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EMPHATICaL – market analysis

An analysis of the market prospects for CCU-based methanol and technologies developed as part of the EMPHATICaL concept

Work package 1, deliverable 1.1

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Executive Summary

The highly energy intensive metallurgical industry and fossil fuel-based methanol production processes together account for over 35% of the overall worldwide industrial CO_2 emissions. The EMPHATICaL project aims to develop innovative technologies to reduce these emissions, while realising industrial symbiosis by producing e-methanol from the captured CO_2 from the metallurgical industry. In this report, D1.1. of the project, a market analysis is presented for e-methanol and the technologies that are developed in EMPHATICaL. The focus areas of the market analysis are presented in Figure 0.1.

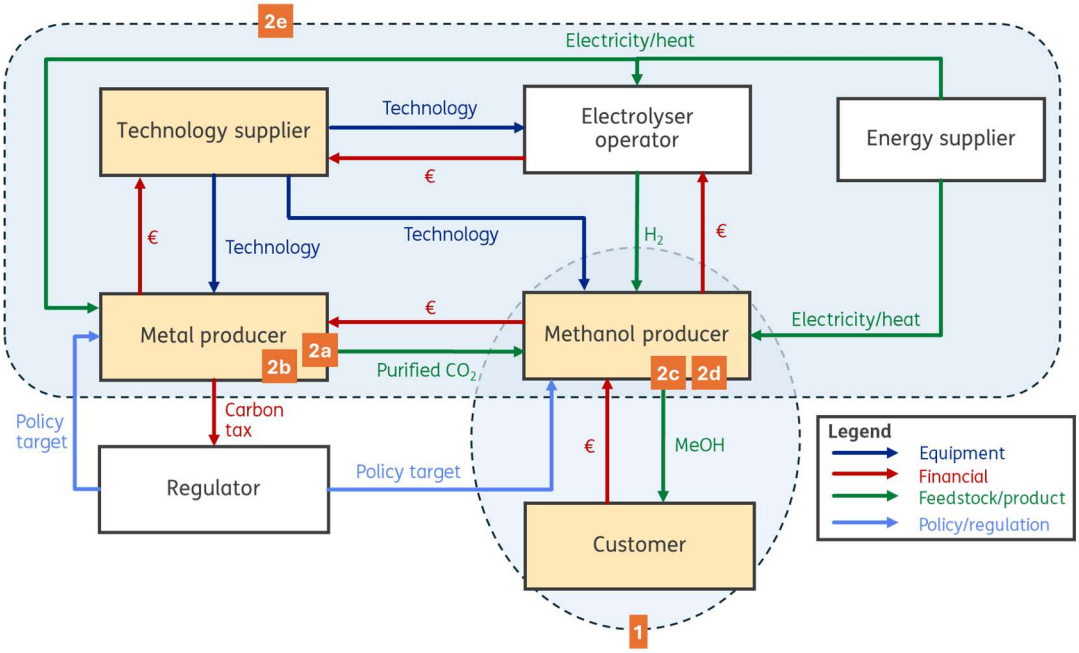


Figure 0.1 EMPHATICaL value chain and focus areas of the market analysis: 1. Market for e-methanol; 2. Market for technologies developed in the project, including 2a. Calcium Looping carbon capture; 2b. Digital technologies for pollutant monitoring; 2c. Flexible methanol synthesis; 2d. Closed-loop heat pump-assisted distillation (cl-HPAD); 2e. Integrated technology concept

Market for e-methanol

Sustainable methanol (bio-methanol and e-methanol) is widely expected to play a significant role in the defossilization of industry and transport. IRENA and the Methanol Institute project that global production will grow from 120 megatons per year today to 500 megatons per year in 2050 (IRENA and Methanol Institute, 2021). Methanol is especially relevant for transport sectors where electrification is challenging, such as aviation and maritime shipping. Moreover, it offers a way of defossilizing the production of chemicals like olefins, which form the building blocks for many materials.

While currently much more costly to produce compared to both fossil- and bio-based production pathways, e-methanol production costs are expected to decrease significantly as the technology becomes more mature, making it a cost-competitive alternative in the long term.

The EU's regulatory environment is increasingly favourable for CCU-based fuels, with clear mandates and financial incentives driving market uptake (Figure 0.2). Further policy development is needed to stimulate demand for CCU-based chemicals and materials. EMPHATICaL methanol is well-positioned to benefit from existing transport fuel mandates and emerging industrial strategies, provided that certification frameworks and market mechanisms continue to evolve in support of circular carbon solutions.

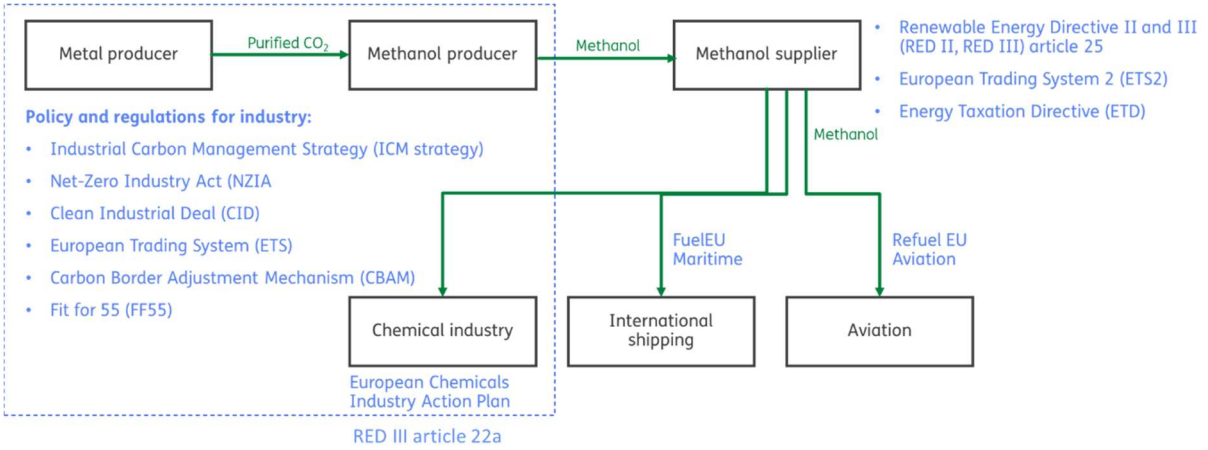


Figure 0.2 Overview of relevant policies, regulations and mandates throughout the value chain

E-methanol production from CO_2 captured from residual gases of the metals industry - the focus of EMPHATICaL - offers an opportunity to reduce emissions in both the metals and the chemical industries while creating economic opportunities. Moreover, this concept can enhance strategic autonomy by reducing reliance on fossil and biomass feedstock for the production of fuels and chemicals. However, due to the energy-intensive nature of Carbon Capture & Utilization (CCU), the emission reduction achieved by such CCU-based methanol hinges on the availability of sufficient renewable electricity.

Market for EMPHATICaL technologies

Besides tapping into the market for e-methanol, which has a multitude of applications, EMPHATICaL also offers opportunities for the EU to become a global technology provider in the various technologies that are being advanced as part of the EMPHATICaL concept.

- **Calcium looping (CaL) carbon capture**. Regarding CaL, Europe is at the forefront of its technological development. A pilot plant has already been realised in Spain and more pilots will follow in several European countries. As CaL operates at high temperatures (~650-900°C) its application potential mainly lies in industrial contexts with high-temperature heat.
- **Advanced digital technologies for pollutant monitoring** offer a way to monitor the quality of CO_2 streams while reducing the reliance on physical sensors and physical measurements. This is especially relevant for CO_2 transport and storage applications and CCU applications in which CO_2 is important to the functioning of downstream processes.
- **Flexible methanol synthesis** has significant market potential given the projected growth in the market for sustainable methanol and the further adoption of renewables. As e-methanol is ideally powered by renewable electricity to unlock its emission reduction potential, e-methanol production should be able to deal with the intermittency of renewable electricity. The flexible methanol synthesis technology developed within EMPHATICaL is targeted at this aspect. Moreover, the flexible synthesis concept may

be applicable to other gas-based synthesis processes as well, such as ethanol. This will further expand the market potential for the technology.

- **Closed-loop heat pump-assisted distillation (cl-HPAD)** offers potential for considerable energy saving (60-80%) in distillation processes by reusing and upgrading waste heat. It can not only be applied to methanol but also to other mixtures with constituents with close boiling points, such as in ethanol and formic acid distillation. Therefore, cl-HPAD has considerable market potential. However, it should be noted that methanol synthesis represents only a small part of costs of e-methanol production (~5%). To reduce the costs of e-methanol, it is mainly the hydrogen production costs that need to be lowered.
- **Integrated technology concept.** The EMPHATICaL project does not only develop single technology elements. The power of the project is also in the integration of the different technology components and the integration and exchange of resources between companies and sectors. This enables a new kind of industrial symbiosis, where energy and material flows are optimized across the entire value chain. EMPHATICaL is a showcase for the performance of such an industrial symbiosis concept and value chain. This is especially relevant since the EMPHATICaL concept features intermittent streams, requiring flexible operations: flue gases from metal production, waste heat streams and renewable electricity. As such, this integrated concept could provide a blueprint for other industrial symbiosis concept with intermittent resource streams.

Way forward

A key step is the implementation of these technologies in First-of-a-Kind (FOAK) plant, followed by large-scale rollout across member states. This will help establish the EU's global position in advanced industrial technologies. Achieving this requires close cooperation among R&D institutions, component producers, OEMs, EPC contractors and end-users of the technologies in the metallurgical, chemicals and fuels industry. Only through coordinated efforts the can EU fully leverage its technological potential and compete effectively on the world stage.

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List of abbreviations

ANOVA	Analysis of variance
CAPEX	Capital Cost
CAPM	Capital asset pricing model
CCUS	Carbon capture, utilisation and storage
CEPCI	Chemical Engineering Plant Cost Index
CO_2	Carbon dioxide
COGM	Cost of goods manufactured
COGS	Cost of goods sold
ETS	Emission trading system
FCI	Fixed capital investment
FOAK	First of a kind
GWP	Global warming potential
H2	Hydrogen
IRR	Internal rate of return
ISO	International standardization organization
LCA	Life cycle assessment
LCC	Life cycle costing
LCI	Life cycle inventory
LCOE	Levelised cost of electricity
LHV	Lower heating value
MADM	Multiple attribute decision making
MCDA	Multicriteria decision analysis

1 Introduction

1.1 The EMPHATICaL project

The highly energy intensive metallurgical industry and fossil fuel-based methanol production processes account for over 35% of the overall worldwide industrial CO_2 emissions. The EMPHATICaL project aims to develop an innovative technology to reduce these emissions. EMPHATICaL stands for Efficient Methanol from Pumped Heat and Calcium Looping (EMPHATICaL). The technology targets to process residual CO/CO_2 containing gases from the metallurgical industry through the energy efficient integration of innovative oxy-blown calcium-looping capture technology, purification and conversion of CO_2 to e-methanol with green H_2 as a feedstock. The project culminates in a first-of-a-kind TRL7 demonstration for establishing the economic viability and sustainability of the integrated process capable of achieving net zero for the metallurgical and methanol production industries. **Error! Reference source not found.** shows the work packages in the project and their relations. This report is part of work package 1.

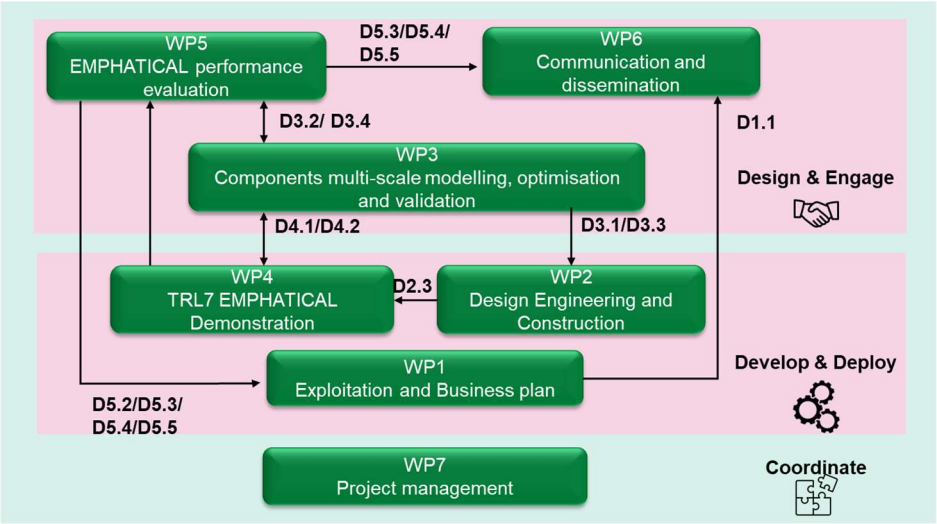


Figure 1.1 Overview of the work packages in the EMPHATICaL project.

1.2 The EMPHATICaL concept

The EMPHATICaL concept is based on the notion of "industrial symbiosis": the integration industrial sectors in a sustainable way, while utilizing residual or waste streams. As such, EMPHATICaL integrates steel and ferrochrome production with e-methanol synthesis by repurposing residual gases. The process (see Figure 1.2) involves:

1. Residual gases conditioning: residual gases from the metals industry are treated using oxy-blown calcium looping (CaL) carbon capture technology to produce a steady stream of purified CO_2. Bio-methane fuels the CaL system to minimize fossil fuel use and downstream CO_2 purification efforts.
2. Methanol synthesis: CO_2 is combined with hydrogen from a high-temperature solid oxide (SOE) electrolyser to produce methanol. Heat produced by the methanol synthesis powers the generation of steam for the SOE electrolyser.

3. Methanol purification: crude methanol is refined using an innovative distillation technology called cl-HPAD (closed-loop heat pump-assisted distillation), enabling full electrification and reducing energy use.

