LIDP - Veolia WP2 Report

January 2024 - December 2024

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Executive Summary

The Solent Region, represents the largest cluster of industrial greenhouse gas (GHG) emissions (approximately 5MtCO2e/year) not included in the Industrial Decarbonisation Challenge. This makes it a strategic priority for UK decarbonisation efforts. The region encompasses the Isle of Wight, Portsmouth and Southampton City Councils, and the southern districts of Hampshire County Council, including New Forest, Eastleigh, Fareham, Gosport, and Havant Borough Councils.

The UK's Carbon Capture, Utilisation, and Storage (CCUS) vision targets carbon sequestration volumes of 20-30MtPa total and 5-6MtPa of Greenhouse Gas Removal (GGR) credits. However, the National Audit Office reports that the current deployment will likely achieve only a quarter of the 2030 carbon reductions and even less of the GGR credits target. Supporting non-tracked clusters and Non-Pipeline Transport (NPT) solutions within the Track clusters process can accelerate decarbonisation and help meet government ambitions. The development of the Solent Cluster would add 10MtPa of storage capacity to the UK, significantly contributing to the government's CCUS Vision targets.

Energy-from-waste facilities are uniquely equipped to support the decarbonisation targets highlighted. Emissions associated with the incineration and energy recovery of residual waste are of fossil and biogenic origin. Capturing carbon emissions from energy-from-waste can reduce the carbon budget and facilitate the formation of GGR credits or the production of low-carbon products, which can support hard-to-abate industries.

Marchwood Energy Recovery Facility (ERF), is participating in the Local Industrial Decarbonisation Plan (LIDP) grant project. This initiative, funded by the government in partnership with Innovate UK, aims to collaborate with industries to find decarbonisation solutions and share knowledge and resources for regional development.

Veolia has conducted a pre-FEED study into carbon capture at Marchwood ERF, designing a capture plant to remove over 95% of the site's carbon emissions (both fossil and biogenic). Future development depends on the accessibility of a viable Transport and Storage (T&S) network and stronger commercial signals.

The development of a T&S network solution in Southampton would significantly increase the viability of carbon capture at Marchwood ERF. ExxonMobil's proposed pipeline solution, currently under public consultation, may offer the most cost-effective and carbon-efficient storage solution for the site. Implementing this solution would support the UK CCUS vision by reducing fossil carbon emissions by ~90,000tPa and generating negative emissions (or 'carbon removal') from ~110,000tPa of biogenic CO2.

While pipeline connection to Fawley and subsequent connection to storage facilities may present the lowest associated levelised cost and carbon footprint, NPT solutions such as rail and shipping infrastructure are a promising alternative. NPT solutions could provide strategic benefits to the region but require accelerated clear messaging on NPT business model support for investors and participation from multiple emitters to reduce capital costs.

The current state of the Emissions Trading System (ETS) and limited funding under the Industrial Carbon Capture (ICC) scheme pose challenges for project development. Stronger ETS signals aligned with carbon values and net-zero targets would support investment. Extending the ICC business model to support NPT and non-tracked clusters could also accelerate development.

Biogenic emissions from Marchwood ERF could be utilised in carbon capture and utilisation pathways, such as e-methanol production. This synthetic fuel, created from biogenic CO2 and green hydrogen, could significantly reduce emissions in the maritime sector, which is particularly active and a major economic contributor to the Solent region.

However, the high cost of green hydrogen production (accounting for about 80% of e-methanol production costs) presents a challenge. The price of green hydrogen needs to decrease by approximately 300% to £3/kg for e-methanol to be price-competitive. This could be achieved by the implementation of a smart grid system with short-term revenue support.

To support the decarbonisation of the maritime sector and promote innovative carbon utilisation, the UK could expand the Hydrogen Allocation Rounds (HAR) subsidy to allow hydrogen use in fuel creation, implement a buy-out mechanism similar to the Sustainable Aviation Fuel (SAF) mandate, and increase the obligation price under the Renewable Transport Fuel Obligation (RTFO). These measures, along with exploring funding opportunities similar to the European Union's HORIZON-CL5-2024-D3-02-11 and HORIZON-CL5-2024-D3-02-02 programs, could accelerate the development of low-carbon fuels and support the UK's decarbonisation goals.

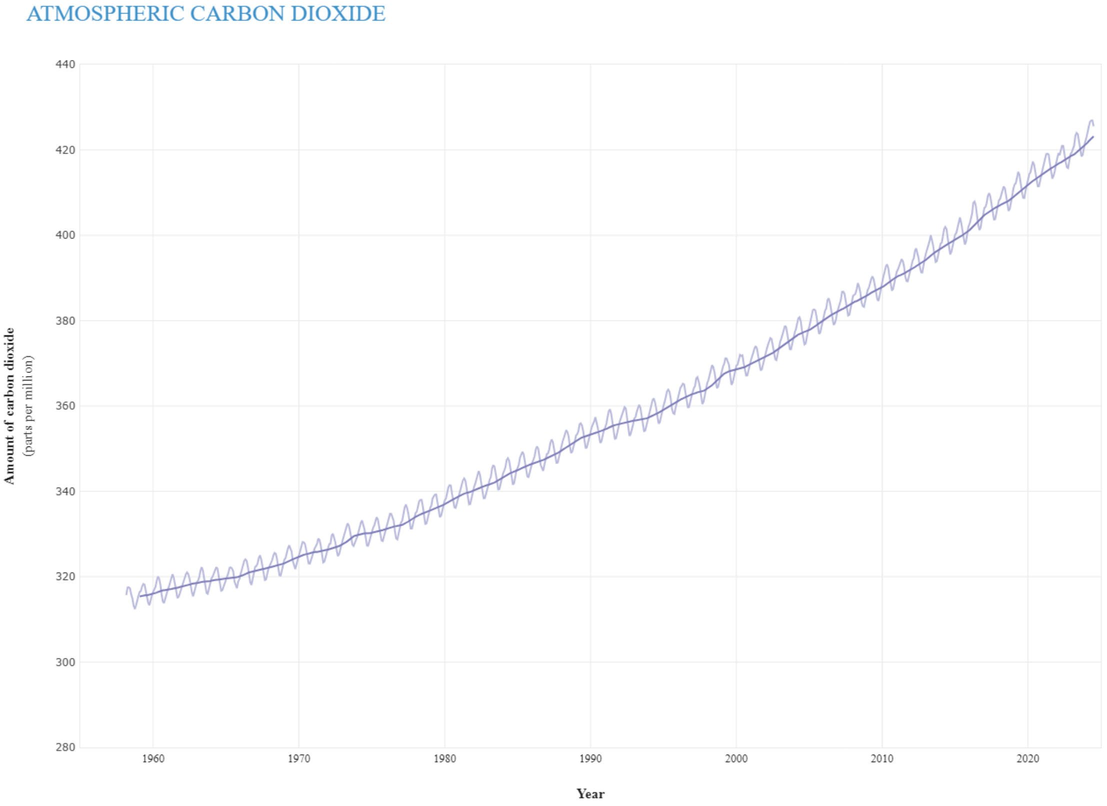
1. Context and Framework

This chapter provides an overview of the global and national policy landscape that shapes industrial decarbonisation efforts. Understanding this context is crucial for developing the Local Industrial Decarbonisation Plan for the Marchwood EfW site, as it informs the justification and future direction of our project.

1.1. Climate Change Context

Global warming has become increasingly tangible to people worldwide through its effects on extreme weather conditions and biodiversity. The root of this phenomenon can be traced back to the first Industrial Revolution, and the drastic increase in the use of fossil fuels.

Since the Industrial Revolution, human activities have significantly altered the carbon cycle by emitting huge amounts of carbon dioxide into the atmosphere. The concentration of CO2, which had been fairly stable at around 280 parts per million (ppm) in the 18th century, has risen rapidly due to the burning of fossil fuels, deforestation, and other industrial processes. As of 2023, the yearly average has reached 419 ppm, surpassing the 400 ppm mark and showing no signs of slowing down.



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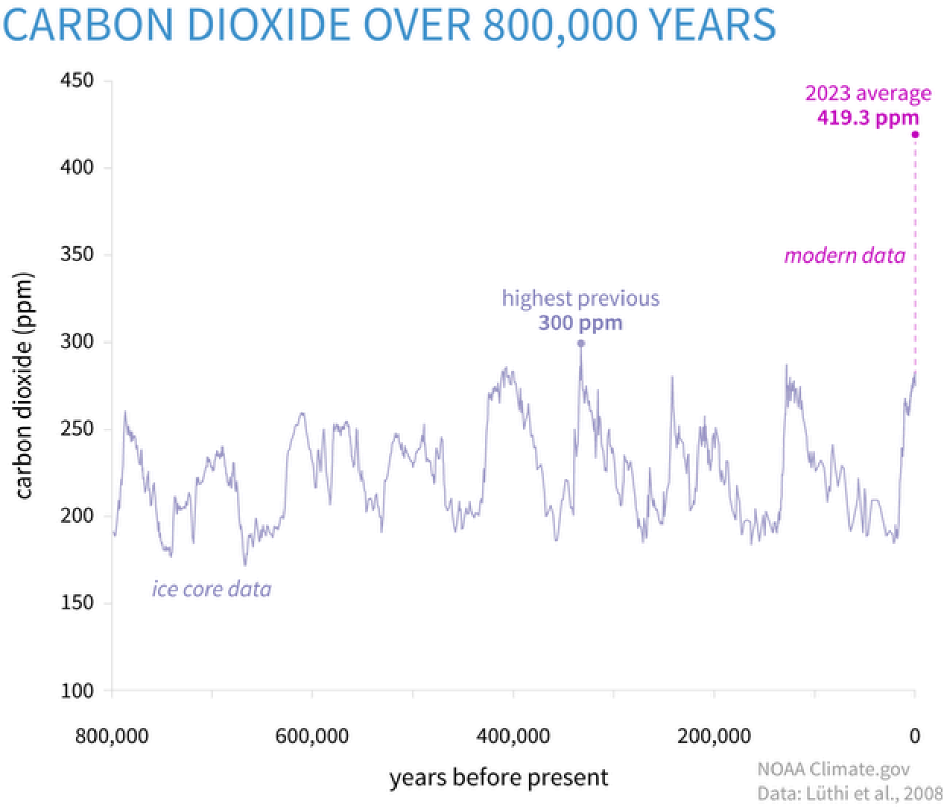
Historical CO2 concentrations can be determined by evaluating ice cores and measuring the amount of CO2 trapped inside ice at different depths. This data reveals that the highest historical measurement of atmospheric CO2 was around 300 ppm, emphasising the unprecedented nature of current levels and the profound impact of human activities in recent years.



Carbon dioxide is a greenhouse gas that retains the sun's infrared radiation in the atmosphere. While this greenhouse effect is naturally occurring and essential for maintaining viable temperature conditions for life on Earth, the imbalance brought about by human activities endangers these conditions. The higher concentration of CO2 in the atmosphere leads to global warming, affecting the entire planet's systems - atmosphere, biosphere, and hydrosphere - which are intricately linked.

Despite the clear evidence of climate change and its impacts, the global economy and industry have been deeply rooted in fossil fuel use for centuries. Transitioning to a low-carbon world requires not only technological innovations but also comprehensive global policies and concerted efforts across all sectors.

Exploring decarbonisation strategies such as Carbon Capture and Storage (CCS) and Carbon Capture and Utilisation (CCU), we are directly addressing one of the primary drivers of climate change. Our efforts align with the urgent need to reduce CO2 emissions and mitigate the impacts of global warming, contributing to the broader global initiative to combat climate change.

1.2. International Commitments and Policies

The international community has responded to the climate crisis through various agreements and frameworks:

- United Nations Framework Convention on Climate Change (UNFCCC): Established in 1992, the UNFCCC provides a platform for global cooperation on climate action through annual Conferences of the Parties (COPs).
- Kyoto Protocol (1997): This marked the first significant step in implementing cap-and-trade mechanisms for carbon emissions.
- Paris Agreement (2015): A landmark accord bringing 191 countries together to limit global temperature rise to well below 2°C above pre-industrial levels. Key elements include:
    - Nationally Determined Contributions (NDCs): Countries' climate action plans.
    - Article 6: Allows for voluntary cooperation between countries, including carbon credit trading.

Country	NDC Target
United Kingdom	68% reduction in emissions by 2030 (from 1990 levels)
European Union	At least 55% net reduction by 2030 (from 1990 levels)
United States	50-52% reduction by 2030 (from 2005 levels)
China	Peak CO2 emissions before 2030, carbon neutrality by 2060
India	45% reduction in emissions intensity by 2030 (from 2005 levels

Complementing these governmental efforts, the private sector has also stepped up. Initiatives like the Science Based Targets initiative (SBTi) have seen over 2,000 companies commit to science-based emission reduction targets. The RE100 initiative has united more than 300 influential businesses in a commitment to 100% renewable electricity use. Additionally, over 2,600 organisations have adopted the recommendations of the Task Force on Climate-related Financial Disclosures (TCFD), improving transparency around climate-related risks.

Carbon markets have emerged as a crucial mechanism for emissions reduction, enabling both global and company-specific targets to be met. These markets include compliance schemes such as the EU Emissions Trading System (EU ETS), the UK Emissions Trading Scheme (UK ETS), and China's National ETS, as well as the growing Voluntary Carbon Market. The EU ETS, launched in 2005, remains the world's largest multi-country, multi-sector greenhouse gas emissions trading system. The UK ETS, established post-Brexit, closely mirrors its EU counterpart. China's ETS, while currently focused on the power sector, is the world's largest carbon market by volume. The Voluntary Carbon Market is expected to reach a value of $50 billion by 2030 and allows companies and individuals to offset their emissions beyond regulatory requirements.

For CCUS projects, understanding these international commitments and carbon market mechanisms is essential for exploring potential revenue streams and ensuring alignment with broader climate mitigation efforts. This comprehensive framework guides our Local Industrial Decarbonisation Plan, making it both locally impactful and globally relevant in the fight against climate change.

