CO2 map-it CCU

# E-fuels case study

Part B: Methanol

30/06/2025

# 1 Introduction

Methanol is a major chemical commodity with an annual production of about 100 Mt[1]. The main applications of methanol include the production of formaldehyde, acetic acid, olefins and methyl tert-butyl ether (MTBE), which in turn are used in the production of other chemicals and materials, which ultimately can be found back in many daily life applications[2]. In addition, methanol is also sometimes used as fuel additive due to its attractive fuel properties[3].

Today, methanol is largely produced from natural gas, and to some extent also from coal (mostly in China). The resulting global $CO_2$ emissions amount to ~ 0.3 Gt/yr, which is ~10% of the whole chemical industry[4] and, by means of illustration, more than Belgium's national emissions (~ 0.1 Gt/yr)[5]. As such, switching to renewable methanol production is of high importance. Two main types can be distinguished. First, there is biomethanol, which is produced from various kinds of biomass (usually waste streams). Secondly, there is e-methanol, whereby $CO_2$ is converted into methanol using renewable electricity (e.g. solar, wind) as energy source. From a technical point of view, using $CO_2$ as feedstock for methanol production is a fairly evident choice as both are C1 molecules and in terms of conversion technology, existing processes with certain modifications can be used. To meet the demand, biomethanol and e-methanol will both need to be deployed at scale[6].

The energy transition may entail a role for methanol much larger than the applications it serves today. Renewable methanol is also often considered as transport fuel for cases that are hard to electrify directly, e.g. shipping. As methanol has a reasonable volumetric and gravimetric energy density and is very convenient to handle and store, it could be competitive against other clean energy carriers such as $H_2$ or ammonia. Furthermore, renewable methanol could also be used to produce olefins, monomers of commonly used plastics, which are today still produced mostly from petrol (this is discussed in more detail in the polyolefins case study). For these reasons, methanol has been of interest to both industry, scientists, and policy makers for decades, with activity gaining steam over the past years.

# 2 Technology description

## 2.1 Overview

Several pathways to produce either fossil or renewable methanol exist (Figure 1). In the fossil pathways, natural gas is most often used as feedstock. The first step is the reforming of methane into syngas ($CO+H_2$), which can be done by adding steam and/or $O_2$ at very high temperature (>700°C), depending on the type of technology chosen[7]. After syngas conditioning, methanol synthesis takes place, which is a thermocatalytic process usually performed at 50-100 bar and between 250-300°C[8]. The reaction is:

$$CO + 2H_2 \leftrightarrow CH_3OH$$

[1] IRENA (2021). Innovation outlook renewable methanol
[2] About Methanol | Methanol Institute
[3] Blending-Handling-Bulletin-Final.pdf (methanol.org)
[4] IRENA (2021). Innovation outlook renewable methanol
[5] indicators.be - Greenhouse gas emissions (i59)
[6] IRENA (2021). Innovation outlook renewable methanol
[7] Reforming | Methanol | MeOH | CH3OH | Catalyst | Technology | Topsoe
[8] Sehested, Jens. "Industrial and scientific directions of methanol catalyst development." *Journal of Catalysis* 371 (2019): 368-375.

After methanol synthesis, unreacted gases are separated and recycled, and subsequently the methanol is separated from water and by-products to obtain the industrial grade (>99% purity). If biogas is used instead of natural gas, bio-methanol is obtained. It is also possible to mix natural gas and biogas, in which case the amount of bio-methanol formed can be allocated based on mass balance, as is already commercially done today[9].

In case coal is the feedstock, gasification at high temperature in the presence of oxygen (for partial combustion of coal to provide heat to the gasification process) and steam needs to be performed. In case of biomass (e.g. municipal solid waste, waste wood or agricultural residues) the same principles apply, although specific operational conditions are always tailored to the feedstock type. A common challenge with both coal and biomass gasification is that, unlike natural gas reforming, the $H_2$/CO ratio will be lower than 2, which is the stoichiometric requirement for methanol synthesis. Therefore, typically a water gas shift (WGS) reaction is performed whereby part of the CO is converted together with water into $CO_2$ and $H_2$, altering this ratio in the right way. The extra emission of $CO_2$ in this step is one of the reasons why coal-based methanol is more $CO_2$ intensive than natural gas-based methanol, which is why they are labelled as black and grey methanol, respectively, in IRENA terminology. Gasification processes also require significantly more conditioning of the syngas (removal of tars, dust, inorganic substances) compared to the natural gas-based process[10].

