CO2 Transport for e-Fuels Production in Europe

PREPARED FOR
T&E

DATE
30 September 2025

DOCUMENT DETAILS

DETAILS	
DOCUMENT TITLE	CO_2 Transport for e-Fuels Production in Europe
PROJECT NUMBER	0777397
DATE	30 September 2025
VERSION	2
AUTHOR	Alexander Sneyd, Samuel Chan, Amelia Mitchell, Jo Howes, Silvian Baltac
CLIENT NAME	Transport & Environment

DOCUMENT HISTORY

			ERM APPROVAL TO ISSUE	
VERSION	AUTHOR	REVIEWED BY	NAME	DATE
1	Alexander Sneyd, Samuel Chan	Amelia Mitchell, Jo Howes, Silvian Baltac	Silvian Baltac	8 September 2025
2	Alexander Sneyd, Samuel Chan	Jo Howes	Jo Howes	30 September 2025

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ACRONYMS AND ABBREVIATIONS

Acronym	Description
BECCS	Bioenergy with Carbon Capture and Storage
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilisation, and Storage
CDR	Carbon Dioxide Removal
CEF	Connecting Europe Facility
DA	Delegated Act
DAC	Direct Air Capture
EfW	Energy from Waste
ETS	Emissions Trading System
FID	Final investment decision
FT	Fischer-Tropsch
GHG	Greenhouse gas
IEP	Industrial emissions portal
MMV	Monitoring, Metering and Verification
MTJ	Methanol to Jet
OPEX	Operating Expenditure
PCI	Project of Common Interest
PMI	Project of Mutual Interest
PPA	Power Purchase Agreement
PtL	Power-to Liquid
RCF	Recycled Carbon Fuels
RED	Renewable Energy Directive
RFNBO	Renewable Fuels of Non-Biological Origin
ROW	Right-of-Way
RWGS	Reverse water gas shift
SAF	Sustainable Aviation Fuel
STIP	Sustainable Transport Investment Plnace
TEA	Techno-economic assessment
TEN-E	Trans-European Networks for Energy
TRL	Technology Readiness Level
VCM	Voluntary Carbon Market

EXECUTIVE SUMMARY

This study examines the critical role of CO_2 sourcing and transport infrastructure for e-fuels production in Europe. E-fuels are produced from renewable electricity, water, and captured CO_2, and can help to decarbonize hard-to-abate sectors such as aviation and shipping. The European Union (EU) has introduced ambitious policies to drive the deployment of e-fuels in Europe, such as the Renewable Energy Directive (RED) III, ReFuel EU Aviation, and FuelEU Maritime. These policies have helped e-fuels attract significant interest, with over 90 e-fuels projects in Europe.

A key challenge for e-fuels in Europe is sourcing suitable CO_2 feedstock. Crucially, e-fuels used to contribute to EU policy targets must satisfy certain constraints on their sourcing of CO_2. Fossil CO_2 is ineligible after 2036/2041, which, combined with the high costs of CO_2 from direct-air capture, means that biogenic CO_2 is a key target for many developers. However, EU supplies of biogenic CO_2 are limited, and low-cost electricity supply is not always co-located with biogenic CO_2 sources. As a result, **transport of CO_2 from industrial sources to e-fuels production sites is a key challenge facing many developers.**

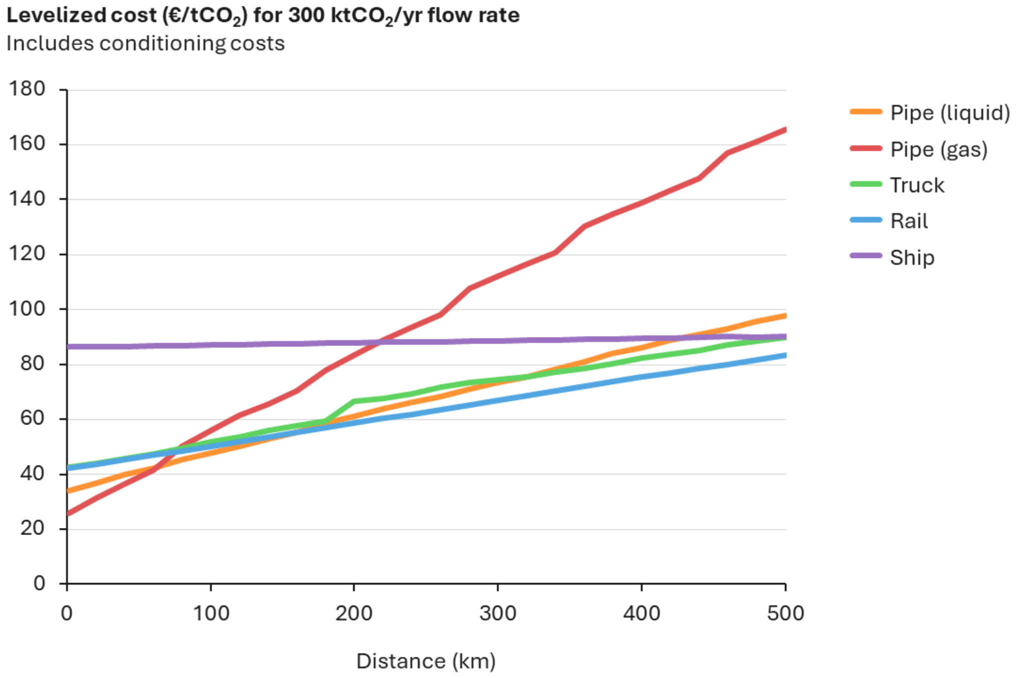
In this study, a comprehensive analysis of CO_2 sourcing for e-fuels in Europe is undertaken, with a focus on CO_2 transport. The study outlines different sourcing strategies, opportunities to unlock more suitable CO_2, and the potential role of policy.

The analysis shows that Pulp & Paper, Biomass Power, EfWs, Ethanol, and Biogas Upgrading are particularly attractive CO_2 sources. They offer significant accessible biogenic CO_2 volumes across Europe, along with low-to-moderate capture costs. Pulp & Paper is particularly attractive, and many current e-fuel projects are located near Pulp & Paper sites.

To transport CO_2 from source to e-fuels site, a **variety of modes are important – particularly pipelines for short-range connections, rail for longer distances, and trucking for aggregation of CO_2 from small sources**. Trucking may be attractive for existing e-fuels project due to the flexibility it offers. Levelized cost analysis shows that these transport modes tend to have comparable costs at CO_2 flow rates relevant for e-fuels, and could add an **additional €20-50/tCO_2 for routes up to 200 km**. These costs are relatively low compared to the expected capture costs of biogenic CO_2 of €20-150/tCO_2.

The analysis also highlights barriers for establishing these CO_2 transport routes. For example, pipelines need to acquire rights-of-way along the transportation route, and rail transport needs access to rail networks.

Support from both the EU and Member States can help to overcome barriers for CO_2 sourcing. This could include, for example, national policy and /or regulation to facilitate access to and transport of CO_2 via rail networks, or to assist permitting for CO_2 pipelines.



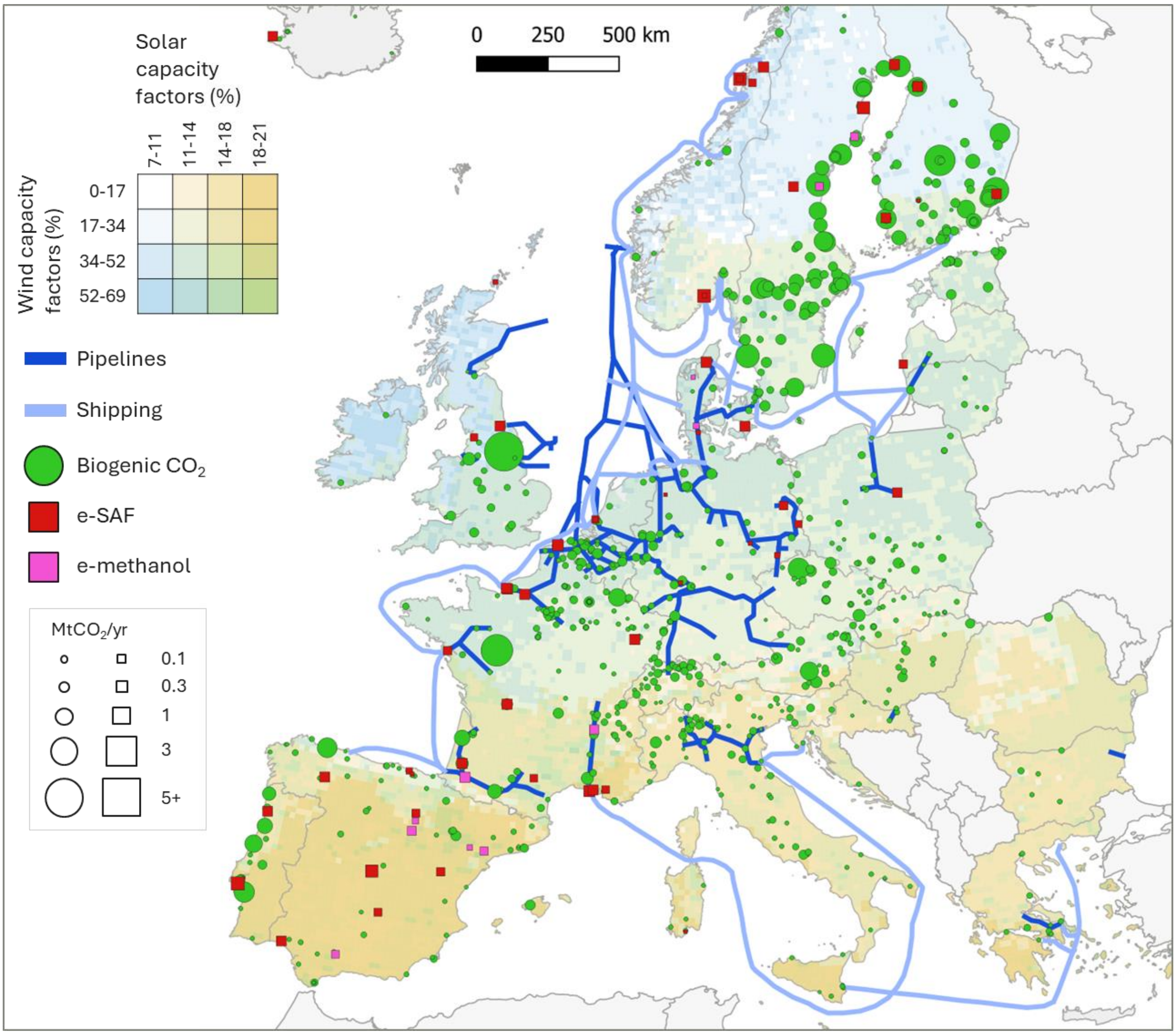
LEVELIZED COSTS OF CO_2 TRANSPORT

There is a large potential synergy between e-fuels CO_2 sourcing and planned CO_2 infrastructure focused on CCS. Large-scale CO_2 pipeline networks are planned throughout much of Europe, particularly in the centre of Europe to connect to geological storage in the North Sea. Importantly, these CO_2 networks have significant biogenic CO_2 nearby, with 23 and 33 $MtCO_2$/yr within 50 km and 100 km of planned routes, respectively. Additionally, the potential for wind and solar tends to be limited in the centre of Europe, but significant near the North Sea. This overall suggests there is a significant opportunity for CCS-focused networks in Europe to assist the transport of biogenic CO_2 for e-fuels.

EU policy should allow and encourage CO_2 networks to give e-fuels access to CO_2. Currently, EU support for cross-border CO_2 transport appears to be limited to networks pursuing geological storage. Expanding the scope of projects eligible for funding under Connecting Europe Facility (CEF) to those allowing utilisation could help to unlock further e-fuels production. It could also help to provide e-fuels developers with flexibility in CO_2 sourcing, and provide wider synergies to the CO_2 network. Encouraging developers to allow access for utilisation early-on can help to provide useful lessons from 'learning-by-doing'. Such access will be reliant on clear MMV (measurement, metering and verification) in the CO_2 network to track biogenic CO_2.

While planned CO_2 pipelines are extensive**, there are some areas in Europe with 'untapped' biogenic CO_2**, with significant volumes not proximal to planned CO_2 infrastructure, or to any e-fuels projects. For example, there is ~9 $MtCO_2$/yr of untapped biogenic CO_2 in eastern Central Europe (Slovakia and parts of neighboring countries). Extension of current planned CO_2 pipelines in nearby areas could facilitate access to this CO_2 and help to transport it to areas with more favourable renewables potential. Additionally, there is ~15 $MtCO_2$/yr located in inland Sweden and Finland. **Aggregation and transportation of this CO_2 to the coasts** (where e-fuels projects tend to be located) **could facilitate further**

e-fuels production. Policy support to develop networks to aggregate CO_2 in these areas (which is primarily biogenic) can help to derisk such projects and improve their financial viability.



COMPARISON OF BIOGENIC CO2 TO PLANNED E-FUELS PROJECTS AND TRANSPORT INFRASTRUCTURE, AND RENEWABLE POTENTIAL

There are additional ways policy can help to accelerate the deployment of e-fuels in Europe. For example, the **forthcoming Sustainable Transport Investment Plant (STIP) should consider the costs and CAPEX implications of transport options for biogenic CO_2 sourcing** alongside other project costs when evaluating support needed for e-fuels.

1. INTRODUCTION

1.1 CONTEXT

E-fuels can help to decarbonize sectors such as aviation and shipping. These fuels are produced from renewable electricity, water and captured carbon, and can be used at certain blending percentages in existing engines that burn fossil fuels. Key e-fuels include e-kerosene, often termed e-SAF, which can be blended into jet fuel, and e-methanol, which can be used in shipping.

The European Union (EU) promotes the use of e-fuels through ambitious policies such as the Renewable Energy Directive (RED) III, ReFuel EU Aviation, and FuelEU Maritime, with significant financial incentives in place.[1,2,3] Importantly, e-fuels used to contribute to EU policy targets must **satisfy certain constraints on their sourcing of feedstocks** and requirements on lifecycle greenhouse gas emissions. When these rules are satisfied, the resulting fuels are termed "Renewable Fuels of Non-Biological Origin" (RFNBOs).[4]

While e-fuels have attracted significant interest with at least 80 e-fuels projects across Europe in various stages of development,[5] many of these projects are struggling to reach FID. A well-known challenge is a lack of willingness from customers to sign offtake agreements due to the high prices of e-fuels relative to their fossil counterparts even with the policy support in place today.[6,7,8] **However, another key challenge can be finding sufficient volumes of CO_2 meeting sustainability requirements to produce them**.[9]

Current EU rules restrict the eligibility of fossil CO_2 after 2036/2041, and combined with the high costs of CO_2 from direct-air capture, biogenic CO_2 is left as a key target for many developers. However, EU supplies of biogenic CO_2 are limited, and it can be difficult to co-locate e-fuel plants with biogenic sources whilst also having access to a low-cost source of (eligible) renewable electricity. This could mean a requirement for transport of the CO_2 from the industrial source to the e-fuels production site. However, there is lack of clarity on which modes of transport (e.g. pipelines, trucking) are feasible for e-fuels, how different modes compare in costs, and how planned CO_2 transport infrastructure in Europe could facilitate CO_2 transport for e-fuels. The potential role of EU policy regarding CO_2 transport for e-fuels is also unclear.

1.2 OBJECTIVES & SCOPE

In this study, **a comprehensive analysis of CO_2 sourcing for e-fuels in Europe is undertaken**, with a focus on CO_2 transport. The study **outlines sourcing strategies**, provides a window into how to **unlock access** to more sources of eligible CO_2, and provides

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[1] EU, 2023. Directive - EU - 2023/2413 - EN - Renewable Energy Directive - EUR-Lex
[2] EU, 2023. Regulation (EU) 2023/2405
[3] EU, 2023. Regulation - 2023/1805 - EN - EUR-Lex
[4] EU, 2023. Delegated regulation - 2023/1184 - EN - EUR-Lex
[5] Source: T&E database of planned e-fuels projects
[6] T&E, 2024. The challenges of scaling up e-kerosene production in Europe
[7] Hydrogen Insight, 2024. 'Airlines are not willing to pay a premium for green hydrogen-based e-kerosene'
[8] BCG, 2025. Sustainable Aviation Fuels Need a Faster Takeoff
[9] Mærsk Mc-Kinney Møller Centre, 2024. Global Availability of Biogenic Carbon Dioxide and Implications for Maritime Decarbonization

insight into how EU policy can support CO_2 transport to accelerate the deployment of e-fuels.

1.3 REPORT STRUCTURE

The analysis begins with an overview of carbon capture and utilisation **(CCU) value chains** in the context of e-fuels. **Key barriers for CO_2 transport are assessed**, and the attractiveness of different CO_2 sources and transport modes are evaluated. Next, **cost models are developed** for five key transport modes to establish the costs of CO_2 sourcing for different distances and flow rates, along with key sensitivities. To provide a basis for how CO_2 sourcing may play out in Europe, the **geographic distribution** of CO_2 sources and e-fuels is analyzed, along with planned CCUS infrastructure in Europe and regional potential for renewable electricity generation. Finally, five **archetypal CO_2 sourcing scenarios** are developed to illustrate how all these factors may interact together.

2. UNDERSTANDING CO_2 SOURCING AND TRANSPORT FOR E-FUELS

To understand CO_2 sourcing for e-fuels it is necessary to consider each part of the CCU value chain. This includes an assessment of the available CO_2 sources, the CO_2 requirements from e-fuels producers, the different CO_2 transport modes available, and how these aspects interact with each other.

2.1 INDUSTRIAL SOURCES OF CO_2

2.1.1 EU RULES ON ELIGIBLE CO_2 SOURCES FOR E-FUELS PRODUCTION

EU rules on CO_2 eligibility set the scene for evaluating CO_2 sources for e-fuels in Europe. In particular, the EU Delegated Act (DA) on RFNBO GHG methodology determines eligible CO_2 sources for e-fuels sold in the EU to enable contribution towards a range of EU policy targets, including the Renewable Energy Directive III, Refuel EU Aviation, and FuelEU Maritime.[4,10] Eligible sources include:

- **Direct Air Capture (DAC):** Atmospheric CO_2 captured from the air.
- **Biogenic:** The captured CO_2 stems from the production or the combustion of biofuels, bioliquids or biomass fuels complying with the sustainability and greenhouse gas saving criteria of the Renewable Energy Directive.
- **Point source captured fossil CO_2**
    - CO_2 that has been captured from an activity listed under the EU ETS (e.g. cement or iron production) and is incorporated into the chemical composition of the fuel before **2041**.
    - For CO_2 that stems from combustion of fuels for electricity generation, the deadline for eligibility is **2036**.
- Combustion of RFNBOs, RCFs, and geological CO_2 if it was previously released naturally

Crucially, the DA places time limits on the eligibility of fossil CO_2 for e-fuels production, depending on the type of fossil CO_2. This time limit also reduces the attractiveness of fossil CO_2 *prior* to the end-dates of 2036 and 2041. This is because reliance on its use could limit the time available for an e-fuels facility to operate and recover its initial investment (unless alternative CO_2 sources can be obtained before the end-dates).

2.1.2 SUITABILITY OF DIFFERENT CO_2 SOURCE TYPES

Europe has a diverse range of CO_2 sources of various scales, and Table 1 gives an overview of the suitability of 10 promising CO_2 source types for e-fuels production.[11] The selection of CO_2 source types was weighted towards those with significant biogenic CO_2 content due to the limits on fossil CO_2 eligibility. Suitability is evaluated against several factors:

- **Available CO_2:** higher total CO_2 amounts (particularly the total biogenic CO_2) in Europe means that the sector can play a larger overall role as a feedstock for e-fuels.

[10] CIRCABC, 2024. Q&A Implementation of hydrogen delegated act
[11] This is non-exhaustive list, and additional industrial sectors may also be of interest for e-fuels production

- **Emitter size:** larger emitter sizes allow for economies of scale, which helps to reduce the costs of CO_2 capture and transport (see later analysis), and can help avoid the complexity that results from an e-fuels site needing to source from multiple emitters.[12]
- **CO_2 concentration prior to capture:** higher CO_2 concentrations reduce the costs of capture.
- **Growth prospects:** possible future changes in CO_2 output.
- **Time variation in CO_2 output:** high variability in the CO_2 output – including day-to-day and longer (e.g. seasonal) variation – increases sourcing costs and reduces the resilience of CO_2 supply.
- **Other factors:** examples include the complexity of on-site carbon capture integration, sustainability considerations regarding the sourcing of biogenic feedstocks, and the necessity of carbon capture for the sector compared with other emissions reduction options.