1.3. Scientific report for policymakers: the role of carbon capture

The Intergovernmental Panel on Climate Change (IPCC), established in 1988, provides crucial scientific evidence to inform climate policy. Its most recent Synthesis Report (2023) offers key insights on carbon capture technologies [3][4]:

- Necessity of Carbon Dioxide Removal (CDR): CDR is deemed essential to achieve net negative CO2 emissions.
- Carbon Capture, Use, and Storage (CCUS): Critical for hard-to-abate industries to meet Paris Agreement objectives.
- Key CDR Methods: Carbon Capture and Storage (CCS) of biogenic carbon, Direct Air Carbon Capture and Storage (DACCS)
- Hard-to-Abate Sectors: Residual emissions from agriculture, aviation, and shipping require CDR to achieve net zero.
- Carbon Capture and Utilisation (CCU): Recognised as valuable in reducing emissions in chemical production and sustainable fuel alternatives.

These findings justify exploring both CCS and CCU options. They underscore the project's potential contribution to broader decarbonisation goals and its significance in achieving global climate targets.

1.4. Decarbonisation policies in the UK

As a signatory to the Paris Agreement, the United Kingdom has developed its Nationally Determined Contribution (NDC) to outline its commitment to achieving net-zero emissions. The UK's approach to decarbonisation is multifaceted, encompassing several legal frameworks and strategies designed to encourage and support the transition to a low-carbon economy.

Key elements of the UK's decarbonisation strategy, as highlighted in its NDC report, include:

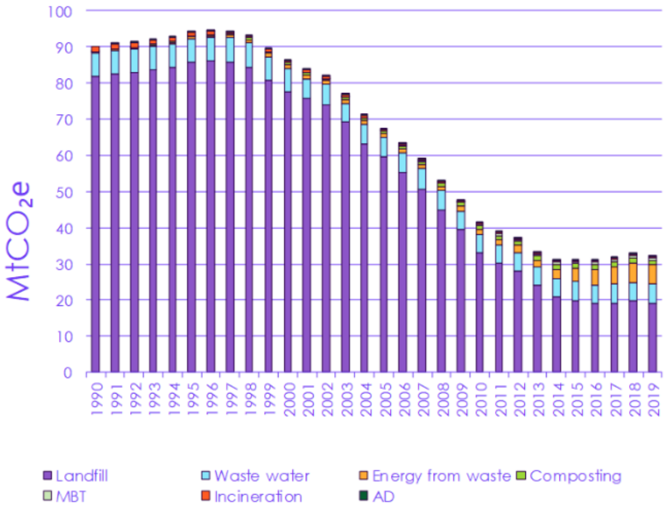
- A comprehensive roadmap for hydrogen and Carbon Capture, Utilisation, and Storage (CCUS) technologies (UK NDC, page 12)
- A resources and waste strategy to promote circular economy principles (UK NDC, page 32)

These initiatives, among others, form the backbone of the UK's efforts to reach its net-zero target. They provide a framework for various sectors, including energy, industry, and waste management, to align their operations and future plans with national climate goals.

1.4.1. Waste management

In 2021, the waste sector accounted for 6% of the UK's total greenhouse gas emissions. This includes emissions from various sources such as landfills, Energy from Waste (EfW) plants, wastewater treatment facilities, and other waste treatment processes.

Significant progress has been made in reducing these emissions over the past three decades. The key factor behind this improvement has been the reduction of waste processed in landfills, as shown in Figure 1.2.1.a. Landfills, which are designated areas for containing municipal waste, produce significant amounts of methane as organic waste decomposes. By diverting waste away from landfills, the UK has effectively cut down on this major source of greenhouse gas emissions.



Source: BEIS (2020) *Final UK greenhouse gas emissions national statistics 2018*; BEIS (2020) *Provisional UK greenhouse gas emissions national statistics 2019.*

Figure 1.2.1.a: Breakdown of waste sector emissions (1990-2019) (CCC, [6])

In 2018, the UK government introduced the "Resources and Waste Strategy for England," aimed at accelerating the transition to a circular economy, supporting increased recycling, addressing plastic pollution, and reducing food waste.

The Waste Management Plan of the UK outlines several key objectives, as depicted in Figure 1.2.1.b:

- Reduction of waste per household
- Prevention of waste through improved product design
- Increased recycling rates

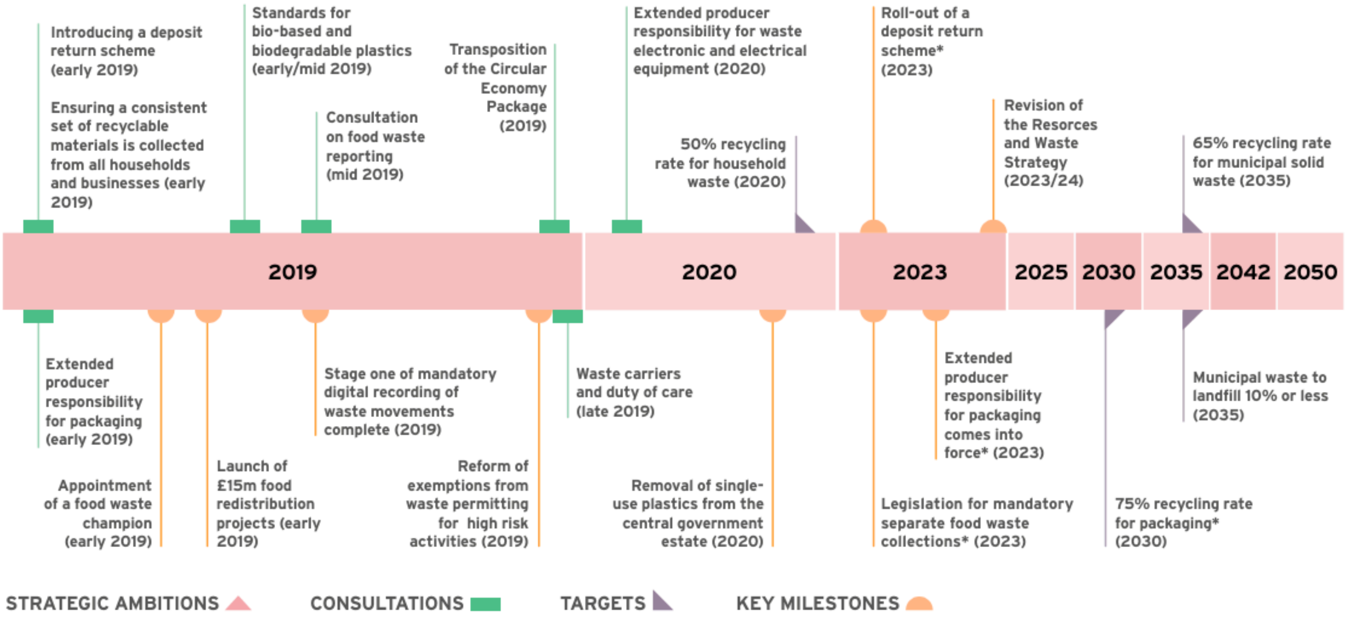


Figure 1.2.1.b: Timeline of the objectives for waste management in the UK (UK government, [8])

These priorities reflect a shift from waste management to resource efficiency, viewing waste as a valuable resource and aiming to minimise waste production at the source.

As the UK progresses towards its waste reduction and recycling targets, the role of EfW plants in managing residual waste remains significant.

1.4.2. UK Emission Trading Scheme

The UK ETS is a crucial mechanism in the country's strategy to achieve net-zero emissions by 2050. It operates on a cap-and-trade principle, setting a limit on greenhouse gas emissions for participating sectors. Key Features:

- Cap-and-Trade System:
    - A cap is set on total allowable emissions.
    - The cap decreases annually, encouraging emissions reductions and decarbonisation investments.
    - Emitters receive or purchase emission allowances, which can be traded as needed.
- Allowances:
    - Free allowances are granted to certain industries to maintain competitiveness and prevent carbon leakage.
    - Additional allowances can be purchased on the compliance market.
    - Emissions exceeding the cap incur penalties.
- Scope and Coverage:
    - Currently applies to energy-intensive industries, the power sector, and aviation.
    - Aviation coverage includes domestic flights and those from the UK to the European Economic Area.

On July 3, 2023, the UK ETS Authority proposed significant reforms to expand the scheme's scope. These reforms include extending coverage to the waste sector, specifically Energy from Waste (EfW) plants, by 2028. To facilitate this transition, a two-year phasing period from 2026 to 2028 will be implemented, during which EfW plants will be required to monitor their emissions. This gradual approach aims to incentivise EfW plants to adopt decarbonisation solutions, with a particular emphasis on Carbon Capture and Storage (CCS) technologies (UK government, [10]).

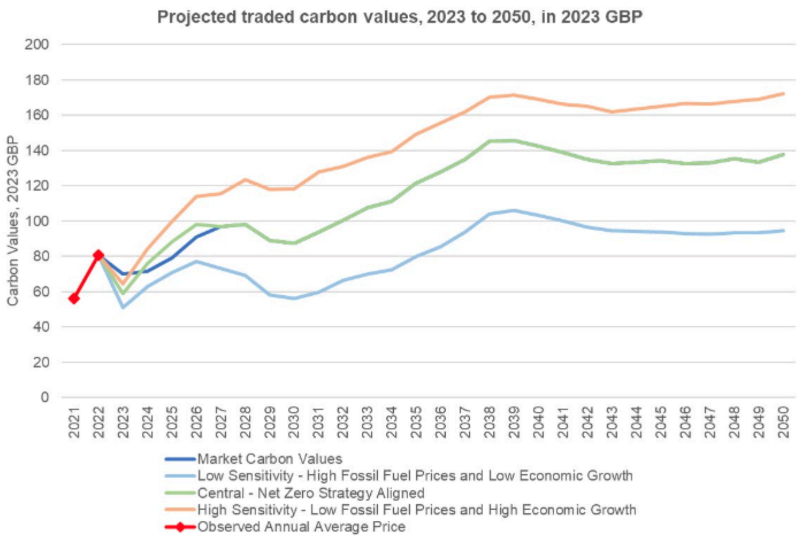
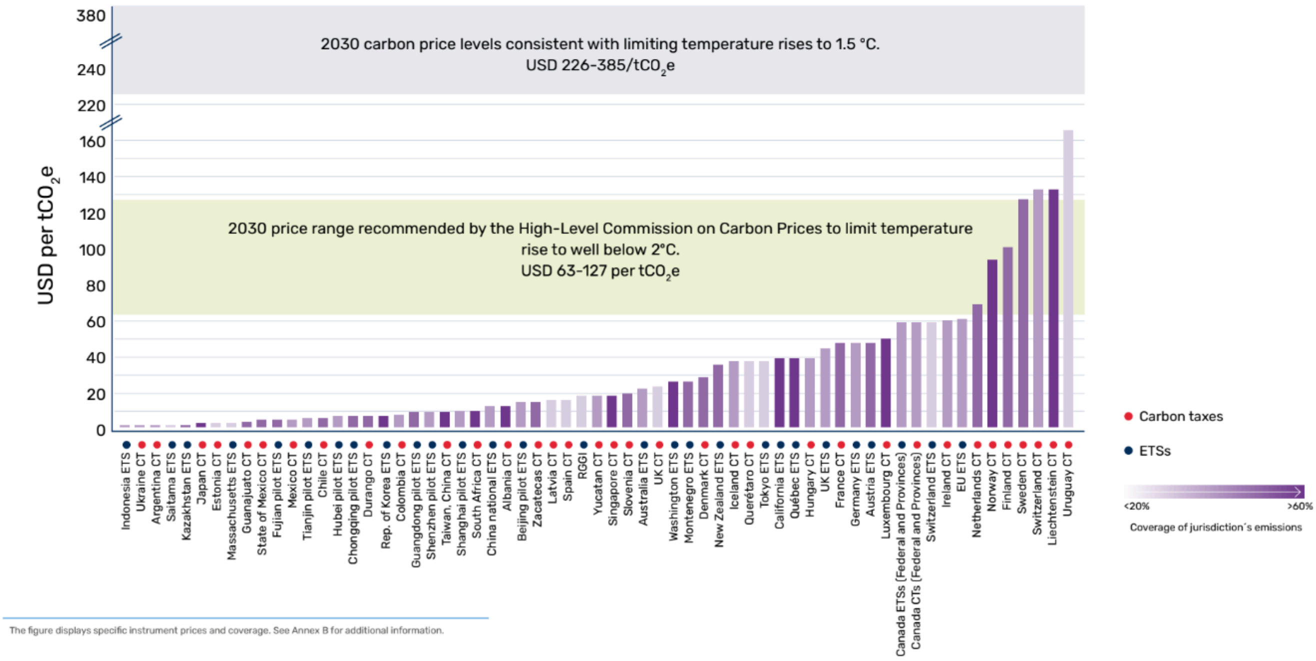


Figure 1.2.2.a: Traded carbon values for modelling purposes, £/tCO2e (real 2023) (UK government, [11])

From 2027, the UK ETS is set to undergo a significant change as traded carbon values are expected to align with the Net Zero Strategy, as illustrated in Figure 1.2.2.a. This alignment represents a crucial step in the UK's decarbonisation journey, potentially leading to an increase in carbon prices within the scheme. Such an increase would create stronger financial incentives for participating industries to reduce their emissions, thereby accelerating decarbonisation efforts across the economy. This move underscores the government's commitment to using market mechanisms to drive the transition to a low-carbon future and highlights the increasing importance of emissions reduction strategies for businesses operating within the UK ETS framework.

An opposing report by the World Bank notes that the carbon price is likely not high enough to incentivise the cost of decarbonisation. To align with the 1.5°C target, the carbon price should be over 226 £/tCO2 in 2030 which is almost 5 times more than the current price on the market.



The figure displays specific instrument prices and coverage. See Annex B for additional information.