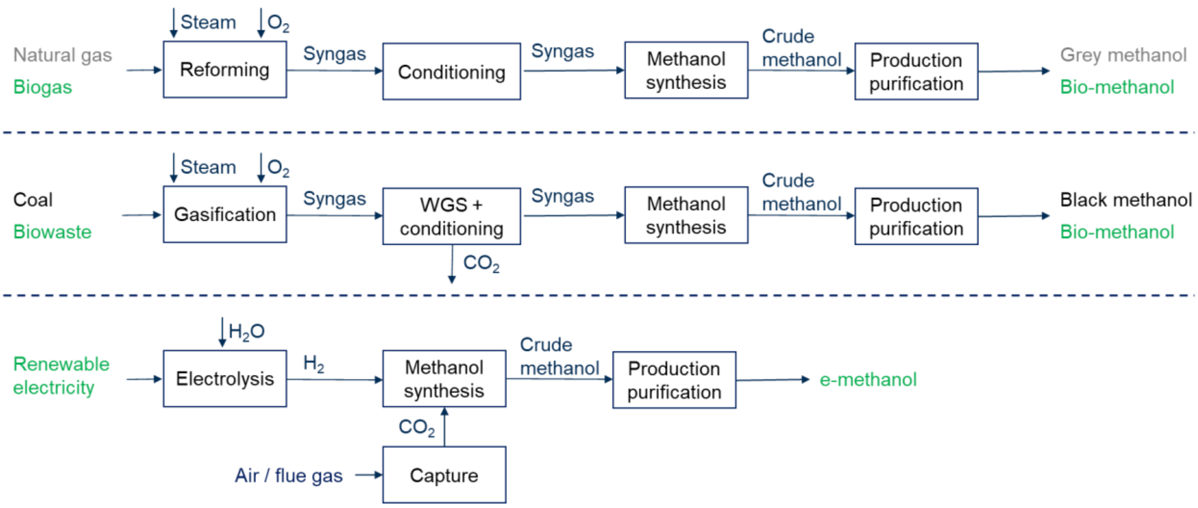


*Figure 1 Block flow diagrams for different production routes*

The third pathway involves the production of $H_2$ through electrolysis using renewable electricity, and the capture of $CO_2$ from either a point source or the air. Subsequently, both feedstocks are fed to a methanol synthesis unit, in a process that is quite similar to methanol synthesis from syngas in the other two pathways. The reaction for the $CO_2$ based pathway is:

$$CO_2 + 3H_2 \leftrightarrow CH_3OH + H_2O$$

However, catalysts used for syngas as feedstock do not work as well when $CO_2$ and $H_2$ are the feedstock, as generally lower yields are observed here. Moreover, this feedstock change also implies that more water is generated during the reaction impeding conventional catalyst performance, which has led researchers to investigate catalysts that are more resilient to water[11]. Nevertheless, commercial

[9] Equinor and Maersk partner up to ensure continued green methanol supply for the world's first methanol-enabled container vessel | Maersk

[10] IRENA (2021). Innovation outlook renewable methanol

[11] Fulham, George J., et al. *Chemical Engineering Journal* 480 (2024): 147732.

catalysts are already available today for direct $CO_2$ hydrogenation[12], and several projects at pilot and even commercial scale are operating or scheduled[13]. In addition, on a process level the direct hydrogenation of $CO_2$ has been claimed to have several advantages over the use of syngas as feedstock, among others because it is less exothermic which simplifies reactor design and because of the lower formation of by-products, which facilitates product purification[14].