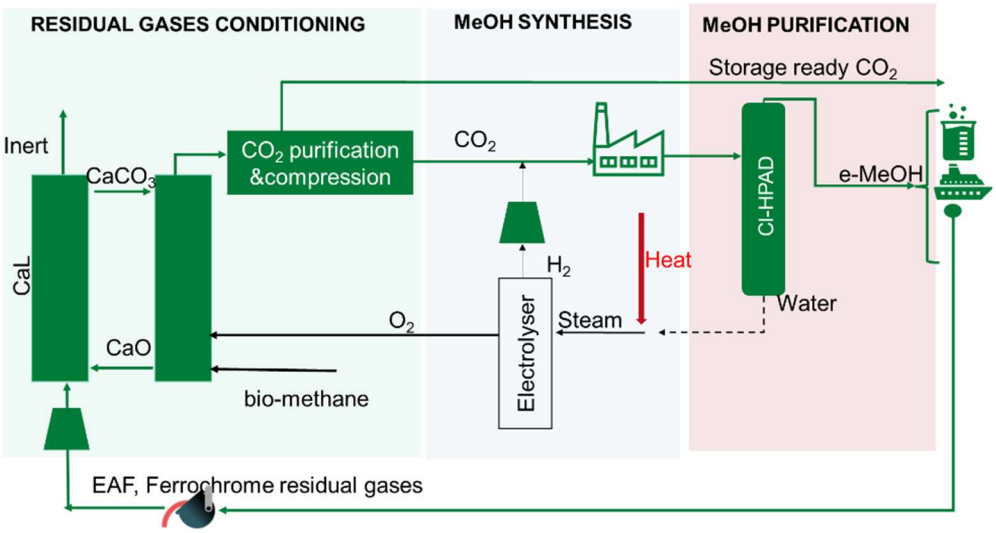


Figure 1.2 Visualization of the EMPHATICaL concept, showing the main process steps and resource streams. Source: (EMPHATICaL consortium, 2024).

1.3 Work package 1

Work package 1 comprises “Exploitation and business plan”. The specific objectives of this work package are:

(i) characterise the markets, the stakeholders and their needs;

(ii) assess the outstanding features of our exploitable results;

(iii) manage, protect and find agreements on the foregrounds;

(iv) identify proper business models for each result and set a plan for commercialisation & market uptake;

(v) prepare pre-FEED for FOAK (first of a kind) taking into account the five feasibility areas: technical, economic, legal, operational and scheduling for one of selected use cases;

(vi) characterise the different risks and identify solutions to mitigate them.

The objectives will be realised by execution of the following tasks:

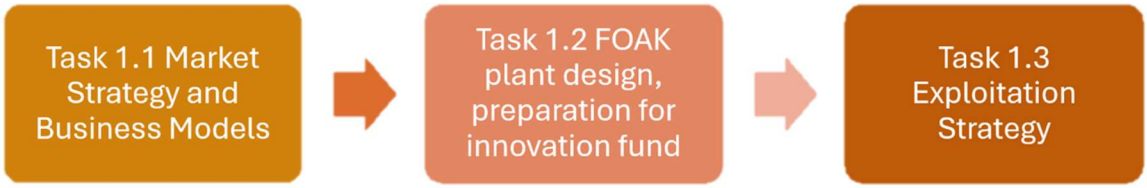


Figure 1.3 Overview of work package 1 of the EMPHATICaL project.

1.4 Goal and contents of this report

This report is part of Task 1.1 and aims to give insight in the market potential for the results of the EMPHATICaL project. In this report, D1.1. of the project, a market analysis is presented for e-methanol and the underlying technologies.

To frame the scope of this market analysis, a simplified value chain is presented in Figure 1.4. A more detailed value chain and value proposition analysis will follow in D1.2. of the project, but the simplified version will serve as the basis for this deliverable.

The diagram shows four types of flows: dark blue for technology transfer, red for financial (including carbon taxes), green for energy and feedstock materials, and light blue for policy & regulation. The yellow boxes highlight stakeholders central to this analysis; white boxes indicate supporting roles. Orange numbers mark the focus areas of the market analysis, which are introduced below.

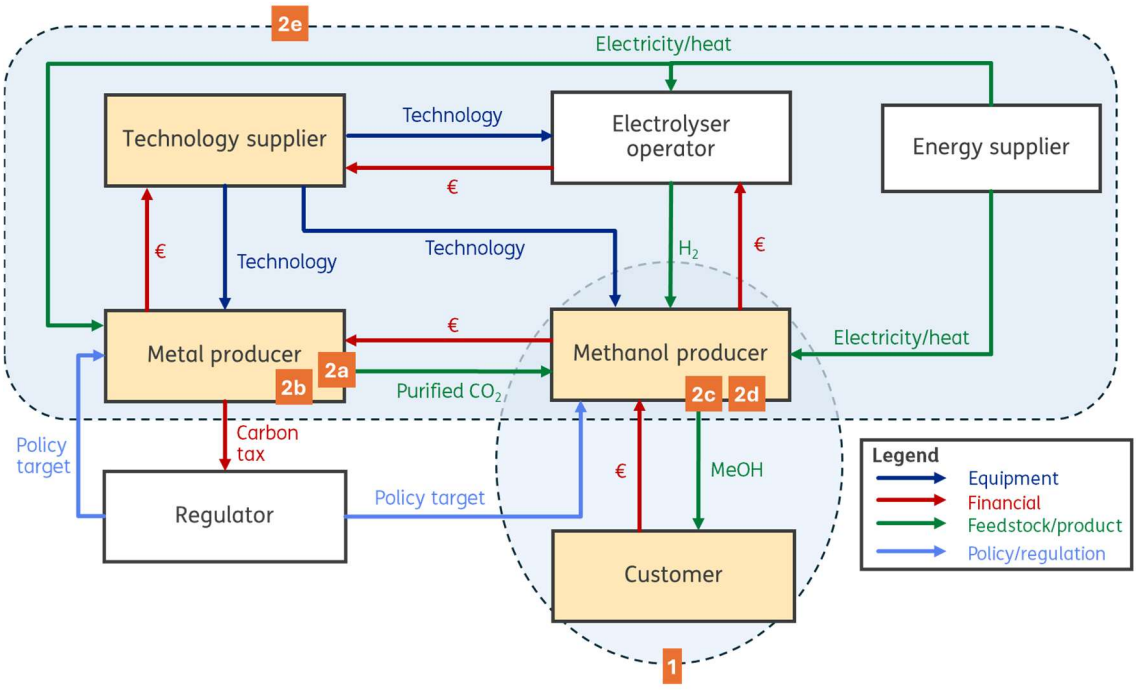


Figure 1.4 Simplified diagram illustrating the value chain relevant to the EMPHATICaL project. The highlighted segments are numbered according to the focus areas for the market analysis listed below. Created by authors.

The market analysis focuses on the following areas:

1. **End Market for e-Methanol:**
   Examines the e-methanol that is supplied by methanol producers to end customers.
2. **Market for EMPHATICaL Technologies:**
   - **2a. Carbon capture (Calcium looping):** Explores the use of calcium looping for carbon capture in metal production.
   - **2b. Pollutant monitoring**: advanced digital technologies for pollutant monitoring

- **2c. Flexible methanol synthesis**.
- **2d. Methanol distillation (cl-HPAD):** Focuses on cl-HPAD adoption by methanol producers.
- **2e. Integrated Technology Concept:** Assesses the commercial potential of EMPHATICaL's full technology platform.

1.5 Relevance of this report to other work packages

This report provides a market analysis of CCU-based e-methanol and technologies developed as part of the EMPHATICaL concept. It is therefore relevant to the following work packages:

- WP5. In this work package, a Life Cycle Analysis (LCA) of the EMPHATICaL concept is performed. For the LCA it is important which end-use sectors are considered.
- WP6. Communication and dissemination of the results of EMPHATICaL. It is important to show the market potential of the EMPHATICaL concept; the market for e-methanol and the markets for the technologies being developed. As such, the results from WP1 can enable WP6 to pave the way for commitment from the industry, policy support and long-term financing.

1.6 Reading guide

The report is structured along the focus areas for the market analysis, presented in Figure 1.4. Chapter 2 elaborates on the end market for e-methanol: market segmentation, relevant regulations and policies, competing products and pathways and opportunities for the EU. In chapter 3, the market analysis for EMPHATICaL technologies is presented: calcium looping (CaL) carbon capture technology, advanced digital technologies for pollutant monitoring, flexible methanol synthesis, closed-loop heat pump-assisted distillation (cl-HPAD) and the integrated technology concept. Moreover, innovation opportunities for the EU are discussed in this chapter. In chapter 4 overall conclusions of the market analysis are presented.

2 Market for e-methanol

2.1 Introduction

Methanol is a key platform chemical and energy carrier with applications across the chemical and transport sectors. Global methanol production capacity is currently around 120 million tons per year. By 2050, it is expected to grow five-fold to 500 million tons, with bio-methanol and e-methanol making up 80% of total output (IRENA and Methanol Institute, 2021). Traditionally methanol has been produced almost exclusively from fossil fuels, but the technological advancements of recent years have made it possible for alternative renewable methanol pathways to be created. E-methanol, produced from green hydrogen and captured CO_2, represents a renewable alternative to fossil methanol. Its integration into existing infrastructure is seamless due to identical molecular properties, while its production pathway enables significant lifecycle CO_2 reductions (65–90%).

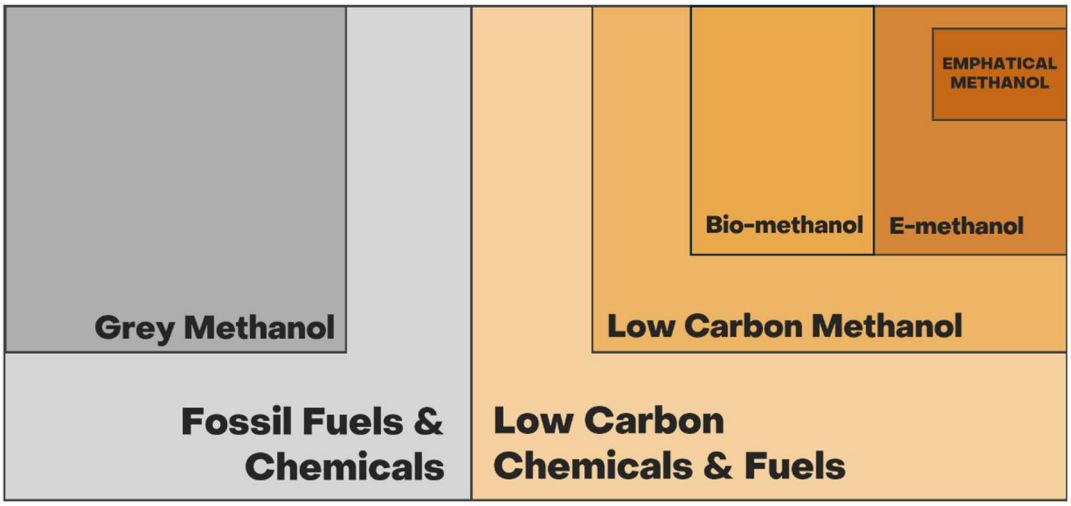


Figure 2.1 Overview of Methanol Types, with emphasis on EMPHATICaL Methanol.

The EMPHATICaL project focuses on e-methanol produced from CO_2 captured from the metals industry, using calcium looping for carbon capture and hydrogen produced by renewable electricity-powered electrolysis. EMPHATICaL methanol can be classified as a Renewable Fuel of Non-Biological Origin (RFNBO) under EU rules, even if the CO_2 used originates from fossil sources—since it is captured from an ETS-obligated facility. These are industrial installations covered by the EU Emissions Trading System (ETS), such as those in the metals sector, which must pay for their carbon emissions. However, this eligibility is time-limited. According to the EU's Renewable Energy Directive (RED III) and associated delegated acts, CO_2 from fossil sources in ETS-covered facilities will only be eligible for RFNBO classification until the end of 2041. Hence, from 2041 onwards, the metals sector needs to switch to biogenic carburisation agents (European Commission, 2023; European Commission, 2023; Platform Hernieuwbare Brandstoffen, n.d.).

However, as of today, EMPHATICaL methanol is positioned as a strategic enabler for industrial decarbonisation and circularity.

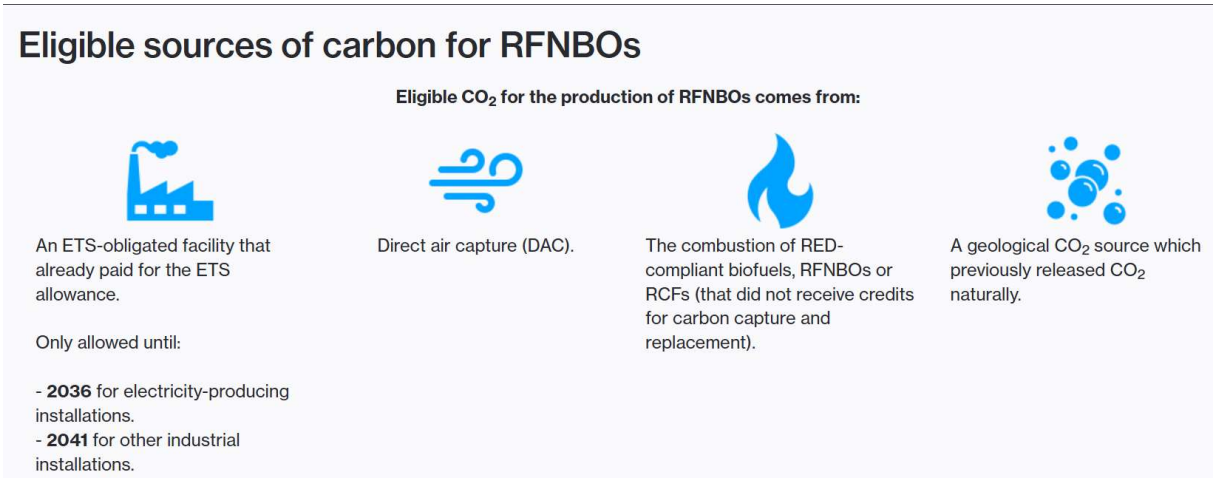


Figure 2.2 – Overview of eligible carbon sources for Renewable Fuels of Non-Biological Origin (RFNBOs). EMPHATICaL methanol can be classified as RFNBO even if the CO_2 used originates from fossil sources—since it is captured from an ETS-obligated facility: facilities that need to pay for their carbon emissions under the EU Emission Trading System, like the metals sector. However, this is only allowed until 2041. After that, the metals sector needs to switch to biogenic carburisation agents. Source: (Platform Hernieuwbare Brandstoffen, n.d.)