Figure 1.2.2.b: State and Trends of Carbon Pricing 2024 (World Bank, [66])

1.4.3. CCUS: objectives and support

The UK government has developed a comprehensive CCUS Net Zero Investment Roadmap. This roadmap outlines ambitious objectives and support mechanisms for Carbon Capture, Utilisation, and Storage (CCUS) deployment. The key objectives include:

- Capture 20 to 30 Mt of CO2 per year by 2030
- Deploy at least 5 MtCO2 per annum of engineered greenhouse gas removals (GGRs) by 2030
- Achieve these targets through the selection and funding of 4 CCUS clusters

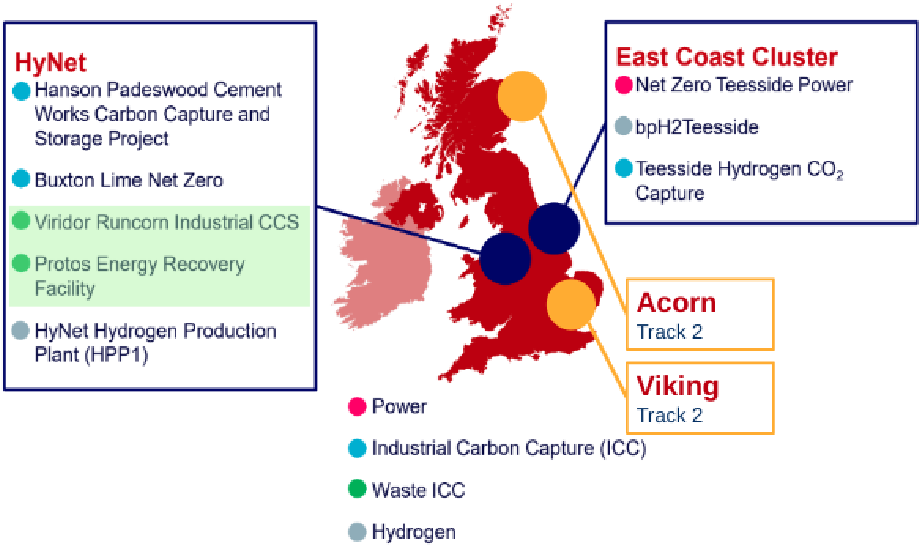


Figure 1.2.3a: Clusters selected during Track 1 and 2 and emitters selected during Track 1 (UK government, [11])

Two EfW plants have already been selected to negotiate contracts under the Waste Industrial Carbon Capture (WICC) business model. This model offers substantial support, including:

- Partial funding for capital expenditure (capex)
- Support for Transport and Storage (T&S) costs
- Revenue support for operational expenditure (OPEX), based on the difference between a carbon market reference price and a negotiated strike price (Contract for Difference. CfD)

The strategy's Track 2 phase further expands CCUS deployment opportunities. It introduces an Anchor phase for T&S companies to contract with initial capture projects, targeting 2028-2029 deployment, followed by a build-out phase. Crucially, this phase includes Non-Pipeline Transportation (NPT) projects, opening up decarbonisation opportunities for facilities not directly connected to pipeline infrastructure, such as the Marchwood EfW plant.

Unfortunately, the progression of Track-1 has delayed both the expansion phase and track-2 phase. The NPT business model crucial for unlocking dispersed emitters' decarbonisation is not currently in place.

On 30th April 2024, the North Sea Transition Authority (NSTA) initiated a competitive process for Carbon Dioxide Appraisal and Storage Licences in the English Channel. ExxonMobil and the Solent Cluster have entered into public consultation for the development of the T&S network. This could significantly enhance the feasibility of CCS projects in the south of England, potentially providing south coast facilities with more accessible and cost-effective CO2 storage options. The development of this non-tracked cluster could also assist in achieving the CCUS vision targets.

1.4.4. Transport: objectives and support

The transport sector is the largest contributor to greenhouse gas (GHG) emissions in the UK, accounting for approximately 26% of the country's total emissions in 2021. Given this significant impact, reducing GHG emissions in the transport sector is crucial for the UK to meet its commitments and achieve net zero by 2050. To support the development of sustainable fuels and drive decarbonisation in this sector, the UK government has implemented several policies. Among these, the Renewable Transport Fuel Obligation (RTFO) stands out as a key initiative.

Renewable Transport Fuel Obligation

The RTFO, introduced in 2008, serves as the UK's primary mechanism to support the supply of renewable fuels for transport. It applies to suppliers of more than 450,000 litres of fuel per year, encompassing a wide range of transport modes including road vehicles, non-road transport, aviation, and maritime (specifically for Renewable Fuels of Non-Biological Origin, or RFNBOs).

The RTFO operates on an obligation system calculated by multiplying the amount of unsustainable fuel by the obligation percentage for a given period. This obligation comprises a "main obligation" and a "development fuel target". Suppliers have two options to meet their obligations: they can either redeem Renewable Transport Fuel Certificates (RTFCs) by producing or purchasing them, or they can pay a fixed sum for each litre of obligated fuel they wish to 'buy out' of their obligation. The current buy-out price is:

- 50 pence per RTFC that would otherwise be required to meet the main obligation

- 80 pence per development fuel RTFC that would otherwise be required to meet the development fuel target

Under the RTFO, non-renewable fuels include petrol, diesel, gas oil, and the non-renewable portion of any partially renewable fuel. Renewable fuels, on the other hand, encompass biofuels, RFNBOs, and the renewable portion of any partially renewable fuel. It's important to note that renewable fuels must meet specific carbon and sustainability (C&S) criteria to be recognised under the RTFO; otherwise, they are treated as fossil fuels.

For EfW facilities like Marchwood, the RTFO presents two main pathways for involvement in renewable fuel production. First, municipal solid waste (MSW) can be used as a feedstock to produce biofuels through processes such as gasification or pyrolysis. Alternatively, CO2 captured from the flue gas of MSW incineration can be combined with hydrogen to produce RFNBOs. In the latter case, MSW is not considered a direct feedstock for renewable fuel; instead, electrolytic hydrogen forms the main component of the RFNBO, with CO2 serving as an additional element to create a more complex fuel.

A significant recent development is the planned inclusion of Recycled Carbon Fuels (RCFs) under the RTFO from July 2024, subject to legislative approval. This expansion will allow RCFs to claim development RTFCs (dRTFCs). Eligible feedstocks will include the fossil component of Refuse Derived Fuel (RDF) from mechanically treated municipal solid waste streams, which is inherently mixed with biological material, and industrial waste process gases containing carbon monoxide that are only suitable for incineration or energy recovery.

Renewable Fuels of Non-Biological Origin (RFNBOs) are eligible for a double reward of RTFCs under the RTFO. These fuels are defined as renewable liquid or gaseous transport fuels for which none of the energy content comes from biological sources. RFNBOs must be produced from either water and/or CO2 using electricity or heat from renewable sources such as wind, solar, aerothermal, geothermal, or water. While hydrogen is the most basic RFNBO, more complex fuels like methanol can be produced by reacting hydrogen with CO2. The renewable electricity used in RFNBO production must meet additionality and regionalisation criteria to ensure it contributes to overall emissions reduction.

The carbon intensity of RFNBOs is calculated by summing emissions from several sources: raw materials (water and CO2 for methanol production), production and processing, transport and distribution, and fuel use. Emissions savings from carbon capture and storage can be deducted. Notably, when green hydrogen and biogenic CO2 from waste incineration are combined, the resulting e-methanol (eMeOH) is considered to have very low, near zero lifecycle GHG emissions. In cases where fossil CO2 is also utilised, there are two accounting options for the associated carbon emissions: they can either be accounted for by the Energy Recovery Facility (ERF), which would reduce the carbon intensity of the fuel, or they can be passed through to the final emitter, who would then be responsible for paying Emissions Trading Scheme (ETS) charges on these emissions. This choice not only affects the carbon accounting but also significantly impacts the cost of CO2 for RFNBO production. If the ERF accounts for the emissions, it may charge a higher price for the CO2, whereas passing the emissions to the end-user could result in a lower CO2 cost but higher emissions liability for the fuel user. This flexibility in accounting allows for optimisation of the overall carbon reduction strategy and economic considerations in the production and use of RFNBOs, while also influencing the commercial dynamics between CO2 suppliers and RFNBO producers (UK government, [18]).

Compliance with the RTFO's carbon and sustainability criteria must be verified by an independent third party, following the requirements of ISAE 3000. For biofuels produced from MSW and RFNBOs, the primary criterion is greenhouse gas emissions savings. Fuels produced in installations built after 2015, as well as all RFNBOs, must achieve at least ***65%*** GHG emissions savings compared to fossil fuels. This translates to a maximum emission factor of ***32.9 gCO2e/MJ*** for renewable fuels, based on an average of ***94 gCO2e/MJ*** for fossil fuels.

Sustainable Aircraft Fuel mandate

In April 2024, the UK government unveiled its ambitious decarbonisation objectives for the aviation sector, accompanied by the full policy details of the SAF mandate. This initiative, set to launch in January 2025, marks a significant step towards greening one of the hardest-to-abate sectors in the UK economy.

The mandate sets a progressive target for sustainable fuel usage in UK aviation. Starting with a requirement for 2% of total UK jet fuel demand to be sourced from sustainable resources in 2025 (equivalent to approximately 230,000 tonnes of SAF), the mandate outlines a linear increase to 10% by 2030, culminating in a 22% target by 2040. This gradual scaling allows the industry to adapt and invest in new technologies over time.

Recognising the need for innovation in fuel production, the government has introduced a separate obligation specifically for power-to-liquid fuels. This obligation, commencing in 2028, aims to reach 3.5% of total jet fuel demand by 2040, driving advancements in synthetic fuel production.

Currently, the primary commercially available SAF is Hydrotreated Esters and Fatty Acids (HEFA), derived from segregated oils or fats. While HEFA is supported under the RTFO, its use will be capped at 71% in 2030 and 35% in 2040 due to concerns about competition with other sectors and land use. Only HEFA produced from waste materials like used cooking oil and tallow will be eligible under the SAF mandate.

A key feature of the SAF mandate is its buy-out mechanism, designed to encourage supply while protecting consumers if suppliers struggle to secure sufficient SAF. This mechanism allows suppliers to pay a fixed amount to the government instead of meeting their SAF obligation. The buy-out price is set at £4.70 per litre for the main SAF obligation and £5.00 per litre for the power-to-liquid (PtL) obligation. This approach provides flexibility for suppliers while maintaining pressure to increase SAF production and use.

The mandate also places a strong emphasis on power-to-liquid fuels, which produce synthetic fuel from nuclear or renewable electrolytic hydrogen combined with captured CO2. The CO2 can be sourced from the atmosphere, naturally-occurring/geothermal sources, biological sources, or waste fossil sources.

Importantly, if the SAF mandate adapts in the future to allow for CO2 from Energy from Waste facilities, it could open up significant new opportunities. In such a scenario, e-methanol (eMeOH) produced using CO2 from EfW plants could potentially be used as a feedstock for SAF production. This would not only provide a valuable use for captured CO2 but also position EfW facilities as key players in the sustainable aviation fuel supply chain.

Sustainable Maritime Fuel

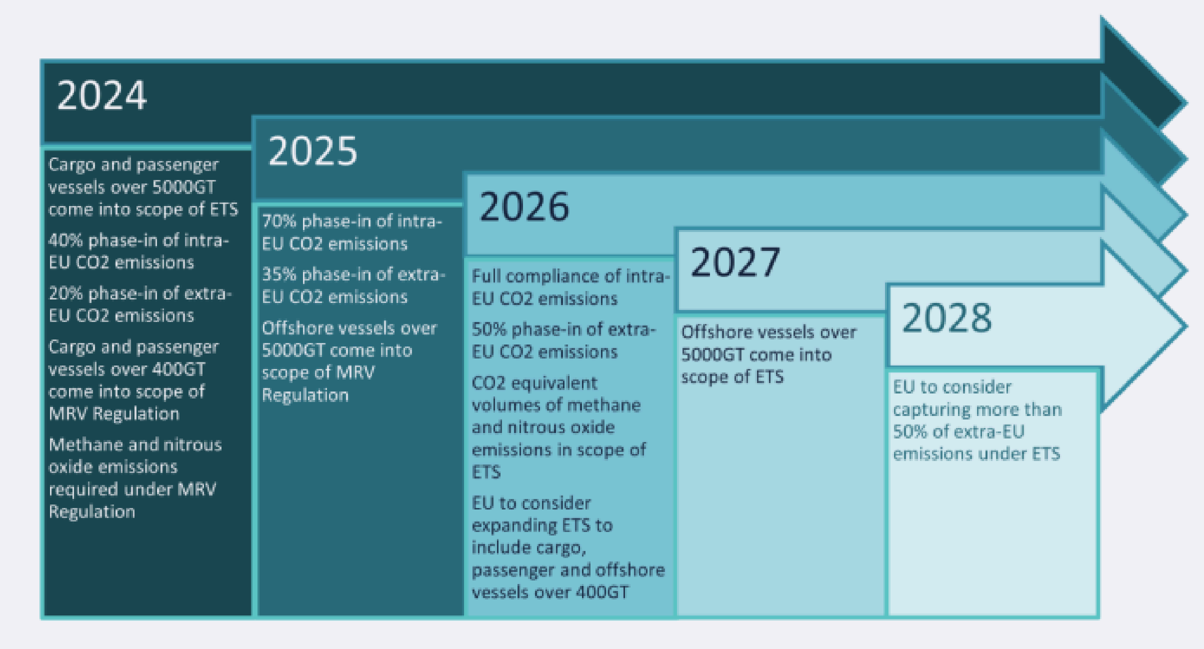
While shipping is one of the most carbon-efficient transport methods for freight, it still accounts for about 5% of the UK's transport emissions. The UK government has taken steps to address maritime emissions through various policy initiatives. In July 2021, the Transport Decarbonisation Plan was published, highlighting the need to refresh the Clean Maritime Plan from 2019. Following this, in July 2022, a consultation on Maritime Decarbonisation was launched, exploring technical, operational, and policy pathways to decarbonise the sector by 2050.

The maritime sector faces several key challenges in its decarbonisation journey. Unlike aviation, maritime transport involves many different types of vessels with varying needs. This diversity means there won't be a one-size-fits-all solution for transition fuels. Additionally, significant capital investment is required to decarbonise the fleet, upgrade port infrastructure, and ensure sustainable fuel availability.

To address these challenges, a range of fuel options are being considered. Batteries are emerging as a suitable solution for smaller vessels, offering zero-emission propulsion for short-distance trips. For larger vessels, e-methanol is showing significant potential as a sustainable fuel option. Biofuels are playing an essential role in the short term, providing a lower-carbon alternative to traditional marine fuels. However, their long-term viability is limited by future biomass availability. To complement biofuels and ensure long-term decarbonisation, synthetic fuels are being developed. These fuels, which can be produced using renewable energy and captured carbon dioxide, offer a scalable solution for the maritime sector's future energy needs.

