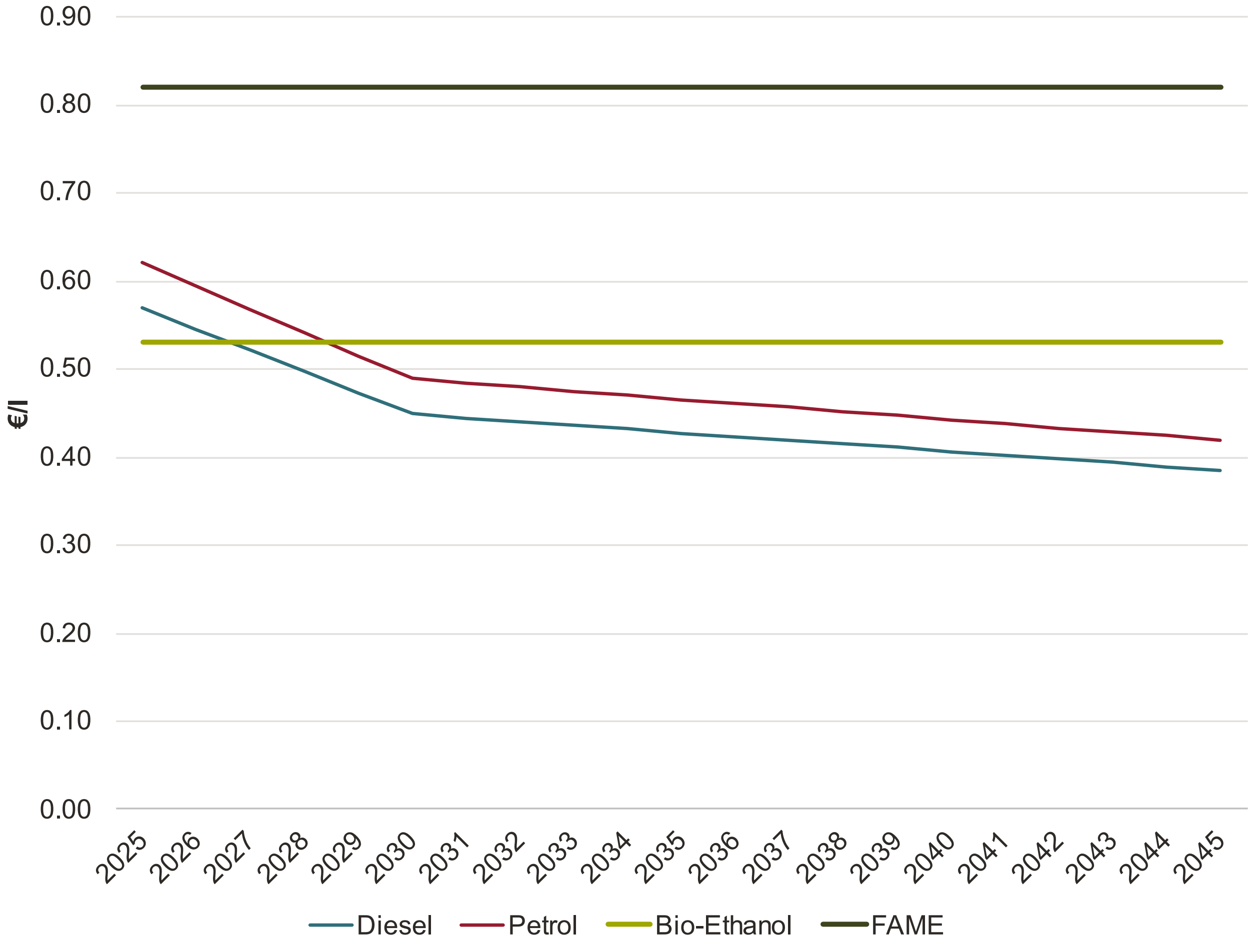


Source *Frontier Economics*

Note *All values in €(2024). The price components of e-diesel (in pure form) are calculated as the average of the upper and lower end of the bandwidths.*