Another distinction that is sometimes used is “grey”, “blue” and “green” methanol, see **Error! Reference source not found.**3. In IRENA’s definition, “green methanol” is produced using green hydrogen and renewable CO_2 (direct air capture or biogenic sources). In this definition, EMPHATICaL methanol would qualify as “blue” instead of “green” unless the metals sectors switches to biogenic carburization agents.

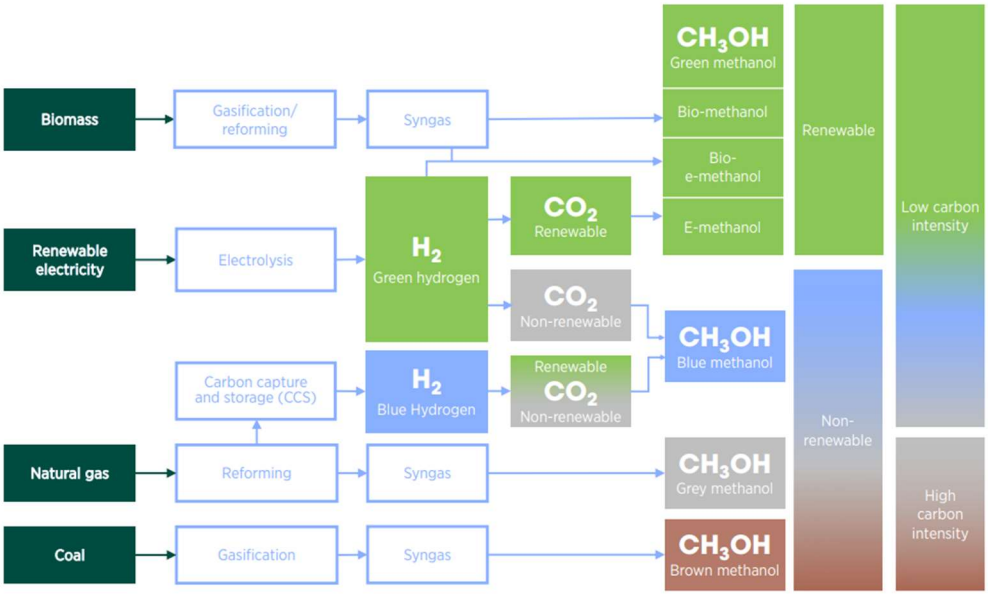


Figure 2.3 - IRENA proposed classification of methanol from various feedstocks (IRENA and Methanol Institute, 2021)

2.2 Market segmentation

Methanol, the simplest alcohol, is a highly flexible building block that plays a role in a wide range of industries. Traditionally, the global methanol market is segmented into chemical and fuel applications. As of 2023, chemical uses account for approximately 72% of total demand, including derivatives such as formaldehyde, acetic acid, olefins, and MTBE. Fuel applications represent around 18% of global consumption, encompassing gasoline blending, methanol-to-diesel and methanol-to-DME technologies (MMSA, 2025). Figure 2.4 shows the global methanol demand by application in 2023 and their shares.

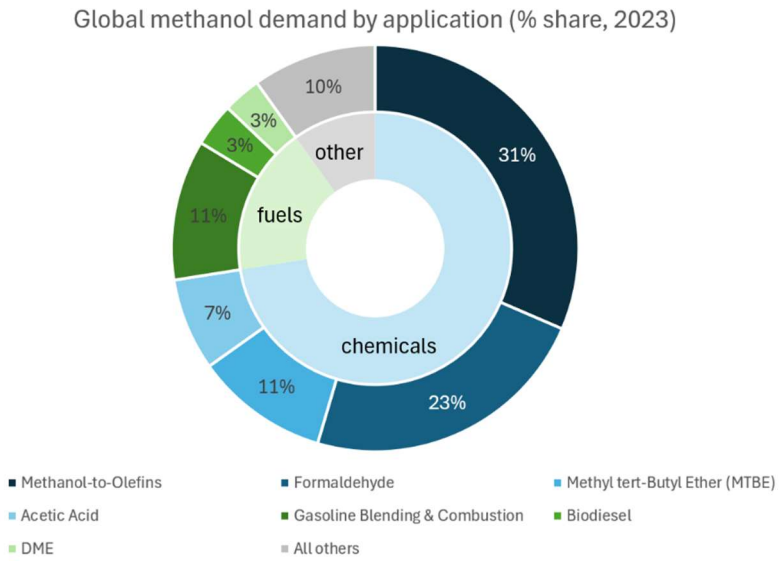


Figure 2.4 – Global methanol demand by application. Created by authors based on data from Methanol Market Services Asia (MMSA, 2025)

While these figures reflect current applications, it is the emerging and future uses, particularly in sustainable fuels (marine fuels and methanol as an aviation fuel intermediate, methanol-to-jet) and green chemical pathways (particularly olefins), that are expected to drive significant growth in the methanol market as it can be seen in Figure 2.5.

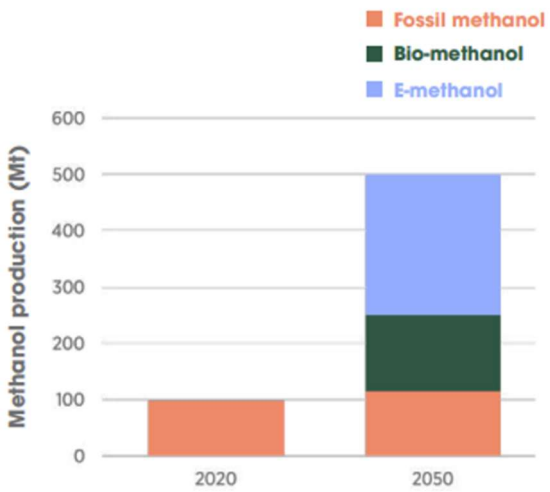


Figure 2.5 – Current and future methanol production by source (IRENA and Methanol Institute, 2021)

Innovations in renewable methanol production and its expanding role in hydrogen carriers and e-fuels are redefining methanol's position in the global energy and chemical landscape, and setting the stage for its evolving applications in both chemical synthesis and low-carbon fuels (IRENA and Methanol Institute, 2021).
The following sections explore methanol's role in both its traditional applications and new opportunities that can be harnessed via EMPHATICaL methanol. While the chemical sector remains the largest consumer, the fuel segment is rapidly evolving, driven by decarbonizing goals.

2.2.1 Chemical applications

The chemical sector remains the backbone of the methanol demand. By far the biggest use of methanol is in the manufacture of other chemicals. EMPHATICaL methanol can serve as a renewable feedstock for the production of key base chemicals such as formaldehyde, acetic acid, olefins, and MTBE, which are foundational to industries like construction, automotive, textiles, and packaging (MMSA, 2025). Because methanol's molecular structure and reactivity remain unchanged regardless of its origin, EMPHATICaL methanol can be directly substituted into existing production processes, facilitating a seamless transition toward more sustainable chemical value chains.

Historically, formaldehyde and acetic acid dominated the methanol-based chemical demand, but in recent years, olefins have emerged as the fastest growing segment, reshaping the landscape (NexantECA, 2022). Formaldehyde, the largest single derivative, is used in resins, plastics, plywood, explosives, and textiles. The EU is the second largest producer after Asia, producing over 4 million tonnes/year accounting for about 30% of global production and generating roughly €9.5 billion in annual sales (Formacare, 2022).

Acetic acid, used in paints, adhesives, and food preservatives, represents a smaller but stable segment of the methanol demand, with over 85% produced via methanol carbonylation. Global demand is projected to grow from 17 million tonnes in 2024 to 24.6 million tonnes by 2030, with growth tied to packaging and textile industries (Mordor Intelligence, 2025a).

Olefins, including ethylene and propylene, are produced via Methanol-to-Olefins (MTO) technology, now the largest single outlet for methanol. Since its commercial rollout in 2010, MTO capacity has expanded rapidly, especially in China, which commissioned over 20 million tonnes/year in facilities (Mohammadi & Harandi, 2023). In 2020 alone, olefins demand grew 16% driven by demand in plastics, packaging, automotive, and textiles and is expected to continue its growth (NexantECA, 2020).

MTBE (Methyl Tertiary-Butyl Ether) is a gasoline additive, with a global market valued at approximately USD 18.2 billion in 2025, projected to reach USD 23.7 billion by 2030. Though declining in North America & Europe due to environmental concerns, MTBE remains important in markets with permissive regulations (Mordor Intelligence, 2025b). For e-methanol, MTBE represents a strategic entry point, as it allows renewable methanol to enter the fuel market indirectly while leveraging existing infrastructure and practices.

2.2.2 Fuel applications

In parallel, methanol's role as a low-carbon fuel is gaining momentum. This means that EMPHATICaL methanol can be used directly in internal combustion engines (ICEs), blended with gasoline, or converted into synthetic

diesel and jet fuels via methanol-to-diesel and methanol-to-jet pathways. These fuel applications currently account for 18% of the methanol demand (MMSA, 2025) and are especially relevant in sectors where electrification is challenging, such as aviation and maritime shipping. The EU regulations, as described in the following section, support (and in some cases drive) a growth in the demand for low-carbon methanol in these areas and thus increase the opportunity landscape for EMPHATICaL methanol.

In the marine sector, sustainable methanol is rapidly emerging as a mainstream fuel, driven by regulation and decarbonization goals. Over 125 methanol-capable vessels were in operation or on order in 2023, with projections exceeding 1000 vessels by 2030 (Marquez, 2023). Major shipping companies like Maersk, COSCO and CMA CGM are leading this change. Methanol is already available in over 120 ports worldwide, including Rotterdam, Singapore and Shanghai. This supports methanol's scalability and bunkering potential (Methanex, 2025). These developments create a strong foundation for EMPHATICaL methanol to enter the marine fuel market through existing infrastructure.

In aviation, EMPHATICaL methanol can be converted into kerosene-type fuels via methanol-to-jet (MTJ) pathways. This fuel is compatible with existing aircraft infrastructure. Growing policy momentum in the EU is expected to drive demand for sustainable aviation fuels derived from renewable methanol (Wormslev & Broberg, 2020). Globally, the MTJ market is valued at € 1.11 billion in 2025, projected to reach € 2.31 billion by 2034 (Bussiness Research Insights, 2025).

In road transport, China leads global adoption, consuming 4.8 Mt of methanol annually for this purpose (Dolan, 2020). Already, methanol powered vehicles such as buses and trucks are commercially available (Farizon, 2025), supported by China's national policy to reduce reliance on imported fuels. In the EU, methanol use in road transport is still emerging but gaining interest, especially for heavy-duty applications, indicating an emerging use case for EMPHATICaL methanol (Iosefa, 2025).

Beyond transportation, methanol is increasingly being used as a low-carbon emission fuel for power generation, particularly in off-grid and remote systems. These systems benefit from methanol's clean combustion profile and compatibility with fuel cells and internal combustion engines, lowering NO_x and SO_x emissions compared to diesel (Menne, 2025). In fact, the steel industry is also considering methanol as a fuel in their systems, especially in locations where alternatives to fossil fuels like natural gas and coke are unavailable. In this context, EMPHATICaL methanol, derived from metallurgical CO_2 sources, presents a strategic opportunity to decarbonize steelmaking while valorising process CO_2 by CCU.

2.3 Relevant regulations and policies

The EU has implemented extensive regulations, policies and mandates to reduce greenhouse gas emissions and to stimulate the use of sustainable fuels and chemicals, including e-methanol. This paragraph elaborates on relevant regulations, policies and mandates for the supplier and user side of the value chain. Relevant regulations and policies for the industrial producers are elaborated in chapter 3.

Figure 2.6 presents the most relevant regulations, policies and mandates for the supplier and user side of the value chain. Many of these apply to the supplier of the methanol. The most important off takers of e-methanol will be the chemical industry, the international shipping sector and the aviation sector.