The development and adoption of sustainable maritime fuels are supported by various policy mechanisms. The Renewable Transport Fuel Obligation (RTFO) plays a crucial role in supporting the development and testing of new fuels for maritime transport, providing incentives for innovation in this sector.

The EU is taking the lead by integrating shipping into its Emissions Trading System (ETS) from 2024. This integration follows a phased timeline, beginning in February 2024 when the EU Commission published a list of covered Shipping Companies. In March 2024, the allocation of Union Registry Accounts (URAs) took place. The process will culminate in 2025 when full compliance begins, including emissions reporting and allowance surrender requirements for shipping companies.



2024

Cargo and passenger vessels over 5000GT come into scope of ETS

40% phase-in of intra-EU CO2 emissions

20% phase-in of extra-EU CO2 emissions

Cargo and passenger vessels over 400GT come into scope of MRV Regulation

Methane and nitrous oxide emissions required under MRV Regulation

2025

70% phase-in of intra-EU CO2 emissions

35% phase-in of extra-EU CO2 emissions

Offshore vessels over 5000GT come into scope of MRV Regulation

2026

Full compliance of intra-EU CO2 emissions

50% phase-in of extra-EU CO2 emissions

CO2 equivalent volumes of methane and nitrous oxide emissions in scope of ETS

EU to consider expanding ETS to include cargo, passenger and offshore vessels over 400GT

2027

Offshore vessels over 5000GT come into scope of ETS

2028

EU to consider capturing more than 50% of extra-EU emissions under ETS

Figure 1.2.4.2: Timeline of the integration of shipping in the EU ETS

Following the Skidmore Review published in January 2023, the UK government has announced plans to expand its own ETS to include domestic maritime activities. This expansion is set to be implemented in 2026. The scheme will apply to vessels over 5000 GT, a threshold that aligns with existing UK Monitoring, Reporting and Verification (MRV) regulations.

To further support the transition to sustainable shipping, the EU has established an Innovation Fund.

- CCU for the production of fuels - HORIZON-CL5-2024-D3-02-11
- Development of next-generation synthetic renewable fuel technologies - HORIZON-CL5-2024-D3-02-02

This funding mechanism represents a significant opportunity for advancing sustainable technologies and practices in the maritime sector.

2. Carbon Capture Utilisation and Storage

The implementation of carbon capture technologies is crucial to achieve Net Zero by 2050. While several carbon capture technologies are currently in use, others are still in various stages of development. To ensure a successful commercial retrofitting of current plants, it is essential to select solutions with the highest level of technological maturity. Less mature technologies may be more suitable for pilot plant applications.

The ideal carbon capture solution should strike an optimal balance between socio-environmental benefits and economic viability. Furthermore, the ultimate destination of the captured carbon - whether for storage or utilisation - significantly impacts the overall environmental benefits of the capture process.

This section of the report aims to provide an evaluation of Carbon Capture, Utilisation, and Storage (CCUS) technologies, addressing:

- Technical feasibility of various carbon capture methods
- Potential pathways for carbon storage and utilisation
- Socio-economic impacts of CCUS implementation
- Environmental implications of different CCUS strategies

The insights provided in this section are based on current literature and summarise the present state of knowledge in the field. This information is intended to guide Innovate UK and local industries in steering decarbonization efforts, particularly in the context of EfW facilities and their role in achieving Net Zero targets.

2.1. Carbon Capture technologies

Carbon capture technologies can be broadly categorised into three main methods: pre-combustion capture, oxy-combustion capture, and post-combustion capture.

2.1.1. Pre-Combustion Capture

Pre-combustion capture, as the name suggests, occurs before the combustion of the fuel. In the context of Energy Recovery Facilities (ERFs), this would be applied to the waste feedstock.

Key Characteristics:

- Applicable only to specific sites using gasification instead of direct combustion
- Primarily suitable for new facilities due to the significant process modifications required

Process Overview:

1. Air Separation: An Air Separation Unit (ASU) processes ambient air to separate oxygen and nitrogen.
2. Gasification: Pure oxygen from the ASU enters a gasification unit. In some variations, gasification may use fuel and air without an ASU.

3. Syngas Production: Fuel reacts with oxygen (and potentially steam) at high temperature and pressure to form syngas, containing CO_2, CO, H_2, and H_2O.
4. Syngas Purification: The syngas undergoes purification processes.
5. Shift Reaction: Purified syngas passes through a shift reaction unit, increasing CO_2 concentration via the Reverse Water-Gas Shift reaction ($CO + H_2O = CO_2 + H_2$).
6. CO2 Capture: The gas mixture enters the capture section where CO_2 is separated through various physical and chemical processes.
7. Compression: The captured CO_2 stream is dried and compressed for transport.

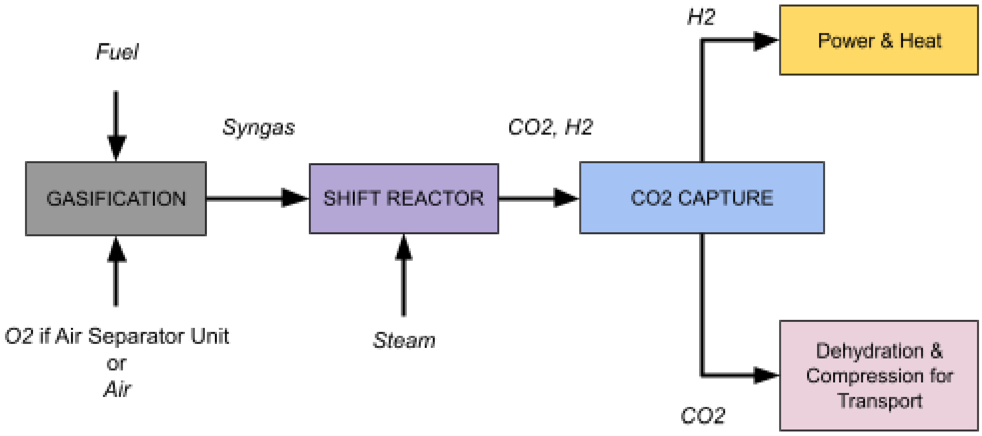


Figure 2.1.1.1: Pre-Combustion Capture Process

Despite the advantages of increased CO_2 concentration for capture and the potential for hydrogen production, pre-combustion capture faces significant challenges in its application to Municipal Solid Waste (MSW) treatment:

1. Feedstock Variability: The heterogeneous nature of MSW makes it difficult to maintain consistent gasification conditions, which are crucial for efficient pre-combustion capture.
2. Limited Retrofit Potential: The technology has very limited applicability to existing Energy Recovery Facilities (ERFs) due to the extensive modifications required to implement gasification and pre-combustion capture systems.

While pre-combustion capture offers theoretical advantages in terms of capture efficiency and potential for hydrogen production, its practical application in the context of MSW treatment and existing ERFs is highly limited. The technology is more suited to new, purpose-built facilities that can be designed from the ground up to incorporate gasification and pre-combustion capture systems. For existing ERFs or those planning to use direct combustion of MSW, alternative carbon capture technologies are likely to be more feasible and cost-effective.

2.1.2. Oxy-fuel combustion capture

Oxy-fuel combustion is the process of burning a fuel using pure oxygen, or a mixture of oxygen and recirculated flue gas, instead of air. This carbon capture method involves significant modifications to the combustion process itself and requires changes to the design of existing power stations or waste-to-energy plants.

1. Air Separation Unit (ASU): Added before the furnace to produce high-purity oxygen. Removes nitrogen from the combustion process
2. Modified Furnace: Designed to withstand higher temperatures due to oxygen-rich combustion. Requires adaptation of materials and cooling systems.
3. Flue Gas Recirculation: Combustion gases are recycled back into the furnace. Acts as a diluent to control furnace temperature.
4. Heat Recovery and Power Generation: Heat generated is used to produce steam. Steam drives turbines for electricity generation (similar to conventional plants)
5. CO2 Separation and Compression: Flue gas contains approximately 90% CO2 (compared to 4-20% in conventional plants). CO2 is separated through condensation after impurity removal. Captured CO2 is compressed for transport.

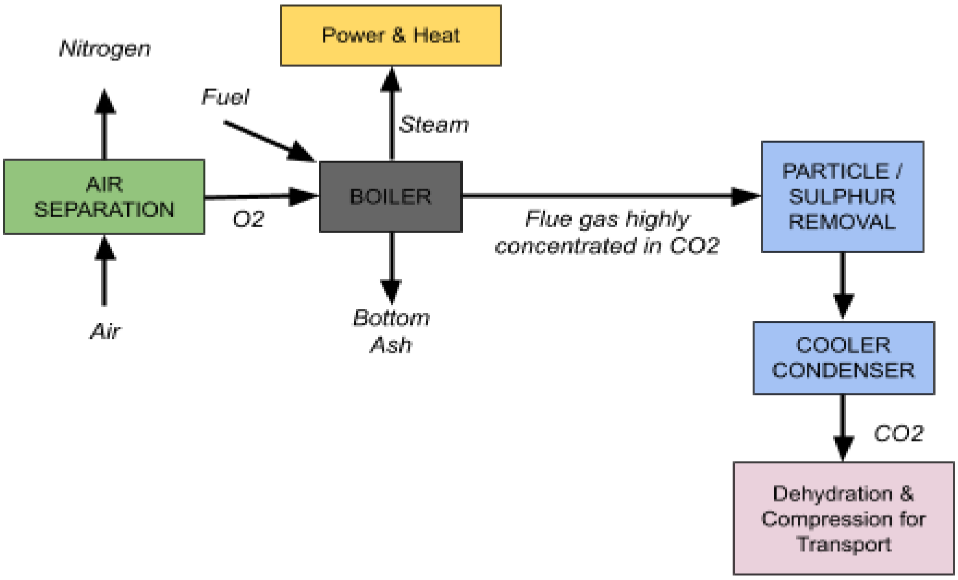


Figure 2.1.1.2: Oxy-fuel Combustion Capture Process

While oxy-fuel combustion offers high capture efficiency, its application to existing Energy Recovery Facilities (ERFs) presents significant challenges:

- Retrofit Complexity: Extensive modifications required to existing furnaces and systems
- Operational Changes: The shift from air-fired to oxygen-fired combustion requires new operational procedures
- Energy Penalty: Additional energy requirements for ASU impact the overall plant efficiency
- Safety Considerations: Handling of pure oxygen requires stringent safety measures

Oxy-fuel combustion capture presents a promising technology for achieving high CO2 capture rates in new facilities. However, its application to existing ERFs is challenging due to the extensive modifications required. For new ERF projects, oxy-fuel combustion could be considered if the design incorporates this technology from the outset. For existing facilities, the feasibility of retrofitting would depend on site-specific factors, including available space, energy balance, and economic considerations.

2.1.3. Post-combustion capture

Post-combustion capture involves adding a CO2 capture plant before the stack to separate CO2 from other components in the flue gas exiting the boiler where combustion occurs. This method is particularly relevant for retrofitting existing facilities as it doesn't require significant changes to the core combustion process.

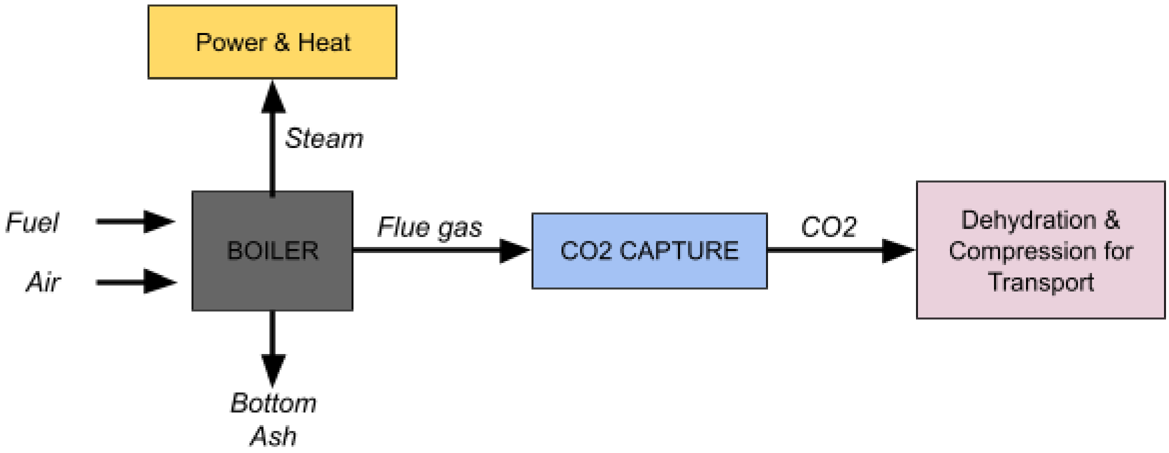


Figure 2.1.1.3: Post-Combustion Capture Process

There are three main processes for capturing CO2 from flue gas in post-combustion capture:

1) Absorption into a Liquid Solvent:

Amine-based absorption is the most mature and widely deployed post-combustion capture technology, with roots dating back to 1930 when R.R. Bottoms first patented it for natural gas sweetening. Adapted for CO2 capture from flue gases in the 1970s, it is now considered the benchmark technology for post-combustion capture.

The process begins as cooled and treated flue gas enters the bottom of an absorption column. Simultaneously, an amine solvent, typically monoethanolamine (MEA) or more advanced formulations, is injected at the top, creating a counter-current flow. This design maximises contact between the CO2-laden flue gas and the solvent, allowing for efficient CO2 absorption. The CO2-rich solvent is then heated and sent to a stripper (regenerator) where the CO2 is separated from the solvent. The captured CO2 is subsequently dried and compressed for transport, while the regenerated solvent is recycled back to the absorber for reuse.