TABLE 1 OVERVIEW OF KEY SOURCES OF CO_2 FOR E-FUELS IN EUROPE

Sector	Total CO_2 in Europe ($MtCO_2$/yr)	Average size of emitter ($ktCO_2$/yr)	CO_2 conc. before capture (vol%)	Time variation in CO_2 output	Sector growth prospects	Other factors
Pulp & Paper	75	(green) 740	(amber) 10-21	(lime)	(amber)	(lime)
Biogas Combustion	43	(red) 1	(amber) 10-15	(amber)	(lime)	(amber)
Energy-from-Waste	72	(green) 300	(amber) 10-14	(lime)	(lime)	(lime)
Biomass Power Plant	42	(green) 540	(amber) 10-15	(amber)	(lime)	(amber)
Cement	128	(green) 600	(lime) 15-30	(green)	(amber)	(green)
Biogas Upgrading	9	(orange) 6	(green) >90	(amber)	(green)	(amber)
Ethanol	5	(amber) 60	(green) 99	(amber)	(orange)	(orange)
Distilleries /Breweries	33	(orange) 1-20	(green) 99	(amber)	(amber)	(orange)
Iron & Steel	119	(green) 900	(amber) 2-90	(lime)	(orange)	(orange)
Direct air-capture	0.01	(light green) 3-300	(red) 0.04	(green)	(green)	(lime)

Biogenic CO_2 Fossil CO_2

The evaluation shows that the most suitable CO_2 sources for e-fuels include large point sources combusting biomass, smaller sources with high CO_2 concentrations,

[12] Global CCS Institute, 2025. Advancements in CCS Technologies and Costs

and DAC – see Appendix for additional details. A standout is Pulp & Paper; this sector has strong prospects given the large total and biogenic CO_2 volumes from each plant, moderate CO_2 concentrations, and relatively low variation of CO_2 output over time. Biomass Power Plants and Energy-from-Waste plants (EfWs) have similar strengths, albeit with slightly lower biogenic CO_2 volumes per plant. Other attractive prospects include Biogas Upgrading and Ethanol, which have high purity CO_2 streams – although the lower average CO_2 volumes per plant can introduce complications as discussed later. Finally, DAC offers several advantages, particularly the possibility to locate and size capture plants flexibly. The main challenge with DAC is low atmospheric concentration of CO_2, which increases capture costs.

The cement sector is a moderate prospect but may be limited by low biogenic CO_2 volumes. Lesser prospects include Iron & Steel (minimal biogenic CO_2 content), and Biogas Combustion (small emitter sizes). We note here that an important consideration is feedstock sustainability – for example, previous work by T&E highlights that a significant proportion of biogenic CO_2 may not regarded as 'sustainable' by all stakeholders, even if it is eligible under RFNBO rules.[13]

2.2 CO_2 REQUIREMENTS FOR E-FUELS PRODUCERS

Next, it is important to consider the requirements of e-fuels producers for the CO_2 feedstock. Table 2 outlines key considerations in terms of CO_2 volumes, physical conditions, and purity for three different e-fuels pathways.

CO_2 purity is important because 'primary' contaminants can rapidly deactivate catalysts in e-fuels production processes. These contaminants can originate from the CO_2 source (see Appendix for more details), or from shared transport infrastructure. The primary contaminants for most e-fuels pathways are sulphur, halides and metals, with concentration thresholds in the parts-per-billion (ppb) range needed - e.g. a threshold of 10-25 ppb for SO_x. However, all the purity specifications for CO_2 transportation modes allow for higher concentrations of contaminants (e.g. the limit ranges from ≤1 ppm to ≤100 ppm for SO_x) – see Appendix. Additionally, it is unlikely that capture processes would yield CO_2 with the required levels of purity. As such, "**polishing**" – to reduce primary contaminant levels – **will likely be required regardless of the transportation method and CO_2 source**.[14] Standard designs for e-fuels processes have polishing units such as ZnO guards and activated carbon beds[15] to reduce sulphur and metals content, respectively.

'Secondary' non-condensable contaminants (e.g. O_2, N_2, CO) tend to pose less of a direct risk for the e-fuels production process, with their main impact being to dilute the CO_2. These non-condensables may be present in higher concentrations (<4 vol%) for CO_2 supply via pipelines, while supply via other transport methods (i.e. truck, rail, ship) will have lower concentrations (<1%).[16]

In terms of physical conditions, gaseous CO_2 is required for e-fuel production, with reactions occurring at elevated pressures. This means regasification is needed if the CO_2 is supplied in

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[13] T&E, Ricardo, 2022. Scaling up Direct Air Capture

[14] There may be some exceptions to this such as direct connections to very high purity CO_2 sources such as fermentation CO_2 from bioethanol.

[15] Pet et al., 2024. Recent Developments in the Implementation of Activated Carbon as Heavy Metal Removal Management

[16] This arises because liquefaction is necessary for intermittent transport modes, and this liquefaction step inherently removes non-condensables.

liquid form. Supply of gaseous CO_2 at elevated pressures (if convenient) can help to save on compression costs at the e-fuels site.

TABLE 2 OVERVIEW OF CO_2 REQUIREMENTS FOR E-FUELS PATHWAYS

Feed gases	Conversion	Fuel products	Slate Share[17] (wt%)	CO_2 requirement (tCO_2/t e-fuel)		Reaction pressure & tempera-tures	Purity considerations
				All-fuels[18]	SAF[19]		
CO_2 + H_2	Methanation	Methane	100%	3	N/A	1.5-2.5 MPa 200-400 ^0C[20]	Sulphur contents should be below 10 ppb, and halides (e.g. chlorine, fluorine, etc) have limits <10 ppb to avoid catalyst poisoning.[21] Feed gases should be metal-free (e.g. arsenic and lead)
	Methanol synthesis + Methanol to Jet (MTJ)	**SAF**	65-95%	3.3	3.5 – 5.1	200–260°C 5-10 MPa [22]	Similar contaminant limits in the feed gas as required for methanation of CO_2 to avoid catalyst poisoning.[23] The gas should also be free of metals, particularly arsenic and iron.[24] Feed gas should be dry to limit inhibition by water[25]
		Diesel	12-15%				
		Naphtha	10-22%				
	Reverse Water Gas Shift + Fischer-Tropsch (RWGS+FT)	**SAF**	25-75%	3.3	4.4 – 13	800-900°C [26] 3 MPa [8]	Sulphur, NH_3 and halides should be limited to 25, 45 and 10 ppb, and be free of metals, particularly lead and silver[27] to avoid catalyst poisoning.
		Diesel	25-50%				
		Naphtha	0-50%				

It is also important to consider the total CO_2 volume requirements per e-fuels plant. Figure 1 gives a histogram of the projected CO_2 requirement (based on Table 2) for announced e-fuels projects in Europe, as of August 2025.[28] This demonstrates that **CO_2 requirements vary significantly**, with a cluster of smaller projects at the lower end (<150 $ktCO_2$/yr), a cluster of mid-sized projects centred around ~250-300 $ktCO_2$/yr, and a few outliers with large CO_2

[17] Slate share – proportion of fuel co-products from a multi-product process
[18] Specific mass of CO_2 requirement relative to mass of all fuels produced
[19] Specific mass of CO_2 requirement relative to mass of sustainable aviation fuel (SAF) only
[20] MAN Energy Solutions, 2018. Patent DE102018113735A1
[21] Harms et al., 1980. Methanization of carbon monoxide-rich gases for energy-transport ; Strucks et al., 2021. A Short Review on Ni-Catalyzed Methanation of CO2
[22] JM, 2025. Patent US7786180B2; ScienceDirect. Methanol synthesis
[23] Saché et al., 2022. Analysis of Dry Reforming as direct route for gas phase CO2 conversion
[24] Alpteken et al., 2022. Sorbents for High Temperature Removal of Arsenic from Coal-Derived Synthesis Gas; Clariant, 2017. Catalyst for Methanol Synthesis
[25] Bukhtiyarova et al., 2016. Methanol Synthesis from Industrial CO2 Sources
[26] Abbas et al., 2024. Experimental assessment of reverse water gas shift integrated with chemical looping for low-carbon fuels
[27] Ma et al., 2020. Quantitative comparison of iron and cobalt based catalysts for the Fischer-Tropsch synthesis under clean and poisoning conditions
[28] Based on the database of announced e-SAF and e-methanol projects from T&E. This database includes both 'pilot' and large-scale commercial projects.

requirements up to ~500 ktCO_2/yr. The cluster around ~300 ktCO_2/yr reflects a significant proportion of planned e-fuels production output (in terms of tonnage) and hence was selected as a focus of this study. A flow rate of 300 ktCO_2/yr aligns relatively well with biogenic CO_2 volumes from Pulp & Paper, EfW, and Biomass Power, further underlining their attractiveness.

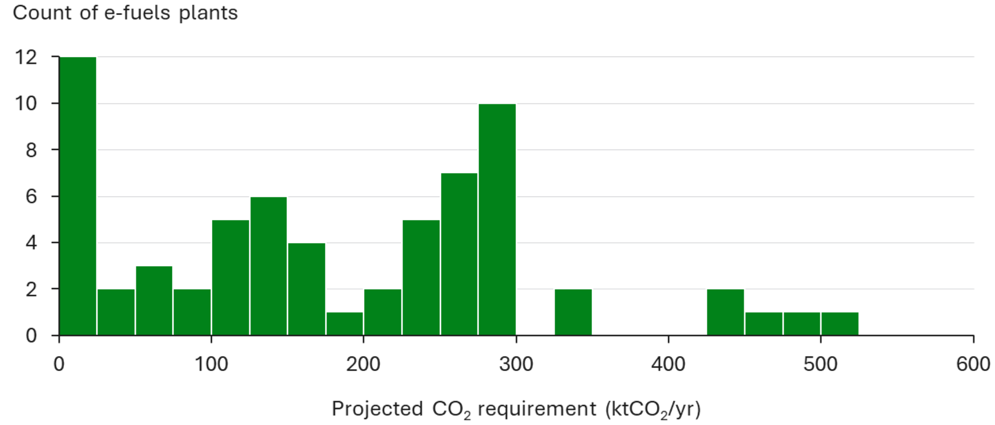

FIGURE 1 HISTOGRAM OF PROJECTED CO_2 REQUIREMENTS FOR ANNOUNCED E-FUELS PROJECTS IN EUROPE[29]

2.3 CO_2 TRANSPORT OPTIONS

2.3.1 AVAILABLE TRANSPORT MODES

There are a number of available modes of CO_2 transport as shown in Table 3. These modes can be divided into 'fixed' modes of pipelines, where the CO_2 flow is continuous, and intermittent modes (rail, truck, ship, barge), where vessels move back and forth between the CO_2 source and end-user.

TABLE 3 OVERVIEW OF AVAILABLE CO_2 TRANSPORT MODES

Transport mode	Description	Typical relevant scale of deployment	
		Capacity	Distance
Pipeline (dense-phase liquid)	High-pressure liquid CO_2 is transported[30]; booster pumps may be needed along the pipeline to maintain CO_2 pressure due to friction losses	0.5-10 MtCO_2/yr	>10 km
Pipeline (compressed gas)	Pressurized CO_2 gas is transported[30]; compressors may be needed along pipeline to maintain pressure	<1 MtCO_2/yr	<50 km
Pipeline (offshore)	High-pressure liquid CO_2 is transported[30,31]	0.5-10 MtCO_2/yr	>10 km

[29] The projected CO_2 requirements are given for the full e-fuels plant including for co-products.
[30] CO_2 pipelines are generally constructed from steel, however other types of materials such as fiberglass are also possible
[31] Booster pumps may not be viable offshore, and so larger diameter pipes may be desired to minimize friction losses

Transport mode	Description	Typical relevant scale of deployment	
		Capacity	Distance
Rail	Liquified CO_2 is transported in specialized[32] CO_2 wagons.	<100 ktCO_2/yr; ~80 tCO_2/wagon; <2 ktCO_2/trainload	50-500 km
Truck	Liquified CO_2 is transported in a specialized[32] trailer tank, which is pulled by a truck unit	<20 ktCO_2/yr; ~20 tCO_2/truck	<200 km
Ship	Liquified CO_2 is transported in a specialized CO_2 vessel	>1 ktCO_2/yr; 1-10 ktCO_2/ship	>200 km
Barge	Liquified CO_2 is transported via containers loaded on a barge	Expected deployment: >100 ktCO_2/yr; 1-25 ktCO_2/barge;	Expected deployment: <100 km

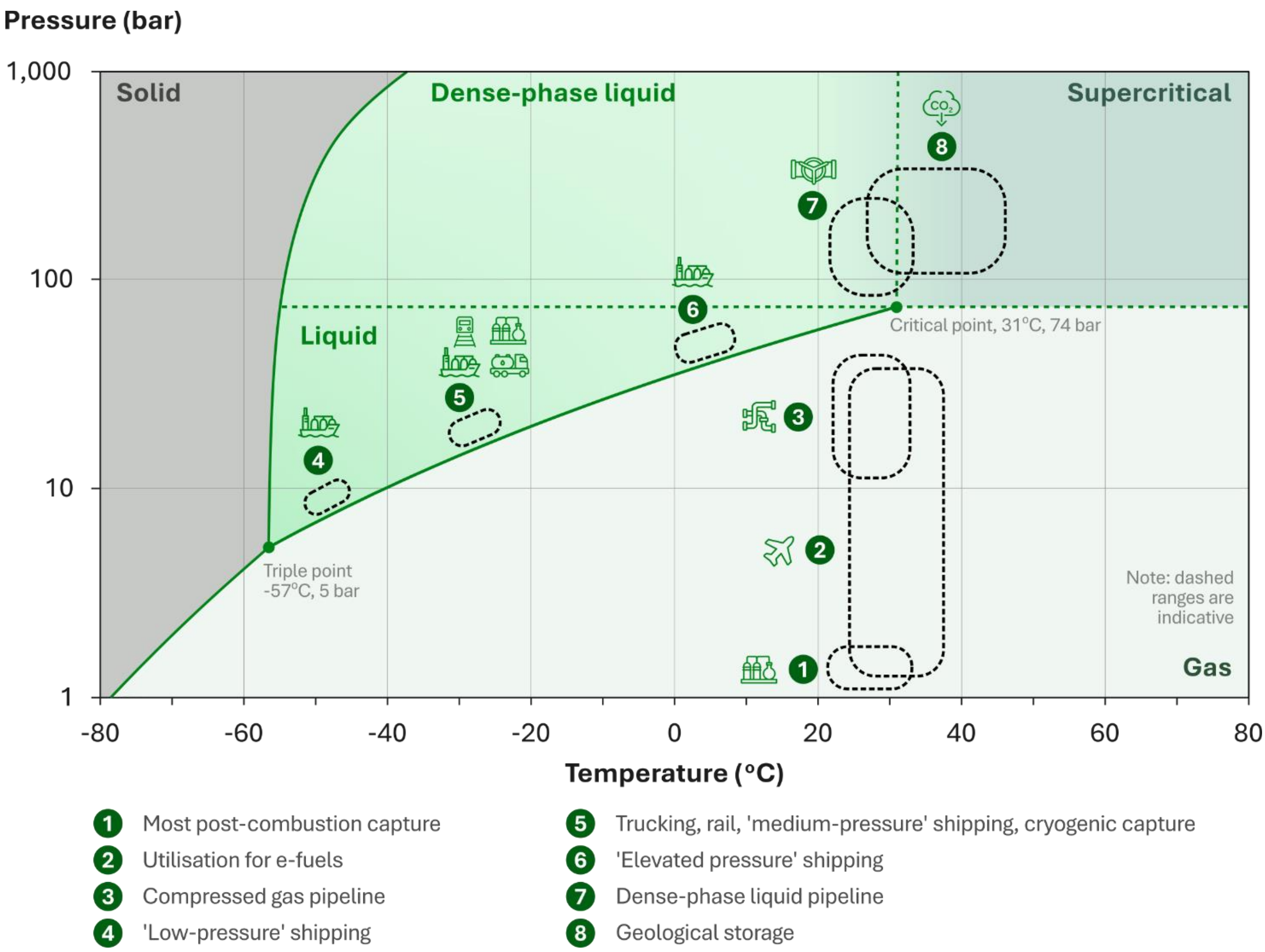

FIGURE 2 CO_2 PHASE DIAGRAM AND RELEVANT CONDITIONS FOR CCUS VALUE CHAINS

[32] Intermodal CO_2 containers can also be transported via truck and rail, however, Myers et al., 2024 (The cost of CO2 transport by truck and rail in the United States) show that this may be less cost-efficient than specialized CO_2 trailers / wagons, which have a larger capacities.

Importantly, the different transport modes move CO_2 at different conditions in terms of CO_2 temperature and pressure. Figure 2 illustrates how intermittent modes transport cryogenic liquefied CO_2, whereas pipelines can transfer CO_2 as a compressed gas or as dense-phase liquid / supercritical CO_2.[33] **This means that 'conditioning' of the CO_2**, i.e alteration of the CO_2 pressure and /or temperature, **is needed**. This conditioning can be achieved with dedicated conditioning units, e.g. compressors or liquefaction units, which contribute significantly to costs, as outlined in the following section.

2.3.2 INFRASTRUCTURE REQUIREMENTS FOR CCU VALUE CHAINS

Different CO_2 transport modes require different infrastructure, which affects their feasibility and costs. Figure 3 shows how pipelines can require initial CO_2 compression, followed by regasification at the e-fuels site (if using a dense-phase liquid pipeline).

Intermittent modes have more extensive additional infrastructure requirements; CO_2 must first be liquefied (which involves cryogenic cooling) and stored in buffer storage. It is then loaded onto the CO_2 transport vessel. This loading may require additional infrastructure, for example rail sidings or ports / jetties that can accommodate large CO_2 vessels. This loading infrastructure can vary significantly depending on local factors, and needs to be evaluated on a case-by-case basis. The CO_2 is then transported by the vessel (multiple vessels may be needed depending on their capacity, and travel time). Following transport, CO_2 is stored in buffer storage to smooth out the intermittency, and is regasified for utilisation.

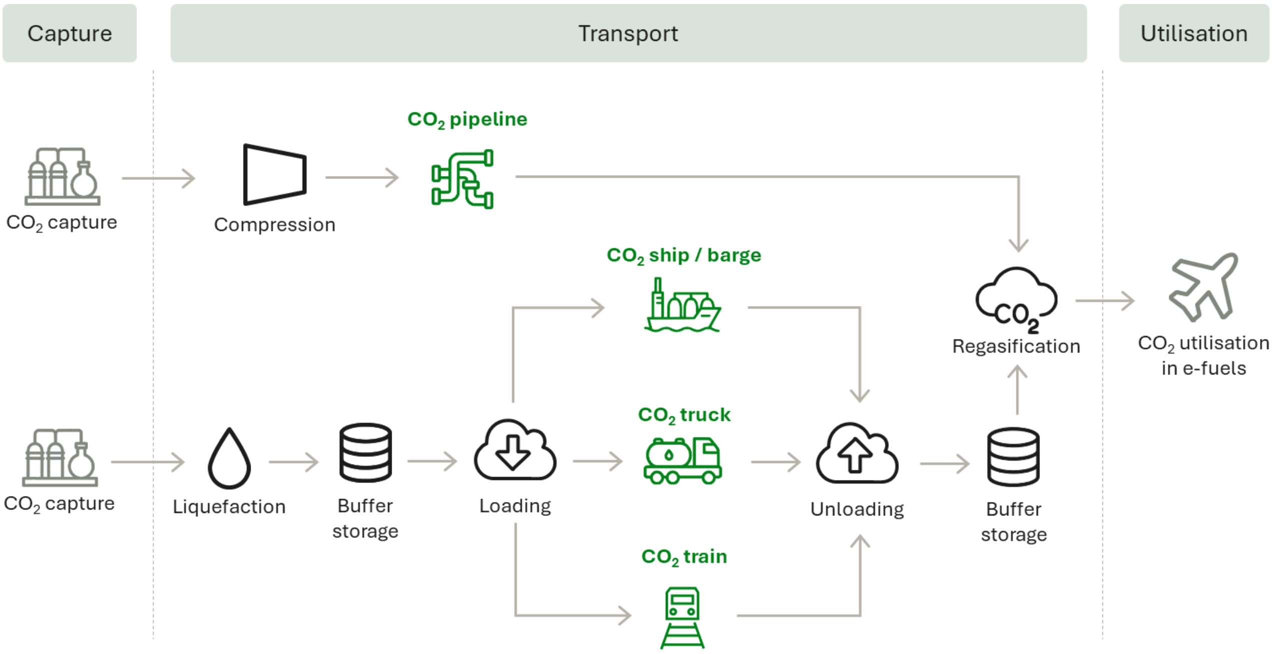

FIGURE 3 SCHEMATIC OVERVIEW OF POSSIBLE INFRASTRUCTURE REQUIREMENTS OF CCU VALUE CHAINS[34]

[33] While pipes can be used to transport cryogenic liquid CO_2 over short distances (e.g. within a site itself), this is less feasible over large distances as active cooling would be need over large distances.
[34] This schematic assumes that after the capture process the CO_2 condition is near ambient. This is expected to be the case for most post-combustion capture processes.

However, several factors can mean that the schematic varies from that in Figure 3. For example:

- If the CO_2 source or e-fuels site does not have direct road, rail, or sea access, additional transport (via a different mode) will be required, which in turn may result in additional CO_2 conditioning.
- If the CO_2 capture process inherently liquefies the CO_2 (this is likely the case for CO_2 capture from biogas upgrading), this removes the requirement for initial liquefaction for intermittent modes. For pipelines, pumps and/or regasification would be needed in place of the initial compression if the capture process liquefies CO_2.

2.3.3 BARRIERS FOR CO_2 TRANSPORT OPTIONS

To understand the feasibility of deploying different transport modes, an assessment was conducted on deployment status, TRL, risks, barriers, and other considerations – see Table 4.