The climate impact of the e-methanol pathway does not only depend on the type of electricity used, but also on the $CO_2$ source. If $CO_2$ is sourced from the air or a biobased process (e.g. fermentations), the carbon cycle is not disturbed and the resulting e-methanol can be classified as entirely renewable. If $CO_2$ is sourced from a process using fossil carbon source (e.g. a refinery or cement production), then a net addition of fossil carbon to the atmosphere will occur if the methanol gets combusted at the end of its life (which depends on the application but is certainly the case when used as fuel). For that reason, the Renewable Energy Directive (RED) makes a distinction between these two types, and only e-fuel projects using non-fossil $CO_2$ will be considered to contribute to the RED targets from 2035/2040[15] onwards[16]. For the same reason, IRENA puts a different label on e-methanol that is produced from fossil $CO_2$, namely 'blue methanol'[17].

Operating conditions for e-methanol production are set considering some trade-offs. Since it is an exothermic reaction, higher conversion rates can be obtained by lowering the temperature, yet it needs to remain sufficiently elevated to support good reaction kinetics. Similarly, higher conversion rates can be achieved by increasing pressure, which also leads to higher selectivity, yet this entails significant extra CAPEX and energy costs. Bowker (2019) proposes a compromise at 230°C operating temperature and 50 bar pressure, where 30% conversion is achieved (implying a significant recycling ratio)[18]. Other scholars have proposed similar operating conditions[19]. Recent scientific work is investigating methanol synthesis catalyst that are active at low pressure and temperatures[11]. Interestingly, technology suppliers BSE and Man Energy Solutions offer a process that operates at low pressure (40 bar) and temperature (240°C)[20,21]. Such processes would not require a (large) $H_2$ compressor since it operates at a pressure delivered by PEM electrolysers today[22].

Another important process aspect is the ability to follow fluctuations of the $H_2$ feed. When the $H_2$ is produced from intermittent renewable energy sources such as solar or wind energy, the $H_2$ output flow will similarly be intermittent. It is highly beneficial if the methanol synthesis can follow this load fluctuation, since otherwise large-scale storage of $H_2$ at elevated pressure may be needed to buffer such fluctuations. This is an aspect that is not extensively covered in literature, with some exceptions for methanation processes[23]. However, it is relevant to note that BSE claims to offer a process that eliminates the need for $H_2$ storage, as the process allows for load variations in the range of 15-120% within 15 seconds[24]. Similarly, MAN Energy offers a process with a 10-100% window for load

[12] MK-417 SUSTAIN™ | Catalysts | Products | Topsoe
[13] IRENA (2021). Innovation outlook renewable methanol
[14] Marlin, Dana S., Emeric Sarron, and Ómar Sigurbjörnsson. *Frontiers in chemistry* 6 (2018): 446.
[15] 2035 for $CO_2$ captured from the combustion of fossil fuels for electricity generation and 2040 for other sectors
[16] Renewable Energy Directive (europa.eu)
[17] IRENA (2021). Innovation outlook renewable methanol
[18] Bowker, M. *ChemCatChem* 11.17 (2019): 4238-4246.
[19] González-Garay, Andrés, et al. "Plant-to-planet analysis of CO 2-based methanol processes." *Energy & Environmental Science* 12.12 (2019): 3425-3436.
[20] FlexMethanol (wirtschaftsforumbioenergie.de)
[21] Power-to-X (man-es.com) (FlexMethanol document)
[22] Hancke, Ragnhild, et al. *Journal of Power Sources* 601 (2024): 234271.
[23] Gorre, J., et al. *Applied Energy* 257 (2020): 113967.
[24] FlexMethanol (wirtschaftsforumbioenergie.de)

variations[25]. The company indicates that the development of a process that operates at only 40 bar (which is lower than what was typically done before) was instrumental to achieve such flexibility.

## 2.2 $CO_2$ input specifications

The $CO_2$ feed needs to be free of any impurities that affect the catalytical performance of the methanol synthesis step. For the commonly deployed copper-based catalyst for methanol production, sulfur and chlorine are two examples that need to be removed[26]. Apart from removing impurities that are harmful to the process, also carrying along inert compounds (e.g. $N_2$) in the process needs to be limited. These compounds will accumulate over time and purging will therefore be required, losing some valuable reactants alongside it. Their presence (at a given reactor pressure) also lowers the partial pressure of reactants, which negatively impacts the synthesis process. For these reasons, methanol synthesis with high purity (>99%) $CO_2$ is generally recommended[27].