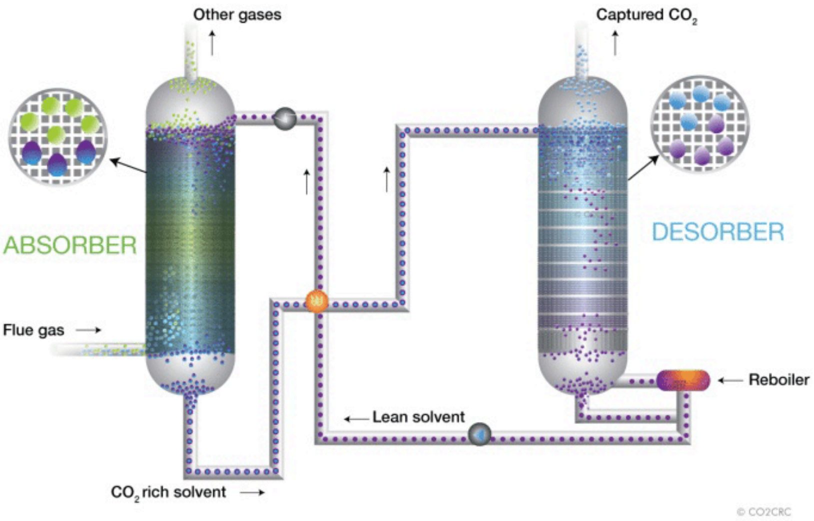


Figure 2.1.1.4: Carbon dioxide removal by absorption (Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC), 2012)

This technology boasts several advantages, including high absorption capacity and selectivity, making it particularly effective for CO2 capture. Its well-established nature means that operational expertise is widely available, and the process of solvent regeneration and recycling is well understood.

However, amine-based absorption is not without challenges. The regeneration process is energy-intensive, typically imposing a 15-30% energy penalty on the host plant. There's also potential for solvent degradation and corrosion, necessitating the use of inhibitors and corrosion-resistant materials. Environmental concerns exist regarding amine emissions, though recent developments have focused on solvents and improved emission control to reduce amine slip.

Advanced solvents like those containing piperazine and mixed amine systems offer improved performance and energy efficiency. For instance, Shell's CANSOLV technology, used at Boundary Dam, claims 20-30% lower energy consumption compared to conventional MEA systems. Process improvements such as split-flow configurations and advanced heat integration are further reducing energy penalties. The EU-funded OCTAVIUS project has demonstrated significant reductions in regeneration energy, achieving 2.1 GJ/tonne CO2, down from 3.5-4.0 GJ/tonne in early designs.

Additional EU funding is supporting continued development and optimisation via the Accelerated Deployment of Integrated CCUS Chains Based on Solvent Capture Technology Project. AURORA is a collaborative project funded by the European Union’s HORIZON EUROPE programme dedicated to optimising and qualifying the open, non-proprietary CESAR1 amine-based solvent technology for commercial deployment.

Looking forward, amine-based systems are expected to dominate the near-term CCS market. Ongoing research focuses on developing more stable solvent formulations, advanced materials to combat corrosion, and optimising designs for different flue gas compositions and plant sizes. The integration of amine absorption with other technologies, such as membrane pre-concentration, may further enhance performance and reduce costs.

For Energy Recovery Facilities considering carbon capture, amine-based absorption offers a proven technology with a track record of commercial deployment ([29] AECOM ‘Next Generation Carbon Capture Technology, Techno-Economic Analysis’ Work Package 6. May 2022.). While the energy penalty and infrastructure requirements are significant considerations, the high capture rates (typically 85-95%) and ongoing efficiency improvements make it a compelling option for facilities looking to dramatically reduce their CO2 emissions.

It should be noted that amine-based solvent capture technology produces some additional emissions of amine and nitrosamine components which require additional monitoring and permitting. Currently, the most efficient amines also have the highest emissions hence final technology selection may be a balance between optimum energy efficiency, amine emissions and any additional CAPEX required for monitoring and reduction of emissions from advanced amines.

2) Adsorption on Solid Sorbents

Adsorption-based CO2 capture using solid sorbents is an emerging technology that offers potential advantages over liquid solvent absorption. This method relies on the selective adsorption of CO2 onto the surface of solid materials, followed by regeneration to release the captured CO2.

Solid sorbents for CO2 capture can be broadly categorised into two main groups:

a) Carbonaceous Materials:
- Examples: Activated carbons, carbon molecular sieves, graphene-based materials
- Advantages: Low cost, simple composition, good porous features, high surface area
- Notable developments:
    - Nitrogen-doped porous carbons showing enhanced CO2 selectivity
    - Graphene oxide frameworks with high CO2 uptake capacity

b) Non-carbonaceous Materials:
- Zeolites: Aluminosilicate materials with well-defined pore structures
    - Examples: 13X, 5A zeolites
    - High CO2 adsorption capacity at low temperatures
- Metal-Organic Frameworks (MOFs):
    - Examples: Mg-MOF-74, HKUST-1, ZIF-8
    - Highly tunable pore size and chemistry
- Amine-functionalized Silica:
    - Examples: MCM-41, SBA-15 functionalized with polyethyleneimine (PEI)
    - Combines high surface area of silica with CO2 affinity of amines

The adsorption process typically involves the following steps:

1) Adsorption: Flue gas contacts the sorbent, and CO2 is selectively adsorbed
2) Desorption: CO2 is released from the sorbent through pressure or temperature swing
3) Regeneration: Sorbent is prepared for the next adsorption cycle
4) Compression: Released CO2 is compressed for transport or utilisation

Adsorption technologies can be categorised based on their regeneration method:

- Pressure Swing Adsorption (PSA)
- Vacuum Swing Adsorption (VSA)
- Temperature Swing Adsorption (TSA)
- Electric Swing Adsorption (ESA)

Adsorption on solid sorbents presents both significant advantages and challenges in CO2 capture. The technology offers potentially lower energy requirements for regeneration compared to amine-based methods, which could reduce operational costs and carbon footprints. Solid sorbents also generally cause less corrosion than liquid amines, potentially lowering maintenance costs. Their higher volumetric capacity could lead to more compact systems, beneficial for retrofitting space-constrained facilities. Additionally, the wide range of available sorbent materials allows for tailored solutions to specific operating conditions.

However, these benefits are counterbalanced by several challenges. Heat management in large-scale adsorption beds remains a significant hurdle, closely tied to scalability issues. Many sorbents that excel in laboratories have yet to demonstrate comparable performance at industrial scales. Sorbent degradation over multiple cycles is another concern, potentially necessitating frequent replacements and increasing costs. Maintaining high CO2 selectivity in complex flue gas mixtures, particularly in the presence of water vapour, also proves challenging.

Despite these obstacles, the potential advantages of solid sorbent adsorption continue to drive research and development. As materials science advances and engineering solutions evolve, many in the industry remain optimistic about overcoming these challenges, potentially leading to more efficient and cost-effective CO2 capture systems in the future.

3) Membrane Separation

Membrane separation technology represents a promising avenue for CO2 capture, offering several advantages over traditional methods. This approach utilises selective membranes to separate CO2 from flue gas, leveraging differences in gas permeability. The technology's appeal lies in its low energy requirements, smaller carbon footprint, and lower operational costs compared to solvent-based systems. Moreover, membrane systems are often modular and can be more easily retrofitted to existing infrastructure, making them an attractive option for upgrading current facilities.

However, membrane technology faces several challenges that have limited its widespread adoption. The primary hurdle is the rapid degradation of membranes, which can lead to a loss of selectivity over time. This degradation is often exacerbated by the harsh conditions present in flue gas streams, including fluctuations in temperature and humidity. Additionally, the presence of contaminants like NOx and SOx can further compromise membrane performance and lifespan.

To address these issues, research has focused on developing more robust and efficient membrane materials. Composite and mixed-matrix membranes (MMMs) have emerged as promising candidates. These advanced membranes integrate inorganic materials, such as metal-organic frameworks (MOFs) or zeolitic imidazolate frameworks (ZIFs), into polymeric structures (Membranes 2023, [31]). This combination aims to enhance both the selectivity and durability of the membranes.

For Energy Recovery Facilities considering carbon capture options, membrane technology presents an intriguing possibility. While it may not yet match the capture rates of amine-based systems, its lower energy requirements and potential for simpler operation could make it an attractive option, particularly as the technology matures and demonstrates long-term reliability at industrial scales.

2.1.4. Socio-environmental benefits

Carbon capture projects offer a range of socio-environmental benefits that extend beyond their primary goal of reducing CO2 emissions. These projects have the potential to create a new ecosystem of employment opportunities, spanning from the initial development phase through construction and into long-term operation. This influx of diverse job opportunities can significantly boost local economies and provide skilled employment in areas that may be transitioning away from traditional industries.

The most significant environmental benefit is the substantial reduction in CO2 emissions from industrial stacks. For Energy from Waste (EfW) facilities, carbon capture technologies can dramatically reduce their carbon footprint, potentially capturing up to 90-95% of CO2 emissions. This level of reduction is crucial for meeting national and international climate targets, particularly in hard-to-abate sectors like waste management. By implementing carbon capture, EfW facilities can transform from significant CO2 emitters to near-neutral or even negative emission facilities when considering the biogenic fraction of waste.

The impact of this CO2 reduction extends far beyond the immediate vicinity of the capture site. It contributes to global efforts to mitigate climate change, helping to slow the rate of global warming and its associated effects such as sea-level rise, extreme weather events, and biodiversity loss.

Furthermore, the implementation of carbon capture technologies can play a crucial role in developing and expanding the carbon market. This market-based approach to emissions reduction can incentivise industries to accelerate their transition towards net-zero operations, creating a ripple effect of environmental benefits across various sectors. As more facilities adopt carbon capture, it could drive down costs and spur further innovation in clean technologies.

However, it's important to acknowledge that carbon capture technologies have potential environmental risks. Depending on the capture method used, there may be concerns about the release of degradation products, particularly with amine-based systems. These byproducts can be harmful to the environment if not properly managed and disposed of. Additionally, the process can generate wastewater that may be toxic to aquatic life, necessitating careful treatment to preserve local ecosystems.

2.1.5. Economic viability of CC for Energy from Waste

Post-combustion carbon capture is widely regarded as the most suitable technology for retrofitting existing Energy Recovery Facilities (ERFs). This assessment is based on its ability to be integrated with minimal disruption to existing operations and its more advanced stage of development compared to other capture methods.

According to the AECOM report "Next Generation of Carbon Capture Technology," the economic viability of different capture technologies can be initially assessed through their Levelized Cost of Carbon (LCOC). The report illustrates that among the various technologies, Molten Carbonate Fuel Cells (MCFC), Hot Potassium Carbonate (HPC), non-amine solvents, and advanced amine solvents demonstrate the lowest LCOC for EfW applications. In contrast, solid sorbents and membrane technologies currently show significantly higher LCOC, making them less economically attractive for immediate large-scale deployment.

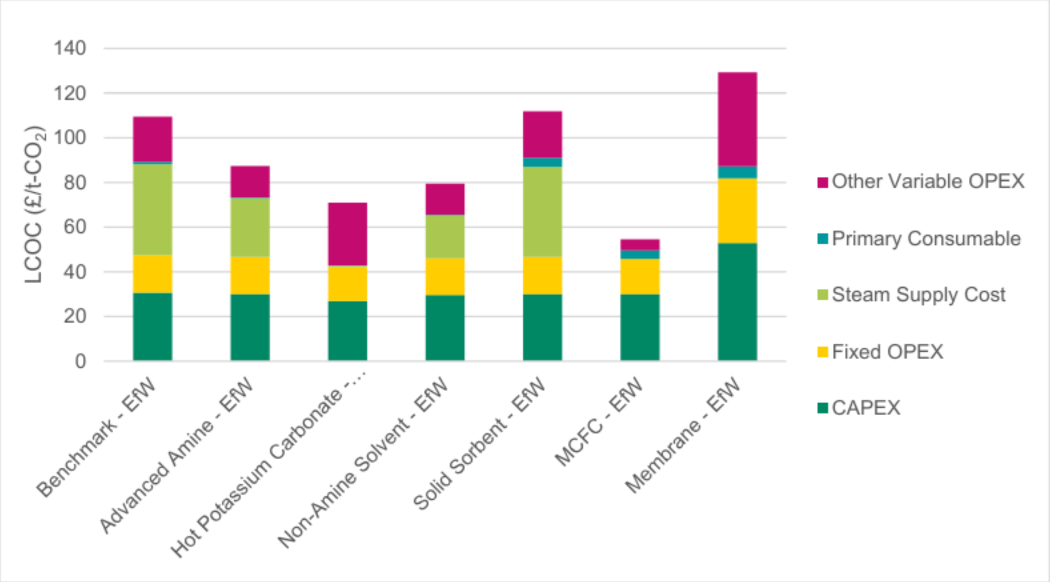


Figure 2.1.4.1: Energy from Waste LCOC (AECOM, [29])

However, LCOC is not the sole determinant of economic viability. Other crucial factors include:

- Technology Maturity: Despite lower LCOC, technologies like MCFC, non-amine solvents, and HPC face significant challenges in terms of commercial readiness. MCFC, for instance, has never been tested on EfW facilities, while HPC has only reached the pre-FEED (Front End Engineering Design) stage for some facilities without actual implementation on EfW flue gas. This lack of operational experience in EfW contexts significantly increases the financial risk associated with these technologies.
- Operational Experience: Advanced amine solvent technology, although not the lowest in LCOC, has been extensively tested and implemented in commercial settings. This operational track record reduces financial risks and increases the likelihood of successful large-scale deployment.
- Energy Penalty: HPC and non-amine solvents generally impose a higher electricity penalty compared to advanced amine solvents. This increased energy demand can significantly impact the overall economics of the ERF operation.
- Capital Expenditure (CAPEX): MCFC technology, while promising in terms of LCOC, requires substantially higher upfront investment compared to other options. It also demands more space

and relies on natural gas input, which could be problematic in terms of long-term sustainability and space constraints at existing facilities.
- Supply Chain Considerations: The AECOM report highlights that amine solvent technology benefits from a more secure and established supply chain, which is crucial for large-scale commercial projects.
- Regulatory Alignment: The Best Available Techniques (BAT) Review, based on the AECOM report, recommends the development of amine solvent solutions as the best available technology for carbon capture in EfW facilities.

While LCOC provides a useful initial comparison, the overall viability of carbon capture technologies for EfW facilities must consider a broader range of factors. Currently, advanced amine solvent technology offers the best balance of economic viability, technological readiness, and risk mitigation for commercial-scale projects in the EfW sector.

Veolia has conducted a preFEED study into the development of amine carbon capture at the Marchwood ERF. The progression of the project is now subject to economic feasibility and the development of a viable transport and storage network and utilisation pathway.