TABLE 4 MATURITIES AND IDENTIFIED RISKS AND BARRIERS FOR CO_2 TRANSPORT MODES

Mode	Current deployment	TRL	Technical risks	Barriers	Other considerations
Pipeline (dense-phase liquid)	Widely used in enhanced oil recovery applications[35].	9	• Very high pressure, and risk of leaks, corrosion, and ruptures • Hydrate formation[36] at low temperatures and high pressures	• Land acquisition • Public acceptance • Regulatory hurdles • Geographical barriers	• Possibility to repurpose existing infrastructure • Potential to become stranded asset
Pipeline (gas)	Less widely deployed compared to dense phase, though notable projects e.g. Porthos and HyNet use gas-phase for onshore pipeline segments[37]	9	• High pressure, and risk of leaks and corrosion	• Land acquisition • Public acceptance • Regulatory hurdles • Geographical barriers	• Possibility to repurpose existing infrastructure • Potential to become stranded asset
Pipeline (off-shore)	Key projects include Sleipner, Northen Lights, and Snøhvit;[38] more expected to come online as CCS projects advance to FID	9	• Very high pressure, and risk of leaks, corrosion, and rupture • Additional material concern from corrosion by seawater	• Geographical barriers and complexity of seabed[39] • Impacts on marine life • Regulatory hurdles	• Possibility to repurpose existing infrastructure • Potential to become stranded asset
Rail	Used for CO_2 utilisation for decades[40]	9	• Rail transport delays • Derailment could result in CO_2 release	• Rail access dependency • Congestion risks	• Rail network may affect

[35] The National Petroleum Council, 2019. Meeting the Dual Challenge
[36] Tang et al., 2024. Prediction of Hydrate Formation in Long-Distance Transportation Pipeline for Supercritical-Dense Phase CO2 Containing Impurities
[37] Porthos. Project overview and technical components; HyNet CCUS Pre-FEED. Onshore CO2 pipeline Design Study Report
[38] IEEFA, 2023 – Norway's Sleipner and Snøhvit CCS
[39] Makrakis et al., 2022. Optimal route selection of Offshore Pipelines Subjected to Submarine Landslides
[40] Kleinman Centre for Energy Policy, 2024. The Right Track: Advancing CO2 Transport by Rail

Mode	Current deployment	TRL	Technical risks	Barriers	Other considerations
				• Regulatory hurdles	travel times and costs • May be some environmental impact from rail transport
Truck	Widely used for CO_2 utilisation. Emerging use in CCUS applications	9	• Accidents and spills • Traffic congestion and other aspects of the road network giving rise to delays	• Contributes to congestion • Site logistics may prevent trucks from entering site • Public acceptance of transport on public roads	• Environmental impact of truck (dependent on type of truck) • Flexibility for remote emitters
Shipping	Deployed in CO_2 utilisation industry (food and beverage) at small-scale, and Northern Lights ships now operational.	6-9 [41]	• Shipping times may be affected by weather events and other external factors • Lack of clarity of behaviour of CO_2 in presence of impurities near triple point	• Ports need dedicated infrastructure and significant depths/jetty lengths • Long lead times • Varying pressures may hinder CO_2 offloading • Regulatory hurdles	• Supports port–to-port or port-to-offshore connections • Environmental impact of shipping emissions (dependent of ship's energy source)
Barge	Deployment for CO_2 transport may begin in 2026/27 [42] Extensive use in transporting other liquefied gases and chemicals.	5	• May be affected by weather events and other external factors	• Ports/docks need dedicated infrastructure and appropriate depths/jetty lengths • Regulatory hurdles • Traffic in waterway could be a bottleneck	• Possibility of repurposing existing barge fleets • Barges can offer landlocked emitters connection through inland waterways

From Table 4, there is no one 'stand-out' CO_2 transport mode with significantly higher feasibility than the rest; each has a different set of barriers, risks, and wider considerations. However, (large-scale) **CO_2 shipping and CO_2 barge transport may face larger challenges in the short-term** given the nascence of these sectors, while pipelines, rail, and truck transport benefit from extensive deployment over decades.

It is worth highlighting that the transport modes all have significant reliance on external elements; pipelines need to acquire right-of-way (ROW), while intermittent modes need access to road, rail and water networks with available capacity. Another key point is that the severity of the barriers is dependent on scale and distance. This is particularly true for trucking with regard to site access. For instance, a 300 $ktCO_2/yr$ flow-rate would likely require upwards of 34

[41] Large-scale (>2000 m^3), medium pressure – TRL: 8; Small-scale (<2000 m^3), medium pressure – TRL: 9; Large-scale, low pressure – TRL: 6
[42] Carbon Collectors. CO2 transport and storage: This is how it is done

trucks movements in and out of a facility per day, which may cause significant issues in terms of site logistics.

The transport modes also have significant risks involved. These are related to potential uncontrolled releases of CO_2, which is an asphyxiant. It is important to note that these are considered manageable risks, and CO_2 transport has a strong safety record.[43] Additionally, evidence indicates that risks associated with CO_2 pipelines are comparable to or less than those of other pipeline types.[44,45]

A point of contrast between the modes is flexibility; pipelines have the potential to become stranded assets if the CO_2 source for utilisation site becomes unavailable, whereas intermittent modes have higher flexibility. Finally, it is important to note that this is a generalized assessment of feasibility, and the relative suitabilities of different modes for a given project will strongly depend on site-specific and local factors.

[43] GPI, 2024. Examining the Safety Record of Carbon Dioxide Pipelines.
[44] Duguid et al., 2022. CO2 Pipeline risk assessment and comparison for the midcontinent United States
[45] Wilday, et al., 2009. A comparison of hazard and risks for carbon dioxide and natural gas pipelines

3. COSTS OF CO_2 SOURCING

3.1 CAPTURE COSTS

This section considers costs of CO_2 sourcing, beginning with the costs of CO_2 capture. Indicative levelized costs of capture are presented in Figure 4 for five promising CO_2 sources of biogenic CO_2

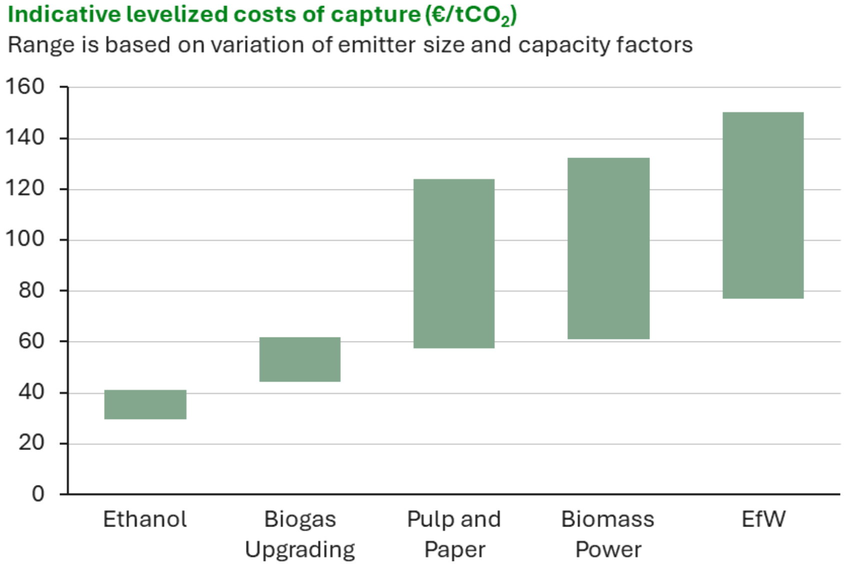

FIGURE 4 INDICATIVE LEVELIZED COSTS OF CAPTURE[46]

CO_2 from ethanol production has the lowest capture cost, primarily due to the high CO_2 concentrations of ~99% - which enables a relatively simple capture process of compression and dehydration. Biogas upgrading has higher costs than ethanol, mainly due to the smaller CO_2 volumes and hence lower economies of scale. Pulp and Paper, Biomass Power, and EfW have moderate CO_2 concentrations, and require post-combustion capture technology,[47] which tends to be more costly. Importantly, there is expected to be significant variation in the costs of post-combustion capture due to variation in CO_2 volume, capacity factors, and other site-specific factors at individual Pulp and Paper, Biomass, and EfW sites.

3.2 CO_2 TRANSPORT COSTS

3.2.1 TOTAL COSTS

To evaluate the levelized costs of transport, comprehensive techno-economic assessments (TEAs) for five transport modes were developed: pipelines (dense-phase liquid and gas), rail,

[46] The costs of capture have been obtained by combining costings from: IEA, 2020. Levelised cost of CO_2 capture by sector and initial CO2 concentration; GCCSI, 2025. Advancements in CCS Technologies and Costs; and Mærsk Mc-Kinney Møller Centre, 2024. Global Availability of Biogenic CO_2. Note that the costs presented here include the costs of compression. Because the capture costs come from multiple references, it is possible that different assumptions are used in the respective analyses (e.g. differing electricity costs). As such, caution must be applied when comparing the costs of capture between different sectors. Site-specific modelling of capture costs is required to gain a more accurate understanding of capture costs for a particular CCUS project.

[47] Prominent examples of post-combustion capture technologies relevant for these sources include advanced amines and hot potassium carbonate – see GCCSI, 2025. State of the Art: CCS Technologies 2025

trucking, and shipping. These TEAs include calculation of the capital expenditure (CAPEX), operations and maintenance expenditure (O&M OPEX), variable OPEX, and energy costs for each of the components required for transport. These components include aspects such as CO_2 conditioning, loading and unloading, buffer storage, and regasification. Additional details on the input assumptions are given in the Appendix.

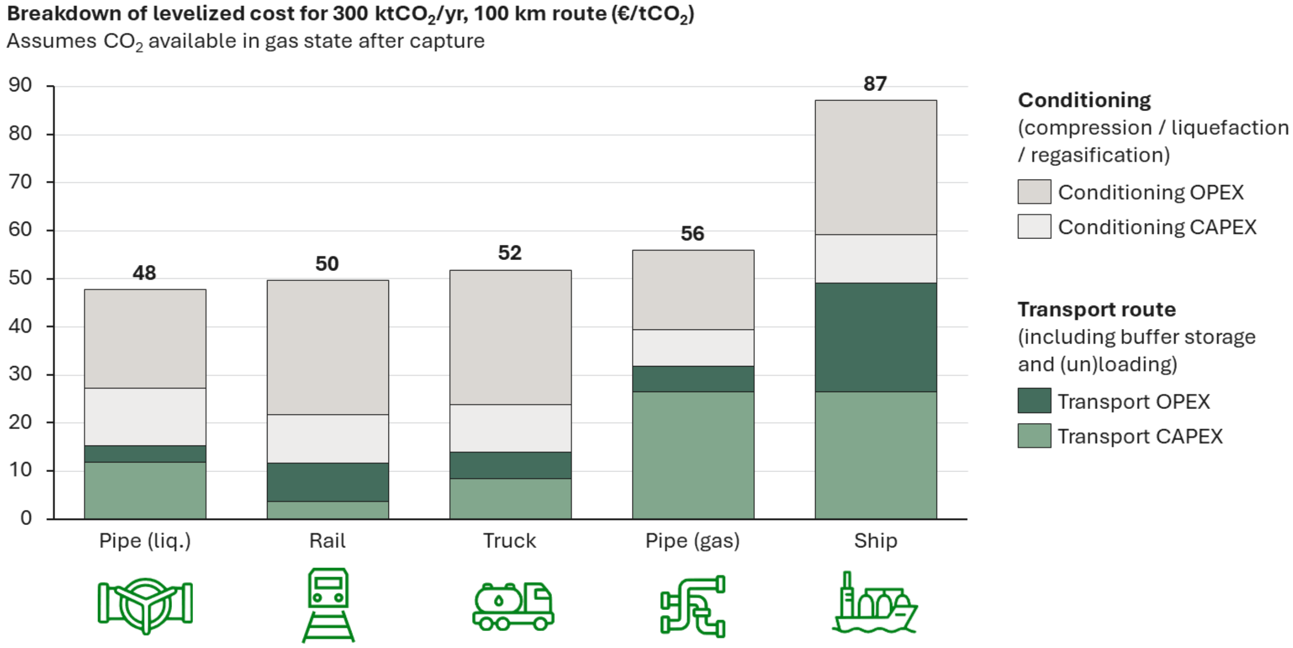

FIGURE 5 BREAKDOWN OF LEVELIZED COST OF CO_2 TRANSPORT

As demonstrated in Figure 5, **the total levelized transport costs range between €48-87/tCO_2 for an indicative route of 100 km for 300 $ktCO_2$/yr**, depending on the mode. **CO_2 conditioning contributes a significant share to these overall costs** (an average of 60% for a 300 $ktCO_2$/yr, 100 km route). Of the conditioning costs, a significant portion is OPEX-related due to the energy-intensive nature of compression / liquefaction. Note that this conditioning dominates the energy requirements and associated CO_2 emissions for CO_2 transport – see Appendix for more details. For instance, in the case of a 300 $ktCO_2$/yr, 100 km route, conditioning results in an additional 6 to 11 $ktCO_2$/yr of emissions, while the transport step only contributes 0.5 to 1 $ktCO_2$/yr, depending on the mode.

For the transport step, pipelines tend to have a large CAPEX contribution (80%), while the intermittent modes have relatively lower CAPEX contribution (an average of 50%). It should be noted that at longer distances, CAPEX makes a progressively smaller relative contribution for intermittent transport.

Figure 6 outlines how the transport costs vary with distance in two cases: (a) 300 $ktCO_2$/yr (relevant for sources such as EfWs) and (b) 10 $ktCO_2$/yr (relevant for Biogas Upgrading). In both cases, the **incremental cost per distance for pipelines is higher than the intermittent modes** at these volumes, with shipping having the lowest incremental costs. This is understandable given that every additional km for a pipeline involves significant additional CAPEX spend, whereas every additional km for a ship mainly results in a slightly higher fuel cost. For 300 $ktCO_2$/yr, the result is that **pipelines tend to be cost-effective at**

short distances, and intermittent modes cheaper at longer distances. For 10 ktCO_2/yr, the trucking is cheapest at both short and long distances, with trucking transport costs ranging from **€20-30/tCO_2** for 1-200 km. These relatively low costs are enabled, in part, due to availability of a capture process for Biogas Upgrading which inherently liquefies CO_2 – namely cryogenic distillation.[48] This removes the need for an additional costly liquefaction step prior to transport. A final comment is that costs do not always increase linearly with distance. This is notable for trucking, where once the distance exceeds a certain threshold (in this case 200 km),[49] trucks cannot make multiple trips within a single day, resulting in additional trucks being required.

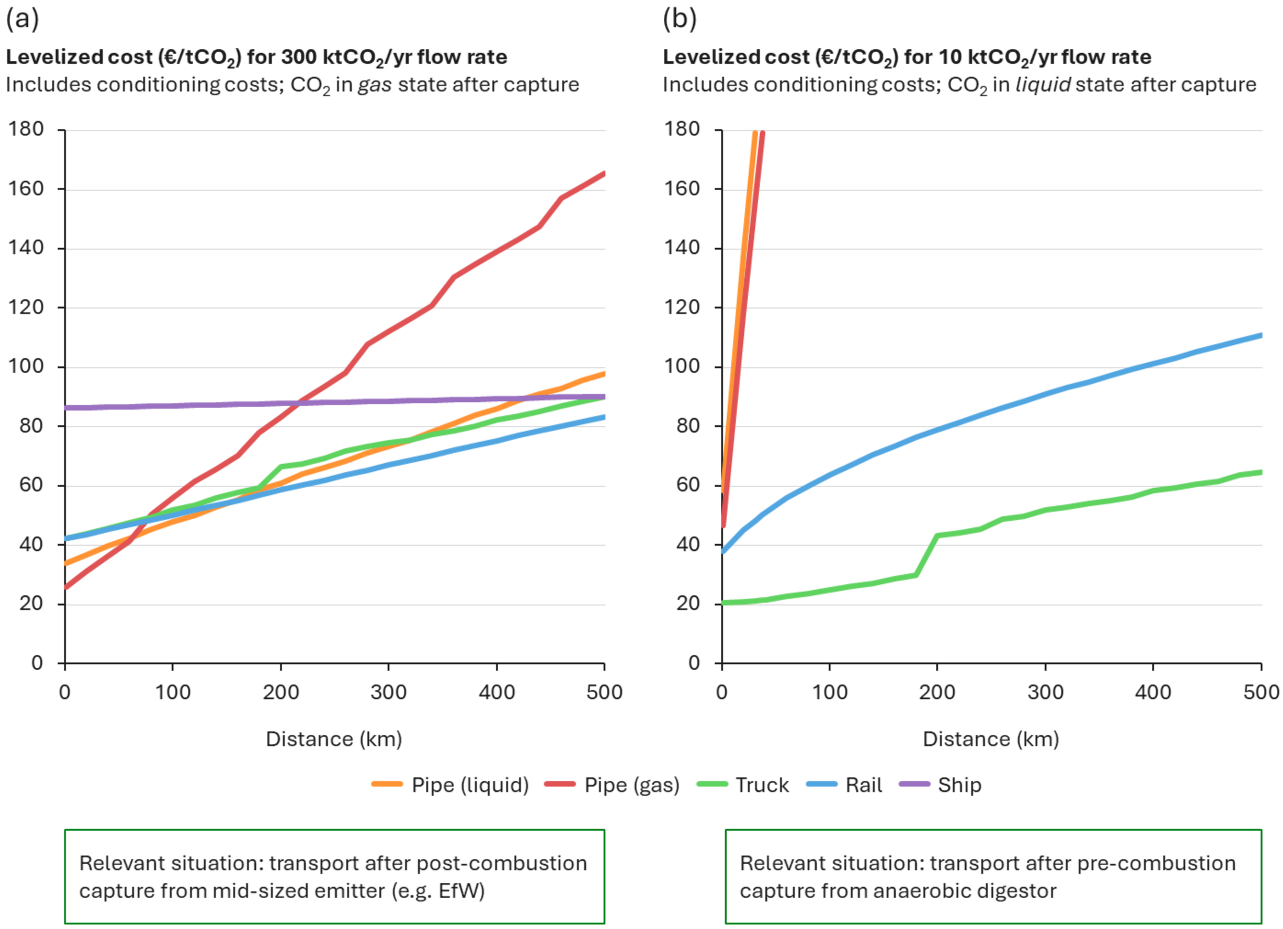

FIGURE 6 CO_2 TRANSPORT COSTS AT DIFFERENT DISTANCES[50]

As demonstrated in Figure 6, transport costs can vary considerably at different flow rates due to economies of scale. Figure 7 shows that **the economies of scale are very significant for pipelines**, where larger diameter pipelines are a cost-effective means of accommodating

[48] EBA, 2025. Biogenic CO2 from Biogases
[49] This threshold will depend on the speed of the truck, as well as the operational hours.
[50] Note on assumptions: Discount rate of 10% for both cashflows and carbon, 25 years of operation, 90% capacity factor for transport route. Routing factors are not included. In (a), it is assumed CO_2 is available in the gas phase at ambient conditions after capture, and so compression is needed for the pipelines prior to transport, and liquefaction is needed for the intermittent modes. In (b), it is assumed CO_2 is available as a (cryogenic) liquid after capture, and so pumping / regasification is needed prior to the pipelines, while no conditioning is needed prior to intermittent transport. In both (a) and (b) regasification is included.

larger flow rates. For example, at 100 km, the cost (excluding conditioning) of a 300 $ktCO_2$/yr pipeline is 5x higher than that of a much larger 5 $MtCO_2$/yr CO_2 pipeline. This shows that significant transport cost savings could be achieved if e-fuels are able to source CO_2 from large-scale shared pipeline infrastructure.

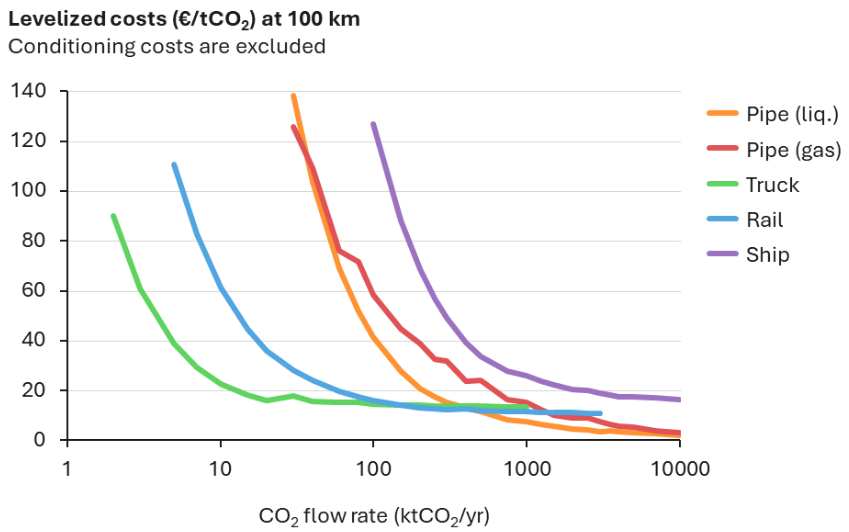

FIGURE 7 ECONOMIES OF SCALE OF CO_2 TRANSPORT[51]

Ships also have strong economies of scale, with levelized costs increasing significantly at flow rates below 1 $MtCO_2$/yr. Rail has moderate economies of scale, with costs plateauing at >100 $ktCO_2$/yr. Finally, trucking has relatively low economies of scale, as higher flow rates essentially results in larger numbers of trucks.[52]

3.2.2 LOWEST COST TRANSPORT OPTIONS

A key question to understand is: **for a given distance and flow rate, what may be the most cost-effective transportation mode?** Figure 8 illustrates the lowest cost options, with the implicit assumption that all transport modes are available and that each mode would cover the same distance. Several interesting trends emerge:

- **Trucking is cheapest at low CO_2 flow rates**, with the cost advantage larger at shorter distances. This highlights trucking's important role for CO_2 transport from ADs.
- **Gas-phase pipelines are cheapest at short distances (ca. <50 km) and medium-to-large flow rates (ca. >200 $ktCO_2$/yr).** This arises due to their reduced initial CO_2 conditioning needs versus other modes. At longer distances, dense-phase liquid CO_2 pipelines are more cost-effective than gas-phase pipelines, as the higher CO_2 pressures / densities allow for smaller diameter (and hence cheaper) pipes.

[51] Levelized costs are plotted over the ranges where the cost models are deemed to be relevant. Note that the models assume dedicated transport routes, and more complex logistical solutions (e.g. milk runs) can help to reduce costs for intermittent modes at lower volumes.
[52] Note that the model does not take into account any additional site modification costs that may be needed to allow a site to receive a large number of trucks each day.