# 3 Market aspects

## 3.1 Market volumes & trends

In two decades, the methanol market has more than doubled, exceeding 100 Mt in 2023[28]. The largest growth was recorded in the period 2009-2019, driven in particular by the launch of large-scale of methanol-to-olefins (MTO) processes in China, however organic growth in many other applications such as formaldehyde and acetic acid have contributed significantly as well (Figure 2). More recently, over the period 2019-2023, growth has been more moderate (~2.6%/yr) due to consecutive economic crises. However, for the period until 2030, growth rates in the range of 5-9%/yr are expected[29,30].

In the longer term, towards 2050, fundamental changes may affect the methanol market. As explained above, in addition to the existing applications for methanol (which are on a steady growth path), some major new applications may emerge or further grow, in particular the use of methanol to produce olefins and the direct or indirect use of methanol as clean fuel. In the 'Transforming Energy Scenario' defined the International Renewable Energy Agency (IRENA), which is a scenario that meets the 2°C global warming threshold by focusing mainly on renewable energy and energy efficiency, a methanol production of no less than 500Mt/yr is foreseen. This figure includes 235 Mt e-methanol and 135 Mt bio-methanol, with the rest supplied by fossil methanol. It would require about 280 GW electrolyser capacity (assuming continuous operation), and about 280 methanol plants with a capacity of 0.9Mt/yr (comparable to the typical size of fossil methanol plants today). While evidently uncertain, this scenario shows that the role of methanol could even be much larger than it currently is, and that upscaling production of enough renewable methanol will be a key challenge given that the current capacity is only 0.2 Mt/yr, mostly bio-methanol[31].

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25 Power-to-X (man-es.com) (FlexMethanol document)
26 Twigg, M. V., & Spencer, M. S. (2003). *Topics in Catalysis*, *22*, 191-203.
27 Ho, Hsing-Jung, Atsushi Iizuka, Etsuro Shibata. *Industrial & Engineering Chemistry Research* 58.21 (2019): 8941-8954.
28 Methanol Price|Methanol Institute|www.methanol.org
29 Methanol Market Size, Share & Growth Analysis Report 2030 (grandviewresearch.com)
30 Methanol Market Size, Value & Trends (2022-2030) (researchdive.com)
31 IRENA (2021). Innovation outlook renewable methanol