2.2. CO2 Transport and Storage Options for Marchwood ERF

2.2.1. Overview

Marchwood Energy Recovery Facility (ERF) is located in the Marchwood Industrial Park, Southampton. As part of its decarbonisation strategy, the project is evaluating three distinct Transport and Storage (T&S) networks for captured CO2:

1) Pipeline connection to Fawley and utilisation of the Solent Cluster pipeline and storage location in the English Channel
2) Rail transport to an alternate aggregator and shipping to a tracked storage location
3) Development of local port infrastructure adjacent to the Marchwood ERF to ship directly from the site to the aggregator and store

Each of these options presents unique opportunities and challenges in the context of Marchwood ERF and the broader UK decarbonisation landscape. The evaluation of each of these options is based on the economic and technical feasibility and life cycle assessment.

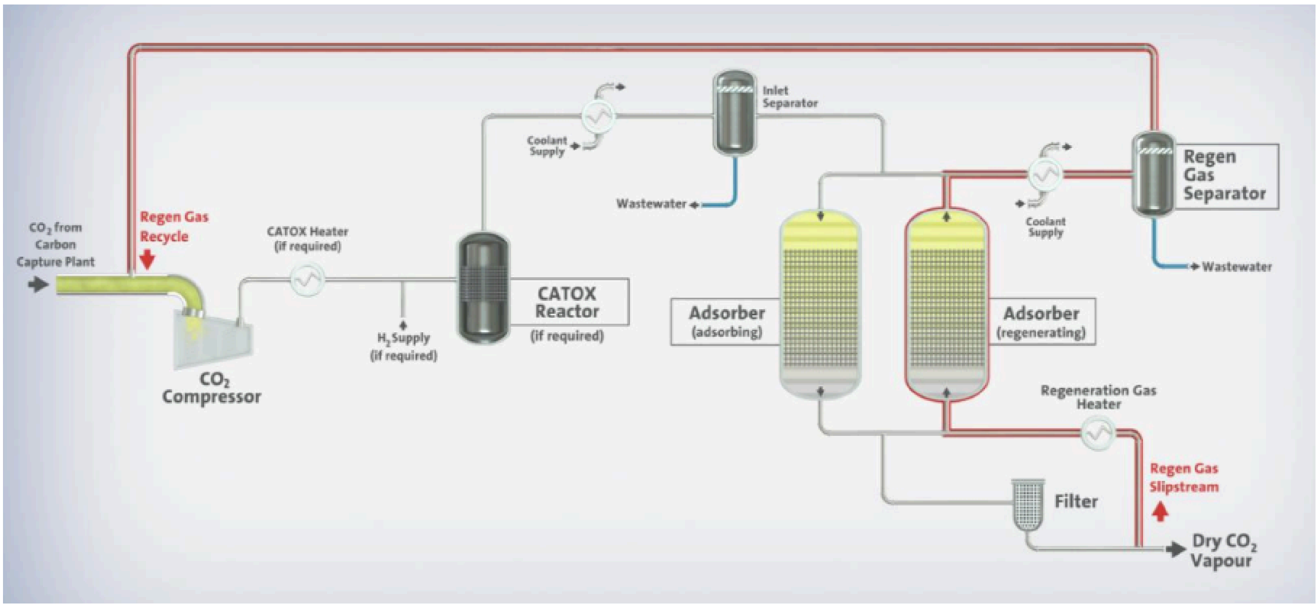
2.2.2. CO2 Conditioning

For CO2 to be transported, it first has to be conditioned to meet the specifications of the transportation model. The specification and composition required for the onshore Pipeline connection to the Fawley and the MP liquid CO2 (LCO2) considered for rail and shipping options are summarised:

Parameter	Pipeline Specification	LCO2 Specification [Northern Lights]
Pressure (bar)	30	18.5
Temperature (°C)	<40	<-25
CO2 Purity (mol %)	<95.5%	<99.81%
H2O (ppm-mol)	<100	<30
O2 (ppm-mol)	<50	<10
SOx (ppm-mol)	<10	<10
NOx (ppm-mol)	<10	<1.5
H2S (ppm-mol)	<10	<9
*FG impurities and trace elements (ammonia, mercury, formaldehyde, acetaldehyde, carbon monoxide and hydrogen) included in detailed specification for design.		

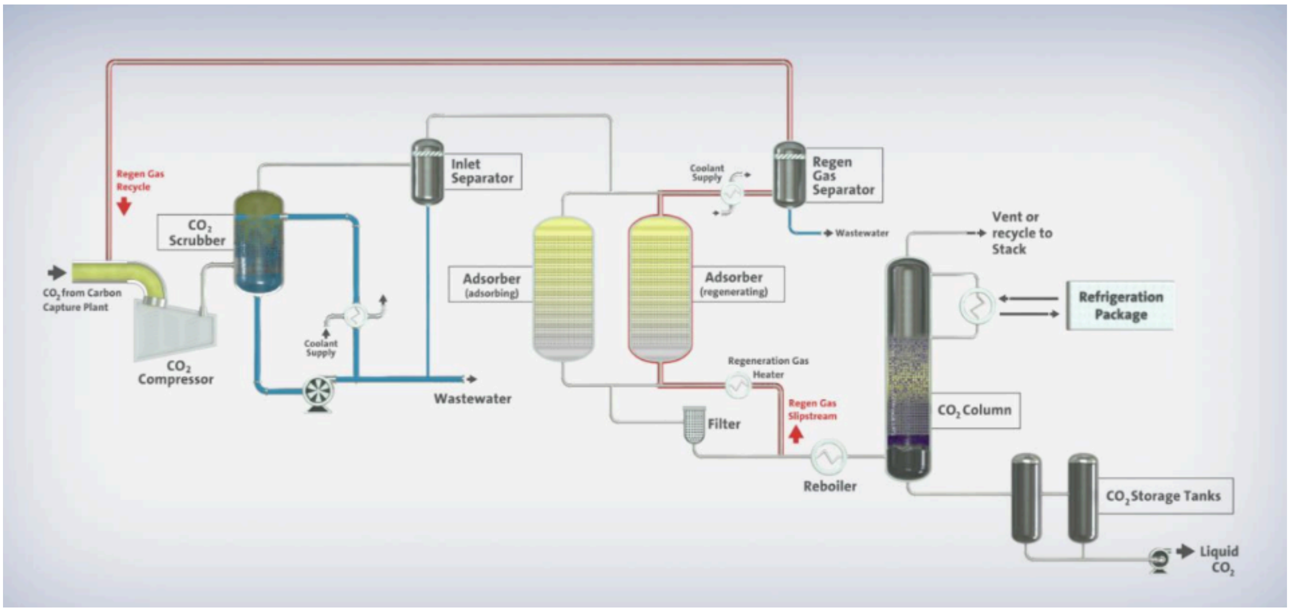
Further conditioning that may be required for storage is encompassed in the levelised cost of the T&S network and may not be explicit in this report.

For the onshore pipeline connection, the CO2 from the capture plant must undergo compression and dehydration. The post-treatment plant consists of a multistage Co2 compressor and two silica gel adsorbent dehydration beds.



Typical CO2 compression and dehydration process

Both the rail and shipping scenarios required CO2 to be liquified. The liquefaction process is similar to the compression and dehydration train but includes an additional Chiller and Reboiler package. The liquid CO2 formed from the refrigerant distillation process is sent to cryogenic storage tanks ready for use or transport. During the liquefaction process up to 2-3% of CO2 is vented, reducing the total CO2 capture from the project.



Typical CO2 Liquefaction process

For Marchwood ERF, it is calculated that the liquefaction process will have a levelised cost x2-2.2 that of conditioning for pipeline specification. Furthermore, the levelised cost for onsite storage for the rail and shipping scenarios are £3.3/TCO2 and £8.9/TCO2 respectively. The higher costs for the shipping scenario are due to the larger volume required to warrant dedicated ship collection. This value could be reduced in future if a milk round model for LCO2 shipping is developed.

The levelised cost of the condition impacts the economic viability of the project. The development of specific T&S networks dictates the conditioning route for the project.

2.2.3. Pipeline connection to Solent Cluster Store

The Solent Cluster is a pioneering decarbonisation initiative and the only CO2 network planned for the south coast of England. While previous government support has primarily focused on northern clusters such as HyNet, East Coast, Viking, and Acorn, the Solent Cluster represents a crucial opportunity for southern industrial decarbonisation.

Key Features of the Solent Cluster:

- Storage Capacity: Aims to store 10 million tonnes per year (MTPa) of CO2
- Infrastructure: Development of CO2 transport infrastructure from the Fawley refinery to an offshore storage location in the English Channel
- Leadership: The Transport and Storage (T&S) network is being developed and led by ExxonMobil

Current Status:

- Licence Application: ExxonMobil has applied for a storage licence under the North Sea Transition Authority (NSTA). A future commercial licence will be required for external emitter connections such as Marchwood ERF.
- Public Consultation: Three pipeline corridors have been submitted for public consultation
- Future Steps: Planning permission and Development Consent Order (DCO) process to follow
- Pipeline Transport Advantages: Pipeline transport of CO2 offers significant advantages over alternative methods, particularly for shorter distances.

According to the IPCC Special Report on Carbon Dioxide Capture and Storage (2005), offshore pipeline transportation is the most cost-effective option for routes under 1,000 km, making it ideal for large-scale CO2 transport in many scenarios. Key benefits include:

- Continuous, uninterrupted CO2 flow, crucial for the efficient operation of capture sites and storage facilities
- Lower overall CO2 emissions compared to alternatives like truck or rail transport
- Cost-effectiveness, especially for shorter distances

The development of this T&S network is subject to government support for storage licences and successful planning permission. The July 2024 National Audit Office Report on the CCUS program highlights significant challenges in meeting the government's 2030 carbon sequestration targets. If supported, the Solent Cluster could play a crucial role in accelerating decarbonisation for the Solent region and help the government achieve its targets (20-30 MTPa by 2030) by providing an additional 10 MtPA of storage capacity, significantly contributing to bridging the gap identified.

The T&S network connection from Fawley to the storage location in the English Channel is estimated to have the lowest levelised cost of the three options evaluated. This connection also removes some of the logistical and economic challenges of developing T&S infrastructure for a single emitter.

The Marchwood Energy Recovery Facility (ERF), situated approximately 10km from the Fawley refinery, presents an ideal opportunity for integration with the Solent Cluster's carbon capture infrastructure. The levelised cost of the 4-inch pipe onshore pipe connection is estimated to be £4-6/tCO2 (Source: Element Energy for BEIS, "The cost of CO2 transport and storage in global integrated assessment modelling"). The Pipeline transport allows for uninterrupted CO2 flow, ensuring consistent operation of the capture site at Marchwood ERF and limiting on-site storage requirements.

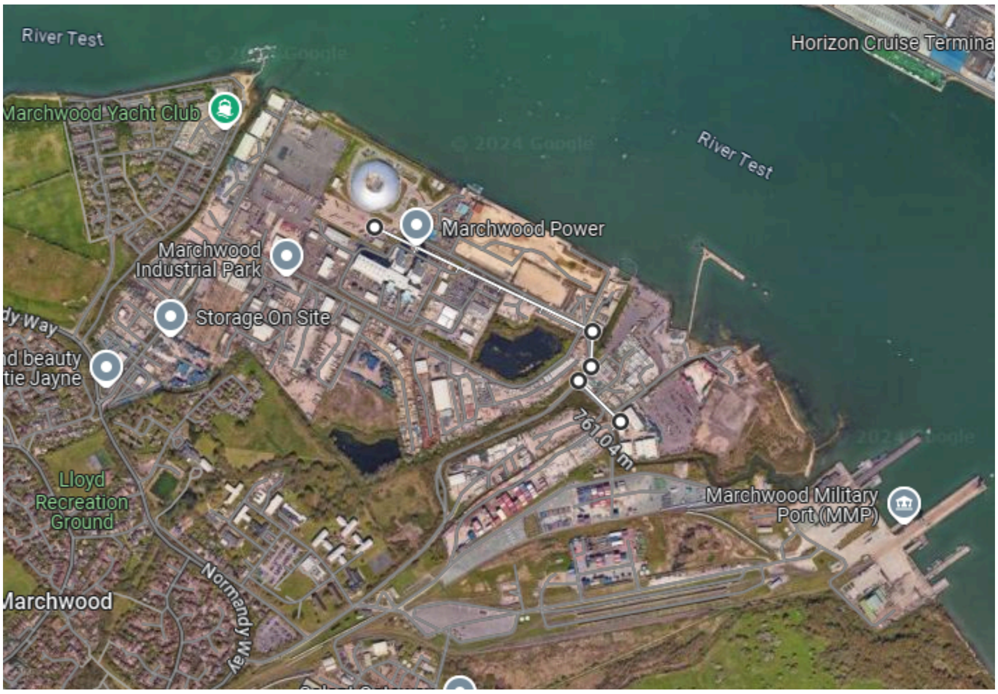
The life cycle assessment conducted by Veolia for the development of post-combustion carbon capture at Marchwood ERF and T&S network estimates pipeline connection would reduce transmission losses by 2.7% when compared to alternate T&S routes available.

2.2.4. Rail & Shipping connection to alternate store

The utilisation of the rail network has been highlighted as having a significant opportunity to accelerate the decarbonisation of dispersed emitters through a low-cost and scalable transport network. Rail network is available now and usage for T&S networks would leverage fully depreciated and underutilised national infrastructure assets. Depicted are some large-scale emitters in the south-west and their proximity to existing GB rail lines.

Railcar manufacturer VTG currently operates a fleet of dedicated liquid CO2 wagons in Europe with a capacity of 62 tonnes per wagon and is designing a UK loading gauge wagon with a capacity of 72 tonnes. GB Rail Freight Ltd. has confirmed that trains of up to 30 waggons can be accommodated giving a maximum capacity of approximately 2,000 tonnes per train with the exact capacity being determined based on the design of the loading/unloading system and the heel of CO2 left in the wagon.

Marchwood ERF is located in close proximity (800m) to the GB rail network, terminating in the Marchwood industrial estate.



To connect Marchwood ERF to a tracked store, investment in an onshore pipeline, intermediate storage and LCO2 rail loading system would be required. Discussions with rail freight operators indicate that once loaded, ongoing service rail service would have low additional costs for the project.

The estimated levelised cost for an onshore pipeline to connect Marchwood ERF and subsequent development of rail connection is low in comparison to the levelised cost of capture and T&S charges for shipping. Rail connection could be an economically viable option for connection to existing tracked clusters if supported by a non-pipeline transportation business model.