- **Rail tends to be the cheapest mode at 'medium' flow rates (ca. 100-400 ktCO_2/yr) and at longer distances of >100 km**. This range of flow rates is highly relevant for e-fuels – see Figure 8.
- **Shipping tends to be most cost-effective at large flow rates and distances.** This arises primarily due to the low incremental cost per distance of shipping – see Figure 6.

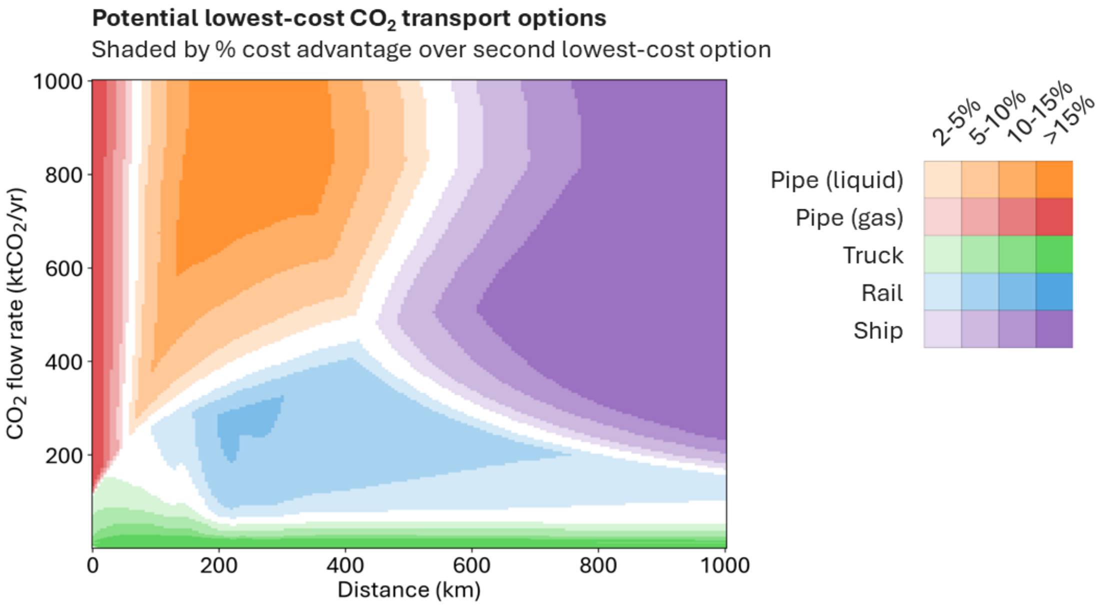

FIGURE 8 POTENTIAL LOWEST COST CO_2 TRANSPORT OPTION BY FLOW RATE AND DISTANCE[53]

Overall, the lowest-cost transport option can vary significantly across CO_2 flow rates relevant for e-fuels. For mid-sized ~300 ktCO_2/yr e-fuels plants, pipelines are the cheapest at short distances, while rail is more cost-effective at longer distances. At very large distances, shipping becomes cheapest for 300 ktCO_2/yr.

However, a key point is that the cost advantage of a particular mode tends to be relatively low. This emphasizes the role that non-cost-related factors - e.g. public acceptance or permitting – will play in decision-making. In some instances, certain transport modes will simply not be available – for example a lack of waterways would preclude shipping. Additionally, the small cost differences mean that sensitivities in costs can result in different transport modes becoming cheaper at certain distances and flow rates.

3.2.3 SENSITIVITIES OF CO_2 TRANSPORT COSTS

Several sensitivities can cause costs to vary between projects including:

- **Routing factor, geography and terrain**: routing factor refers to the ratio of the actual distance of a transport route to the distance 'as the crow flies' between the start and end point. This routing factor is highly dependent on local geographic factors e.g. coastlines, geographic barriers such as mountains, road access, rail networks, and population

[53] Smoothing filters have been applied to the cost data to improve the visual presentation of this graphic

density.[54,55] As such, this must be evaluated on a project-by-project basis. Differences in routing factors between different transport modes can affect their relative attractiveness.

- **Logistics optimization and sharing of infrastructure**: in the cost models developed in this study, it is assumed that a dedicated transport route is established between the start and end point. However, other types of logistical solutions such as 'milk runs' are possible for intermittent modes, and the sharing of infrastructure can improve cost efficiency. Sharing of infrastructure is also possible for CO_2 pipelines, and can help to harness economies of scale.
- **Business model:** this analysis focuses on the overall costs to the system of establishing a CO_2 route. However, the costs attributed to an e-fuels developer will depend on the business model of the CO_2 transportation service provider, who is likely to be a third party.
- **CAPEX, OPEX, Energy costs**: variation in these items will affect the overall levelized cost – see Appendix for more information. In particular, the cost of electricity, which can vary significantly in Europe,[56] and has a large contribution to total levelized cost due to energy-intensive nature of CO_2 compression / liquefaction.

3.3 HYDROGEN AND ELECTRICITY TRANSPORT COSTS

It is worth considering **how CO_2 transport costs compare to the equivalent costs of transporting H_2 or electricity to an e-fuels site**. This may help to determine, for example, whether it is preferable to locate an e-fuels site so to minimize H_2 transport costs or to minimize CO_2 transport costs.

For every tonne of useful product, the methanol-to-jet pathway requires 3.3 tCO_2, 0.5 tH_2, and 0.5 MWh (see Appendix for details on other pathways). Assuming a MtJ e-fuels plant producing 100 kt of e-fuels products per year, we then compare the cost of a dedicated new-build for a 330 $ktCO_2$/yr dense-phase CO_2 pipeline, a 50 ktH_2/yr gas-phase H_2 pipeline, and a 50 GWh/yr overhead cable.[57] For each asset, the respective contribution to the levelized cost of e-fuels production is compared by evaluating the net present value (NPV) of costs divided by the NPV of e-fuels products.

As shown in Figure 9, **CO_2 transport is expected to be cheaper than the transport of the required quantity of H_2 or electricity for the plant**. Despite the lower resource requirement for H_2, the lower densities for H_2 result in levelized costs above that of CO_2 transport. This is the case for all the evaluated e-fuels pathways. The electricity transmission costs are much higher than CO_2 and H_2 transport costs. This means that it may be preferable to locate a site to minimize H_2 and / or electricity costs, instead of locating to minimize CO_2 transport costs.

[54] Wang et al., 2024. How much longer do you have to drive than the crow has to fly?
[55] IEAGHG, 2014.
[56] Statista, 2025. Electricity prices for non-household consumers in the European Union in 2024, by country and consumption band
[57] Assumptions: 10% discount factor applied to cashflows and product. 20-year operational lifetime is assumed. 95% capacity factor assumed for CO_2 and H_2 pipelines. Key reference for H_2 pipeline: David et al., 2024. FECM/NETL Hydrogen Pipeline Cost Model (2024). Key reference for electricity transmission: Lauf et al., 2023. Costs of building new energy infrastructure and transporting energy for a future sector-integrating energy system with a focus on Europe. Routing factors are 100% in each case, and conditioning costs are excluded. Also considered: Solomon et al., accessed 2025. Hydrogen Transport Cost Calculator

Note that the required CO_2 and H_2 conditioning may vary depending on the type of capture and H_2 production process, and may result in additional costs. Additionally, there are other factors beyond cost to consider when choosing how to transport feedstocks to an e-fuels facility (e.g. GHG emissions, safety, regulations, risks)

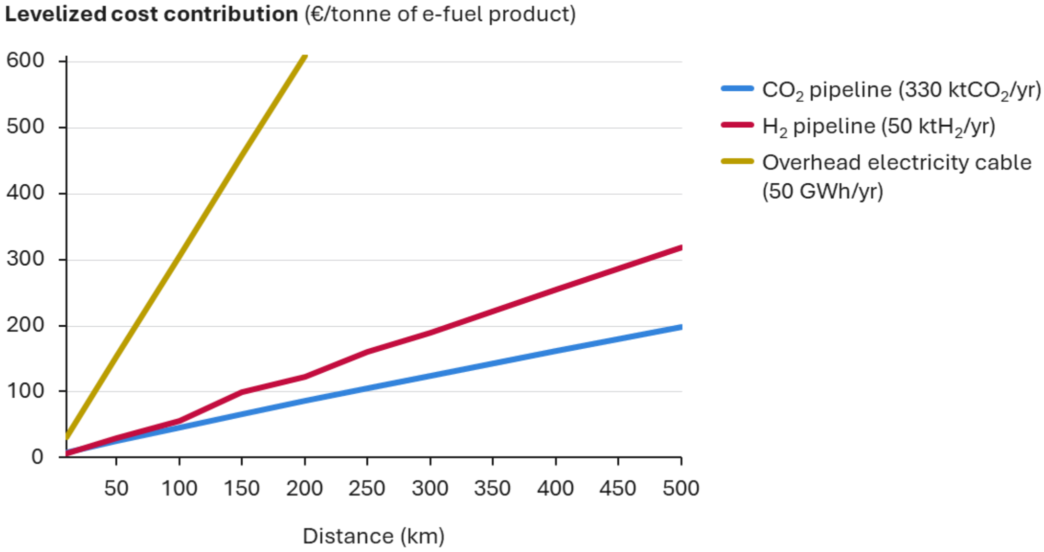

FIGURE 9 COMPARISON OF CO_2, H_2, AND ELECTRICITY TRANSPORT COSTS

4. MAPPING OF CCUS INFRASTRUCTURE FOR E-FUELS

To further understand how CO_2 sourcing can play out in Europe, this section considers the geographic distribution of CO_2 sources, renewables capacities, and planned CCUS infrastructure. This can help to further inform which transport modes may be most relevant, as well as key barriers and opportunities.

4.1 DISTRIBUTION OF INDUSTRIAL CO_2 EMISSIONS

The Industrial Emissions Portal (IEP) is used to obtain CO_2 emissions from industrial sites in Europe, with Figure 10 illustrating the biogenic CO_2 from these sites. As explained previously, biogenic CO_2 is of strongest interest for e-fuels due to EU limitations of fossil CO_2 eligibility. It is important to note that there is uncertainty associated with the biogenic CO_2 quantities due to limitations in IEP reporting – see Appendix for full details.

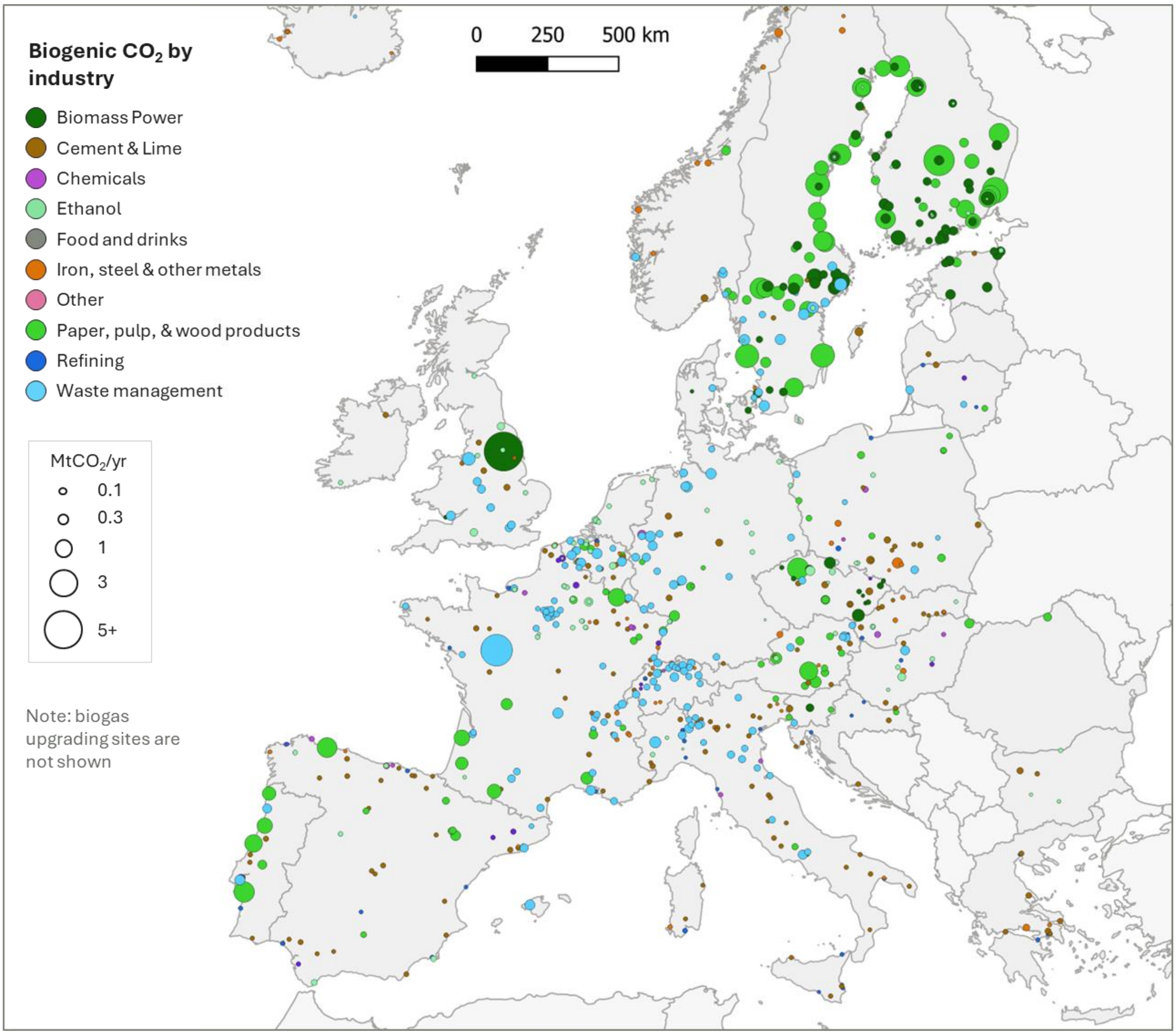

FIGURE 10 BIOGENIC CO_2 FROM INDUSTRIAL SITES IN EUROPE

There is significant clustering of biogenic CO_2 from Pulp & Paper and Biomass Power in the Nordics, particularly in Sweden and Finland. There are also notable CO_2 volumes from

Pulp & Paper and Biomass Power throughout Europe, for example in Czechia, Austria, and the coast of Portugal. EfWs are present in significant numbers throughout Europe, with a tendency for clustering near population centres. There are additional smaller biogenic CO_2 volumes from cement and ethanol distributed throughout Europe.

There is also significant biogenic CO_2 from a large (and increasing) number of distributed biogas upgrading sites;[58] as of June 2025, there are 1678 upgrading sites in Europe, an 8% increase from 2024.[59] Significant quantities of biogenic CO_2 from biogas upgrading are available in Germany, France, Italy, UK, and Denmark – see Appendix for further information.

4.2 WIND AND SOLAR POTENTIAL

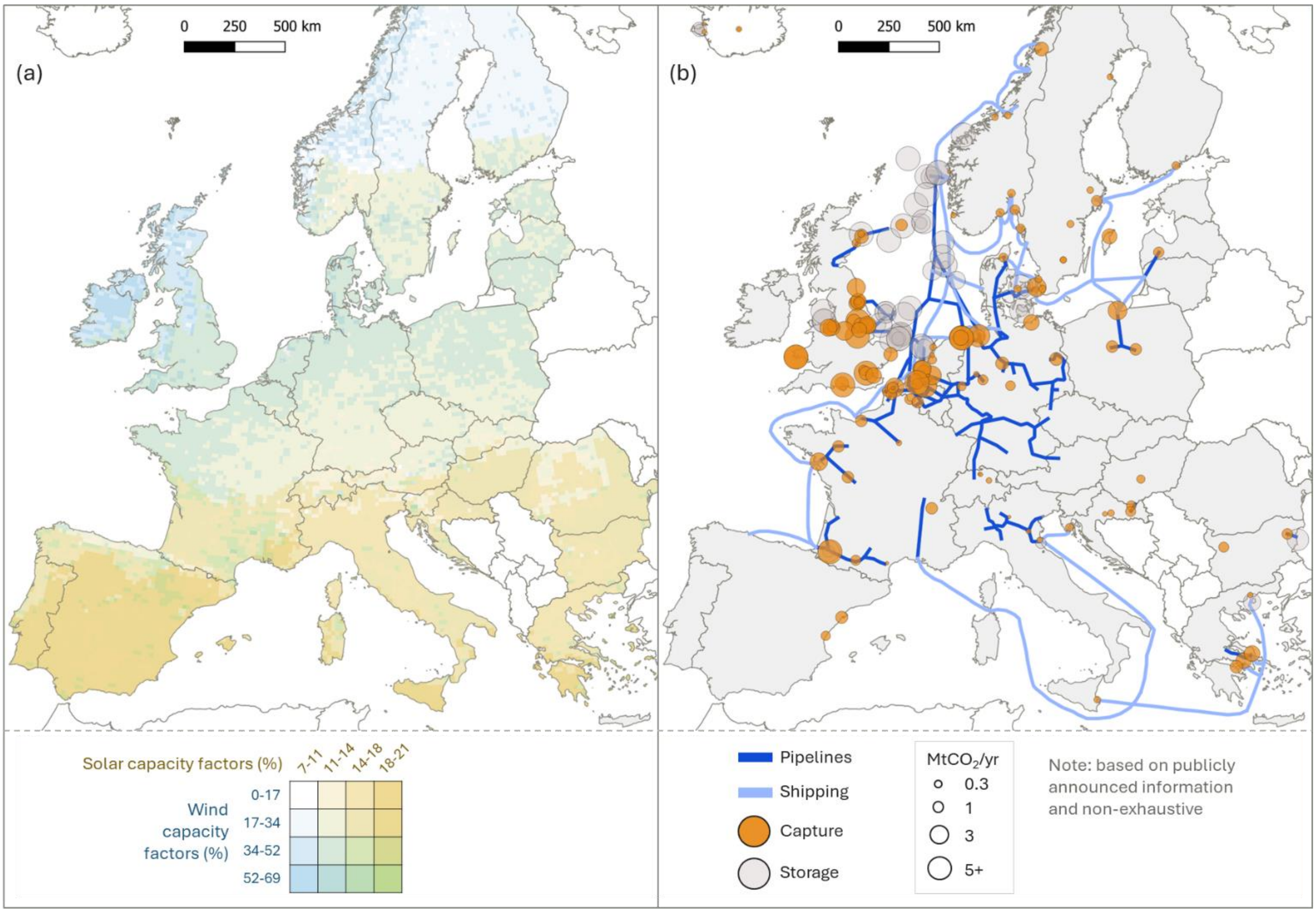

FIGURE 11 WIND AND SOLAR CAPACITIES IN EUROPE (A), AND PLANNED CCUS INFRASTRUCTURE (B)

Here we consider the distribution of renewable electricity potential from wind and solar. This is relevant as high wind and solar capacity factors are indicators of potentially favourable areas to source renewable electricity for e-fuels production, and hence favourable locations for e-fuels production.

[58] Biogenic CO_2 from upgrading has not been mapped due to the large number of sites and relatively small CO_2 amounts from each site.
[59] EBA, 2025. European Biomethane Map 2025

As shown in Figure 11 (a), there is **significant solar potential in the South of Europe**, particularly in Spain and around the Mediterranean. **Wind capacities are significant in Ireland and the UK, as well as around the North Sea and Baltic Sea**. There are some areas of both high wind and solar potential – for example around the south of France and the northeast of Spain. Notably, there tend to be low wind and solar capacities in the inland, middle-latitudes of Europe (e.g. central France, south Germany, Czechia, Slovakia).

However, renewable potential is not the sole determiner of ideal areas to source electricity for e-fuels. There are other forms of low-carbon power such as geothermal, hydro, and nuclear power. Additionally, the EU Delegated Act[60] on renewable electricity sourcing for RFNBOs permits sourcing of electricity with a PPA that fulfills requirements on additionality, temporal correlation, and geographical correlation (as determined by EU bidding zones and their interconnections), and grid electricity with certain constraints on grid renewables penetration and time of offtake.[61]

With these caveats in mind, **the renewables capacities overall suggest that there could be an opportunity to transport biogenic CO_2 from the inland middle-latitudes** – particularly countries such as Czechia and Slovakia which have relatively high grid emission factors[61] – **to regions with more favourable renewables potential**. These regions include the North Sea where wind capacity factors are higher, as well as the Mediterranean where solar capacity factors are higher.

4.3 PROPOSED CCS INFRASTRUCTURE AND PROJECTS

Planned infrastructure focused on CCS could help to provide CO_2 transport for e-fuels and could act as competition for CO_2. Figure 1 (b) highlights the are a large amount of operational or planned CCUS infrastructure[62], with 136 projects for carbon capture[63], 14 for CO_2 pipelines and shipping,[64,65] and 62 for CO_2 storage.[66] Note that the presented projects are based on publicly announced information (as of September, 2025), and that an assessment of project likelihood or feasibility is not undertaken.[67]

Many capture projects tend to be located in the North Sea, as do CO_2 storage projects due to the favourable geology in this area.[68] There are also several capture and storage projects in the Mediterranean. **Notably, there are plans for large CO_2 pipelines networks in the centre of Europe, particularly in Germany**. These networks are focused on transporting CO_2 to geological storage. Several CO_2 shipping routes are also present to transport CO_2 to geological storage sites.