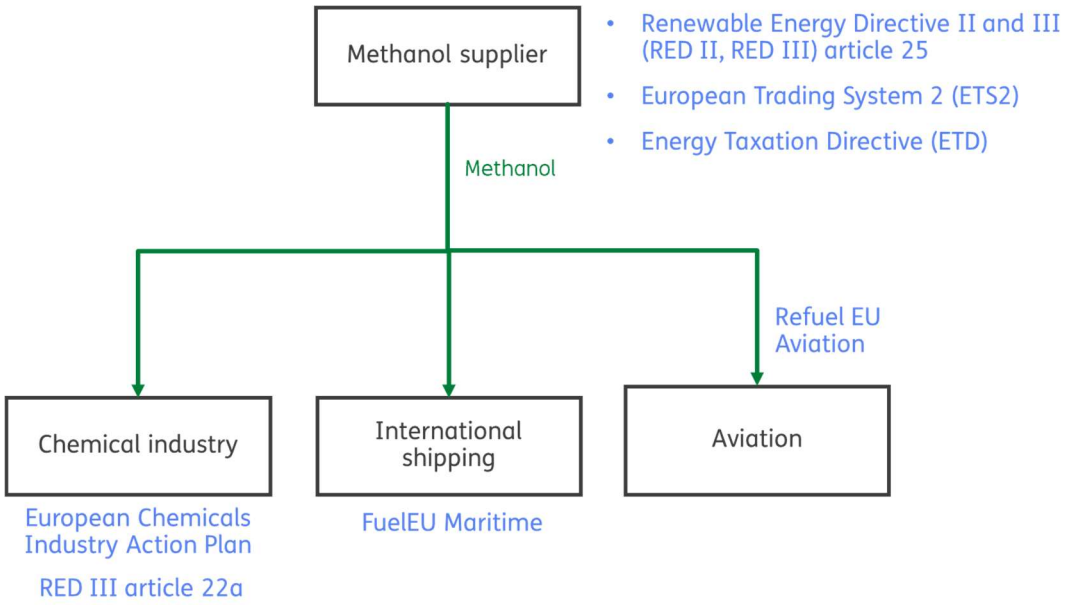


Figure 2.6 Relevant regulations and policies for methanol suppliers and users

Specific mandates for CO_2-based fuels are already embedded in several EU legislative instruments. To qualify as a Renewable Fuels of Non-Biological Origin (RFNBO) under current EU regulations, e-methanol must meet strict sustainability criteria. These include the use of renewable electricity for hydrogen production and a carbon source that is either biogenic, atmospheric, or industrial fossil CO_2, provided the latter is used before the 2040 phase-out date. Certification schemes like ISCC EU verify compliance with these criteria (ISCC EU, 2024), including traceability and mass balance (European Commission, 2023). Additionally, e-methanol must demonstrate at least 70% greenhouse gas savings compared to fossil fuel benchmarks. These conditions ensure that EMPHATICaL methanol can be classified as RFNBO until 2040, assuming all inputs meet the required standards.

The following regulations and policies should be met by e-methanol suppliers (European Commission, 2025):

- The **Renewable Energy Directive III (REDIII)** requires that at least 1% of transport fuels are RFNBOs by 2030 (article 25).
- **ETS2** is aimed at the use of fuels that are not subject to ETS1. It will become operational by 2027. Suppliers of fuels, including suppliers of e-methanol, will be subject to the emission trading system of CO_2, including reporting obligations. ETS2 favours the use of fuels with low CO_2 emissions, thus stimulating market uptake of e-methanol, produced from renewable energy sources and from circular CO_2.
- The revised **Energy Taxation Directive (ETD)** proposes to tax fuels by energy content and environmental impact. This stimulates the market for sustainable fuels, including e-methanol.
- The **ReFuelEU Aviation** regulation sets binding subtargets for the use of SAF starting at 6% in 2030 and increasing to 70% in 2050. Within this target, there is a subtarget for e-SAF increasing

from 1.2% in 2030 and increasing to 35% by 2050. These targets apply to fuel suppliers. (European Commission, n.d.)

FuelEU Maritime mandates a progressive reduction in greenhouse gas emission intensity for ships, from 2% in 2025 to 80% in 2050, with a fallback RFNBO sub target of 2% from 2034 if minimum thresholds are not met. In contrast to RefuelEU Aviation, this target applies to the maritime sector, instead of the fuel supplier.

These instruments create direct market pull for EMPHATICaL methanol, particularly in the transport sector. In contrast, comparable mandates for CCU-based chemicals are currently lacking. However, the **European Chemicals Industry action plan** proposes to implement fiscal incentives and market creation mechanisms for clean chemicals, including e-methanol. Also **RED III article 22a** is relevant to the chemical industry. Article 22a states that in 2030 at least 42% of hydrogen in industry should be RFNBOs, rising to 60% in 2035. If e-methanol meets RFNBO criteria, it contributes to this target.

2.4 Competing products and pathways

EMPHATICaL methanol competes not only with conventional and renewable methanol production pathways but also with alternative fuels and chemicals across sectors such as maritime transport, aviation, and petrochemicals. This section analyses the competitive landscape of EMPHATICaL methanol in three parts:

1. **Assessment Criteria:** Key performance indicators and regulatory frameworks used to evaluate competitiveness.
2. **Methanol Production Pathways:** Comparison of production pathways (fossil, biomass, renewable) based on cost, emissions, and maturity.
3. **End Use Alternatives:** Review of alternatives to methanol in key applications like fuels, chemicals, and energy storage.

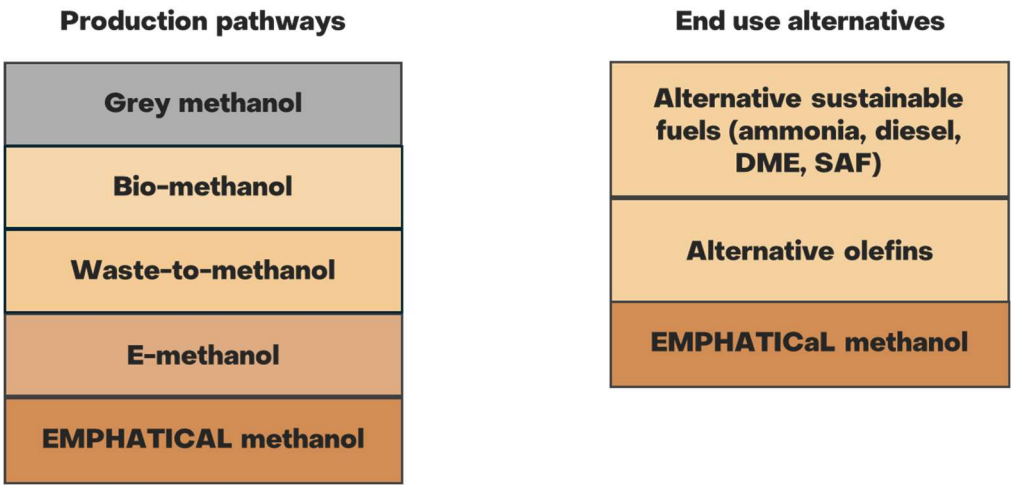


Figure 2.7 List of competing methanol production pathways and end use alternatives for EMPHATICaL methanol

2.4.1 Assessment Criteria

The competitiveness of EMPHATICaL methanol to other production pathways or products can be compared using a set of qualitative and quantitative performance indicators. These include lifecycle greenhouse gas emissions, production cost per unit of energy or chemical output, technology readiness level (TRL), feedstock availability and scalability, and compatibility with existing infrastructure. In addition to these technical and economic indicators, regulatory compliance plays a critical role in determining market viability.

As described before, EMPHATICaL methanol qualifies as a Renewable Fuel of Non-Biological Origin (RFNBO) under current EU legislation, provided that the CO_2 feedstock is either of non-fossil origin or captured from industrial processes (European Commission, 2023; European Commission, 2023; Platform Hernieuwbare Brandstoffen, n.d.). This qualification enables EMPHATICaL methanol to contribute to sectoral targets under the Renewable Energy Directive III (REDIII), the FuelEU Maritime Regulation, and the ReFuelEU Aviation Regulation until 2040 (IRENA and Methanol Institute, 2021). Its alignment with these frameworks positions it favourably for deployment in sectors where regulatory compliance is a prerequisite for market access.

2.4.2 Methanol Production Pathways

Methanol can be produced via several distinct pathways, each with its own technical, economic, and environmental characteristics.

Fossil methanol is produced through the conversion of syngas resulting from methane reforming or coal gasification. It represents the most cost-effective and technologically mature option with former being the dominating feedstock. However, they both have high carbon footprint and, if unabated, cause high GHG emissions, thus they do not qualify under EU sustainability frameworks. Their main advantage is the low cost of production due to the widespread global deployment of these methods (Blumberg et al., 2019), In comparison, EMPHATICaL methanol achieves significantly lower lifecycle emissions and meets the relevant regulatory criteria; however, it is currently more expensive and less mature in terms of deployment.

Bio-methanol is derived from biomass such as woody biomass, agricultural residues etc. via gasification or pyrolysis and presents a renewable alternative. Its production costs are moderate and the technology is at a medium level of maturity with TRL levels ranging from 7 to 9. It can also achieve much lower net life-cycle GHG emissions than the fossil alternatives and even be net-negative in some biomass/CCS (carbon capture storage) scenarios because biogenic CO_2 can be removed/offset (Harris et al., 2021).However, in many regions bio-methanol is constrained by feedstock availability, spatial limitations and not-yet-established value chains for biomass (IRENA and Methanol Institute, 2021). Although its production costs are slightly higher than fossil routes, many TEAs find bio-methanol to be the near-term economically viable renewable option due to costs and the utilization of existing infrastructure and compatibility with EU sustainability goals (Harris et al., 2021).

Waste-to-methanol (WtM) technologies, commonly categorized as a subset of bio-methanol technologies, convert municipal or industrial waste into methanol and offer significant benefits in terms of circularity (Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2024). Considering that this pathway utilizes waste that would otherwise be left to decompose and emit methane, it can have near-zero or low life cycle greenhouse gas (GHG)

emissions. Several demonstration and commercial-scale plants are already operational. However, the availability of suitable waste feedstock is highly location-dependent, resulting in variable production costs (IRENA and Methanol Institute, 2021). Compared to other bio-methanol types, WtM feedstock costs are very low, or even negative, but the presence of contaminants makes preprocessing more complex. While waste-to-methanol technology has a somewhat lower maturity than bio-methanol, it is still more mature than EMPHATICaL methanol, but faces similar challenges in regulatory clarity and scalability (Harris et al., 2021).

In addition to EMPHATICaL methanol, other forms of **e-methanol** are being developed across the world. These e-methanol pathways (namely indirect and direct electrolysis) have different maturity levels and vary significantly in sustainability performance depending on the source of electricity, hydrogen, and CO_2. They can achieve very low life-cycle GHG emissions if powered by renewable electricity and supplied with low-carbon CO_2 (IRENA and Methanol Institute, 2021). Current production costs are still well above fossil methanol but are expected to fall with cheaper renewable power and electrolysers (Fasihi & Breyer, 2024). The technology is moving from pilot to early commercial scale (Carlsson, 2025), with scalability mainly limited by renewable energy and CO_2 availability.

2.4.3 End Use Alternatives

In addition to competing methanol production pathways, EMPHATICaL methanol faces competition from alternative sustainable fuels and chemical feedstocks in the aforementioned target market segments. This section reviews the most relevant end-use alternatives to EMPHATICaL methanol in both the fuel and chemical domains.

On the sustainable fuel side, **green ammonia** is a promising hydrogen carrier and low-carbon fuel due to its high hydrogen density and carbon-free combustion. Its advantages are supported by established global production and transport infrastructure, as well as the ability to convert it back to hydrogen at the point of use (Cao et al., 2025). However, its toxicity, handling challenges and lower energy density - compared to e.g., methanol, diesel and kerosene -, limit its appeal in many fuel applications (Sánchez et al., 2024). Regarding direct utilization, methanol has a higher technology readiness level compared to ammonia and offers compatibility with existing ship engines with some adaptations (Marquez, 2023). Therefore the adoption of e-methanol has lower transition costs, enabling earlier adoption by the marine industry.

In road transport, methanol competes with other sustainable carbon based fuels, particularly in diesel applications where electrification faces significant barriers. **Renewable diesel (RD)**, produced via hydrotreating of waste oils or biomass, offers a drop-in solution for the existing diesel engines, especially found in long-haul trucks, and is already deployed at a commercial scale (Pratama, 2024). It enables immediate CO_2 reductions, with significantly lower infrastructure costs compared to battery electric vehicles (BEV) (ATRI, 2024). **Dimethyl ether (DME)** is another promising diesel substitute. It can be synthesised from methanol via dehydration and is commercially mature. DME offers clean combustion and low particulate emissions, making it suitable for freight and heavy duty transport. While it is not fully drop-in like renewable diesel, vehicles require modifications to fuel injection systems and pressurized storage tanks, these adaptations are relatively minor compared to converting engines for pure methanol, which has corrosive properties and lower energy density (Putrasari, 2021).
Importantly, DME and renewable diesel are not only competitors to methanol, they are also potential revenue avenues. Methanol can serve as a feedstock for both fuels, expanding its market relevance. DME production from

methanol is already commercialized, offering high conversion efficiency and low operating costs. Renewable diesel can be produced via methanol-to-olefins (MTO) followed by oligomerization (MOGD), enabling integration into existing fuel infrastructure. While this route is less mature, it is technically feasible and offers long-term potential (Ruokonen, 2021).

In **gasoline** applications, on the other hand, methanol is not expected to play a significant role. BEVs are emerging as the dominant decarbonatization pathway in these applications due to their high energy efficiency compared to internal combustion engines using methanol or other e-fuels. While methanol can be blended with gasoline to reduce emissions, these blends often result in lower engine power and higher fuel consumption, making them unfavourable. Especially with the expansion of charging infrastructure and the decreasing costs of batteries, BEVs are becoming more and more prevalent across the world. Therefore, methanol is expected to have no significant role to play in gasoline applications (Iliev, 2021).

While methanol's role in road transport is largely limited to diesel applications, its potential in aviation is more expansive, particularly as a feedstock for synthetic jet fuels. **Sustainable Aviation Fuels (SAFs)** are the main focus for making the aviation sector sustainable since electrification is not feasible except for short-haul flights. Two types of SAFs are being considered: bio-SAF and e-SAF. Different routes for each of these fuel types exist. For e-SAF the main routes are:

- Fischer-Tropsch fuels, which involve the production of synthetic kerosene from renewable syngas through the Fischer-Tropsch fuels.
- Alcohol-to-jet fuels, which are synthetic kerosenes produced from alcohols. Kerosene can be produced from methanol; this route is called methanol-to-jet (MtJ).

e-SAF and bio-SAF routes vary widely in cost, scalability, and regulatory qualification. Currently, the production costs for e-SAF are up to 9 times as high as conventional kerosene, while bio-SAF costs are 3 times as high (EASA, 2024; Deloitte & to70, 2025). Bio-SAFs, such as HEFA fuels derived from bio-based oils and fats, are already commercially available and can be blended with conventional jet fuel without engine modifications (Van Dyk & Saddler, 2024). However, while HEFA SAFs are more cost-effective and readily deployable today, their scalability is constrained by limited feedstock availability (Elwalily et al., 2025). Moreover, bio-SAF uses 10-20x more land than e-SAF (Boter, 2023).