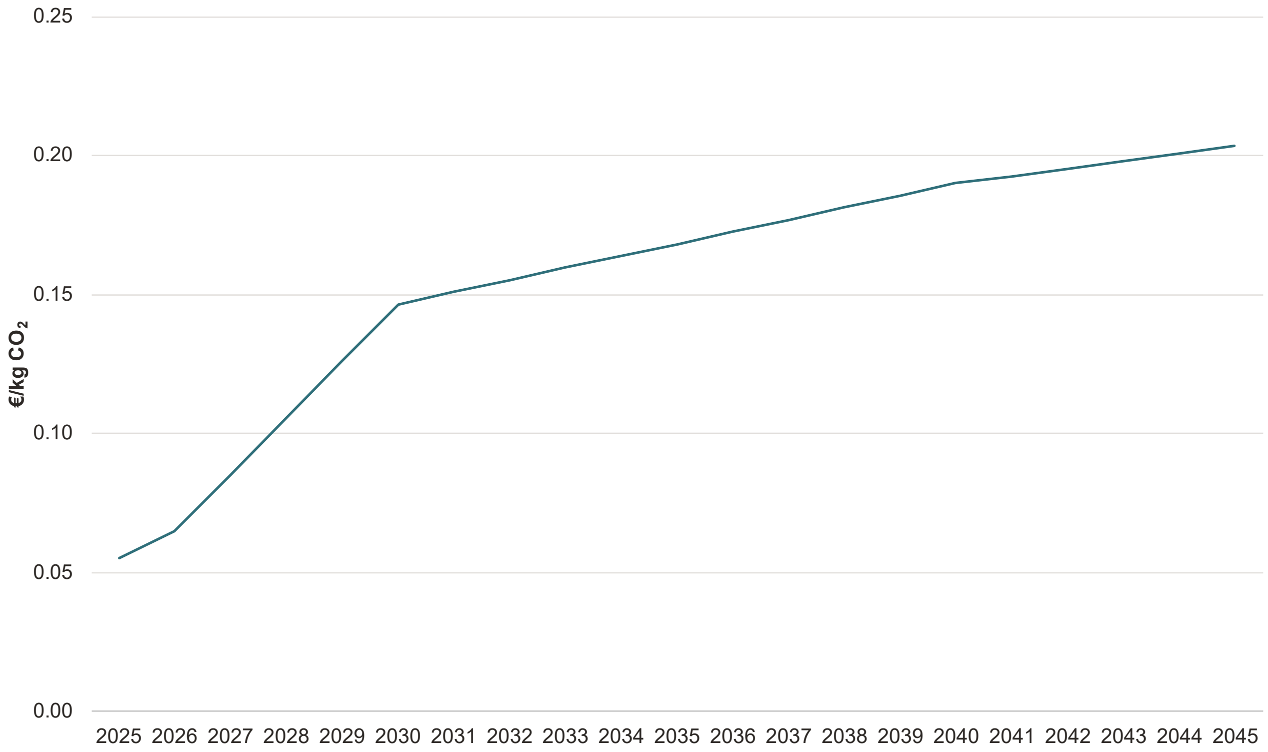
B.3 Assumptions on price trends

Figure 22 Development of the production costs of fossil diesel and petrol, bio-ethanol and biodiesel (FAME)



Source: Frontier Economics based on wholesale prices from www.boerse.de and www.wallstreet-online.de, as well as price expectations for crude oil from IEA (2023d). The cost assumptions for bioethanol are based on data from www.finanzen.net and the assumptions for FAME are based on data from www.cmegroup.com .

Figure 23 Development of CO_2 prices



Source: Frontier Economics based on BMWK (2024a) and IEA (2023d).