Overall, the mapping suggests that there may be competition between storage and utilisation, particularly near the North Sea. This is because CCS-focused infrastructure gives the option for emitters of biogenic CO_2 to pursue storage – and potentially receive a financial benefit through

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[60] European Union, 2023. Delegated regulation - 2023/1184 - EN - EUR-Lex
[61] Hydrogen Europe, 2023. Impact-Assessment-on-the-RED-II-DAs.
[62] The large majority of this infrastructure is currently in the planning phase.
[63] CATF, 2025. Carbon Capture Project Table
[64] JRC, 2024. Shaping the future CO2 transport network for Europe
[65] CATF, 2025. Building Future-Proof CO2 Transport Infrastructure in Europe
[66] IEA, 2025. CCUS Projects Database
[67] Also note that due to the fast-moving pace of the CCUS sector, the presented projects may not be an exhaustive list.
[68] CATF, 2023. Unlocking Europe’s CO2 Storage Potential

mechanisms such as the voluntary carbon market (VCM) for carbon removal (CDR) credits. The degree of competition will vary depending on the price of CO_2 payable by BECCS projects as a result of this support, which will affect the price an e-fuels producer may need to pay.

4.4 COMPARISON OF BIOGENIC CO_2 WITH CCUS INFRASTRUCTURE

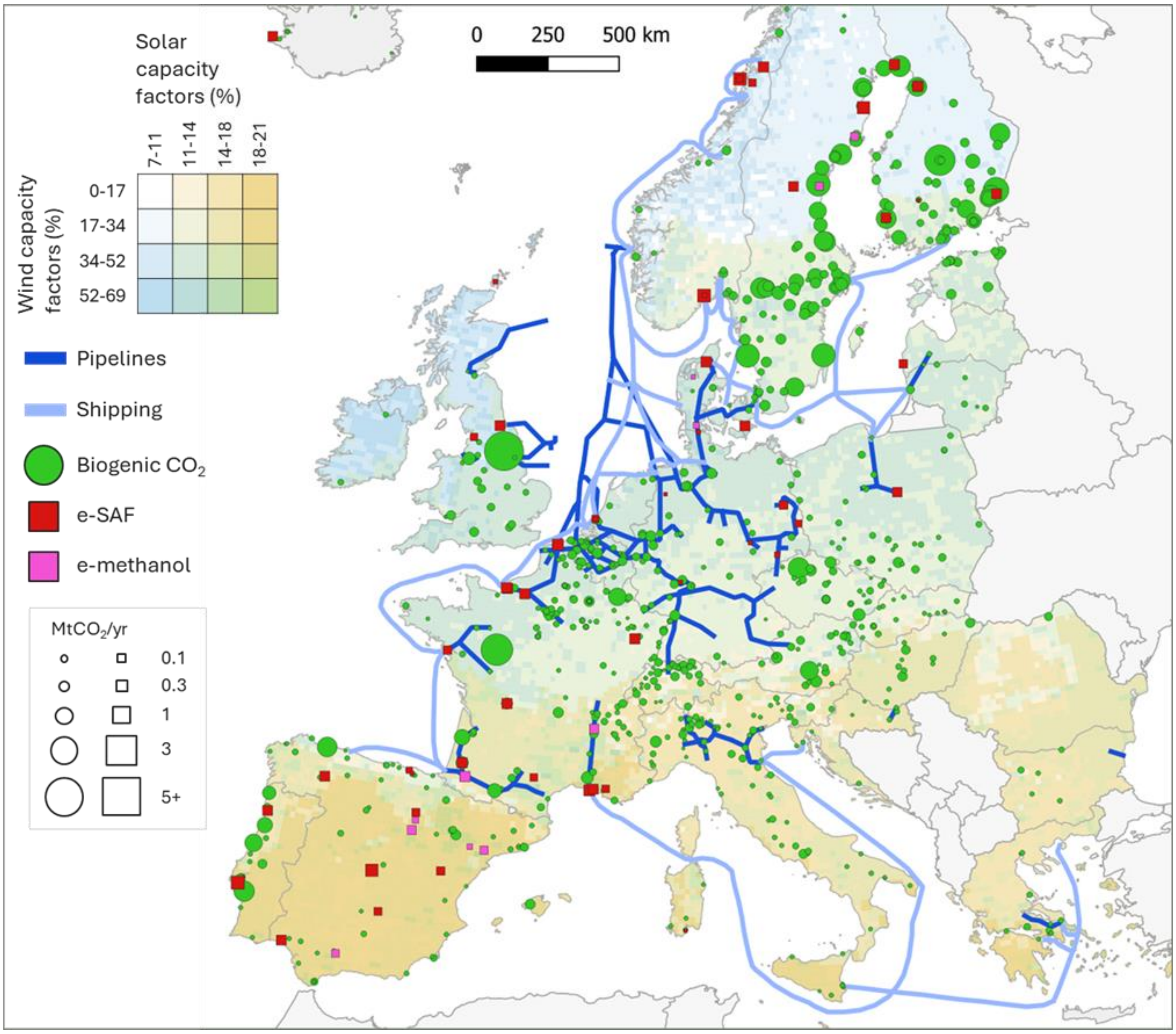

FIGURE 12 COMPARISON OF BIOGENIC CO_2 TO PLANNED E-FUELS PROJECTS AND TRANSPORT INFRASTRUCTURE, AND RENEWABLE CAPACITIES

We now consider the overall system, and how the different examined elements interact together – see Figure 12. This map also shows planned e-SAF and e-methanol projects in Europe sized by their projected CO_2 requirement, as determined by the announced capacities for e-fuels projects and the CO_2 requirements in Table 2.[69] Note that there is significant uncertainty associated with this projected CO_2 requirement.[70]

[69] Based on public announcements as of August 2025 as compiled in T&E's database.
[70] For instance, the actual production output of e-fuels projects could change compared to announced capacities. Additionally, not all e-SAF projects specify the split between different co-products. If not provided, co-products splits of 95% and 75% e-SAF are assumed for MtJ and RWGS+FT, respectively.

The comparison shows that planned CO_2 pipelines tend to be correlated with biogenic CO_2. This is understandable given that many industrial sites that emit fossil CO_2 – which the pipelines are designed to connect to – also emit biogenic CO_2. To quantify how much biogenic CO_2 is in the vicinity of the planned CO_2 pipelines, we consider 'buffer' regions of 50km and 100km around the planned pipeline routes, with the quantity of biogenic CO_2 within the buffer regions summed. A further adjustment is made to convert the biogenic CO_2 quantity into the 'accessible' biogenic CO_2 quantity which could feasibly be captured. This takes into account expected capture rates and the minimum economies of scale for capture – see Appendix for details. As shown in Figure 13, **there is 33 and 23 $MtCO_2$/yr of accessible biogenic CO_2 within 100 km and 50 km of planned CO_2 pipelines**, respectively. These are large quantities; 23 $MtCO_2$/yr represents 21% of total accessible CO_2 in Europe, and exceeds the total projected CO_2 requirement from current planned e-fuels projects. For further context, the CO_2 needed to fulfill the power-to-liquid (PtL) sub-target for e-SAF in ReFuelEU Aviation is estimated to be 2, 18, and 62 $MtCO_2$/yr by 2030, 2040 and 2050, respectively.[71] It is important to note that there is uncertainty over future jet fuel demand and therefore also uncertainty over the future corresponding CO_2 demand.[72] It is also important to bear in mind that the total biogenic CO_2 available in Europe is projected to increase over time.[73]

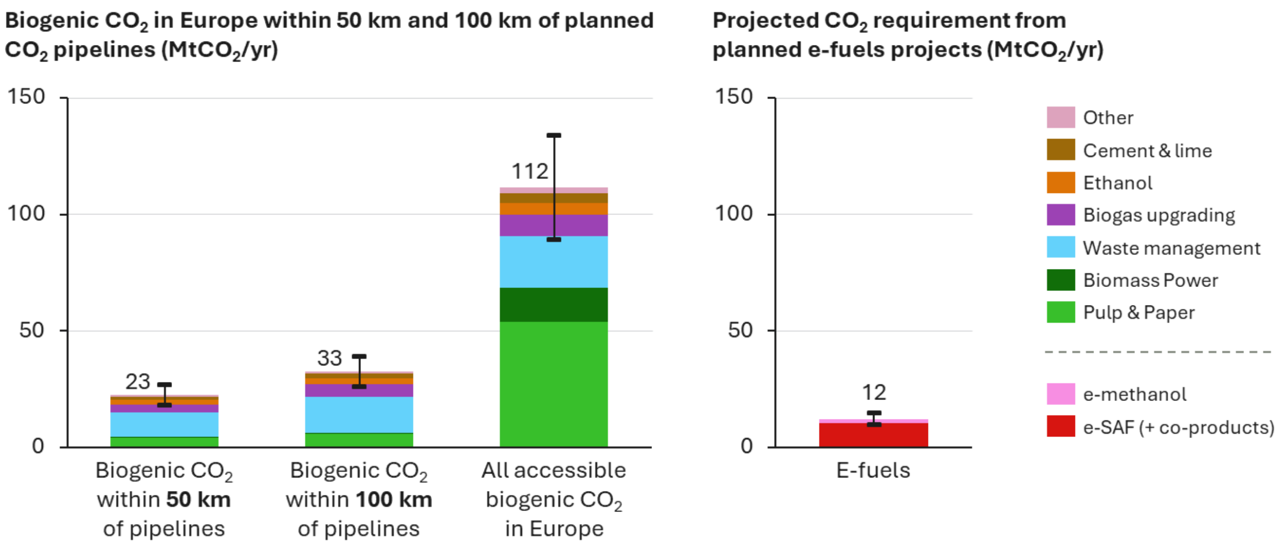

FIGURE 13 ACCESSIBLE BIOGENIC CO_2 PROXIMAL TO PLANNED CO_2 PIPELINES

Notably, the majority of CO_2 proximal to planned pipelines is from EfWs. These sites emit significant fossil CO_2 (~45% of total CO_2) and may have an incentive to connect to CCS networks to geologically sequester the fossil portion.[74] Assuming EfWs aim to capture

[71] Assumes total projected jet fuel demands (% e-SAF targets) of 43.7 (1.2%), 44.0 (10%), and 43.2 (35%) Mt/yr in 2030, 2040, and 2050, and 4.1 tCO_2 per tonne of e-SAF (includes CO_2 required for co-products). These projections are based on the projections (Policy Option A1 scenario) in the EU impact assessment of ReFuelEU Aviation: Study supporting the impact assessment of the ReFuelEU Aviation initiative - Publications Office of the EU.
[72] T&E Ricardo 2022. European CO2 Availability from Point Sources and DAC; T&E, 2025. Down to Earth; Future Cleantech Architects, 2024. ReFuelEU Aviation's Targets: A Feasibility Assessment
[73] E-fuels Alliance, Frontier Economics, 2025. CO2 point source potential in Europe
[74] Ashurst, 2025. Energy from Waste to be included in the EU Emissions Trading System

maximum[75] emissions (to achieve the best economies of scale),[76] there will likely be significant biogenic CO_2 volumes in these networks. **If e-fuel sites can access these networks, this would be a convenient and likely cost-effective means of sourcing biogenic CO_2**. Furthermore, these networks may be able to facilitate the movement of biogenic CO_2 from middle latitudes to regions near the North Sea with potentially lower cost renewables.

The possibility for CCS-focused networks to assist transport of biogenic CO_2 for e-fuels is **contingent on these networks having a policy of open-access and / or allowing** e-fuels sites to offtake CO_2 downstream. This would have to be accompanied by the relevant MMV (Monitoring, Metering and Verification) facilities and protocols to track biogenic CO_2 flows in and out of the pipelines. An initial assessment of CO_2 networks suggests that there are a range of policies: for example, the GOCO2 project in France is considering allowing downstream access to CO_2 for e-fuels,[77] while other projects such as Hynet are exclusively focused on transporting CO_2 to geological storage.[78]

Allowing network access for e-fuels could have multiple implications: on the one hand it would reduce the quantity of CO_2 taken to geological storage, which could reduce the economies of scale for geological storage.[79] This may create a disincentive for storage developers to allow removal of CO_2 from the network for e-fuels. Geological storage of biogenic CO_2 (BECCS) is also an important EU climate objective in its own right.[80] e-fuel access would also likely increase the already significant commercial and legal complexity of developing CO_2 networks. Conversely, e-fuel access could encourage the addition of further biogenic CO_2 to the network, improving the economies of scale for transport (and potentially counterbalancing any reduction in volumes sent to storage). It could also effectively create economic competition for biogenic CO_2, as biogenic CO_2 sources connected to the network may have the option to choose between geological storage of the CO_2 (supported by policy and/or credit sale), or to sell the CO_2 to e-fuels. Clearly**, there are many potential implications** for allowing e-fuels access to CO_2 networks. A recommended action is for further assessment on the potential impact and benefits.

While planned CO_2 pipelines are extensive**, there are some areas in Europe with 'untapped' biogenic CO_2**, with significant volumes not proximal to planned CO_2 infrastructure, or any e-fuels projects. An example is eastern Central Europe (Slovakia and parts of neighboring countries), with approximately 9 $MtCO_2$/yr of biogenic CO_2 in this area. Extension of current planned CO_2 pipelines in nearby areas could facilitate access to this CO_2. Other notable examples include central Sweden and Finland, where e-fuels projects tend to be located along the coast, but there is significant clustered biogenic CO_2 located inland (~15 $MtCO_2$/yr of biogenic CO_2). Aggregation and transportation of this (primarily biogenic) CO_2 to the coasts could facilitate further e-fuels production.

As a final note, the comparison in Figure 12 suggests that **the role of CO_2 shipping for e-fuels may be limited**. This is because in the coastal regions of Europe there tends to be either significant wind potential (e.g. North Sea) or solar potential (e.g. Mediterranean). While

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[75] This maximum is determined by the maximum feasible capture rate, typically 95% for post-combustion capture technologies.
[76] ERM, 2025. EfW with CCS: a key pillar for net zero in the UK.
[77] Elengy, accessed 2025. GOCO₂, Grand-Ouest CO₂
[78] Hynet, accessed 2025. About HyNet
[79] ZEP, 2011. The Costs of CO2 Capture, Transport and Storage
[80] ERCST, 2025. Bioenergy with CCS in the EU – Challenges and Opportunities

there is biogenic CO_2 near the coastlines, the high renewables potential locally suggests there is a low need to transport biogenic CO_2 over long distances at sea.

4.5 BIOGENIC CO_2 VOLUMES PROXIMAL TO E-FUELS PROJECTS

The mapping in Figure 12 also shows that planned e-fuels projects tend to be located near to biogenic CO_2 volumes. To quantify this, buffer areas are again used to assess the total accessible biogenic CO_2 within 50 km and 100 km of planned e-fuels projects.[81] Figure 13 shows that 36% and 62% of the e-fuels projects[82] have enough biogenic CO_2 to exceed their projected CO_2 requirement within 50 km and 100 km, respectively. This corresponds to 29% and 50% of the total tonnage of e-fuels products for 50 km and 100 km, respectively (including co-products).[83] One area of challenge to note is Spain, where, according to this analysis, very few projects have sufficient biogenic CO_2 within 50 km. Overall, the data shows that many, but not all, e-fuels projects will be able to source sufficient nearby biogenic CO_2, meaning they will need to transport biogenic CO_2 further, and/or use DAC or fossil CO_2.

It is also interesting to note that, as shown in Figure 13, that the majority of nearby biogenic CO_2 comes from Pulp & Paper. This again highlights the important role of Pulp & Paper as outlined previously.

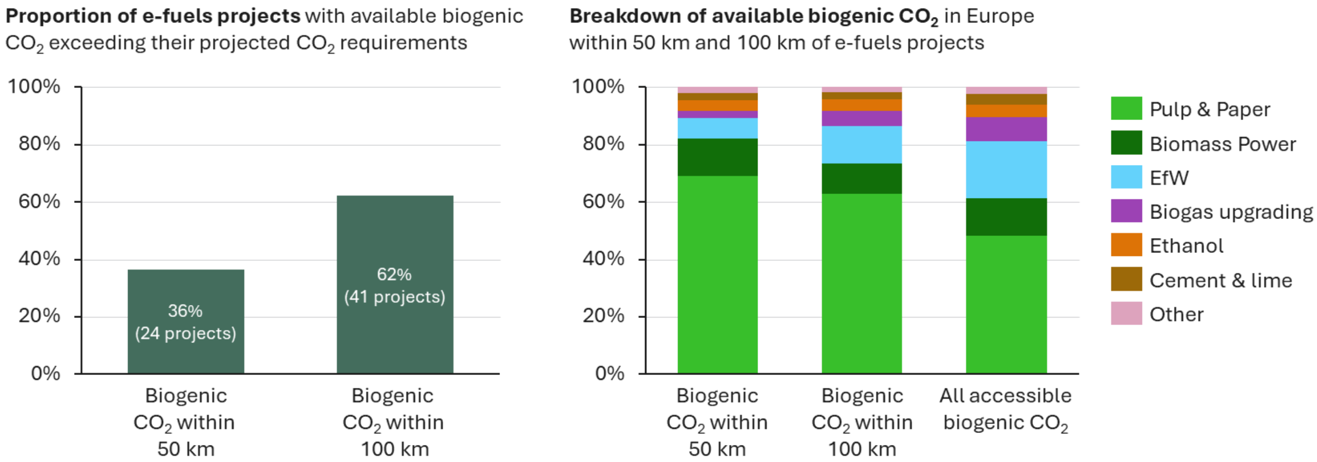


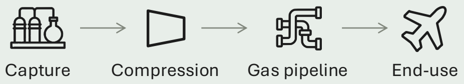
FIGURE 14 BIOGENIC CO_2 PROXIMAL TO E-FUELS PROJECTS

[81] Care is taken to avoid 'double-counting' biogenic CO_2 i.e. if a CO_2 source is within 50 km or 100 km of two or more e-fuels sites, all of the CO_2 cannot be supplied to all of the e-fuels plants; a division of CO_2 would need to take place. For simplicity, it is assumed that CO_2 is equally divided amongst e-fuels sites when a particular source is proximal to multiple e-fuels sites.
[82] Including e-fuels projects with announced e-fuel production quantities and those with non-zero CO_2 projected demand.
[83] Note that this corresponds to 0.8 Mt e-SAF/yr and 1.5 Mt e-SAF/yr of e-SAF production volumes for 50 km and 100 km, respectively

5. CASE STUDIES ON CO_2 SOURCING

Finally, we combine insights from throughout this study to develop five archetypal case studies for how CO_2 sourcing could play out in Europe. The case studies highlight pros and cons of various strategies, and how different factors may interact with one another. Archetype 1 is motivated by the significant co-location of e-fuel projects and Pulp & Paper. The opportunity to tap into larger CO_2 networks is inspiration for Archetype 2. Archetypes 3-5 also help to illustrate the potential roles of other transport modes besides pipelines.

Archetype 1: Direct pipeline from large biogenic CO_2 emitter

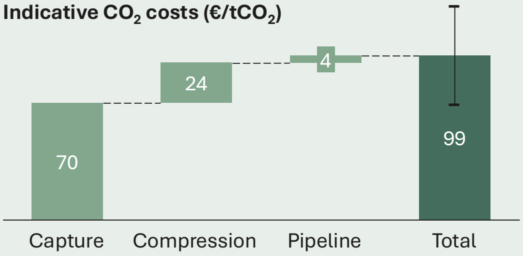


CO_2 source: pulp and paper site, moderate CO_2 concentration (12%) with 300 ktCO_2/yr captured, 100% biogenic CO_2, high capacity factor (>90%)

CO_2 transport and conditioning: CO_2 compressed for 10 km gas-phase CO_2 pipeline

Geographic relevance: many pulp and paper sites in Nordics, and some throughout Europe

Indicative CO_2 costs (€/tCO_2)



Pros

- ✓ Low logistical complexity
- ✓ No reliance on external projects or infrastructure
- ✓ Cost-effective at short distances

Cons

- × Pipeline development could take significant time
- × Lack of dedicated CO_2 buffer storage could lower consistency of CO_2 supply

Risks

- Stranded asset risk if CO_2 source no longer available

Barriers

- Acquisition of ROW for pipeline may be a challenge

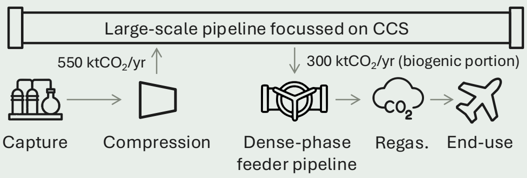
Other considerations and sensitivities

- Additional €13/tCO_2 for every additional 50 km of pipeline
- CO_2 buffer storage and associated liquefaction may be required if capacity factor of CO_2 source is <90% (with an estimated total additional cost of €15/tCO_2)

Takeaways

Archetype has a relatively high overall suitability for supplying CO_2 for e-fuels. Costs are moderate, and the overall logistical complexity of supply chain is low. The main challenge may be ROW for the pipeline. Liquefaction and buffer storage can be added if capacity factor of CO_2 source is low.

Archetype 2: Connection to a wider CO_2 network

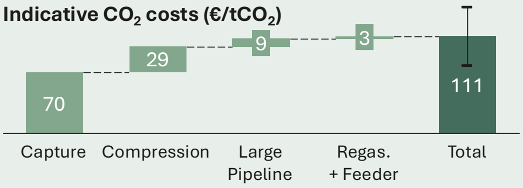


CO_2 source: EfW, moderate CO_2 concentration (12%) with 550 ktCO_2/yr captured, (300 ktCO_2/yr of biogenic CO_2), moderate capacity factor (~80%)

CO_2 transport and conditioning: CO_2 compressed for transport over 200 km in larger dense-phase 2 MtCO_2/yr CO_2 pipeline, with additional 10 km feeder pipeline to e-fuel site, and regasification prior to use

Geographic relevance: there are EfWs and plans for large-scale CO_2 throughout Europe (e.g. France, UK)

Indicative CO_2 costs (€/tCO_2)



Pros

- ✓ Potential for cost sharing of infrastructure
- ✓ Flexibility in e-fuels site location
- ✓ Flexibility in sourcing CO_2 from different emitters if needed

Cons

- × Reliance on external projects
- × Development of large shared CO_2 pipeline could take significant time
- × CO_2 from larger pipeline could have relatively high levels of impurities

Risks

- Potential competition for CO_2 from storage & other e-fuels producers

Barriers

- Acquisition of ROW for pipeline may be a challenge

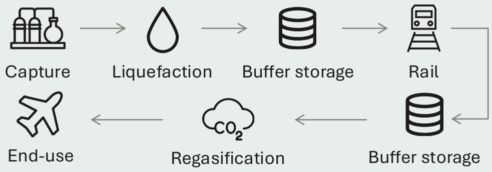
Other considerations and sensitivities

- Additional €0.9/tCO_2 on average for every additional 5 km of feeder pipeline
- Large scale CO_2 pipelines can use line-packing to store and release CO_2, providing a buffer to smooth out short-term fluctuations

Takeaways

Archetype has a moderate overall suitability for supplying CO_2 for e-fuels. There is a potential for low transport costs due to cost sharing, and high flexibility in CO_2 sourcing and site location, but the reliance on the development of large shared infrastructure could introduce delays. Additionally, offtaking CO_2 from a shared network may increase the levels of impurities in the CO_2 stream.