As ReFuelEU Aviation stipulates targets for the adoption of e-SAF specifically (see *Relevant regulations and policies*), there is a market potential for e-SAF. Hence, EMPHATICaL methanol can compete in this space as a methanol-to-Jet (MtJ) pathway, offering feedstock flexibility and potentially lower carbon intensity when produced renewably. The first commercial plants producing e-SAF through MtJ are under development: for example in the Port of Rotterdam (Netherlands), where Power2X and Advario are planning a 250 kilotons/year plant, which is the largest announced plant to date (Advario, 2024). However, MtJ still facing challenges in catalyst stability and process integration (Elwalily et al., 2025). This positions EMPHATICaL methanol as a long-term alternative, providing flexibility in feedstocks and potential sustainability benefits, though adoption will depend on overcoming technical and economic hurdles.

On the chemical side, methanol also competes with alternative feedstocks in the production of key petrochemicals, most notably olefins.

Olefins, such as ethylene and propylene, are key building blocks in the chemical industry like methanol and are traditionally produced via steam cracking of hydrocarbons. This conventional route is well-established and commercially mature but is energy-intensive and relies heavily on fossil fuels, resulting in significant greenhouse gas emissions (IEA, 2023). Methanol offers an alternative pathway as a feedstock for producing olefins through Methanol-to-Olefins (MTO) processes. When produced from renewable sources, methanol can reduce carbon intensity and provide greater feedstock flexibility. With the maturation of MTO technology in the recent years, this new market has been able to become commercialized; however, MTO technology is still relying on energy intensive distillation and faces challenges such as catalyst stability and process integration (Tang et al., 2025).

Other sustainable alternatives in the production of olefins include electric cracking, hydrogen-fired cracking and bio-naptha. Electric cracking and hydrogen cracking are sustainable alternatives for the natural gas-based heat supply in steam crackers, while bio-naphtha is a sustainable alternative for fossil naphtha or ethane feedstock that are currently being used. Electric cracking, powered by renewable electricity can eliminate 95% of combustion emissions and is moving towards commercialization with operation pilot plants (Tijani et al., 2022). Hydrogen fired cracking also removes combustion emissions but has some safety challenges. However, electric cracking and hydrogen cracking do not address the feedstock-related emissions. Bio-naphtha, derived from biomass or waste oils, is a sustainable feedstock alternative. However, due to feedstock variability, high production costs, and limited scalability, it is generally considered a short- to mid-term solution (Adekeye et al., 2025). Overall, while conventional olefin production remains dominant due to cost and infrastructure advantages, EMPHATICaL-methanol based routes present a promising low-carbon alternative for the chemicals sector.

2.5 Opportunities for the EU

2.5.1 Competitiveness under pressure

Competitiveness is under pressure in the metals and chemicals industries in the EU. Even though their share in global value added has decreased over the last years, the EU base metals (25% share) and fabricated metals (33% share) industries are still significant global players (WIIW, 2025). The EU's Competitiveness Compass recognizes the metals sector's strategic importance and the European Steel and Metals Action Plan outlines measures to boost the industry's position amid competitiveness challenges, including measures to support sustainability projects through shaping lead markets and public support (European Commission, 2025), including valorising captured CO_2.

The EU has the second largest chemicals industry in the world by sales value. However, its share in the global chemicals market has decreased from 28% in 2003 to 13% in 2023, though sales have increased in absolute sense over this time period. After a rapid decline between 2003 and 2015, EU's chemical industry's market share has stayed relatively stable but in recent years, the decline has steepened once again. Since 2022, EU's chemicals sales have also been decreasing in absolute sense. Meanwhile, China's chemical industry's market share has increased, while in developed countries (e.g., USA, Japan and South Korea) it has decreased, like in the EU (Cefic,

2025; Cefic, 2025). Like the metals sector, the EU has recognized the chemicals industry as a strategic sector and strives to boost its competitiveness through the Chemicals Industry Action Plan (European Commission, 2025).

As Mario Draghi outlines in his report *The future of European competitiveness*, energy-intensive industries in the EU are under pressure: their production has decreased between 10 and 15% between 2021 and 2024 (see Figure 2.8) and major production sites are closing. The reasons for this development are manifold, but high energy prices form a key factor. At the root of this problem lies Europe's lack of natural resources and its limited collective bargaining power, as well as the structure of the EU's energy market. In the case of the chemical industry, there is a "dual dependency" on fossil fuels as the sector is reliant on imported fossil fuels not only for energy but also for feedstock. Hence, the sector is especially vulnerable to price volatility and supply chain disruptions associated to fossil fuels. On the other hand, the EU metals sector is vulnerable to disruptions in the import chains of critical raw materials needed as alloying elements and is affected by 25% import tariffs introduced by the US on steel and aluminium.

To resolve the high energy prices, Draghi suggests a "joint competitiveness and decarbonisation plan": lowering energy prices and reducing reliance on imported fossil fuels with volatile global markets by switching to renewable energy sources, which also offers an opportunity to enhance energy security. (Draghi, 2024; European Commission, 2025; European Commission, 2025)

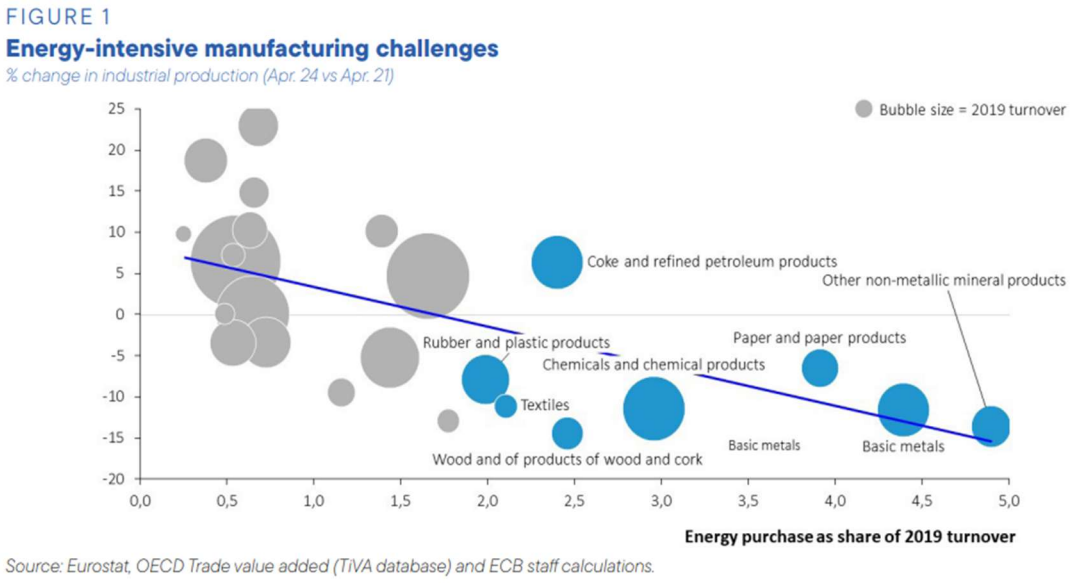


Figure 2.8 – Share of energy purchase in 2019 turnover versus percent change in industrial production between 2021 and 2024, for industrial sectors in the EU. Highlighted are the EU's energy-intensive industries. Source: (Draghi, 2024).

2.5.2 Additional economic value & emission reduction through industrial symbiosis

The EMPHATICaL concept creates an opportunity for both the chemical and metals industry to generate additional economic value while reducing emissions through industrial symbiosis. The EMPHATICaL concept is an example of "industrial symbiosis", visualized in Figure 2.99. According to (Lombardi & Laybourn, 2012), industrial symbiosis "is a systems approach to a more sustainable and integrated industrial system, which identifies business opportunities that leverage underutilized resources (such as materials, energy, water, capacity, expertise, assets

etc.)" As such, industrial symbiosis has potential economic benefits by generating additional value added, while also contributing to a circular economy and climate change mitigation.

In the Horizon 2020 project SCALER, the socio-economic impact of 81 industrial synergies was assessed through a model-based approach. 91% of these synergies resulted in a positive economic value, while mitigating greenhouse gas emissions, improving human health and ecosystem quality and reducing the use of resources. Hence, it was demonstrated that industrial symbiosis has the potential to generate not only economic but also environmental, societal and ecological benefits (Quintana, Sockeel, & Bredimas, 2019).

In the context of CCU, industrial symbiosis can serve to resolve resource scarcity of individual companies in an industrial ecosystem (Kant, 2017). Moreover, CCU can complement other routes for the production chemicals and fuels based on sustainable carbon sources: biomass-based or waste-based. For example, the production of biofuels through fermentation still generates CO_2, which can be captured and utilized as a CCU feedstock. In this manner, CCU can improve overall system efficiency (Dowling, et al., 2025).

This is also true for the metals industry: even as the sector switches to biogenic carbon instead of fossil carbon as a reduction agent, the industry will continue to emit CO_2, which can be either stored or utilized for the production of methanol. As such, in the EMPHATICaL concept, residual gases which are currently emitted and therefore wasted, are recognized as a valuable resource while reducing overall greenhouse gas emissions. Currently, the EU's metallurgic industry's greenhouse gas emissions represent a significant share of total greenhouse gas emissions in the EU. The steel industry alone is responsible for 5% of the EU's greenhouse gas emissions (JRC, 2022).

In the EMPHATICaL concept, industrial symbiosis does not only apply to the utilization of CO_2 but also to the utilization of oxygen produced by the electrolyser in the CaL system, the heat produced by methanol synthesis in the electrolyser and the supply of water produced by the methanol distillation process to the electrolyser.

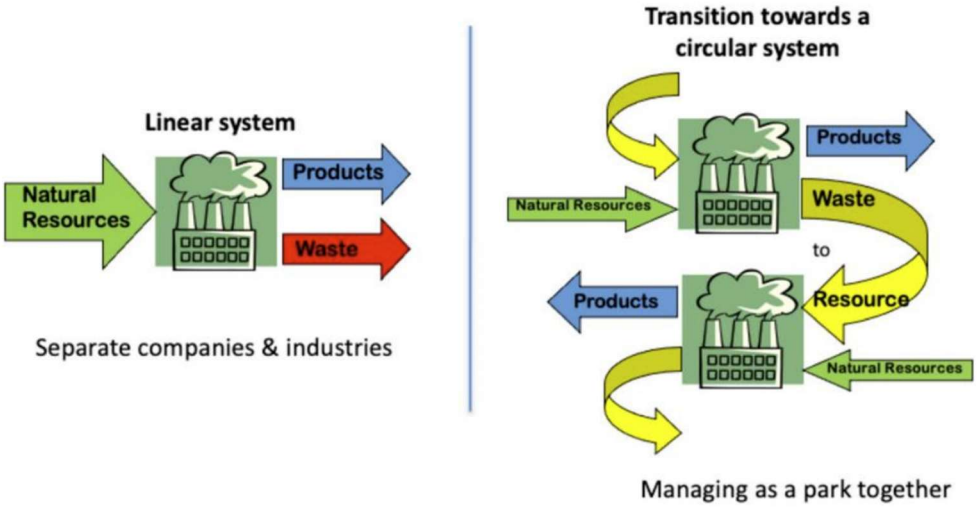


Figure 2.9 - Visualization of a linear industrial system concept (left) versus an industrial symbiosis concept in which synergies are leveraged. (Dong, Liu, & Bian, 2021)

If the EMPHATICaL concept is rolled out throughout the EU in 2050, it has the potential of reaching a 4% share of the global e-methanol market and creating 14,000-17,000 jobs while converting 15 Megaton/year (Mt/y) of CO_2

captured from residual metallurgical gases and generating 41 Mt/y CO_2 ready for storage. In a full roll-out scenario, 104 TWh of renewable electricity will be needed (EMPHATICaL consortium, 2024).

It should be noted that the potential of the EMPHATICaL concept to reduce greenhouse gas emissions hinges on the availability of sufficient renewable electricity. Especially the production of electrolysis-based hydrogen requires a significant amount of electricity. Given the current emission intensity of the electricity grid, lifecycle analysis (LCA) by TNO has shown that e-methanol production with grid electricity has a higher global warming potential than conventional (fossil) methanol production as of today (see Figure 2.10). On the other hand, this LCA also shows that e-methanol production can result in negative production if renewable electricity is used (Dowling, et al., 2025).