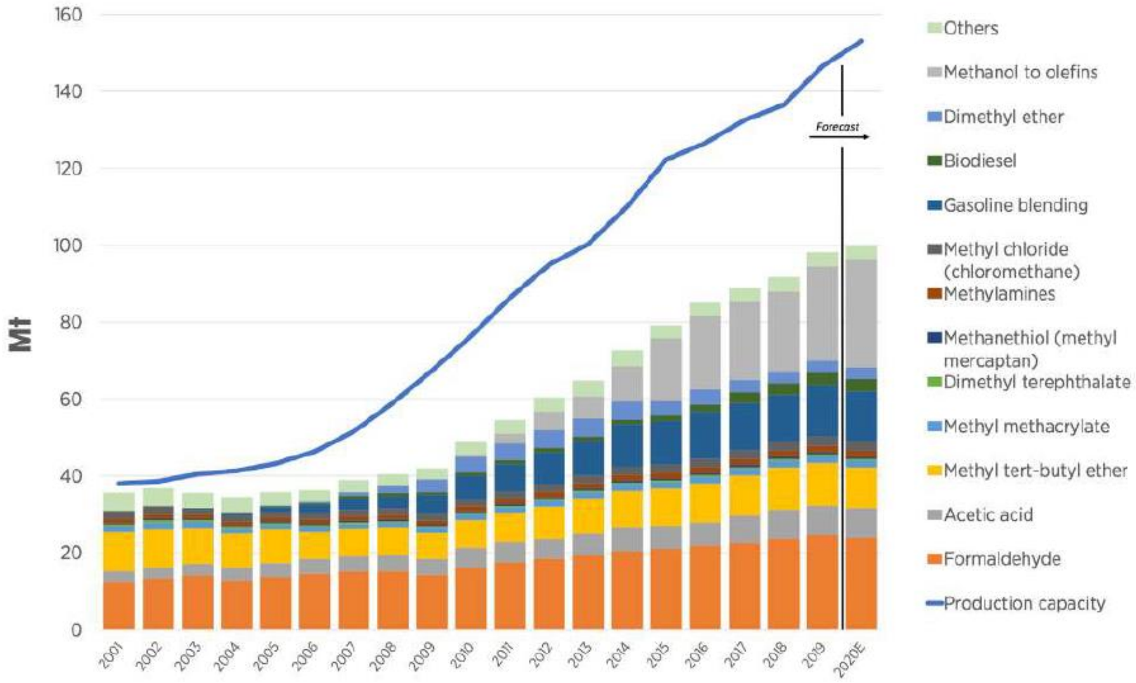


*Figure 2 Methanol market in 2001-2020*[32]

The proposed increase in methanol production volumes by IRENA may appear unrealistically high at first sight but is in fact plausible if methanol use for olefin production and clean transport fuels would make a big leap forward. For example, shipping is one the areas where large scale adoption of renewable methanol in the future is considered likely. International shipping consumes about 9 Exajoule (~2,500 TWh) of fuel annually, with a marginal share of low-emission fuels (Figure 3). Clearly, this market will not be entirely served by methanol only as there are many other alternatives ($H_2$, ammonia, biofuels, etc.). However, even a 25% market share for renewable methanol in international shipping would by itself already require a production of 99 Mt/yr. The importance of the volumes required is underscored by the ambitions of Maersk, which aims to source 25% of its fuel from renewable methanol by 2030, which will by itself already require the production of 5 Mt/yr[33]. In other words, transport fuels may be a second major growth pole for renewable methanol in addition to olefins. In addition, methanol use for polyolefins and aviation fuels production may also become substantial, as explained further in their respective case studies.

[32] IRENA (2021) based on data from Methanol Institute

[33] It is still uncertain when Maersk's new vessels can sail on green fuels (shippingwatch.com)

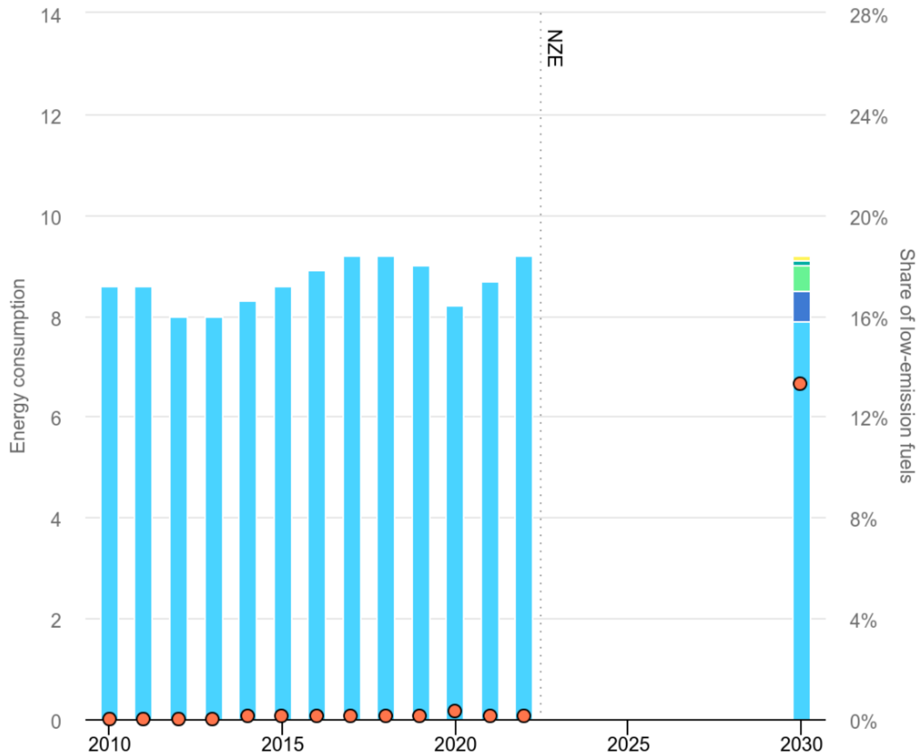


*Figure 3 Energy consumption in international shipping by fuel in the Net Zero Scenario, 2010-2030[34]. Vertical axis unit is EJ.*