Note: From 2040 onwards, there is great uncertainty at European level regarding the development of the CO_2 price, as the EU ETS I is currently due to expire around 2040.

B.4 Alternative assumptions for the blending of e-fuels

In addition to the blending path used in the main text under stylised assumptions, we show another blending scenario based only on technical restrictions. In the following we present

- the alternative blending scenario; and
- the long-term price development of the blended fuel (petrol and diesel) resulting from blending under the assumption of the discussed energy tax reform.

Alternative blending scenario taking into account purely technical restrictions

The alternative scenario is based on an optimisation model from Frontier Economics, which was created as part of a study for the FVV in 2022.[52] It models the fastest possible global ramp-up of production capacities for e-diesel (via Fischer-Tropsch synthesis) and e-petrol (via methanol

[52] Frontier Economics (2022): Future Fuels: FVV Fuel Study IVb.

synthesis), taking into account potential bottlenecks along the entire value chain.[53] Bottlenecks include technical restrictions such as R&D lead times, plant construction times and the availability of raw materials. Otherwise, it is assumed that investments are made under ideal political conditions (e.g. with fast authorisation procedures for plants) and without financial restrictions. Accordingly, this ramp-up can be assessed as optimistic. The actual blending rate could therefore increase more slowly if the financial and regulatory framework is not as optimal in reality as assumed here.

Figure 24 shows the composition of the petrol and diesel fuel mix from 2025 to 2045. According to this chart **e-petrol** could substitute almost 10 % of fossil petrol in the next five years up to 2029. From 2037 onwards, sufficient production capacity could – from a purely technical perspective – be available to completely substitute fossil petrol with e-petrol in Germany. The ramp-up will essentially be determined by the speed at which electrolysis and methanol synthesis are developed, which still has to take place in this decade and the next.

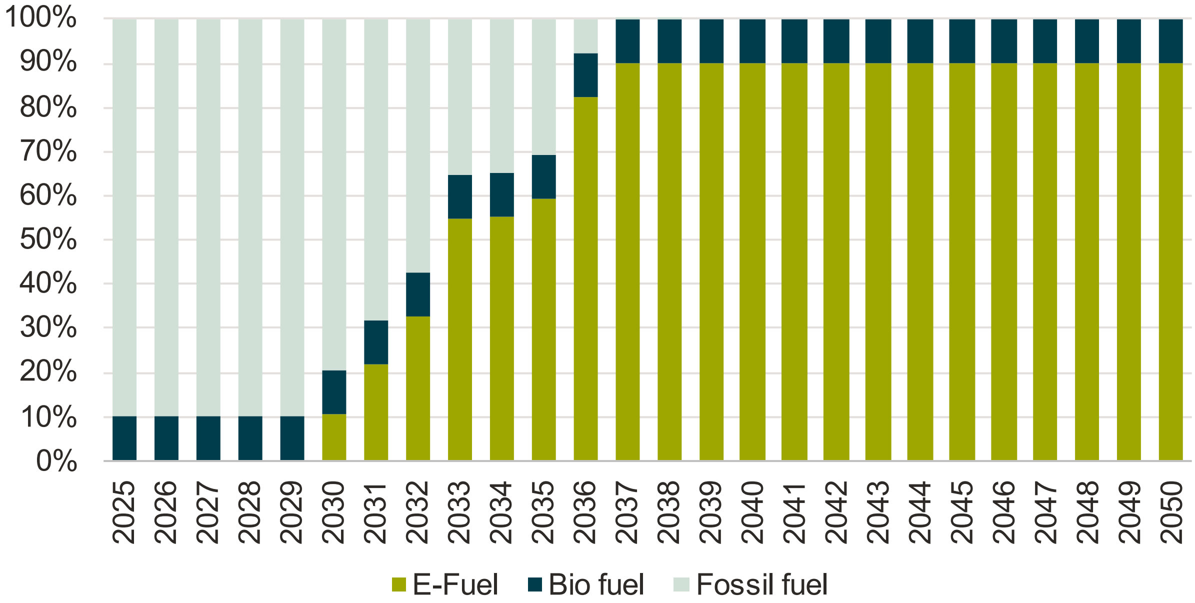
In contrast to e-petrol, relevant blending volumes of **e-diesel** can only be produced from the early/mid-2030s. This is due to the fact that the reverse water gas shift (RWGS) process for the production of carbon monoxide for Fischer-Tropsch synthesis is currently still at a low level of technical maturity. According to experts, it is unrealistic to expect integrated plants to be available on an industrial scale before 2030-34. Possible alternatives to the RWGS process are co-electrolysis[54] and dry reforming, which could be available earlier but were not considered in the modelling.