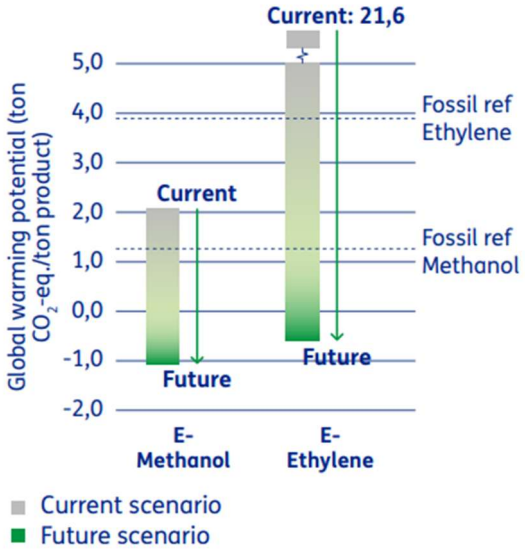


Figure 2.10 – Global warming potential (ton CO_2-equivalent/ton product) for e-methanol and e-ethylene produced with grid electricity according to the current emission intensity of the electricity grid (Current) and a future scenario in which the electricity from the grid is fully renewable (Future). The global warming potential of conventional methanol and ethylene production based on fossil resources is also shown. Source: (Dowling, et al., 2025)

By contrast, some industrial symbiosis pathways for the metals industry have the potential of reducing greenhouse gas emissions even without the availability of renewable electricity. In the Horizon 2020 project INITIATE, the environmental performance of the production of chemicals from residual gases from blast furnace-based steelmaking was assessed. These residual gases already contain hydrogen; hence, hydrogen is not produced via electrolysis. A symbiotic industrial system featuring methanol synthesis from these residual gases yields an emission intensity reduction of 49% (in terms of ton CO_2 per ton of hot-rolled coil steel product). In this case, electricity is provided by a natural-gas-combined-cycle plant (NGCC). Hence, with renewable electricity, the emission intensity can be even reduced further (Sebastiani, Zecca, Del Fabbro, & Mariani, 2023).

All in all, EMPHATICaL project offers an integrated technology concept that answers to Draghi's call to boost the European industry's competitiveness while reducing greenhouse gas emissions, and aligns directly with the EU's ambitions in the Steel and Metals Action Plan to capture and valorise CO2 from the metallurgic industry.

2.5.3 Contribution to strategic autonomy

The EMPHATICaL concept creates an opportunity for sustainable materials and fuels while enhancing strategic autonomy. Through deployment of renewable electricity capacity and electrification of industry, transport and the built environment, a large part of society can be decarbonised. However, some sectors will continue to require carbon. To achieve climate goals, these sectors should defossilize, replacing fossil carbon with sustainable carbon from waste, biomass and CCU.

As outlined before, sustainable methanol is a key molecule for decarbonizing various sectors, including aviation, shipping and olefins. Bio-methanol, produced through gasification of biomass feedstock, is currently the cheapest way to produce methanol, see Figure 2.1111. However, the biomass supply in the EU is be limited. To take the chemical industry as a showcase: there will be sufficient biomass in the EU to defossilize 30% of chemicals (Uslu, Oliveira Machado dos Santos, & Moncada Botero, 2020). Hence, to further defossilize the chemicals, either biomass should be imported or other sustainable carbon sources (i.e., waste or CCU) should be leveraged.

An important consideration is that there will also be limits to biomass imports as global availability of biomass is limited (IRENA and Methanol Institute, 2021). Moreover, biobased feedstocks are required for other chemicals and fuels as well. Consequently, European bio-methanol production is expected to be competing with other sustainable applications and demand areas elsewhere in the world. (IRENA and Methanol Institute, 2021; Uslu, Oliveira Machado dos Santos, & Moncada Botero, 2020)

Therefore, e-methanol will most likely form a necessary complementary route to bio-methanol. Using CO_2 from industrial point sources, Direct Air Capture (DAC), Direct Ocean Capture or biogenic sources in the EU and locally produced hydrogen, e-methanol produced in Europe offers a pathway to “sustainable and resilient production”, contributing to open strategic autonomy, as proposed in the EU’s Clean Industrial Deal (European Commission, 2025). Moreover, it is expected that the costs for e-methanol will decrease as this route becomes more technologically mature and economies-of-scale are introduced. The production costs of e-methanol are mainly governed by the costs of electrolysis-based hydrogen production; these make up 85% of current e-methanol production costs (TNO, 2025).

According to TNO, with electricity prices of 0-10€/MWh and a 50% reduction in CAPEX throughout the production chain, e-methanol production costs become comparable to those of bio-methanol. Further cost reductions can be achieved with higher utilization rates of installed production capacities. Also IRENA and the Methanol Institute expect that e-methanol production costs will be comparable to those of bio-methanol when e-methanol production reaches technological maturity. (Uslu, Oliveira Machado dos Santos, & Moncada Botero, 2020; IRENA and Methanol Institute, 2021)

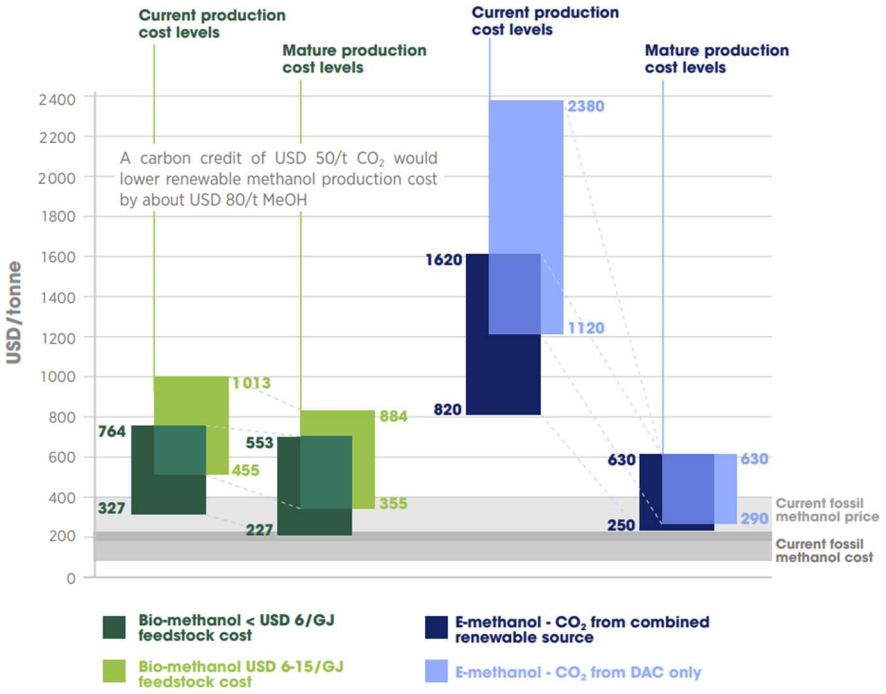


Figure 2.11 – Production cost ranges of bio-methanol and e-methanol, current and projected (at full technological maturity). Also shown are current fossil methanol production cost and price ranges. Source: (IRENA and Methanol Institute, 2021)

3 Market for EMPHATICaL technologies

3.1 Introduction

In this chapter a market analysis for technologies developed in EMPHATICaL is presented. **Error! Not a valid bookmark self-reference.** shows the technology value chain for the EMPHATICaL project.

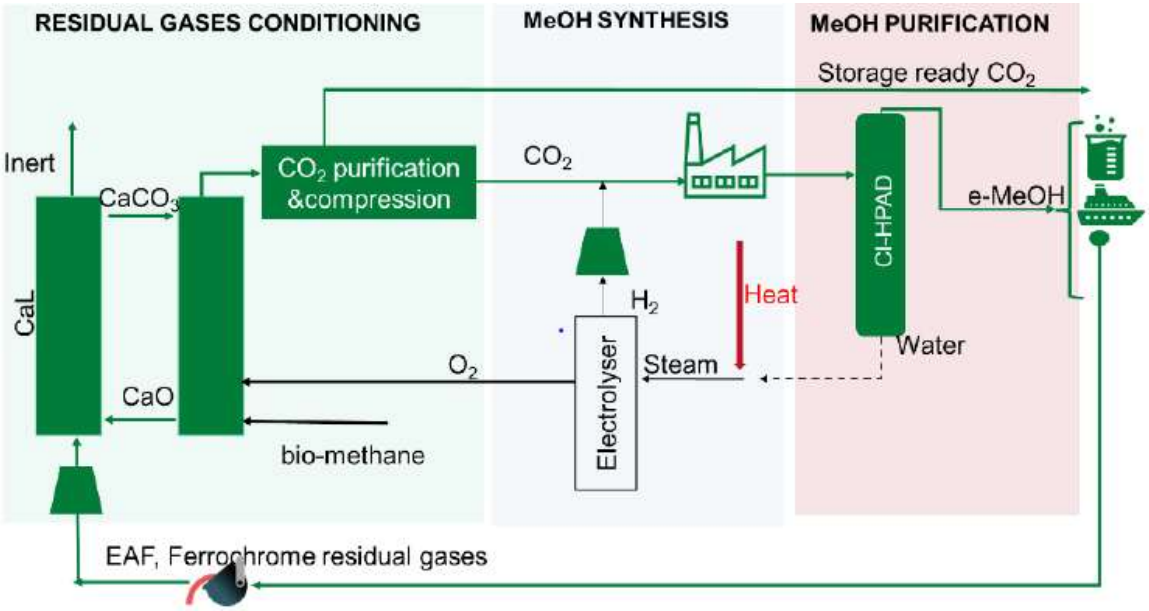


Figure 3.1 Technology value chain for the EMPHATICaL project.

The EMPHATICaL concept comprises a symbiotic system, utilizing residual gases from steel and ferrochrome alloy plants to produce e-methanol. The technology value chain consists of the following three steps:

1. Residual gases conditioning:
   Residual gases come from an Electric Arc Furnace (EAF, used in secondary steel production) or submerged arc furnaces (semi-closed SAF, used in ferrochrome production). The CO_2 in these residual gases is captured by using Calcium Looping technology.
2. Methanol synthesis:
   Production of e-methanol from the capture CO_2 and hydrogen that is produced in an electrolyser.
3. Methanol purification:
   The methanol is purified by application of cl-HPAD technology.

The market analysis will focus on the following five technology areas:

1. Calcium looping (CaL) technology for CO2 capture from residual gases of the metallurgic plant
2. Advanced digital technologies for pollutant monitoring

3. Flexible methanol synthesis
4. Closed-loop heat pump-assisted distillation (cl-HPAD) technology for methanol distillation
5. Integrated technology concept

Because the market for e-methanol is highly impacted by policies and regulations, the most relevant policies and regulations for the production part of the value chain, where EMPHATICaL technologies will be applied, are discussed in the next paragraph.

3.2 Relevant regulations and policies for the production value chain

The regulatory landscape for carbon capture and utilisation (CCU) technologies, including e-methanol, is evolving rapidly in the EU. These developments are increasingly recognising CCU as a strategic enabler for industrial decarbonisation and energy system transformation. Figure 3.2 presents the most relevant policies and regulations for industrial decarbonisation of industrial players within the EMPHATICaL value chain.

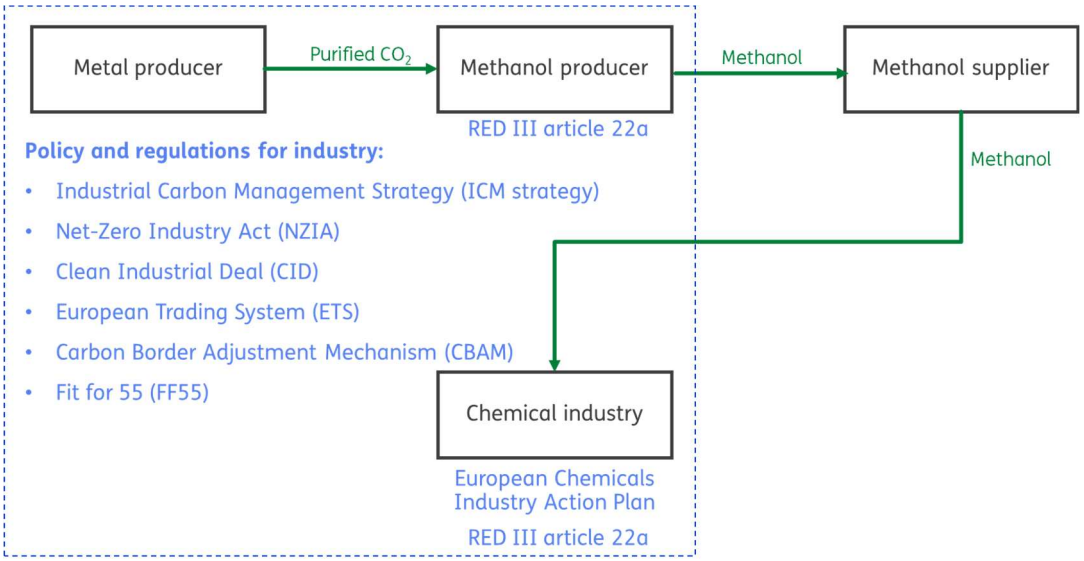


Figure 3.2 Relevant policies and regulations for industrial producers (within the dashed box) in the EMPHATICaL value chain

At the European level, several overarching frameworks now explicitly support the deployment of CCU-based solutions:

- The **Industrial Carbon Management Strategy** and the **Net-Zero Industry Act** identify CCU as a key technology for achieving climate neutrality in hard-to-abate sectors.
- The **Clean Industrial Deal**, published in early 2025, further reinforces this position by promoting the use of captured carbon in a broader range of industrial products, including fuels and chemicals.
- In parallel, the **European Chemicals Industry Action Plan** (July 2025) describes CCU as a "fundamental net-zero technology" essential for reducing fossil dependency and enhancing the resilience of European chemicals industry. Notably, the Commission has announced its

intention to explore mechanisms for rewarding the temporary storage of CO_2 in CCU fuels, such as e-methanol.

- The EU **Emissions Trading System (ETS)** and the **Carbon Border Adjustment Mechanism (CBAM)** also play a critical role in shaping the economic viability of CCU technologies. Under the **Fit for 55 Package (FF55)**, free emission allowances in ETS will be phased out between 2026 and 2034, increasing the cost of carbon-intensive production. CBAM ensures that imported goods face equivalent carbon costs, thereby levelling the playing field for EU producers. Iron and steel are already subject to CBAM, but chemicals like methanol are not yet included in CBAM.
- E-methanol contributes to RFNBO targets from RED III article 22a (see chapter 2).