## 3.2 Commercial projects and pioneers

An absolute pioneer in $CO_2$ based methanol processes is Carbon Recycling International (CRI), located in Iceland. This company operates a 4,000 t/yr plant since 2012 using geothermal electricity to drive electrolysis and $CO_2$ from flue gases from the geothermal plant[35]. It brands its product as 'Vulcanol' and has ever since improved and licensed the plant design to other parties, leading to the establishment of a 100 kton/yr plant in China[36].

On the demand side, the shipping company Maersk is playing a leading role. It has set targets (i) to be climate neutral by 2040 (ii) to have at least a quarter of its fleet operating on renewable methanol. It has expressed its conviction that methanol will have a key role as shipping fuel, noting that ammonia may have a role there as well in the longer term, but that concerns over the toxic nature of this molecule would need to be addressed[37]. To reach its objectives, it is sourcing methanol from different companies including Equinor (bio-methanol produced from biogas on mass balance[38]), European Energy (which inaugurated an e-methanol plant in Denmark in 2025[39]), OCI Global[40] and the Chinese company Goldwind[41]. It has two methanol fueled vessels (with dual engines that can also operate on

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34 Energy consumption in international shipping by fuel in the Net Zero Scenario, 2010-2030 – Charts – Data & Statistics - IEA

35 Marlin, Dana S., Emeric Sarron, and Ómar Sigurbjörnsson. *Frontiers in chemistry* 6 (2018): 446.

36 About CRI - Producing Methanol from Carbon Dioxide Emissions — CRI - Carbon Recycling International

37 It is still uncertain when Maersk's new vessels can sail on green fuels (shippingwatch.com)

38 Equinor and Maersk partner up to ensure continued green methanol supply for the world's first methanol-enabled container vessel | Maersk

39 Kassø e-methanol facility officially inaugurated - European Energy

40 OCI Global fuels first ever green methanol powered container vessel – OCI (oci-global.com)

41 Maersk signs landmark green methanol offtake agreement | Press Release | Maersk

conventional bunker fuel) and has an outstanding order for 23 more[42]. However, critics have indicated that while Maersk deserves praise for its leadership, its targets may be difficult to achieve[43].

The fact that roll-out of e-methanol is not without challenges is demonstrated by the Northern Lights project developed by Orsted. This project was announced in 2022 and targeted a 55 kton/yr scale, powered by wind energy and using biogenic $CO_2$ from a nearby biomass fired CHP plant. However, in August 2024 Orsted communicated the intention to cancel the project, citing problems to secure the necessary offtake from customers. At the heart of the problem lies the large price premium of green methanol compared to fossil methanol, which in turn is already more expensive than the conventional bunker fuel used by shipping companies[44]. This aspect is discussed in more detail in the next section.

# 4 Economics

To better understand the economic challenges that the e-methanol sector is facing, a simple techno-economic assessment is conducted. A value chain including a $CO_2$ capture step, a green $H_2$ production step and a fuel synthesis step are considered. Regarding the first two steps, the assumptions are the same as in the methane case study. Regarding the methanol synthesis unit, the mass and energy balances were derived from an Aspen model developed by VITO, while the capital cost were taken from a recent estimate from a commercial project[45]. We compare the resulting e-methanol cost with prices of grey methanol[46] and biomethanol[47] in Europe.