53 A detailed description of the model can be found in Frontier Economics (2022). For the purpose of this study, we deviate from the basic assumptions by modelling a scenario in which FT- and MtG-fuels are the only ones permitted until 2050 and no "pre-construction" of production capacity is possible, which would remain unused until the infrastructure along the entire value chain is available. We also use 2025 as the first year of modelling (instead of 2023 in the original model) in order to take into account that two years have passed since the model assumptions were discussed without the ideal framework having materialised.

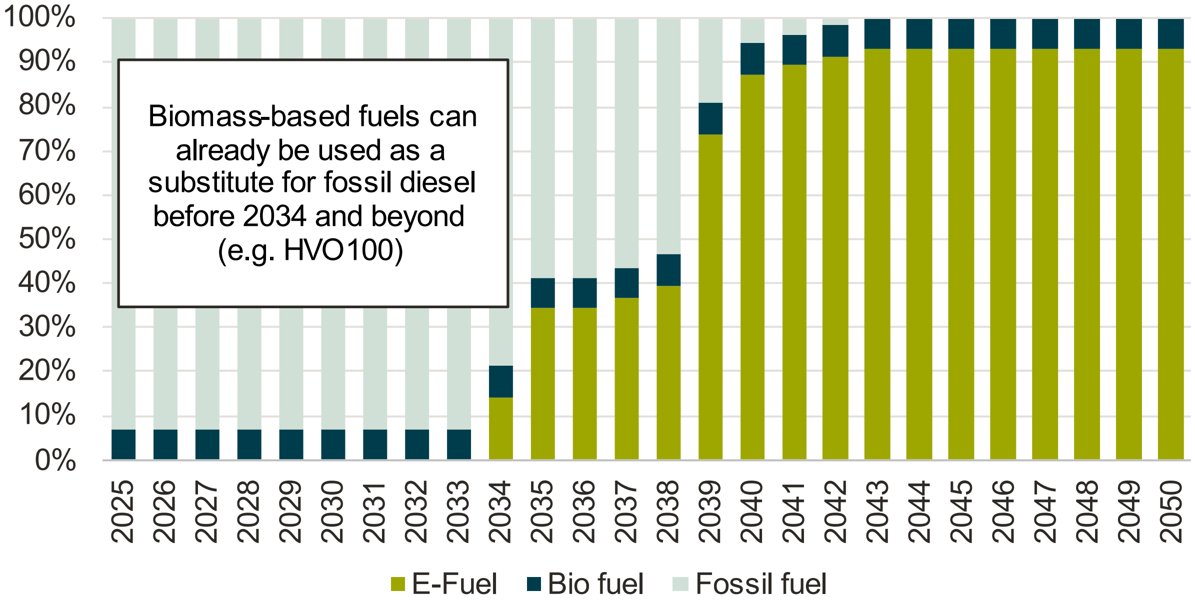
54 Synthesis gas is produced in a single process step using water, CO_2 and renewable electricity.