3.3 Market for Calcium Looping technology

Calcium looping (CaL) is an innovative carbon capture technology that uses calcium oxide (CaO) to absorb carbon dioxide (CO_2) from industrial emissions. The process involves two main steps: capturing CO_2 by reacting it with CaO to form calcium carbonate ($CaCO_3$), and then regenerating CaO by heating the carbonate, releasing pure CO_2 for storage or reuse.

The main industrial CO_2 capture technologies include the following categories:

- solvent-based capture technologies, that use amines or ammonia to absorb CO_2 from flue gases in post-combustion processes and then regenerate the solvent while producing a concentrated stream of CO_2;
- sorbent-based capture technologies, using solid materials to bind CO_2 in their internal surface at nearly and then force its release (e.g. through application of heat, pressure swing, or electricity) in concentrated form at nearly ambient temperature via adsorption;
- membrane separation, utilizing membranes to separate CO_2 from gas mixtures at higher pressure than the product gas concentrated in CO_2;
- cryogenic and physical separation, separating CO_2 via phase change, by reducing temperature and increasing pressure for CO_2 liquefaction;
- oxy-fuel combustion capture, producing flue gases mainly containing CO_2 and water vapour by burning fuels in using a mixture of pure oxygen and recirculated flue gas instead of air.
- high temperature solid looping systems – such as chemical looping combustion or reforming, or calcium looping – operating by reacting a gas (e.g., O_2 or CO_2) with a solid at high temperature in one step and a CO_2 at high temperature is obtained in a different step while regenerating the solid intervening in the first step.

CaL belongs to the high solid temperature looping category. Compared to some alternative capture technologies – such as solvent-based systems, which are already commercially available - CaL currently has a lower Technology Readiness Level (TRL 6/7). However, it shows strong potential in specific industrial contexts. CaL operates at high temperatures (~650-900°C), making it particularly well-suited for sectors with high-temperature processes, such as cement, the metallurgic sector, as well as power generation based on fossil-, biomass- or waste-based

feedstocks (Montiel-Bohórquez, Gatti, & Romano, 2025). Beyond these industrial applications, the technology is also holds promise for onboard CO_2 capture in maritime shipping (Bortuzzo, Bertagna, Braidotti, & Bucci, 2025).

CaL becomes particularly attractive in industrial settings where synergies with existing infrastructure and processes can be realized. When limestone, calcium oxide and/or oxygen are readily available, relatively low operational costs can be achieved compared to alternative capture technologies. This makes the technology especially appealing for the cement industry, where the calcium oxide can be utilized and high temperature heat is available.

In the metallurgic industry, the focus of the EMPHATICaL project, CaL is promising because the operating temperatures are compatible to the high temperature of metallurgic processes, and making reuse of waste heat an interesting option to increase energy efficiency. Moreover, the robustness of CaO-based sorbents enables effective handling of waste gases with high impurity levels, which are typical prevailing in metallurgic plants. Within the EMPHATICaL project, the CaL technology is further developed to improve handling of the intermittent nature -both in volume and in composition- of waste gas streams from metallurgical plants. The main CaL technology to be tested in EMPHATICaL is the interconnected Circulating Fluidized technology to be demonstrated at the SWERIM pilot at TRL6-7, with technology innovations from SFW to allow buffering of solids between reactors that can handle highly dynamic variations of flow and CO_2 content in the flue gas. A relatively modest effort within EMPHATICaL is dedicated to exploring and modeling an alternative process route involving moving beds (TRL4-5), which also shows potential for adapting to highly dynamic flue gas streams.

3.4 Market for advanced digital technologies for pollutant monitoring

In the EMPHATICaL concept, the CaL calciner produces a CO_2 stream (also called the “calciner off-gas”) that enters the methanol synthesis plant, where CO_2 and hydrogen are synthesized into methanol. It is important to monitor pollutants (such as oxygen, sulfur compounds and NO_x) in the CO_2 stream to:

- Detect issues in the performance of the CaL system early.
- Optimise CaL system performance to minimize pollutants; this is important as the pollutant content of the CO_2 should be sufficiently low for the methanol synthesis plant to function well. However, pollutant content should be traded off against production rate and energy consumption.

In the EMPHATICaL concept, advanced digital technologies will be employed to monitor pollutants in the CO_2-stream from the CaL system, as an alternative to conventional physical sensors. This advanced digital method uses virtual sensors instead of physical ones to identify how CaL calciner process variables relate to pollutant concentrations in the CO_2 stream. Although calibrated using experimental pollutant data, the technology minimizes reliance on complex physical process monitoring, which typically requires continuous pollutant measurements via (costly) physical sensors. Virtual sensors require physical measurements only in the design phase.

Advanced digital technologies for pollutant monitoring can in principle also be applied in other industries where continuous emission or pollutant monitoring is important. Especially in CO_2 utilization, storage and transport applications, where pollutants in the CO_2 directly affect downstream processes, the technology can offer system-level benefits. However, if the technology is not utilized by companies to improve system performance, its benefits may not be sufficiently compelling to outweigh the costs. Moreover, in some sectors, emission reporting regulations currently form a barrier for the adoption of this approach. Therefore, Advanced digital technologies for pollutant monitoring can only be used as a supplementary tool to monitoring using physical sensors.

3.5 Market for flexible methanol synthesis technology

The EMPHATICaL value chain will make use of electricity from renewable energy sources that are intermittent. Hydrogen production in the electrolyser can respond to this fluctuating electricity supply, operating at full capacity during low-cost hours. A variable hydrogen supply, in absence of sufficient hydrogen storage capacity, requires flexible methanol synthesis. In EMPHATICaL a flexible e-methanol synthesis unit is designed to sustain efficient production under varying hydrogen supply.

While e-methanol production is approaching commercial scale, its performance under intermittent electricity flow and varied feed composition is only at TRL 6. The aim in the EMPHATICaL project is to develop the technology further to TRL 7.

The system for flexible methanol synthesis developed in the EMPHATICaL project aims to ramp-up and ramp-down from 100% to 50% of full capacity. The concept makes use of dynamic heat exchangers and follows the equilibrium curve of temperature and pressure. Catalyst durability under flexible operation and energy efficiency impact will be validated in the EMPHATICaL project. The concept is well suited for decentralised production at small scale.

Since the market for e-methanol is projected to grow substantially (see Chapter 2), and flexible operation is expected to become increasingly important with the rise of intermittent energy resources, this technology is anticipated to have significant global market potential. Moreover, the flexible synthesis concept may be applicable to other gas-based synthesis processes as well, such as ethanol. This will further expand the market potential for the technology.

Alternative approaches for flexible methanol synthesis are being developed by companies like Zero Emission Fuels (ZEF), which is working on solar-powered microplants (Zero Emission Fuels, sd), and Ineratec, which is developing compact reactors for dynamic synthesis from CO_2 and H_2. (Ineratec, sd). The concept developed in EMPHATICaL distinguishes itself through its dynamic process control capabilities at the scale presented.

3.6 Market for cI-HPAD technology

In the synthesis of methanol from CO_2 and hydrogen, not only methanol (CH_3OH) but also water is produced. To obtain pure methanol, the water needs to be separated from the methanol. This is done through distillation, the

most common separation process in the chemical industry. However, distillation is rather energy-inefficient and currently constitutes 40% of the chemical industry's energy demand (Kiss & Smith, 2020). To improve energy efficiency, several innovative distillation technologies exist, such cyclic distillation which yield an energy saving of up to 35% and also lower capital costs (Interviews, 2025). Even more energy can be saved with heat pump-assisted distillation (HPAD) (Cui, Van Reisen, Tyraskis, & Kiss, 2025).
HPAD reuses waste heat upgraded with a heat pump, thus eliminating need for external heat supply and improving overall energy efficiency. Moreover, HPAD allows for electrification of the distillation process. However, capital costs for HPAD are higher than for conventional distillation because it features a compressor. Several HPAD options exist, of which Vapour Recompression (VRC) (also known as open-loop HPAD or ol-HPAD) has been demonstrated at commercial scale. (Tyraskis, 2023; EMPHATICaL consortium, 2024; Interviews, 2025)

Cl-HPAD (closed-loop heat pump-assisted distillation) is a technology that has not been commercialized yet and features TRL5. Cl-HPAD enables a potential energy saving of 60-80%[1] compared to conventional distillation and 30% compared to commercial ol-HPAD, see Figure 3.3. Moreover, this innovative distillation technology offers a way to fully electricity the methanol distillation process. By using renewable electricity, the distillation process can be carried out with nearly zero CO_2 emissions. Cl-HPAD also allows heat recovery which can be used for multiple purposes; industrial symbiosis purposes like preheating of steel scrap or steam generation but also non-industrial purposes like district heating and agriculture. While capital costs for cl-HPAD are higher (due to the compressor), these are partially offset by operational savings over the lifetime.

Although innovative distillation technologies result in a reduction of e-methanol production costs, it should be noted that methanol synthesis (including distillation) cost only account for around 5% of total e-methanol production costs: 85% is hydrogen production costs using electrolysis and 10% is CO_2 feedstock cost (assuming a CO_2 cost of 62 euro/ton) according to TNO methanol supply chain calculations (TNO, 2025). High-temperature SOE electrolysis, which is employed in the EMPHATICaL concept, can lower hydrogen production costs. Moreover, the energy efficiency of hydrogen production can be improved in EMPHATICaL as the heat produced by methanol synthesis can be used for the generation of steam needed for SOE.

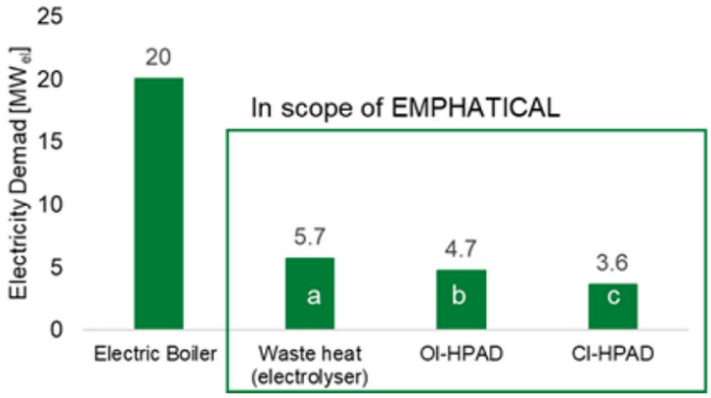


Figure 3.3 - Comparison of electricity demand in MW between several technology options for electrification of the methanol distillation process.

[1] Based on process simulations validated against pilot-scale data at TRL5.

3.7 Market for integrated technology concept

The EMPHATICaL project does not only develop single technology elements. The power of the project is also in the integration of the different technology components and the integration and exchange of resources between companies and sectors. This enables a new kind of industrial symbiosis, where energy and material flows are optimized across the entire value chain.

Three key intermittent sources shape the EMPHATICaL value chain and demand flexible operations of the different technologies that are developed within the project:

- *Flue gasses from metal production* are intermittent, varying in volume, CO_2 and other contents, and temperature. The calcium looping technology for CO_2 capture is designed to handle these fluctuations effectively.
- A number of *waste heat* streams will be reused: waste heat from the metallurgic furnaces and high temperature heat from the calcium looping process may be used to raise steam for high temperature electrolysis. An additional option is to use this heat in other sectors, e.g. for residential heating. The cl-HPAD technology for the distillation process recycles its own waste heat and can also utilise waste heat from hydrogen electrolysis and methanol synthesis.
- *Electricity* from renewable sources will be used for a number of processes in the EMPHATICaL value chain. The electricity is intermittent by nature and in need of flexible demand. Hydrogen production in the electrolyser can respond to fluctuating electricity supply, operating at full during low-cost hours. A variable hydrogen supply requires flexible methanol synthesis and flexible operation of methanol distillation, which is enabled by the cl-HPAD technology.

Optimising energy efficiency throughout the value chain is a key element in the EMPHATICaL project, as are CO_2 emission reduction and industrial symbiosis (see *Opportunities for the EU,* Chapter 2). The result is a value chain that is not only environmentally sustainable but also economically viable.

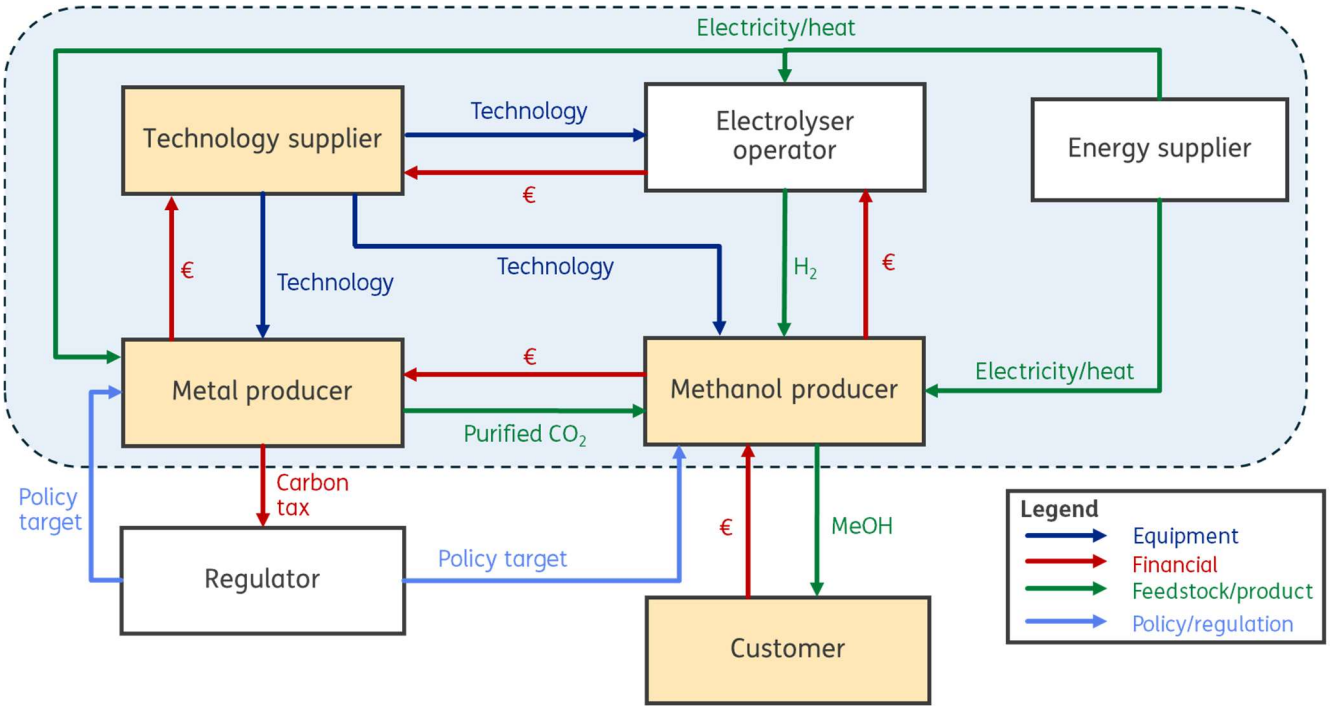


Figure 3.4 - Value chain for the integrated technology concept. Created by authors.