Archetype 3: Biogenic CO_2 source connected via rail

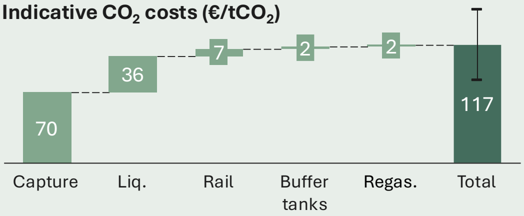


CO_2 source: pulp and paper site, moderate CO_2 concentration (12%) with 300 ktCO_2/yr captured, 100% biogenic CO_2, high capacity factor (>90%)

CO_2 transport and conditioning: CO_2 liquefied for 100 km rail transport, with buffer storage and regasification

Geographic relevance: many pulp and paper sites in Nordics with rail access, and some throughout Europe

Indicative CO_2 costs (€/tCO_2)



Pros
- ✓ Cost effective at moderate distances
- ✓ Flexibility in sourcing CO_2 from different emitters with rail access if needed

Cons
- × Relatively complex value chain logistics

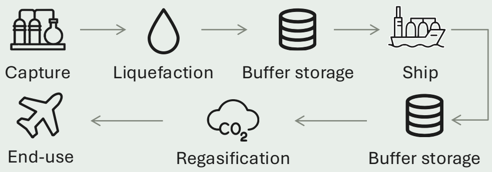
Barriers
- Requires rail access at CO_2 source and e-fuels plant
- Dependent on availability of rail network

Risks
- Transport could be subject to significant rail delays

Other considerations and sensitivities
- If the e-fuels site is not directly adjacent to the rail end point, a connecting feeder pipeline would be required. This would add €1.4/tCO_2 for every additional 10 km of feeder pipeline. Pumping will also be required, adding another €5/tCO_2
- Rail transport costs could vary significantly due to track access charges (up to €11/tCO_2 from the €7/tCO_2 base value)

Takeaways
Archetype has a moderate overall suitability for supplying CO_2 for e-fuels. While costs are moderate, this approach is reliant on both the e-fuels site and CO_2 source having direct rail access, as well as the rail network having availability.

Archetype 4: Biogenic CO_2 source connected via ship

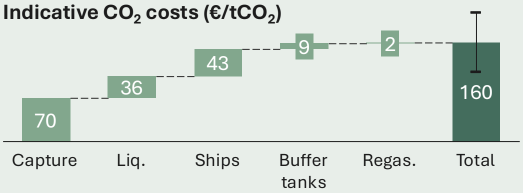


CO_2 source: pulp and paper site, moderate CO_2 concentration (12%) with 300 ktCO_2/yr captured, 100% biogenic CO_2, high capacity factor (>90%)

CO_2 transport and conditioning: CO_2 liquefied for 500 km ship transport, with buffer storage and regasification

Geographic relevance: considerable number of pulp and paper sites near ports in Nordics

Indicative CO_2 costs (€/tCO_2)



Pros
- ✓ Cost-effective at long distances
- ✓ Flexibility in sourcing CO_2 from different emitters with port access if needed

Cons
- × Not cost-effective at short distances
- × Large-scale CO_2 shipping is more nascent than other transport modes (TRL 8)

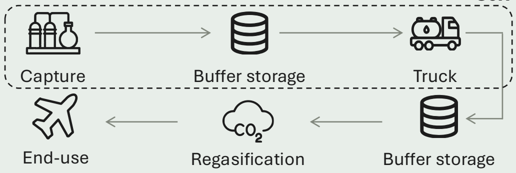
Barriers
- Long lead times for ships
- Requires dedicated port/jetty infrastructure and appropriate water depths

Risk
- Weather events and other external factors could affect shipping times

Other considerations and sensitivities
- Additional €0.8/tCO_2 for every additional 100km of shipping
- Environmental impact depends on the fuel used – for the case of LNG, 4.3 ktCO_2/yr would be emitted for a 500 km route
- There is significant uncertainty on port costs (which contribute €9/tCO_2 to the levelized cost in the base case), and these can vary by location

Takeaways
Archetype has a relatively low overall suitability for supplying CO_2 for e-fuels at present. Costs are high, and the logistics are relatively complex, with CO_2 ships subject to long lead times that could delay deployment timelines.

Archetype 5: Multiple dispersed biogenic CO_2 sources connected via truck

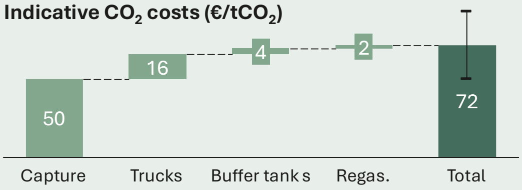


CO_2 transport and conditioning: 30x trucking routes (average distance of 50 km), with buffer storage and regasification

CO_2 source: 30 anaerobic digestors (ADs), 10 $ktCO_2$/yr from each on average for a total of 300 $ktCO_2$/yr captured. 100% biogenic CO_2.

Geographic relevance: High biogenic CO_2 density from ADs in UK, Denmark, Netherlands, Germany, and Italy

Indicative CO_2 costs (€/tCO_2)



Pros

- ✓ Leverages existing road infrastructure to connect to remote emitters
- ✓ Fast deployment times
- ✓ Flexibility in sourcing CO_2 from different ADs

Cons

- × Complex logistics; requires at least 35 truck movements per day in and out of e-fuels site
- × Requires aggregation of many emitters

Risks

- Could face road related challenges such as accidents and congestion

Barriers

- Site constraints may limit ability to accommodate high truck traffic

Other considerations and sensitivities

- The trucking cost depends on the size of the ADs. For example, if the average AD captures 5 or 20 $ktCO_2$/yr, the total transport cost would be €39 and €15/tCO_2, respectively (base case is €22/tCO_2)
- More complex logistical arrangements (e.g. milk runs) could help to reduce costs

Takeaways

Archetype has a low-moderate suitability for supplying CO_2 for e-fuels. While trucking is fast to deploy and costs are relatively low, it is challenging to aggregate CO_2 from many small emitters together, and there would be logistical challenges from the large number of trucks.

The different archetypes present a range of different pros and cons, with Archetype 1 (direct pipeline) likely of highest suitability due to the moderate transport costs and low logistical complexity. Archetype 4 may have a lower suitability due to due to high costs, and barriers such as long lead times for large CO_2 ships. Importantly, these archetypes present generalized considerations, and detailed case / location-specific evaluations are needed to judge the relative attractiveness of different sourcing strategies.

Notably, total costs of CO_2 sourcing (excluding shipping) range between €72-117/tCO_2,[84] with transport contributing €22-47/tCO_2, and capture contributing €50-70/tCO_2.[85] In comparison, the costs of sourcing CO_2 from DAC are expected to be significantly higher due to the low CO_2 concentrations in the atmosphere; estimates for projected DAC costs (assuming scaling-up of the sector) vary from approximately €200-550/tCO_2.[86,87] In other words, the cost from transporting CO_2 when sourcing biogenic CO_2 is still expected to be significantly less than the difference in the cost of DAC versus capture from point sources.

[84] These costs exclude taxes, and potential mark-ups by third-party transportation providers (if relevant)
[85] The cost of capture from Pulp & Paper (Archetypes 1-4) is taken to be €70/tCO_2 based on references and information presented in the "Capture costs" section of this report. Note that €70/tCO_2 is a representative value, and site-specific investigation is needed to refine this cost further. €70/tCO_2 falls towards the lower end of the range of Pulp & Paper capture costs – it is assumed that sites suitable for capture (with favourable capture costs) are prioritized. The cost of capture from biogas upgrading (Archetype 5) is taken to be a representative value of €50/tCO_2 – see Capture costs section for more information. This €50/tCO_2 value is at the centre of the range of capture costs from Biogas Upgrading.
[86] Sievert et al., 2024. Considering technology characteristics to project future costs of direct air capture
[87] See also: T&E, Ricardo, 2022. Scaling up Direct Air Capture; Herzog et al., 2024. Getting real about capturing carbon from the air. IEAGHG, 2022. Global Assessment of Direct Air Capture Costs.

6. CONCLUSIONS AND IMPLICATIONS FOR POLICY

This study presents a wide-ranging assessment of the drivers, costs, barriers, and opportunities for CO_2 sourcing for e-fuels in Europe, with a focus on CO_2 transport. There are a variety of conclusions from this analysis, and these insights have significant implications for policymakers:

- **Attractive CO_2 sources for e-fuels include Pulp & Paper, Biomass Power, EfWs, Ethanol, and Biogas Upgrading**. These sources tend to have significant accessible biogenic CO_2 volumes, along with low-to-moderate capture costs. Pulp & Paper is particularly attractive, and many current e-fuel projects are located near Pulp & Paper sites.
- **Several CO_2 transport methods for e-fuels are expected to be used**, with a variety of pros and cons for each mode, and comparable levelized costs at flow rates relevant for commercial e-fuels plants. Pipelines are the lowest cost for short-range connections, rail for longer distances, and trucking for the aggregation of CO_2 from smaller sources. Notably, the flexibility offered by trucking could make it an attractive solution for existing e-fuels projects – which may not have been located in a way that easily allows for other CO_2 transport modes.
- **Shipping may play a more limited role**, as coastal regions of Europe tend to either have significant wind potential (e.g. North Sea) or solar potential (e.g. Mediterranean). High local renewables potential suggests there is a low need to transport biogenic CO_2 over long distances at sea.
- **There are significant barriers to establishing routes for each of the different transport modes** (e.g. acquisition of ROW, permitting, stakeholder engagement, rail network availability). Government support from both the EU and member states for a variety of different CO_2 transport modes could play an important role in giving e-fuels developers flexibility and helping them to overcome barriers for CO_2 sourcing.[88] Such support could include, for example, national policy and /or regulation to facilitate access to and transport of CO_2 via rail networks, or support to accelerate permitting for pipelines.
- **CAPEX-support from government (e.g. grants) may be important** for transport routes with a high proportion of costs attributed to CAPEX – this is particularly true for pipelines and intermittent modes for short-distance routes. OPEX-related support (e.g. subsidies, tax credits) may be important when OPEX plays a large role i.e. intermittent modes for longer distances. It is also important to highlight that conditioning contributes a significant portion to CO_2 sourcing costs. If government support for CO_2 capture does not also cover the associated CO_2 conditioning costs, greater support for transport is needed.
- **CO_2 transport costs could range between €20-50/tCO_2 for routes up to 200 km**. These costs are relatively low compared to the expected capture costs for biogenic CO_2 of €20-150/tCO_2. Additionally, according to this analysis, approximately 60% of current and planned e-fuels sites today have enough accessible biogenic CO_2 within 100 km to exceed their CO_2 requirement, meaning that biogenic CO_2 transport costs could be moderate for many e-fuels sites. However, not all e-fuels sites have significant nearby biogenic CO_2 volumes – this tends to be case in regions such as Spain and Norway. In these cases,

[88] CCS Europe, accessed 2025. CCS Europe response to the call for evidence on EU Innovation Fund operation evaluation

longer-distance biogenic CO_2 transport will be needed, or alternatives to biogenic CO_2 – DAC and / or fossil CO_2 – may become more attractive.

- **Planned CO_2 infrastructure focused on CCS presents a significant opportunity to aggregate biogenic CO_2 volumes** and to transport this CO_2 to regions with higher potential for lower cost renewable electricity generation; there is 23 and 33 $MtCO_2$/yr of accessible biogenic CO_2 within 50 km and 100 km of planned routes, respectively. **This could unlock substantial e-fuels production if these networks are 'open-access' in the sense that e-fuel sites can offtake CO_2.**
- **EU policy should allow and encourage CO_2 networks to give e-fuels access to CO_2.** Currently, the Trans-European Networks for Energy (TEN-E) Regulation appears to only make cross-border CO_2 networks "for the purposes of geological storage" eligible for Projects of Common / Mutual Interest (PCI/PMI) status and funding from Connecting Europe Facility (CEF).[89] As of September, over €900 mn has been directed to CCS-focussed CO_2 networks.[90] Few (if any) of these projects appear to allow for CO_2 offtake for utilisation, a reflection of the limitation on CCU eligibility from TEN-E. Exclusion of CCU stands in contrast to broader EU policy which recognizes the critical role of e-fuels in decarbonizing the EU. This is despite CO_2 being an essential feedstock for e-fuels. Furthermore, e-fuels access could provide synergies and wider benefits to CO_2 networks – potentially by incentivizing the addition of additional CO_2 volumes (improving economies of scale), and creating healthy competition. Suggested next steps include engagement between policymakers and e-fuels and CO_2 network developers, and an assessment of the potential benefits and impacts of revising TEN-E to support CO_2 transport for e-fuels.
- **Dedicated CO_2 networks to collect CO_2 for utilisation could help to unlock additional e-fuels production.** There is a cluster of ~15 $MtCO_2$/yr of (primarily) biogenic CO_2 in central Sweden and Finland, which is ~14% of the accessible total in Europe. Additionally, there are significant untapped biogenic CO_2 volumes (~9 $MtCO_2$/yr) in central Eastern Europe that are not proximal to planned e-fuels projects or large-scale CCUS infrastructure. Additionally, renewables capacities in this region tend to be limited. The development of CO_2 networks to transport CO_2 in these regions to more favourable locations could facilitate further e-fuels production. Policy support to develop these networks can help to derisk such projects and improve their financial viability.

[89] Based on ERM's reading of the 2022/869 framework law [Link]
[90] Carbon Gap, accessed 2025. Connecting Europe Facility and Trans-European Network for Energy Regulation. CINEA, 2025. CEF Energy 2025 PCIs and PMIs call: Virtual Info Day

7. ACKNOWLEDGEMENTS

ERM and T&E would like to acknowledge the following individuals and organisations for generously lending their insight and expertise in the development of this report:

- Dr. Corey Myers, Anvil Capture Systems
- Dr. Caspar Donnison, Lawrence Livermore National Laboratory
- Global CCS Institute
- Mithran Daniel Solomon, Fraunhofer Institute for Factory Operation and Automation
- Prof. Solomon Brown, University of Sheffield
- Vebjørn Kyerstad, Clarksons

8. APPENDIX

8.1 OVERVIEW OF POTENTIAL SOURCES FOR CO_2 CAPTURE

TABLE 5 DETAILS OF ASSESSMENT OF CO_2 SOURCES

CO_2 source	Description	Available CO_2 in Europe ($MtCO_2$/yr)	Average size of emitter ($MtCO_2$/yr)	Typical key on-site streams	Variation in CO_2 production over time	CO_2 conc. / purity before capture	CO_2 conc. / purity after capture	Type of CO_2 and eligibility of CO_2 for RFNBO* production	Sector growth prospects	Other considerations
Atmosphere	CO_2 is captured directly from the atmosphere via direct-air capture (DAC). There are a variety of DAC technologies in development	0.01†[91] (100% atmospheric)	Average size of 0.003 Mtpa‡ for operational DAC plants, 0.3 Mtpa for operational and planned DAC plants[91]	Single stream of captured CO_2	Likely runs as baseload (>90% load factor)	0.04 vol% CO_2 (atmosphere)	>97 vol% CO_2; depends on DAC process[92]	Atmospheric CO_2; Eligible, with no limits	Significant growth expected, however there is large uncertainty; 0.8 Mtpa in pipeline by 2030[91]	The DAC plant can be sited flexibly
Ethanol Production	CO_2 is produced during the fermentation process in ethanol production	5[93,98] (100% biogenic)	0.057[93]	Potentially 2 key streams: high purity CO2 from fermentation, and low purity CO_2	Seasonable variation due to availability of biomass is common[95]	Fermentation: >99 vol% CO_2, low conc.'s of water, ethanol, and sulphur	~100% CO_2	100% Biogenic CO_2; Eligible, however RED III sustainability criteria	Projected to increase to 5.4 Mpta by 2030, then shrinking to 1 Mtpa by 2050[98]	Sensitive to annual weather patterns / droughts. Sustainability of CO_2

[91] IEA, accessed 2025. CCUS Projects Explorer
[92] Yafiee et al., 2024. DAC vs. DOC - A perspective on scale-up demonstrations and environmental relevance to sustain decarbonization
[93] ERM internal database; and ERM, 2022. Assessment of European biogenic CO2 balance for SAF. Excludes potential fossil CO_2 from sites due to lack to data.
[95] AHDB, accessed 2025. Bioethanol output declines further: Grain market daily
[98] Ricardo, 2022. European CO2 availability from point sources and Direct Air Capture

CO_2 source	Description	Available CO_2 in Europe ($MtCO_2$/yr)	Average size of emitter ($MtCO_2$/yr)	Typical key on-site streams	Variation in CO_2 production over time	CO_2 conc. / purity before capture	CO_2 conc. / purity after capture	Type of CO_2 and eligibility of CO_2 for RFNBO* production	Sector growth prospects	Other considerations
				from biomass boiler[94]		compounds [96,97]		must be fulfilled.		may be in question[98]
Biogas Combustion	Biogas is combusted; it can be produced via anaerobic digestion of organic matter e.g. food & agricultural waste, sewage, manure, and MSW	43[98] (100% biogenic)[99]	0.001[93]	Single stream	Potential seasonality from feedstock availability and composition	10-15%; remainder is H_2O, O_2, N_2. Trace SO_2 may be present if H_2S in biogas has not been removed	~100% CO_2; however further polishing likely needed for waste feedstocks	100% Biogenic CO_2; Eligible, however RED III sustainability criteria must be fulfilled.	Significant growth expected; 174 Mtpa by 2050[98]	Feedstock may affect perception of sustainability[98]
Biogas Upgrading	Biogas is 'upgraded' to biomethane, producing a relatively pure CO_2 stream as a 'by-product'	9[98] (100% biogenic)	0.006[93]	Single stream	Seasonality from feedstock, and also from ability to inject biomethane into grid[100]	>90%; depends on upgrading technology[93]	~100% CO_2; however further polishing likely needed for waste feedstocks	100% Biogenic CO_2; Eligible, however RED III sustainability criteria must be fulfilled.	Significant growth expected; 10 Mtpa by 2050[98]	Feedstock may affect perception of sustainability[98]

94 Ortiz et al., 2019. Mass and Heat Integration in Ethanol Production Mills
96 Huang et al., 2020. Using Waste CO2 to Increase Ethanol Production from Corn Ethanol Biorefineries: Techno-Economic Analysis
97 Keshgi et al., 2005. Sequestration of fermentation CO2 from ethanol
99 Sia Partners, 2023. 7th European Biomethane Benchmark
100 DESNZ, 2024. Future policy framework for biomethane production: call for evidence

CO_2 source	Description	Available CO_2 in Europe ($MtCO_2$/yr)	Average size of emitter ($MtCO_2$/yr)	Typical key on-site streams	Variation in CO_2 production over time	CO_2 conc. / purity before capture	CO_2 conc. / purity after capture	Type of CO_2 and eligibility of CO_2 for RFNBO* production	Sector growth prospects	Other considerations
Distilleries / Breweries	Alcohol is produced (e.g. beer, wine, sprits), with biogenic CO_2 released from fermentation	~3 Mpta from all alcohol production[101,102,103,104] (100% biogenic CO_2); estimated ~30 Mpta fossil CO_2 from on-site boilers[105]	Large range [101]depending on site size; 0.001-0.02 Mtpa for medium–large sites; many microbreweries with CO_2 output in 10's of tCO_2/yr	2 key streams: CO_2 from fermentation, and from on-site boiler	Variation during batches from sugar fermentation process (multiple fermenters can smooth profile). Seasonality of production can be present[106]	Fermentation: >99 vol% CO_2, low conc.'s of water, ethanol, and sulphur compounds[105,107]	~100% CO_2 for capture from fermentation	100% Biogenic CO_2; Eligible, however RED III sustainability criteria must be fulfilled.	Relatively stable, with slight growth projected over time due to growth in alcohol production	Large proportion of CO_2 from breweries may be used on-site for beer carbonation[93,107]
Biomass Power Plant	Biomass is combusted to provide heat and power. In some cases, biomass is co-fired with fossil fuels (e.g. coal)	42 Mtpa (67% biogenic on average)	0.54[93]	Can be multiple flue stacks for large plants	Load factor can vary depending on needs of electricity production (average is 53% in Europe)[108]	10-15 vol% CO_2; can be biomass, alkali metals, other trace metals, sulphur compounds; dependent	Dependent on capture process; representative for amines: 99.8 vol% CO_2, 100-700 ppm H_2O, 1.5-40	Biogenic CO_2 portion is eligible (subject to sustainability criteria); fossil CO_2 portion ineligible from 2036	Significant uncertainty, however, there are some expectations for a growth in	Feedstock sourcing may affect perception of sustainability