Figure 24 Composition of the fuel mix taking into account purely technical restrictions

Petrol



Diesel

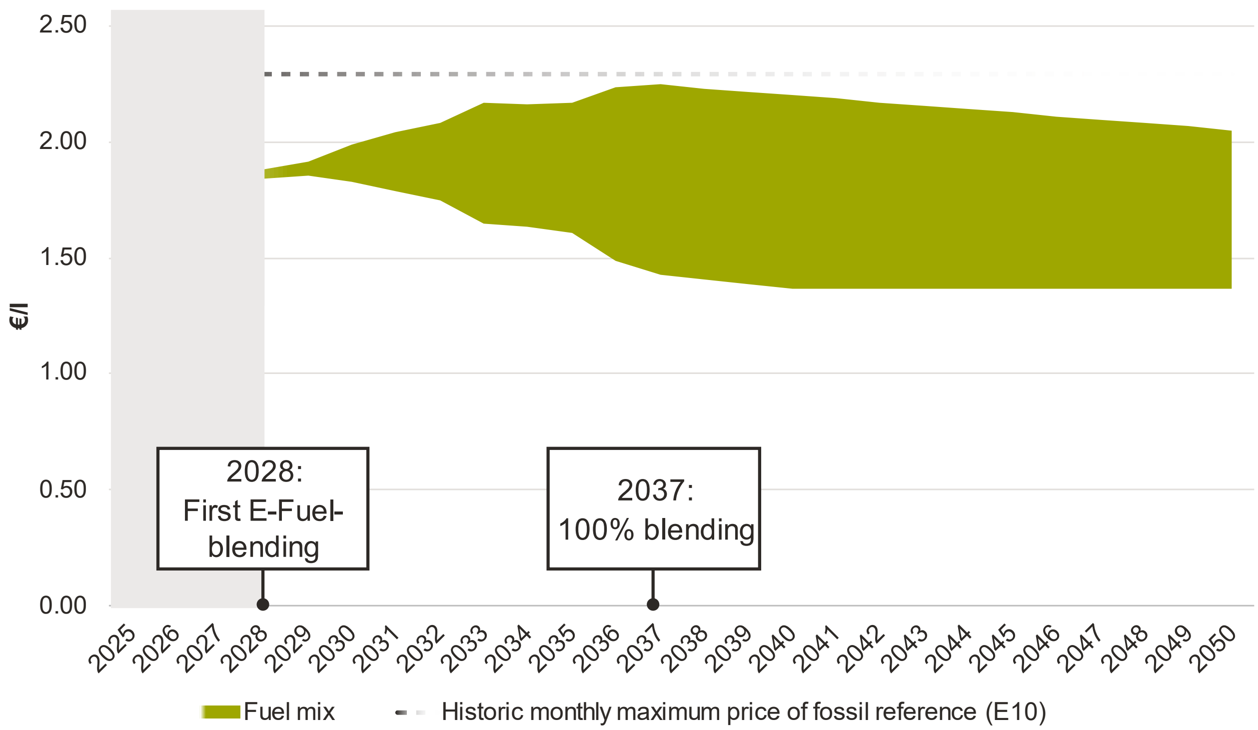


Source: Frontier Economics.

Long-term price developments of fuel mixes (petrol and diesel) under the assumption of the alternative blending scenario and the energy tax reform

The price development of the **petrol** fuel mix differs only slightly in the alternative market ramp-up scenario compared to the stylised blending path (cf. Figure 15). Taking into account only technical restrictions under otherwise ideal framework conditions, a higher share of e-fuels can be blended in at an earlier stage, whereby the higher e-fuels costs in the mix become more pronounced in the fuel mix price and the price range of the fuel mix increases. Under perfect investment conditions, the share of e-fuels could already be more than 50 % by the mid-2030s.