3.8 Innovation opportunities for the EU

The technologies being developed in the EMPHATICaL project will support companies across the value chain to significantly reduce their CO_2 emissions. In addition to advancing sustainability in the metallurgical industry, chemicals and fuels industries, as well as in logistics, particularly maritime shipping and aviation, the technical innovations also enable companies and organisations in the EU to expand their technology position. The EMPHATICaL project plan includes a table of Key Exploitable Results (see Table 2.4 in (Emphatical project consortium, 2024)). Once these Key Exploitable Results are further developed to TRL 9 and commercialized, the technologies can be supplied by technology providers from the EU to companies worldwide. Below an overview is presented of opportunities per technology.

Overview of innovation opportunities per technology:

Companies in the EU are well-positioned to build a position as a global technology provider for the *calcium looping technology*, both for the metallurgic sector and for other carbon-intensive industries. Europe is at the forefront in research, development and demonstration of the technology, supported by Horizon Europe programs like CaLby2030, HERCCULES and EMPHATICaL. CSIC and SFW have been operating a 2 MWth pilot plant in Spain since 2012, and several additional pilots have been built and operated in other European countries over the past decade. This growing activity reflects increasing interest in the technology´s potential to support decarbonization

of hard-to-abate industrial sectors and strengthens the EU's position to play an active role as a global technology provider in this domain.

There is potential for *advanced digital technologies for pollutants monitoring* to be sold globally by the EU, especially for Carbon Capture & Utilization (CCU) applications in which downstream processes are directly affected by the quality of the CO_2 stream and thus require high-purity CO_2. Advanced digital technologies for pollutants monitoring avoid continuous measurement of off-gas concentration, opposed to conventional physical process monitoring using physical sensors. Hence, these digital technologies may offer operational benefits to companies. In some cases (e.g., waste-to-energy) physical sensors will not be entirely eliminated because regulatory bodies require reference monitors (physical sensors) to be active continuously for stack gas monitoring. The technology is currently at the early stages of development (TRL 3, applied in waste-to-energy plants) and requires significant further research and validation before it can be deployed in real-world industrial settings. The concept has potential to be applied to other gaseous streams besides CO_2 as well, in cases where measured continuous Input/Output data can be used to train the model to predict Output data based on Input data.

With the projected increase demand for e-methanol and a growing share of intermittent renewable electricity, the market potential for *flexible methanol synthesis* is substantial. This includes application in remote areas where electricity generation from solar or wind energy can be combined with flexible hydrogen production and small scale flexible methanol production. If the technology proofs to be energy-efficient and also applicable to other gas-based synthesis processes, the market potential will be even bigger. The EU holds a strong position in the development of flexible methanol synthesis, with several European companies and consortia actively working on the technology possessing intellectual property rights.

The *cl-HPAD technology* offers an opportunity for the EU to become a global technology provider as well. The application *of cl-HPAD is not* only limited to methanol distillation but can also be applied to separating other close-boiling-point mixtures in various industries, for example ethanol dehydration, formic acid purification, solvent recoveries and specialty chemicals production (Interviews, 2025). Cl-HPAD technology mainly offers advantages for high-reflux, high-energy-demand separations, as in these cases the additional capital costs are partially offset by operational costs savings, creating a relatively shorter payback time. Therefore, cl-HPAD's suitability—and a company's decision to invest—depends on the specific product and whether the energy savings justify the higher capital costs. Moreover, as cl-HPAD allows flexibility in operations, it can be an attractive option in distillation processes powered by renewable electricity.

The challenges of CO_2 reduction and energy efficiency are global and industrial value chains in many regions are in need of integrated solutions that can handle intermittent streams. The *integrated approach* of the EMPHATICaL project represents a strategic opportunity for the EU. By offering both individual technologies and an integrated system approach, the EU can position itself globally — not just as a technology provider, but also as a system integrator.

Way forward

Although the EU is well-positioned to become a global technology provider and integrator, significant progress is still required. The United States and China currently hold competitive advantages—venture capital in the US and strong government support in China—that may influence global leadership in emerging technologies. To accelerate deployment within the EU, long-term policy support and risk-sharing mechanisms are essential.

A key step is the implementation of these technologies in First-of-a-Kind (FOAK) plant, followed by large-scale rollout across member states. This will help establish the EU's global position in advanced industrial technologies. Achieving this requires close cooperation among R&D institutions, component producers, OEMs, EPC contractors and end-users of the technologies in the metallurgical, chemicals and fuels industry. Only through coordinated efforts the can EU fully leverage its technological potential and compete effectively on the world stage.

4 Conclusions

Already, methanol has a variety of applications, mainly in chemicals production (accounting for 72% of methanol demand) and in fuel applications (18%). Regarding chemicals, it is used for the production formaldehyde, acetic acid, olefins, and MTBE, which are foundational to industries like construction, automotive, textiles, and packaging (MMSA, 2025). Fuel applications include gasoline blending and the production of DME and biodiesel.

Sustainable methanol (bio-methanol and e-methanol) is widely expected to play a significant role in the defossilization of industry and transport. IRENA and the Methanol Institute project that global production will grow from 120 megatons per year today to 500 megatons per year in 2050 (IRENA and Methanol Institute, 2021). Methanol is especially relevant for transport sectors where electrification is challenging, such as aviation and maritime shipping. Moreover, it offers a way of defossilizing the production of chemicals like olefins, which form the building blocks for many materials.

Methanol production is currently based on fossil fuels (through conversion of syngas resulting from methane reforming or coal gasification). Biomethanol production (with syngas feedstock resulting from the gasification or pyrolysis of biomass or biowaste) is at TRL7-9 and is expected to become cost-competitive with fossil methanol in the near term. E-methanol however, is still much more costly to produce: production cost range from 820-1620 USD/ton compared to 100-250 USD/t for fossil methanol and 327-764 USD/t for bio-methanol (IRENA and Methanol Institute, 2021). However, e-methanol production costs are expected to decrease significantly as the technology becomes more mature, making it a cost-competitive alternative in the long term.

The EU's regulatory environment is increasingly favourable for CCU-based fuels, with clear mandates and financial incentives driving market uptake. Further policy development is needed to stimulate demand for CCU-based chemicals and materials. EMPHATICaL methanol is well-positioned to benefit from existing transport fuel mandates and emerging industrial strategies, provided that certification frameworks and market mechanisms continue to evolve in support of circular carbon solutions.

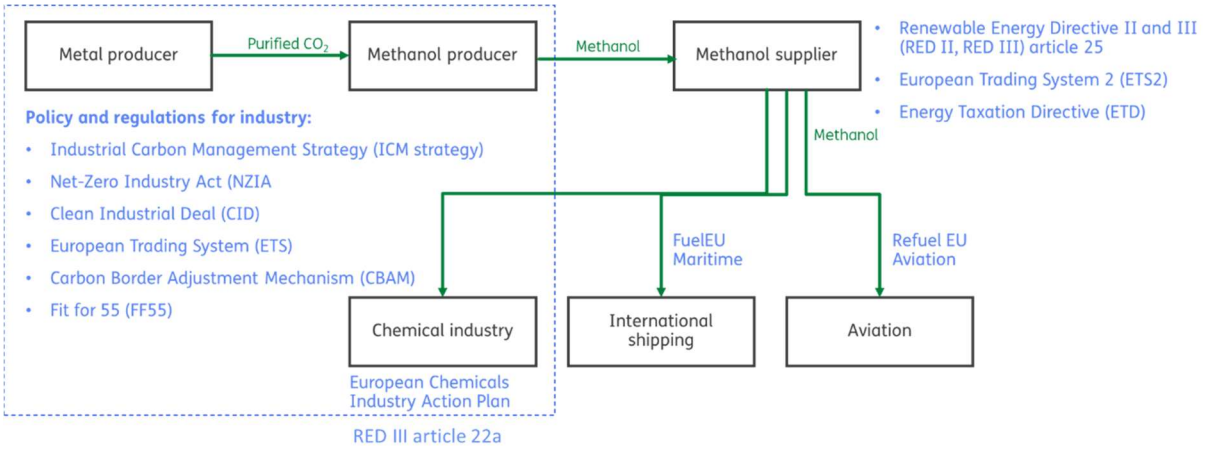


Figure 4.1 Overview of relevant policies, regulations and mandates throughout the value chain

As industry and transport seek to defossilize, e-methanol faces several alternatives depending on the end-use sector.

- Shipping: for shipping, green ammonia is the main sustainable alternative. However, benefits of methanol lie in its compatibility with existing ships engines (with some adaptations) and higher TRL.
- Road transport: both sustainable diesel and DME are alternatives to methanol. Diesel and DME can however be produced from sustainable methanol, while other production pathways are also possible.
- Aviation: in aviation, methanol-based Sustainable Aviation Fuel (methanol-to-jet SAF) competes with biofuels (HEFA-SAF), Fischer-Tropsch SAFs and alcohol-to-jet. At this moment, HEFA-SAF is the only commercially available alternative, although methanol-to-jet SAF production facilities are being developed, pushed by EU mandates for e-SAF.
- Olefins: in olefins production, methanol provides an alternative to steam cracking, reducing carbon emissions and improving feedstock flexibility

The EMPHATICaL concept offers opportunities for the EU. According to Draghi's renowned report, the EU's competitiveness is under pressure. Especially the energy-intensive industries face challenges due to high energy prices and reliance on fossil fuels characterized by volatile prices. The principle of industrial symbiosis, in which industrial systems are integrated in a sustainable way while leveraging underutilized resources, offers an opportunity for European industries to defossilize while generating additional economic value. The economic and environmental benefits of various industrial symbiosis concepts have been demonstrated in previous Horizon 2020 projects SCALER and INITIATE. E-methanol production from CO_2 captured from residual gases of the metals industry - the focus of EMPHATICaL - offers an opportunity to reduce emissions in both the metals and the chemical industries while creating economic opportunities. Moreover, this concept can enhance strategic autonomy by reducing reliance on fossil and biomass feedstock for the production of fuels and chemicals. However, due to the energy-intensive nature of Carbon Capture & Utilization (CCU), the emission reduction achieved by such CCU-based methanol hinges on the availability of sufficient renewable electricity.

Besides tapping into the market for e-methanol, which has a multitude of applications, EMPHATICaL also offers opportunities for the EU to become a global technology provider in the various technologies that are being advanced as part of the EMPHATICaL concept.

- **Calcium looping (CaL) carbon capture**. Regarding CaL, Europe is at the forefront of its technological development. A pilot plant has already been realised in Spain and more pilots will follow in several European countries. As CaL operates at high temperatures (~650-900 °C) its application potential mainly lies in industrial contexts with high-temperature heat.
- **Advanced digital technologies for pollutant monitoring** offer a way to monitor the quality of CO_2 streams while reducing the reliance on physical sensors and physical measurements. This is especially relevant for CO_2 transport and storage applications and CCU applications in which the CO_2 purity grade is important to the functioning of downstream processes.
- **Flexible methanol synthesis** has significant market potential given the projected growth in the market for sustainable methanol and the further adoption of renewables. As e-methanol is ideally powered by renewable electricity to unlock its emission reduction potential, e-methanol production should be able to deal with the intermittency of renewable electricity. The flexible methanol synthesis technology developed with EMPHATICaL is targeted at this aspect. Moreover, the flexible synthesis concept may be applicable to other gas-based synthesis processes as well, such as ethanol. This will further expand the market potential for the technology.

- **Closed-loop heat pump-assisted distillation (cl-HPAD)** offers potential for considerable energy saving (60-80%) in distillation processes by reusing and upgrading waste heat. It can not only be applied to methanol but also to other mixtures with constituents with close boiling points, such as in ethanol and formic acid distillation. Therefore, cl-HPAD has considerable market potential. However, it should be noted that methanol synthesis represents only a small part of costs of e-methanol production (~5%). To reduce the costs of e-methanol, it is mainly the hydrogen production costs that need to be lowered.
- **Integrated technology concept.** The EMPHATICaL project does not only develop single technology elements. The power of the project is also in the integration of the different technology components and the integration and exchange of resources between companies and sectors. This enables a new kind of industrial symbiosis, where energy and material flows are optimized across the entire value chain. EMPHATICaL is a showcase for the performance of such an industrial symbiosis concept and value chain. This is especially relevant since the EMPHATICaL concept features intermittent streams, requiring flexible operations: flue gases from metal production, waste heat streams and renewable electricity. As such, this integrated concept could provide a blueprint for other industrial symbiosis concept with intermittent resource streams.

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