[101] Grand et al., 2024. Valorisation of Carbon Dioxide from Fermentation in Craft Brewing
[102] Eurostat, 2023. Wine production reached 16.1 bn L
[103] Eurostat 2024. 34.3 bn litres of beer produced in the EU
[104] Statista, 2025. Sold production volume of spirits in the European Union in 2023, by segment
[105] EPA, accessed 2025. EPA Facility Level GHG Emissions Data
[106] Chuck Cowdery Blog, accessed 2025. Why Do Whiskey Makers Have Only Two Seasons?
[107] BREWblog, accessed 2025. CO2 capture in a small brewery – a case study
[108] Bolson et al., 2022. Capacity factors for electrical power generation from renewable and nonrenewable sources

CO_2 source	Description	Available CO_2 in Europe ($MtCO_2$/yr)	Average size of emitter ($MtCO_2$/yr)	Typical key on-site streams	Variation in CO_2 production over time	CO_2 conc. / purity before capture	CO_2 conc. / purity after capture	Type of CO_2 and eligibility of CO_2 for RFNBO* production	Sector growth prospects	Other considerations
						on existing flue gas clean-up[109]	ppm NO_x, 10-70 ppm SO_x, <0.1 ppm metals (total)[109]		biomass power[110]	
Pulp and paper	Processes wood into paper. Pulping and papermaking can occur at different sites in some cases. Kraft chemical process is most common, however, there are other pulping methods	75 Mtpa (75% biogenic)	0.74[93]	Kraft pulp mills: 3 key CO_2 streams: recovery boiler (75-90%), lime kiln (5-10% of CO_2, biomass boiler (10-20%, optional)[110]	Typically runs as baseload	Kraft pulp mills: recovery boiler ~13 vol% CO_2, lime kiln ~21%, biomass boiler 10-15%. Trace metal & sulphur compounds can be present	Dependent on capture process; representative purity is similar to Biomass Power Plant case: 99.8 vol% CO_2.	100% Biogenic CO_2; Eligible, however RED III sustainability criteria must be fulfilled.	Relatively stable, with slight growth projected over time due to growth of pulp and paper industry	Feedstock sourcing may affect perception of sustainability
Cement	Clinker is produced in a rotary kiln, with a pre-calciner. Alternative fuels (which	128 (~4% biogenic)[111]	0.6	Single key stream	Typically runs as baseload	15-30 vol% CO_2; NO_x, SO_2, CO also present. Smaller quantities	99.8 vol% CO_2, 0.1-0.3% N_2, 640 ppm H_2O, 1 ppm NO_x, <0.1 ppm SO_x,	Biogenic CO_2 portion is eligible (subject to sustainability criteria), fossil CO_2	Sector overall expected to remain relatively stable, however,	CO_2 produced as part of clinker production process. CCUS

109 Porter et al., 2015. The range and level of impurities in CO2 streams from different carbon capture sources
110 IEA Bioenergy, 2017. Bioenergy's role in balancing the electricity grid and providing storage options – an EU perspective; 2020. Deployment of BECCS/U value chains
111 EEA, accessed 2025. European Industrial Emissions Portal

CO_2 source	Description	Available CO_2 in Europe ($MtCO_2$/yr)	Average size of emitter ($MtCO_2$/yr)	Typical key on-site streams	Variation in CO_2 production over time	CO_2 conc. / purity before capture	CO_2 conc. / purity after capture	Type of CO_2 and eligibility of CO_2 for RFNBO* production	Sector growth prospects	Other considerations
	typically have a biogenic component) are often used as a fuel source					of VOCs, NH_3, chlorine, and HCL may also be emitted[109]	<0.01 ppm metals (total)	portion ineligible from 2041	use of supplementary cementitious materials may reduce clinker use, reducing CO_2 production in turn[112]	widely considered key decarbonisation measure for cement
EfW (Energy-from-Waste)	Residual waste is incinerated as a waste-disposal route. It is common to harness power (and/or heat) from this process to be fed into local energy systems (energy-from-waste)	72 Mtpa (55% biogenic on average)[111]	0.3	Single stream, although there can be multiple flue stacks for large plants	Estimated average load factor of 77%[113], likely affected by seasonality of MSW production[114]	10-14 vol% CO_2; other pollutants dependent on existing flue gas treatment; SO_2, NO_x, dioxins, heavy metals can be present[115]	Dependent on capture process; representative purity is similar to Biomass Power Plant case: 99.8 vol% CO_2.	Biogenic CO_2 portion is eligible (subject to sustainability criteria); fossil CO_2 portion ineligible from 2036	Significant growth expected[116]	CCUS widely considered key decarbonisation measure for EfWs

[112] McKinsey, 2024. The future cement industry: A cementitious 'golden age'?
[113] Project Drawdown, accessed 2025. Waste to Energy
[114] Denafas et al., 2014. Seasonal variation of municipal solid waste generation and composition in four East European cities
[115] GEMCO Energy, 2024. Key Points of Flue Gas Treatment in Waste to Energy Plant
[116] Grand View Research, accessed 2025. Europe Waste To Energy Market Size, Share & Trends Analysis Report By Technology (Technology, Thermal), By Country, and Segment Forecasts, 2023 - 2030

CO_2 source	Description	Available CO_2 in Europe ($MtCO_2$/yr)	Average size of emitter ($MtCO_2$/yr)	Typical key on-site streams	Variation in CO_2 production over time	CO_2 conc. / purity before capture	CO_2 conc. / purity after capture	Type of CO_2 and eligibility of CO_2 for RFNBO* production	Sector growth prospects	Other considerations
Iron and steel	Iron and steel involves a variety of primary and secondary steelmaking processes, e.g. blast furnace & basic oxygen furnaces (BF-BOFs), and electric-arc furnaces (EAFs)	119 (0.4% biogenic)	0.9	Large steel sites could have dozen of onsite streams e.g coke ovens, BF, BOF[117]	Typically runs as baseload	CO_2 vol% heavily dependent on CO_2 stream and process; can range from 2-90 vol% CO_2. CO, O_2, NO_x, SO_x, VOC's can also be present	Dependent on capture process and CO_2 stream	'Process CO_2' portion ineligible from 2041, fossil CO_2 from electricity generation ineligible from 2036	Declining production trend[118], alternative process (e.g. via hydrogen) and more recycling (via EAFs) will lower CO_2	Carbon capture may be difficult to implement at large, complex, interconnected steel plants with multiple CO_2 streams

†: The available CO_2 for DAC is taken to be the current amount of CO_2 captured, *: Renewable fuels of non-biological origin, **: Municipal solid waste, ‡Mtpa is shorthand for $MtCO_2$/yr

[117] Transition Asia, 2024. Explainer - Carbon Capture in the Steel Sector; BF-BOF abatement
[118] EUROFER, 2025. European Steel in Figures, 2025

8.2 VARIATION IN CO_2 VOLUMES FROM INDUSTRIAL SOURCES

It is also useful to consider how the CO_2 volumes from sectors varies from site to site, as shown below:

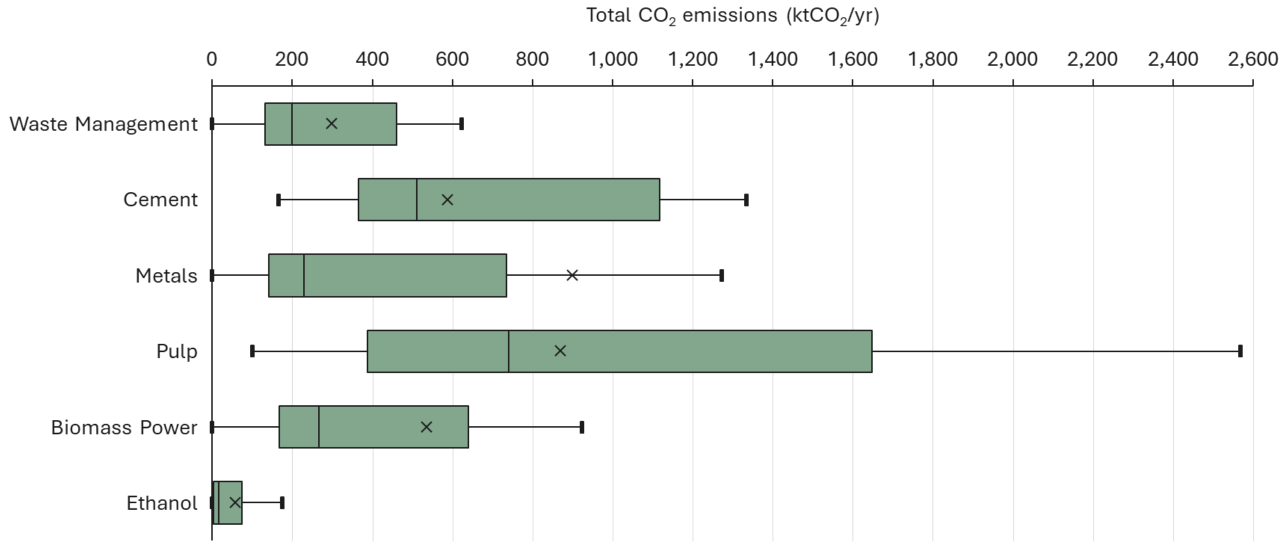


FIGURE 15 VARIATION IN CO_2 VOLUMES BY SECTOR[119]

Biogenic CO_2 volumes from Biogas Upgrading tend to vary depending on the biogas type. Data from the IEA demonstrates that anaerobic digestors for wastewater treatment plants, to treat animal manure, and to treat food and agricultural waste tend to have biomethane production capacities of 30-40 GWh/yr (~5 ktCO_2/yr), while landfills have a much higher average capacity of 250 GWh/yr (~36 ktCO_2/yr of biogenic CO_2).[120]

One point of note is that the % biogenic CO_2 content in cement can vary significantly depending on the level of alternative fuel use. IEP data suggests this % can vary from 0 (i.e. no fuel substitution) up to 16%.

8.3 CO_2 TRANSPORT MODELS

A set of shared assumptions are used across the different transport models. These assumptions are:

- Discount rate of 10% for cashflows as well as carbon
- 25-year operational lifetime
- 156 EUR_{2024}/MWh for electricity[121]

The cost estimates are deemed to be AACE Class 5 cost estimates, and have a ±50% uncertainty.

[119] This plot follows the convention for box plots, where the shaded box represents the 1st, 2nd (middle line), and 3rd quartiles of the data range. The "x" gives the mean (average). The bounds for each plot represent the maximum and minimum values, excluding outliers (data points beyond a distance of 1.5 times the interquartile range (between the 1st and 3rd quartiles) from the box).
[120] IEA, 2020. IEA Bioenergy Task 37 updated list of biogas upgrading plants
[121] Eurostat, accessed 2025. Electricity prices by type of user

8.3.1 ASSUMPTIONS: LEVELISED COST OF TRANSPORT

CO_2 Shipping

CO_2 shipping costs builds upon the established methodology previously applied by ERM for IEAGHG and BEIS, while incorporating updated cost parameters (e.g. ship CAPEX) based on insights from the Clarksons/CCSA report to provide more accurate and current estimates.[122,123,124]

CO_2 rail

The rail cost model assumes a locomotive transporting rail tankers.[125,126] Additional sources such as UKRI were consulted to incorporate infrastructure-related expenses (e.g., loading and unloading) for both CAPEX and OPEX.[127,128,129,130]

CO2 Trucking

The trucking model builds on ERM's internal truck cost modelling tool with additional considerations for CO_2 trailer tankers..[131,132] European Commission's regulations on driving times and rest periods were included to ensure accurate reflection of CO_2 truck operating periods.[133] Additional sources, such as UKRI, were consulted to incorporate relevant infrastructure costs (e.g. loading / unloading) for both CAPEX and OPEX.[134,135]

CO_2 pipelines (compressed gas and dense phase liquid)

CO_2 pipeline costs are based on natural gas pipeline cost data from literature, with additional cost adjustment factors applied to account for variations in pipeline thicknesses for CO_2 pipelines. [136,137,138] It is assumed that the dense-phase pipeline has an input pressure of 150 bar, and that the gas-phase CO_2 pipeline has input pressure of 35 bar. Booster pumps / compressors are included as needed to maintain pressures about 80 bar and 15 bar for dense-phase and gas pipelines, respectively.

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122 IEAGHG, 2020. The Status and Challenges of CO_2 Shipping Infrastructures
123 BEIS, 2018. Shipping CO2 – UK Cost Estimation Study
124 CCSA, 2024. Clarksons/CCSA Report: Updated Costs for CO_2 Ship Transport
125 UKRI, 2024. Industrial decarbonisation: getting ready for non-pipeline transport
126 European Court of Auditors, 2016. Rail freight transport in the EU: still not on the right track
127 Myers et al., 2024. The cost of CO2 transport by truck and rail in the United States
128 Roussanaly et al., 2017. Techno-economic evaluation of CO2 transport from a lignite-fired IGCC plant in the Czech Republic
129 IRG Rail, 2023. Market monitoring
130 Rail Partners, 2024. Rail v Road Cost Analysis
131 DHL Freight, 2024. Truck Speed Limits in Europe – How Fast to Drive in Each Country
132 ASCO, accessed 2025. ASCO Transportable CO2 Tanks / ASCO CO2 Semi-Trailers
133 European Commission, accessed 2025. Driving time and rest periods
134 EVS30, 2017. Maintenance & Repair Cost Calculation and Assessment of Resale Value for Different Alternative Commercial Vehicle Powertrain Technologies
135 Logistics UK, 2019. Manager's Guide to Distribution Costs
136 Knoope, 2014. Improved cost models for optimizing CO2 pipeline configuration for point-to-point pipelines and simple networks
137 Brown et al., 2022. The development of natural gas and hydrogen pipeline capital cost estimating equations
138 NETL, 2023. Energy analysis

8.3.2 ASSUMPTIONS: LEVELISED COST OF CONDITIONING

Cost estimates for the various CO_2 conditioning technologies are derived from a range of publicly available sources.[139,140,141,142,143,144] CAPEX values were scaled using the power law approach to reflect different plant sizes. It is important to note that each technology operates under (multiple) distinct physical conditions, as outlined below:

- Compression: 1 bar – 35 bar, constant 25°C
- Compression: 1 bar to 150 bar, constant 25°C
- Liquefaction: 25 bar – 15 bar, -30°C
- Regasification: 15 bar, -30°C – 1 bar, 25°C
- Buffer storage: constant 15 bar, -30°C

8.3.3 ENERGY REQUIREMENTS AND ADDITIONAL CO_2 FROM CO_2 TRANSPORT

It is also important to consider the energy requirements for the different CO_2 transport modes, along with the associated CO_2 emissions. As shown in Figure 16, the energy requirements for CO_2 transport and associated CO_2 emissions are dominated by CO_2 conditioning. Note that the figure below assumes a grid emission factor of 255 kgCO_2/MWh for Europe.[145]

It is also noted that there can be CO_2 boil-off gas (BOG) during transport. This occurs due to liquefied CO_2 evaporating due to heat transfer from the external environment. Boil-off can be minimized through factors such as thermal insulation, and is likely minimal for trucking and rail CO_2 transport due to transport times usually being short.[146] BOG can be a more important factor to manage for long shipping journeys, and may require dedicated equipment to reliquefy the CO_2.[147] Additionally, interfaces between different parts of the CO_2 value chain can cause CO_2 to be lost. Case-specific investigation should be undertaken to understand the overall impact of the CO_2 losses across a CCU value chain.

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[139] Sydney et al., 2022. Cost of Capturing CO2 from Industrial Sources
[140] Eldrup et al., 2019. A Cost Estimation Tool for CO2 Capture Technologies
[141] Deng et al., 2019. Techno-economic analyses of CO2 liquefaction: Impact of product pressure and impurities
[142] Bjerketvedt et al., 2020. Optimal design and cost of ship-based CO2 transport under uncertainties and fluctuations
[143] BEIS, 2020. CCS deployment at dispersed industrial sites
[144] IEAGHG, 2023. Components of CCS Infrastructure - Interim CO2 Holding Options
[145] Ember, 2023. Report European Electricity Review 2023.
[146] Myers et al., 2024. The cost of CO2 transport by truck and rail in the United States
[147] GCMD, 2024. Concept study to offload onboard captured CO2

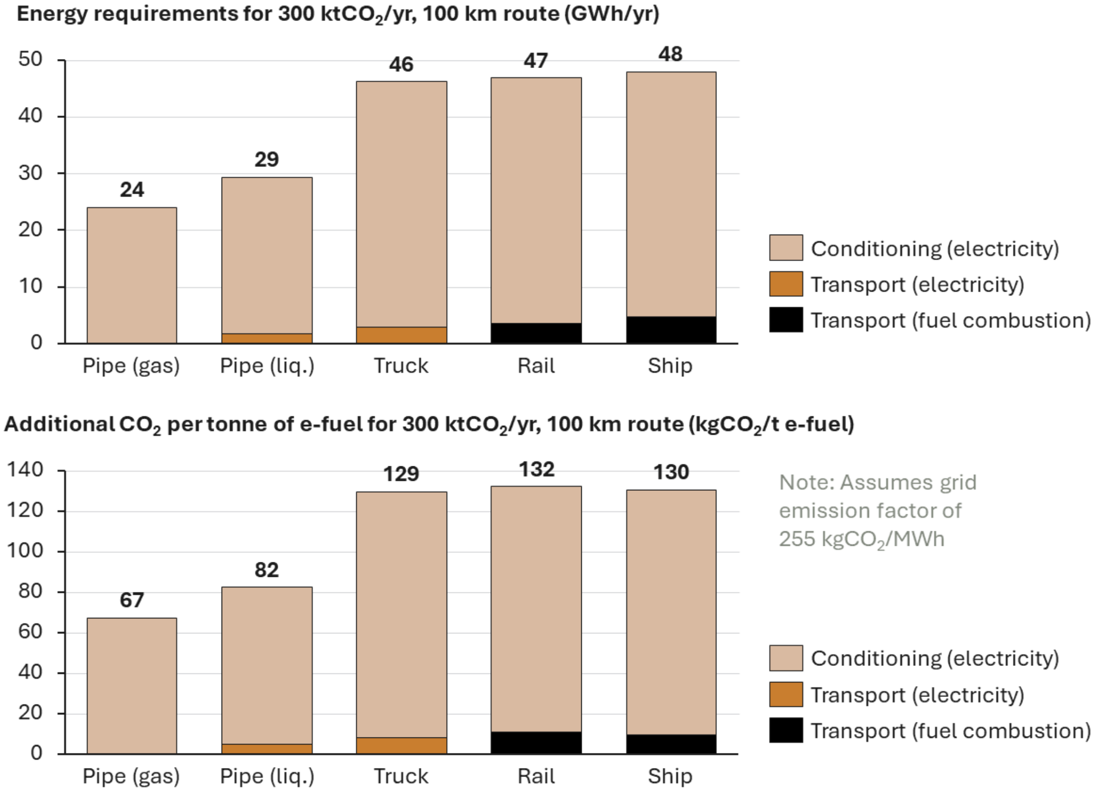

FIGURE 16 ENERGY REQUIREMENTS AND CO_2 EMISSIONS FROM CO_2 TRANSPORT

8.3.4 SENSITIVITIES OF LEVELIZED CO_2 TRANSPORT COSTS

The figure below gives sensitivities of CO_2 transport costs for 300 ktCO_2/yr, 100 km distance route. Note that these sensitivities do not include conditioning costs, and a 90% capacity factor is assumed. There tends to be a large sensitivity on CAPEX for the transport modes.