It is clear the e-methanol is the most expensive of the three (Figure 4). The exact cost difference depends mostly on the electricity cost considered. Only at very low prices (< 40€/MWh) and baseload operation (8,000 hours per year) e-methanol can be competitive with biomethanol. In practice many methanol plants will be coupled to a renewable energy source, which has fewer operating hours (depending on the location and type of energy source(s)). The Renewable Energy Directive also sets out that there needs to be a temporal correlation with, or even direct connection to, a renewable energy source unless the plant is operated in a region where the share of renewables on the grid is already very high[48]. An indicative 4,000 hours per year is assumed here for such a case. In favorable locations, combinations of wind and solar may provide a competitive LCOE, but there will be underutilization of the plant which leads to higher cost, as captured by the 4,000 operating hours scenario. The price of grey methanol is out of reach in all scenarios. While this serves as the most intuitive benchmark, bunker fuel should in fact be considered when evaluating applications as shipping fuel, which is even 40% less costly than grey methanol[44]. In other words, making the transition to renewable fuels will surely entail significant extra costs for shipping companies.

[42] Maersk fuel consumption down on vessel efficiency | Latest Market News (argusmedia.com)
[43] Methanol pioneer Maersk hedging its bets on green fuels, admits boss Vincent Clerc | TradeWinds (tradewindsnews.com)
[44] Orsted scraps Swedish FlagshipONE emethanol project under development | S&P Global Commodity Insights (spglobal.com)
[45] Inside battery limits (ISBL) CAPEX is from: El Periódico de la Energía (2024) Los costes del metanol renovable
To account for outside battery limits (OSBL) CAPEX, a mark-up of 35% was added on top of ISBL CAPEX based on the rules provided for petrochemical processes in: Sinnott, R., & Towler, G. (2020). Costing and project evaluation. *Chemical engineering design*, (2019).
[46] Pricing - Methanex | Methanex (price selected applicable to july-september 2025)
[47] Biomethanol-methanol diff widens, UK demand ticks up | Latest Market News
[48] Renewable Energy Directive | European Hydrogen Observatory

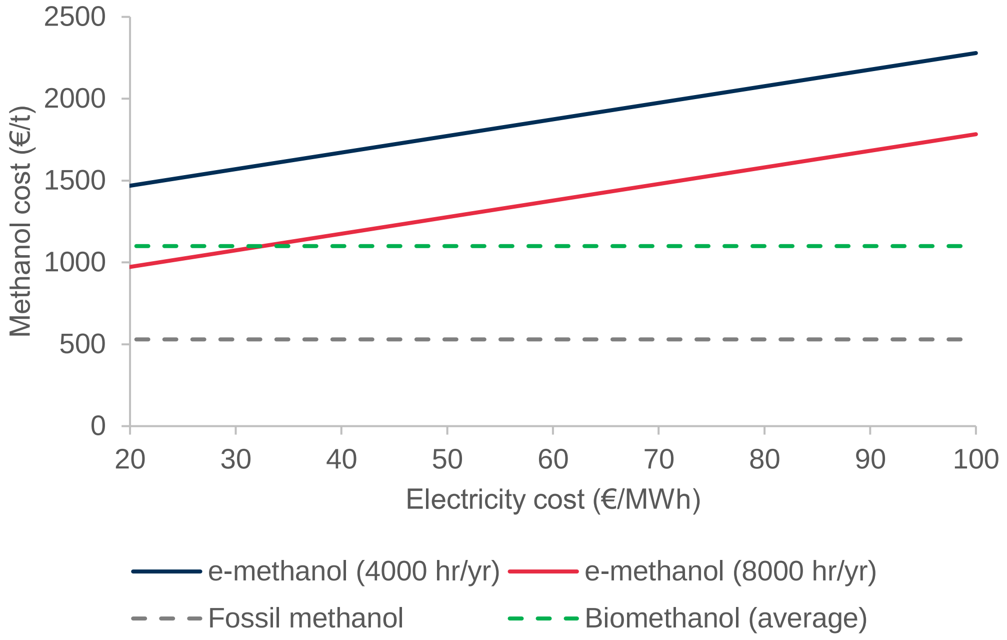


*Figure 4 Cost comparison for different types of methanol*

The results in Figure 4 suggest that the uptake in the market will likely be low due to the significant price premium that is required. Nevertheless, as mentioned above, a number of pioneers have committed themselves to using more renewable fuels. More importantly, the regulatory framework will increasingly push actors to adopt such fuels, and the pace of roll-out of e-methanol for fuel applications in Europe will likely follow very closely the targets set by the Renewable Energy Directive.

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