Transportation by rail and the subsequent shipping is expected to have the greatest CO2 transmission losses. This estimate is based on a 14.7g/CO2/km estimate for rail transportation and figures in the CO2 Shipping Study Final Report for BEIS by ElementEnergy.

2.2.5. Shipping & Port Infrastructure

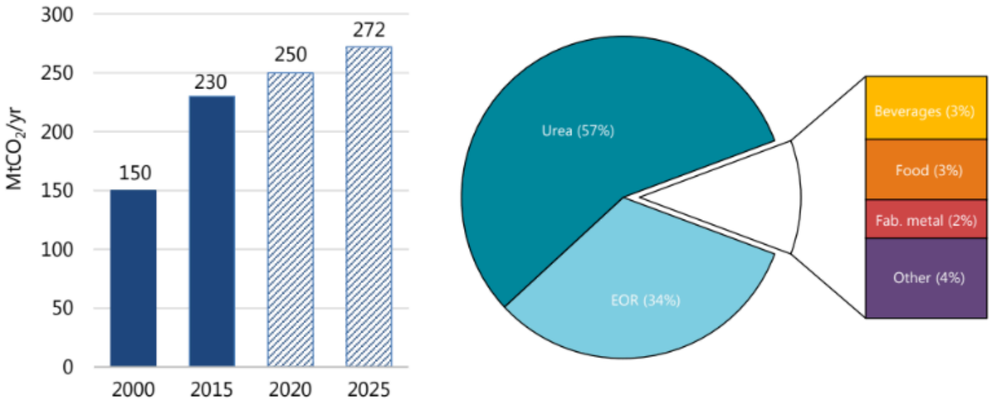
The final option to connect Marchwood ERF to a store would be to develop port infrastructure suitable for LCO2 loading close to the site. Marchwood ERF is located on the quayside and would require significant dredging to facilitate LCO2 ships. Furthermore, to meet the volume requirements for ships significant storage capacity would have to be located on land not currently owned by Veolia.

Future work could focus on the redevelopment of Husband Jetty, 800m from Marchwood ERF. The Jetty is located inside Marchwood Industrial Park and is currently owned by the Crown Estate and leased by ABP. The jetty is close to a rail terminal which could enable the decarbonisation of dispersed emitters in the south of England.

The development of a shipping and rail terminal will require several emitters to collaborate to reduce the cost of capital. The project would also need an aggregator or T&S developer. This is a potential solution if the Solent Cluster store does not develop.

2.3. Use of CO2 in Methanol Production

In 2000, global CO2 consumption was around 150 Mt/year, and the demand for CO2 has grown ever since. In 2015, demand increased rapidly to 230 MtCO2, and in 2020, the level was expected to reach 250 MtCO2. The trend of increasing demand is expected to remain constant due to the economic development of three major CO2 markets, which are the USA (33%), China (22%), together with Europe (16%). Throughout the last decade, total private financing for CO2 utilisation start-ups across the world reached nearly 1 billion dollars and there are now several EU-led innovation funds aimed at acceleration utilisation.

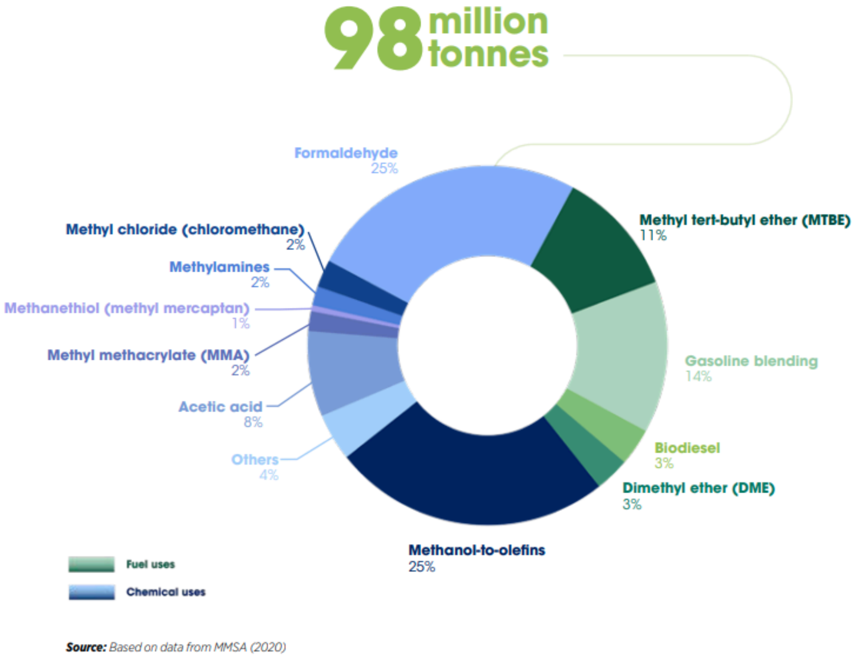


Note: Projections for future global CO_2 demand are based on an average year-on-year growth rate of 1.7%.
Sources: Analysis based on ETC (2018), *Carbon Capture in a Zero-Carbon Economy*; IHS Markit (2018), *Chemical Economics Handbook – Carbon Dioxide*; US EPA (2018), *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2016*.

IEA. Putting CO2 to Use, IEA, Paris https://www.iea.org/reports/putting-co2-to -use].

The global demand for methanol was about 120 Mt per year in 2020 and continues to grow. Only one year before, the demand was only 98 Mt. Methanol is a base chemical and can be used to produce many different chemicals, petrochemicals, pharmaceutical components, plastics and aromatics.

Figure 2.3.2.1: Methanol applications (Methanol Institute)



Source: *Based on data from MMSA (2020)*

Figure 2.3.2.2: Global methanol demand in 2019 ((IRENA and Methanol Institute, [42])

The shipping sector is currently responsible for 3% of all GHG emissions (IRENA, 2019b) and 80-90% of international trade. Even though methanol requires additional energy to be synthesised compared to hydrogen or even electricity, other factors have to be considered such as the conditions of storage on the ship. To be liquified, hydrogen needs to be lower than -253°C which requires a large amount of energy and an unconventional way of storage. Furthermore, Methanol has a greater energy density when taking into account the storage is a lot higher than other substitutes.

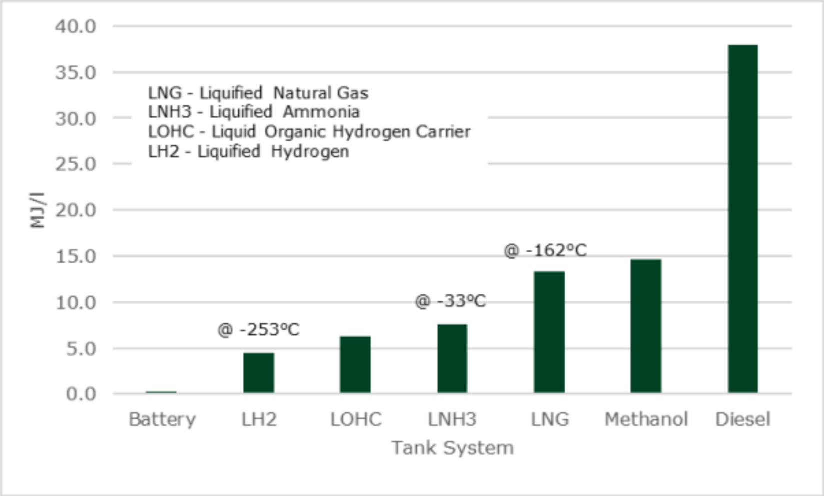


Figure 2.3.2.3: Energy per volume of tank system (Longspur Research, [43])

Additionally, green methanol has one of the lowest associated emissions considering CO2, NOx and SOx. This is an incredibly important feature for ships bunkering in ports close to populations.

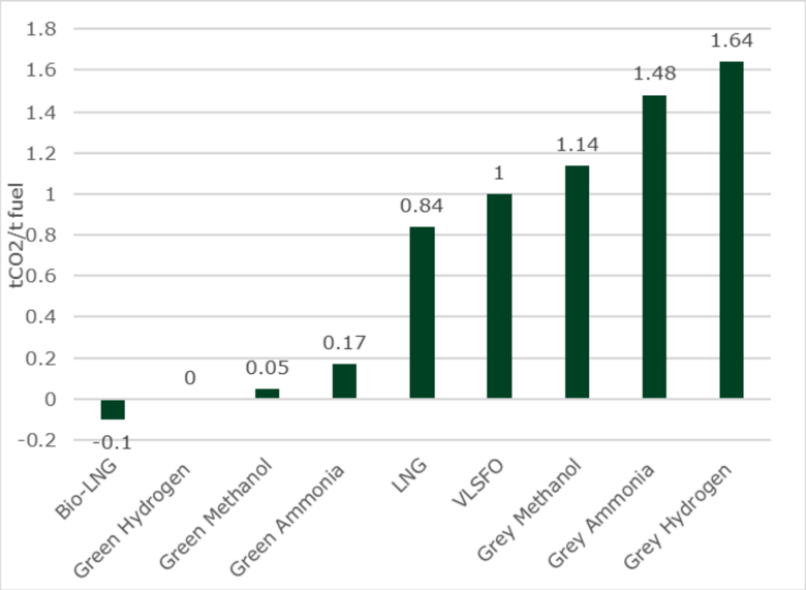


Figure 2.3.2.4: Well-to-wake emissions (Longspur Research, [43])

The shipping sector is estimated to consume more than 9EJ globally. E-methanol could be the best substitute for maritime decarbonisation and given the volume could be significant.

The ports of Southampton and Portsmouth have around 200,000 large vessel movements each year and are major trade and commercial hubs connecting the UK with the global economy. The ports see the operation of many different types of vessels, from those domiciled in port (tugs, etc.), ferry services and international trade (deep water vessels).

Maritime is to be included in the EU ETS, and domestic maritime in the UK ETS. Furthermore, the RTFO supports the transition of the sector to the usage of a lower-carbon fuel. The maritime industry is looking to decarbonise and many of the operators in the Southampton region are keen to explore low-carbon fuel options. Some of the companies currently operating in the region have significant projects globally and could look at developing in the UK:

- **Svitzer:**
    - MOU with MAN Energy Solutions for the development of a methanol-fuelled version of the MAN175D engine and target field-test agreement in 2025 - https://www.man-es.com/company/press-releases/press-details/2024/03/25/svitzer-targets-methanol-fuelled-man-175df-m-engine-for-tug-application
    - Contracted Uzmar shipyard to build first-of-its-kind battery-methanol tug for delivery in H2 2025. The tug will operate x% of its time in the Port of Gothenburg - https://markets.ft.com/data/announce/detail?dockey=1330-1000992064en-05Q8LPVM7JV2SB8PM0MPTOQQRP
- **Wallenius Wilhelmsen:**
    - Recently ordered eight methanol dual-fuel PCTCs with delivery from mid-2026. Eight more options vessels to follow with a commitment to Net-zero emissions end-to-end service by 2027. https://www.offshore-energy.biz/wallenius-wilhelmsen-adds-four-more-methanol-dual-fuel-optional-pctcs-in-china/

- **TUI Cruises:**
    - Finnish shipbuilder Meyer Turku has delivered Mein Schiff 7, a methanol-ready cruise ship,
    - Other cruise operators Cruise Line, Disney Cruise and Costa Cruises are looking at developing new fuel options.
- **Red Funnel:**
    - Collaboration with Artemis, announcing Red Jet - electric e-foiling passenger ferry as look to decarbonise Ferry activity to the Isle of Wight.
- **Maersk:**
    - Maersk has a total of 25 methanol-powered container carriers on order at Hyundai Heavy Industries, Hyundai Mipo Dockyard and Yangzijiang Shipbuilding Group. https://www.offshore-energy.biz/maersk-worlds-second-large-methanol-powered-containership-named-in-yokohama/
- **Methanol Institute summary:** https://www.methanol.org/wp-content/uploads/2023/03/222-Final-MIs-On-the-Water-and-on-the-Way.pdf

Technical overview and challenges

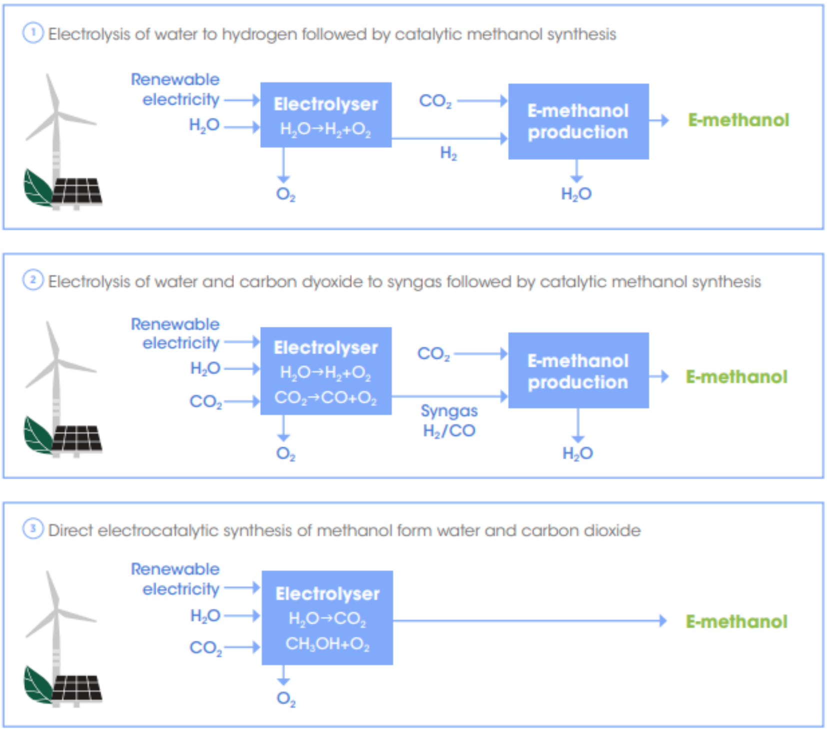
Methanol has been produced from fossil fuels for many years. The conventional way uses steam reforming or autothermal reforming with partial oxidation of the fossil fuel to make synthesis gas which is a mix of CO2, CO and H2. Then, this syngas goes through a methanol converter which catalytically synthesises CH3OH and water. This synthesis of methanol is analogous to that of Fischer–Tropsch-based indirect liquefaction. Finally, the distillation process allows to separate methanol from the water.