Sensitivity	Low	Base	High
CAPEX	50%	100%	150%
Energy OPEX	50%	100%	150%
Non-energy OPEX	50%	100%	150%
Routing factor	100%	125%	100%

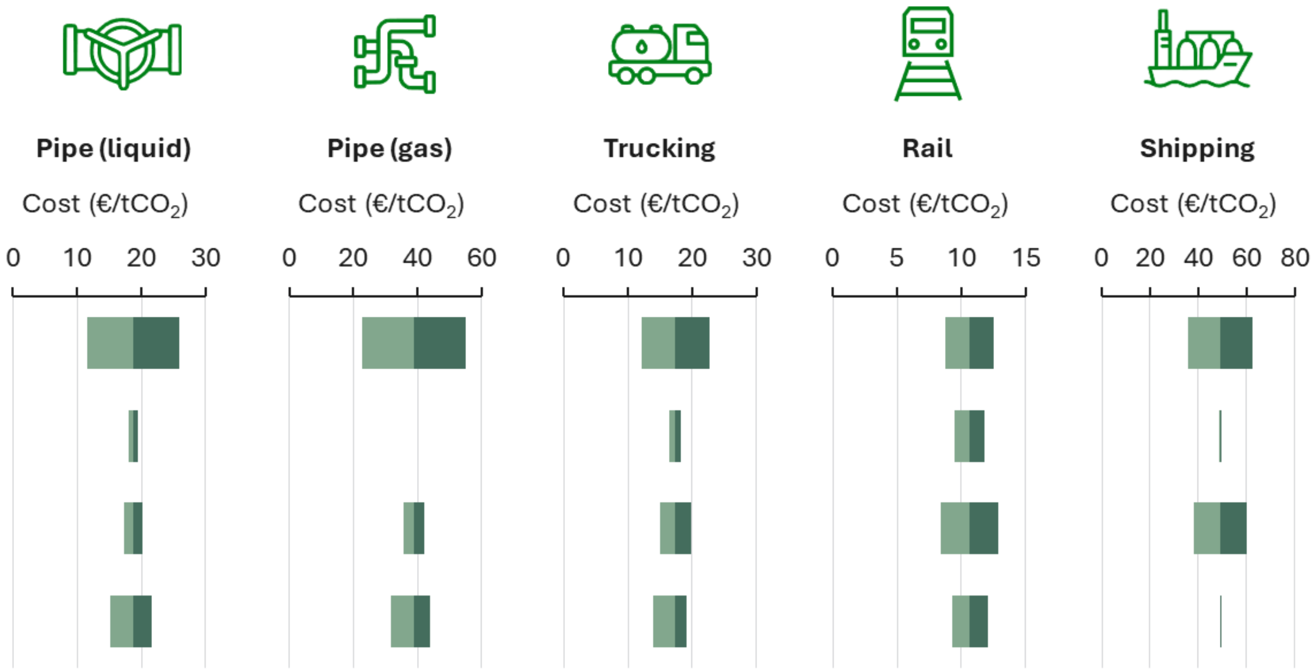

FIGURE 17 SENSITIVITIES OF CO_2 TRANSPORT COSTS FOR 300 KTCO_2/YR, 100 KM DISTANCE

8.4 RESOURCE REQUIREMENTS FOR E-FUELS PRODUCTION

The following assumptions on e-fuels resource requirements are used to develop levelized costs for the transport of H_2, CO_2, and electricity:

TABLE 6 ASSUMPTIONS OF RESOURCE REQUIREMENTS (PER TONNE OF USEFUL PRODUCT)

Pathway	tCO_2/t	tH_2/t	MWh/t
E-methane	3	0.5	0.63
E-methanol	1.45	0.2	1
MTJ	3.3	0.5	0.5
RWGS+FT	3.3	0.5	0.9

8.5 CO_2 PURITY SPECIFICATIONS FOR DIFFERENT TRANSPORT OPTIONS

	Shipping			Pipeline			Compressed Gas Association (LCO_2)		
Component	**Northern Lights**	**EU recommendation**	**Aramis (ships)**	**Project DYNAMIS**	**Aramis (pipeline)**	**Porthos**	**Industrial grade**	**Food grade[a]**	**Beverage grade**
Carbon Dioxide (CO_2)	Balance (≥ 99.81 mol%)	> 99.7% by volume	Balance (≥ 99.79 mol%)	> 95.5%	Balance (≥ 95 mol%)	≥ 95 mol%	≥ 99 vol%	≥ 99.5 vol%	≥ 99.9 vol%
Water (H_2O)	≤ 30 ppm-mol	< 50 ppm	< 30 ppm-mol	≤ 500 ppm	< 70 ppm-mol	≤ 70 ppm-mol	≤ 32 ppm-vol	≤ 20 ppm-vol	≤ 20 ppm-vol
Hydrogen (H_2)	≤ 50 ppm-mol	< 0.3% by volume	< 500 ppm-mol	< 4% by volume	< 7500 ppm-mol	≤ 0.75 mol%			
Nitrogen (N_2)	≤ 50 ppm-mol	< 0.3% by volume		< 4% by volume	< 2.4 mol%	≤ 2.4 mol%			
Argon (Ar)	≤ 100 ppm-mol	< 0.3% by volume		< 4% by volume	< 0.4 mol%	≤ 0.4 mol%			
Methane (CH_4)	≤ 100 ppm-mol	< 0.3% by volume		Aquifer: < 4% by vol, EOR:< 2%	< 1 mol%	≤ 1 mol%	≤ 50 ppm-vol	≤ 50 ppm-vol	≤ 20 ppm-vol
Carbon Monoxide (CO)	≤ 100 ppm-mol	< 2000 ppm	< 1200 ppm-mol	≤ 2000 ppm	< 750 ppm-mol	≤ 750 ppm-mol		≤ 10 ppm-vol	≤ 10 ppm-vol

	Shipping			Pipeline			Compressed Gas Association (LCO_2)		
Oxygen (O_2)	≤ 10 ppm-mol		< 10 ppm-mol	For aquifer sequestration < 4% by volume; for EOR 100-1000 ppm	< 40 ppm-mol	≤ 40 ppm-mol	≤ 50 ppm-vol	≤ 50 ppm-vol	≤ 30 ppm-vol
Total non-condensable		≤ 0.3% by volume (sum of all non-condensables)	≤ 0.2 mol% (sum of all non-condensables)	≤ 4 mol% (sum of all non-condensables)	≤ 4 mol% (sum of all non-condensables)	≤ 4 mol% (sum of all non-condensables			
Nitrogen Oxides (NO_x)	≤ 1.5 ppm-mol		< 1.5 ppm-mol	≤ 100 ppm	< 2.5 ppm-mol	≤ 5 ppm-mol		≤ 5 ppm-vol	≤ 2.5 ppm-vol
Hydrogen Sulphide (H_2S)	≤ 9 ppm-mol	< 200 ppm	< 5 ppm-mol	≤ 200 ppm	< 5 ppm-mol	≤ 5 ppm-mol			
Sulfur Oxides (SO_x)	≤10 ppm-mol		< 10 ppm-mol	≤ 100 ppm				≤ 5 ppm-vol	≤ 1 ppm-vol
Total Sulfur-contained compounds (COS, DMS, H_2S, SO_x, Mercaptan)						≤ 20 ppm-mol			

a: Food grade CO_2 is predominantly transported via road and rail. Application of food-grade specifications will be especially relevant to these modes of transport

Sources: Northern Lights Webinar (2024), "CO2 Specification for the Northern Lights Value Chain"; Ahmad Amirhilmi A. Razak et al (2023), "Physical and Chemical Effect of Impurities in Carbon Capture, Utilisation and Storage"; ZEP/CCSA (2022), "Network Technology Guidance for CO2 Transport by Ship"; Aspelund, A (2010): "Gas Purification, Compression and Liquefaction Processes and Technology for Carbon Dioxide (CO2) Transport"; Richard T.J Porter et al (2015), "The Range and Level of Impurities in CO2 Streams from Different Carbon Capture Sources"; Aramis Project; Porthos Project; Opportunities for Shipping to Enable Cross-Border CCUS Initiatives; BCG (2024)

8.6 MAPPING

8.6.1 MAPPING OF CO_2 SOURCES FROM IEP

The European Industrial Emissions Portal (IEP) 2022 dataset was used to obtain information on fossil and biogenic CO_2 emissions across Europe. Note that of the 31 countries covered, 17 do not report biogenic CO_2 separately from fossil emissions, instead aggregating with fossil sources. These countries are Austria, Belgium, Croatia, France, Greece, Hungary, Iceland, Italy, Latvia, Lithuania, Luxembourg, Malta, Poland, Portugal, Slovakia, Spain, and Switzerland. For this analysis, future emission projections from respective industries were not included and represent each countries reported emissions from 2022.

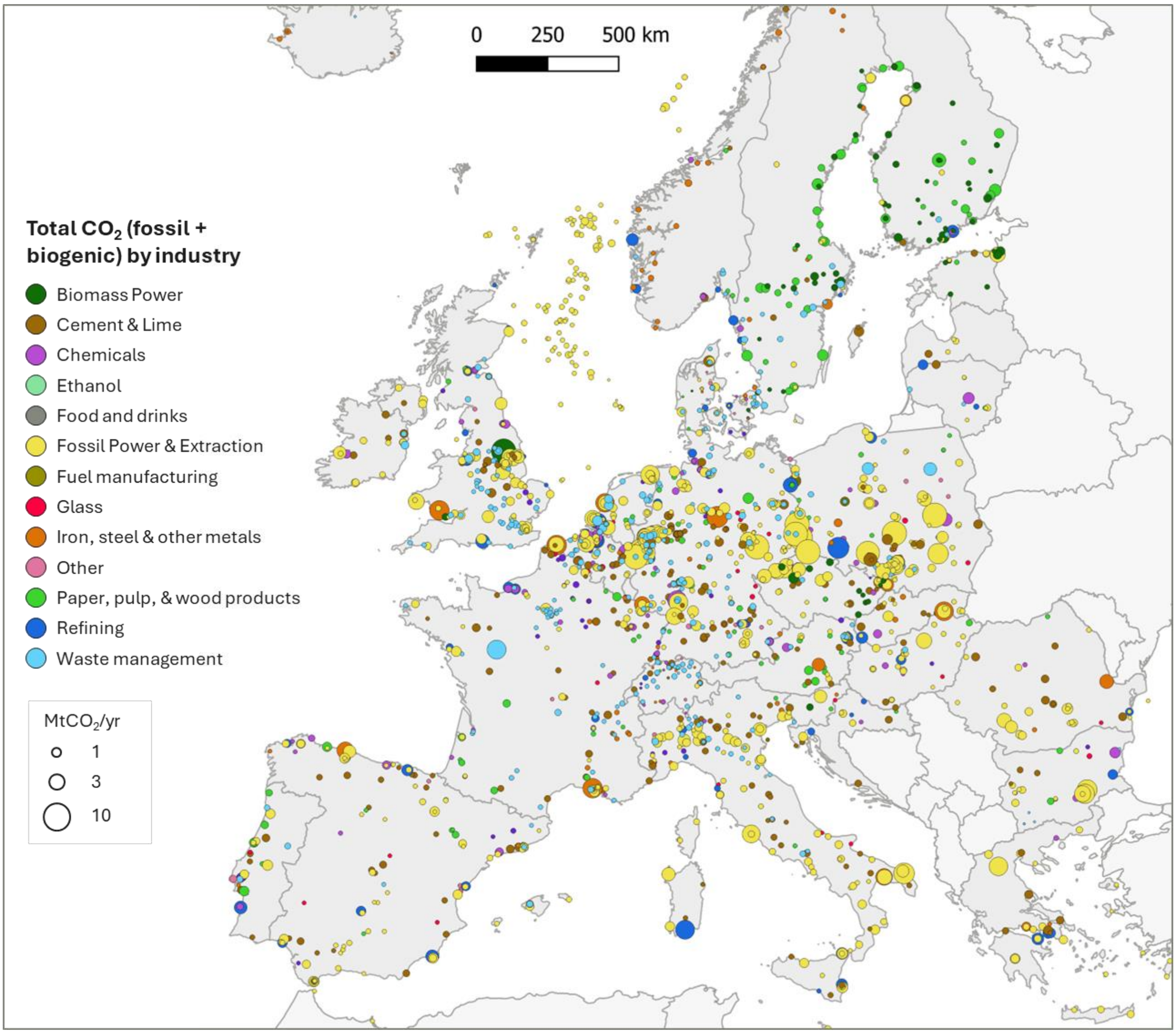

FIGURE 18 TOTAL CO_2 EMISSIONS FROM INDUSTRIAL SITES IN EUROPE

To find the biogenic CO_2 for countries that do not report biogenic CO_2 in the IEP, an extrapolation was made. First, the average biogenic share (%) was calculated by sector based on data available from countries that do report biogenic emissions separately. These sector-specific average biogenic shares were then multiplied with the site's CO_2 emissions to estimate the respective biogenic CO_2 volumes. In the case of EfW, an average biogenic CO_2 % of 55% was assumed. Due to this extrapolation, there is uncertainty associated with the calculation of biogenic CO_2 for countries that do not separately report biogenic CO_2. As such, biogenic emission levels mapped here are accurate as of 2022

8.6.2 MAPPING OF BIOGENIC CO_2 FROM ETHANOL AND BIOGAS UPGRADING

Since ethanol and biogas upgrading sites primarily release biogenic CO_2, these sites tend to not be included in the IEP. CO_2 from ethanol was obtained using ERM's internal database of ethanol sites in Europe, which is updated to reflect recent developments in the sector.

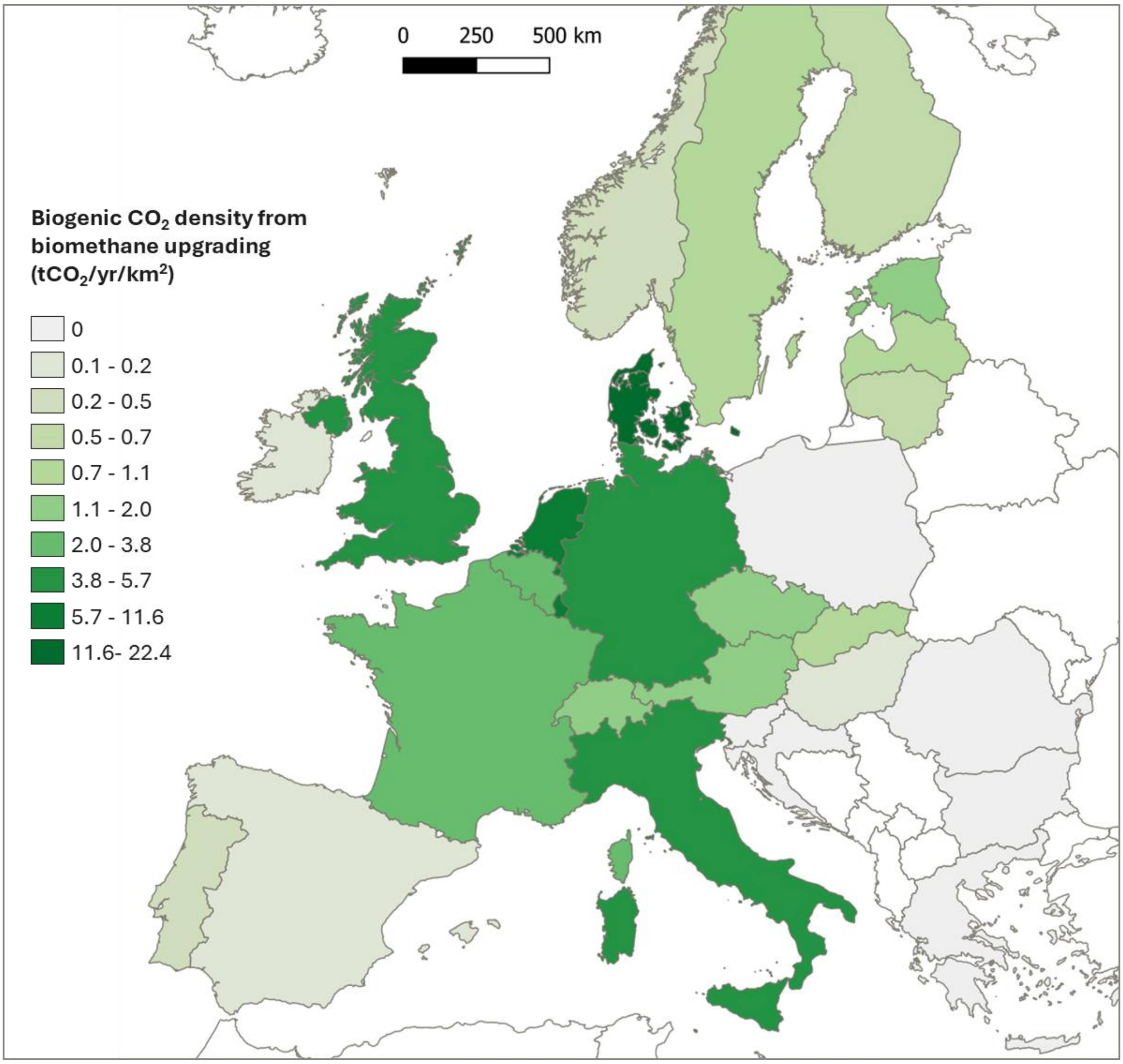

FIGURE 19 AVERAGE DENSITIES OF BIOGENIC CO2 FROM BIOGAS UPGRADING

To find the biogenic CO_2 from biogas upgrading, the number of plants per country is obtained from the EBA's 2025 biomethane map.[148] The average biogas production per plant is then obtained for the countries of Denmark, France, Germany, Italy, Netherlands, Norway, Spain, Sweden, Switzerland, and UK.[149] For the remaining countries of Europe, an average output of 664 m^3/hr is taken. To obtain biogenic CO_2 volumes, an average CO_2 content of 40% is assumed.[150] The total biogenic CO_2 from upgrading per country is then taken as the average

[148] EBA, 2025. European Biomethane Map 2025
[149] GfC, Guidehouse, 2023. GfC Market State Trends
[150] Sia Partners, 2023. Sia Partners_Benchmark_Europe_Biomethane

biogenic CO_2 per plant multiplied by the number of plants in the country. The average 'density' of biogenic CO_2 from upgrading is found by dividing by the total area of each country.

8.6.3 CALCULATION OF ACCESSIBLE BIOGENIC CO_2

The following adjustments are made to total capture volumes to yield the accessible biogenic CO_2 volumes which could feasibly be captured.[151] Note that there are many factors which contribute to whether carbon capture is feasible, and so this analysis should be treated as an approximate method for determining accessible capture volumes.

TABLE 7 FACTORS TO OBTAIN ACCESSIBLE BIOGENIC CO2 VOLUMES

Sector	Sufficient economies of scale to deploy carbon capture?	CO_2 capture rate
Ethanol	If >5 ktCO_2/yr, yes. Otherwise, no. Reasoning: biogenic CO_2 from fermentation is already present at high concentration (~99%), enabling a capture process that essentially consists of compression and dehydration. These processes can be economical at small volumes.	99% capture rate
Biogas upgrading	All included. Capture from biogas upgrading is economical at small volumes, and furthermore if the plant has sufficient economies of scale to deploy upgrading, it is expected to also have sufficient economies of scale to deploy carbon capture	99% capture rate
All other sectors	If total CO_2 >100 ktCO_2/yr, yes. Otherwise, no. 100 ktCO_2/yr is an indicative flow rate where the economies of scale are favourable for post-combustion capture. The total CO_2 (rather than biogenic CO_2) amount is most relevant, since mass balancing can be used to take the biogenic content for utilisation.	95% is an optimal capture rate available for capture technologies such as advanced amines.

8.6.4 MAPPING OF E-FUELS PROJECTS AND PROJECTED CO_2 REQUIREMENTS

As mentioned in the report, T&E's database of e-SAF and e-methanol projects is used to map e-fuels projects. In the mapping, e-fuels projects are depicted based on their projected CO_2 requirement. These projected CO_2 requirements are based off the total projected liquid fuel production volumes in the database (including co-products) multiplied by the respective CO_2 requirement for the pathway (see Table 6). In cases in the database where the total liquid fuel production volume is not known and only the e-kerosene production volume is known, it is assumed that the slate share is 75% and 95% for the FT+RWGS and MtJ processes, respectively. These % slate shares reflect common splits in real-world projects. Note that

[151] GCCSI, 2025. State of the Art: CCS Technologies 2025 - Global CCS Institute

projects that only produce SAF directly from biomass are not mapped since they do not use CO_2 as a feedstock. Additionally, e-fuels projects that do not provide information on projected e-fuel production volumes are not mapped – this is common for pilot/research projects which would have very small production volumes.

8.6.5 SUPPLY CURVE OF BIOGENIC CO_2 ACCESSIBLE TO E-FUELS PROJECTS

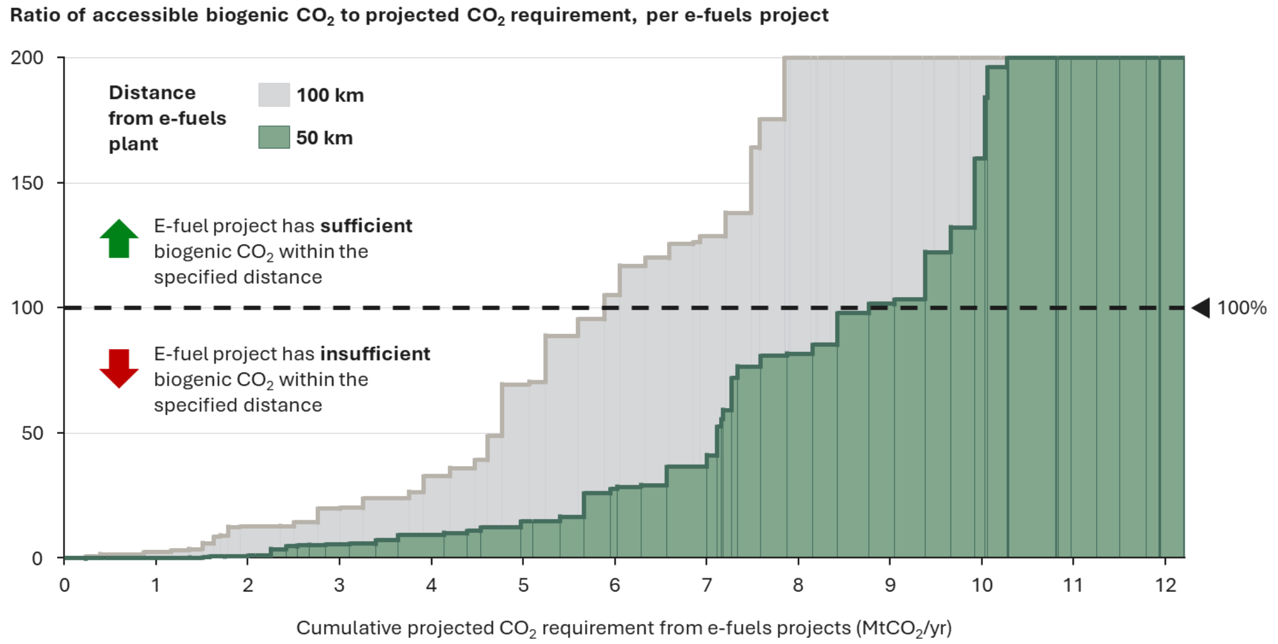

FIGURE 20 ACCESSIBLE BIOGENIC CO_2 FOR E-FUELS PROJECTS IN EUROPE

8.6.6 MAPPING OF RENEWABLES CAPACITIES

The mapping of renewables potential is achieved via an internal ERM python tool which uses information from the public domain (solar from Global Solar Atlas and wind from Global Wind Atlas) to obtain the capacity factor for a defined region and grid size (20 km pixels in this case). The tool first breaks down the region into small pixels, and for each pixel looks at the average capacity factor from the tabular data found from the above sources. It does this for both solar capacity and wind capacity.

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