Figure 25 Development of petrol prices (fuel mix) until 2050, base scenario with energy tax reform



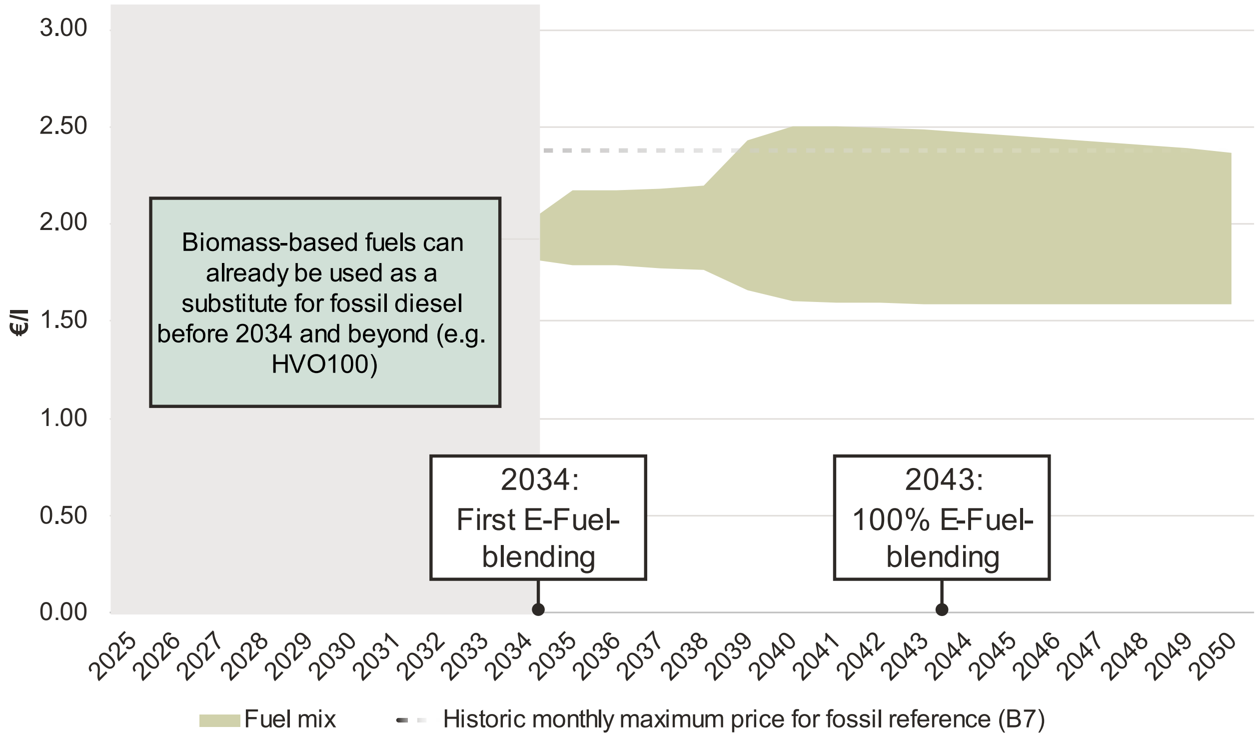
Source: Frontier Economics. Historic monthly maximum price for E10 from ADAC (2024).
Note: All values in €(2024).

In the alternative blending scenario, **e-diesel** is available later than in the stylised market ramp-up, namely from 2034 onwards, due to technical restrictions. However, the blending share rises to around 35% within a short time by 2035, so that the price of e-fuels has a higher impact on the fuel mix price.[55]

[55] However, this leap in the blending share of e-diesel would only be conceivable under ideal conditions. This would mean that integrated Fischer-Tropsch synthesis plants - as soon as they are technically mature - would have to be built directly on an industrial scale (see chapter 4.3).

Even before 2033, the CO_2 intensity of the diesel reference fuel can be reduced through higher blending shares of biomass-based fuels (e.g. HVO 100).

Figure 26 Development of diesel prices (fuel mix) until 2050, base scenario with energy tax reform



Source: Frontier Economics. Historic monthly maximum price for diesel from ADAC (2024)
Note: All values in €(2024).

Annex C Data tables

Table 2 Data table for Figure 4 - Production costs by study, production site and year in €$_{2024}$ /l e-diesel

	2020	2030	2040	2050
Concawe - MENA	2.20	1.91		1.78
Concawe - Spain	2.47	2.11		1.80
Agora - MENA	1.71	1.59	1.34	1.16
Öko-Institut - MENA		1.73	1.34	
Öko-Institut - Spain		2.02	1.64	
Öko-Institut - Patagonia		1.30	1.09	
Fraunhofer - Patagonia - Best location				0.96
Fraunhofer - Patagonia - Average				1.22
Fraunhofer - MENA - Best location				1.12
Fraunhofer - MENA - Average				1.58

Source: Frontier Economics based on study results from Concawe & Aramco (2024): E-Fuels: A technoeconomic assessment of European domestic production and imports towards 2050 - Update, Öko-Institut, Agora Energiewende & Agora Industry (2024): PTX Business Opportunity Analyser, Version 2.1.1, Fraunhofer IEE (2021): Global potential for the production of green hydrogen and climate-neutral synthetic fuels ("Global PtX Atlas") and Frontier Economics (2018): The Future Cost of Electricity-Based Synthetic Fuels.

Note: All Fischer-Tropsch synthesis. Relevant cost estimates are converted to €/l e-diesel and adjusted for inflation based on year 2024.

Table 3 Data table for Figure 9 - Range of production costs for reference years, in €2024 /l

	2025	2030	2035	2040	2045	2050
E-petrol	1.58 – 2.07	1.18 – 1.91	1.08 – 1.84	0.99 – 1.77	0.99 – 1.70	0.99 – 1.63
E-diesel	1.75 – 2.29	1.30 – 2.11	1.20 – 2.04	1.09 – 1.96	1.09 – 1.88	1.09 – 1.80

Source Own calculations.
Note: All values in €(2024).

Table 4 Data table for Figure 14 - Range of customer prices for reference years, in €2024 /l

	2025	2030	2035	2040	2045	2050
E-petrol	2.12 – 2.70	1.63 – 2.51	1.52 – 2.42	1.41 – 2.34	1.41 – 2-25	1.41 – 2.17
Petrol reference fuel E10	1.81	1.90	1.93	1.96	1.97	-
E-diesel	2.38 – 3.02	1.84 – 2.81	1.72 – 2.72	1.60 – 2.62	1.60 – 2.53	1.60 – 2.44
Diesel reference fuel B7	1.68	1.81	1.85	1.89	1.91	-

Source: Own calculations.
Note: All values in €(2024).

Table 5 Data table for Figure 15 to Figure 17- Range of customer prices of the fuel mix, by tax scenario, in €$_{2024}$ /l

	2025	2030	2035	2040	2045	2050
Base scenario with tax reform						
Petrol fuel mix	1.81 – 1.81	1.87 – 1.94	1.79 – 2.03	1.49 – 2.15	1.37 – 2.13	1.37 – 2.05
Diesel fuel mix	1.69 – 1.69	1.81 – 1.89	1.81 – 2.09	1.65 – 2.41	1.59 – 2.46	1.59 – 2.37
No tax reform						
Petrol fuel mix	1.88 – 1.88	1.99 – 2.06	2.06 – 2.31	2.10 – 2.77	2.12 – 2.89	2.12 – 2.81
Diesel fuel mix	1.71 – 1.72	1.88 – 1.96	1.98 – 2.26	2.08 – 2.84	2.12 – 3	2.12 – 2.91
Share of e-petrol of petrol fuel mix	1%	8%	27%	71%	90%	90%
Share of e-diesel of diesel fuel mix	1%	8%	28%	73%	93%	93%

Source: Own calculations.

Note: All values based on the assumption of a stylised ramp-up of the blending of e-fuels. All values in €(2024).