The process occurring in the Reactor under 35-50 bar and 200-300°C on a Cu/ZnO/Al2O3 catalyst is the outcome of three reactions as shown below (Roy, Soumyabrata, et al., [47]):

(1) CO2 + H2 = CO + H2O
(2) CO2 + 3 H2 = CH3OH + H2O
(3) CO + 2 H2 = CH3OH

Reactions (2) and (3) are exothermic and favoured by increasing pressure and decreasing temperature. Reaction (1) is endothermic, called Reverse Water-Gas Shift reaction (RWGS), favoured generally by opposite conditions. Thermodynamics and equilibrium shifts interplay to control the conversion and selectivity of the product MeOH. One way to shift this equilibrium is to remove some products, here water. The preferred direct methanol formation from CO2 is often a combination of (1) and (3) which is used exclusively in what we call the CAMERE process (for carbon dioxide hydrogenation to form methanol via a reverse-water-gas-shift reaction).

Co-electrolysis of both water and biogenic CO2 to produce syngas and direct electrochemical CO2 reduction is a promising synthesis route for the production of E-Methanol. These technologies are less mature with a TRL of 6 and 4 respectively than SMR. The Solid Oxide Electrolyser Cell is at an early commercial stage whereas the electrochemical CO2 reduction would need too much surface area.



Source: *Ellis et al. (2019).*

Figure 2.3.2.6: E-methanol production (IRENA and Methanol Institute, [42])

The mass balance of the production of e-methanol from captured CO2 and electrolytic H2 with the usual catalyst is shown in Figure 2.3.2.7 and Figure 2.3.2.8.

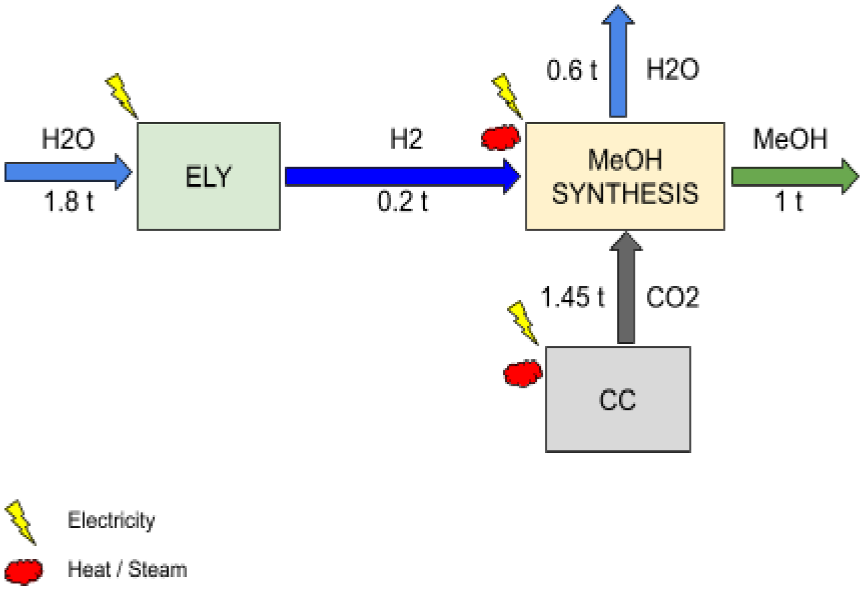


Figure 2.3.2.7: Mass balance of e-methanol production (Technico Economic Assessment by Veolia)

The carbon intensity of methanol will depend mainly on the raw materials used for its production. As for hydrogen production, the carbon intensity of methanol is illustrated by colours attributed to the different pathways of production.

The most carbon-intensive way to produce methanol is from the gasification of coal, the output is called brown methanol. Then, comes the reforming of natural gas which produces grey methanol. Blue methanol is produced either from blue hydrogen and captured CO2 from renewable sources or not, or green electrolytic hydrogen with CO2 from fossil fuels origin, industry. Finally, green methanol can be produced from both gasification and reforming of the biomass or by renewable H2 and CO2 captured (e.g. CO2 from flue gas from biogenic content, direct air capture) respectively called bio-methanol and e-methanol. They have the lowest carbon intensity (IRENA and Methanol Institute, figure 2.3.2.9, [42]).

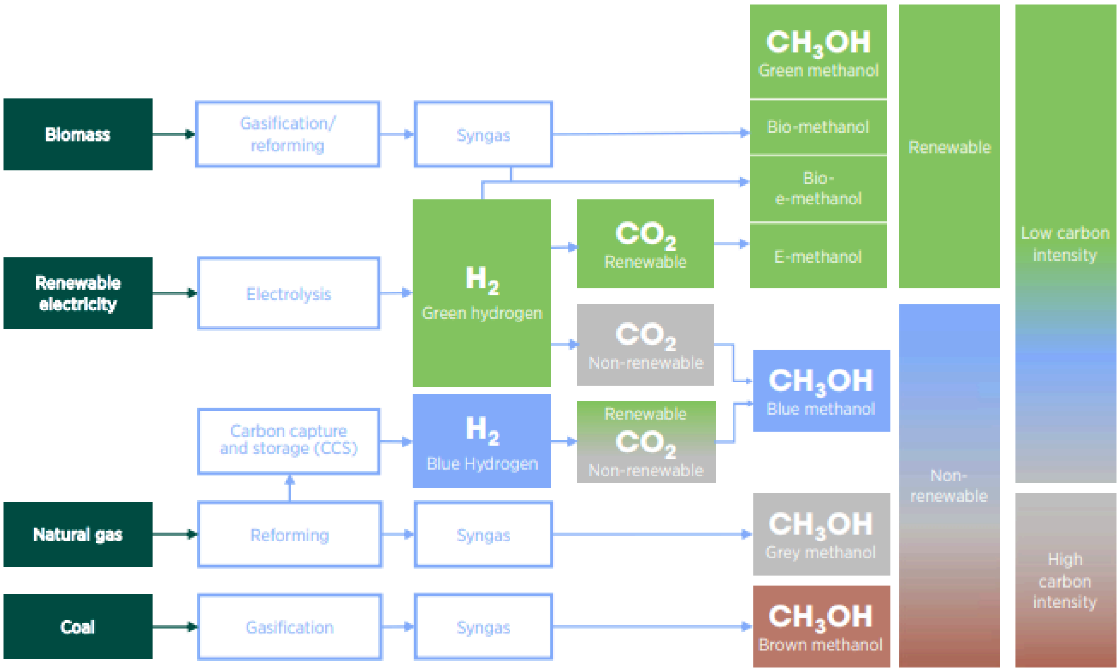


Figure 2.3.2.9: Carbon intensity in the function of the production pathways (IRENA and Methanol Institute, figure 2, [42])

Methanol from CO2 from waste to energy facilities could be both green and blue methanol if produced by electrolytic H2 depending on the biogenic content share of the CO2.

As a reference the lowest CO2 emission from methanol from fossil fuels in the literature is about 90g CO2 eq/MJ with natural gas (raw material to final use GHGs). Power-based methanol ranges from 1.74g CO2 eq/MJ with renewable electricity and biomass plants to 33.1g CO2 eq/MJ with renewable electricity (IRENA and Methanol Institute, [42]).

When produced from CO2 and electrolytic hydrogen, most of the levelised cost of production of e-methanol depends on the costs of its raw materials: captured CO2 and hydrogen (IRENA and Methanol Institute, [42]). Electricity cost represents 80% of the hydrogen cost, to offer a competitive e-methanol price, we need to have a price-competitive renewable electricity.

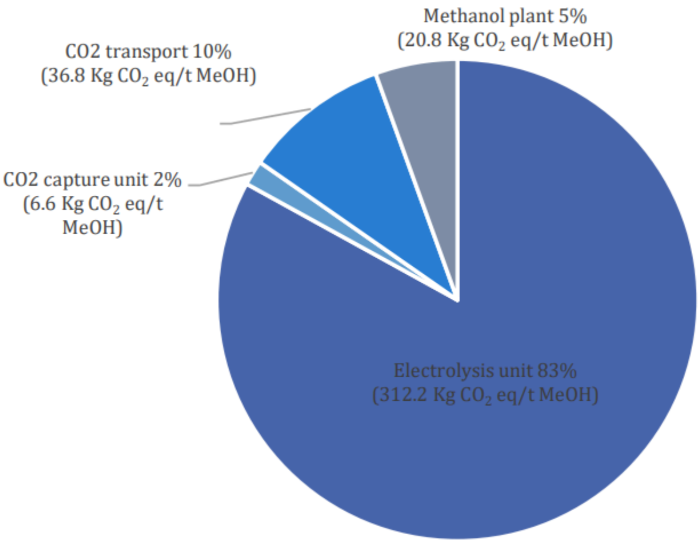
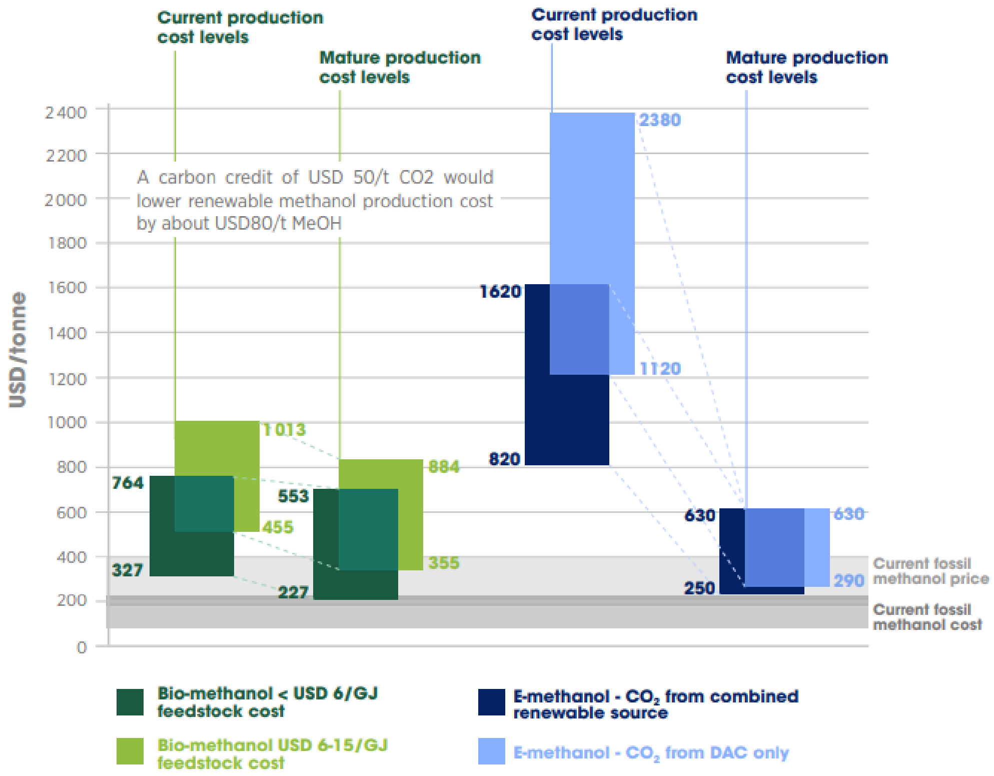


Figure 2.3.2.12: The indirect global warming impacts of the four main processes identified as components of the CCU methanol production process (Global CO2 Initiative, Figure 5, [49])

A study of 2018 (Global CO2 Initiative, [49]) analyses the technical-economical aspects of the production of e-methanol through the capture of CO2, the production of hydrogen from renewable electricity and the synthesis of methanol. The study shows that the minimal price for e-methanol would be around 1,400 €/t (Global CO2 Initiative, Table 5, [49]). A study from the IRENA and Methanol Institute published in 2021 shows similar cost levels with a range from USD 820-1620/t for e-methanol from CO2-combined renewable sources (IRENA and Methanol Institute, Figure 3, [42]).



Note: *Exchange rate used in this figure USD 1 = EUR 0.9.*

Figure 2.3.2.14: Current and future projections costs of bio- and e-methanol compared to methanol from fossil fuel (IRENA and Methanol Institute, figure 41, [42])

Hydrogenation appeared as the highest-cost solution in terms of OPEX and utility consumption for the use of CO2 (Kamkeng, Ariane D. N., et al., [51]). High OPEX is directly linked to the purchase of green H2 and could reach about 90% of OPEX (Kamkeng, Ariane D. N., et al., figure 15. b, [51]). The market price for CO2-derived fuels via hydrogenation is estimated to be 2-7 times higher than current solutions with high intensity on electricity consumption. However, the maturity of the technology gets better as described by the Technology Readiness Level (TRL) which could lead to a decrease in the cost (Kamkeng, Ariane D. N., et al., table 5, [51]). Other solutions to use CO2 seem to have a lower range of operating costs with lower utility consumption such as mineralisation technology (Kamkeng, Ariane D. N., et al., Table 6, [51]).

2.4. Feasibility of Carbon Utilisation from Marchwood ERF Emissions

There is a growing commitment from maritime operators to decarbonise. Veolia has communicated with several stakeholders in the Solent Region and believes there is interest in the development of the e-methanol project. An e-methanol project would decarbonise local maritime, reduce a range of emissions and attract large methanol-ready vessels to the bunker, creating green corridors.

Many possible methanol products could be produced from the combination of Hydrogen and carbon captured from Marchwood ERF.

- Grid Hydrogen - Currently expensive due to high electricity prices and low emission reduction. The ability to transport curtailed renewable power via the national grid would however reduce both cost and CO2 footprint.
- Blue hydrogen - Not eligible for RFNBO status
- Green Hydrogen - significant reduction in emissions but the current price is uncompetitive.
- Smart Grid - The proactive introduction of a local smart grid incorporating battery storage of curtailed renewable power with dispatchable power from Marchwood CCGT and future development of local renewable power could result in an optimum solution of early implementation followed by medium-term cost and CO2 footprint reduction.

The utilisation of grid electricity with the current generation profile for hydrogen production would elicit methanol with too high a carbon footprint and therefore would not be classified as an RTFO. E-methanol, produced from blue hydrogen and biogenic Co2 could reduce carbon emissions significantly but would not currently be eligible for E-methanol/bio-methanol status.

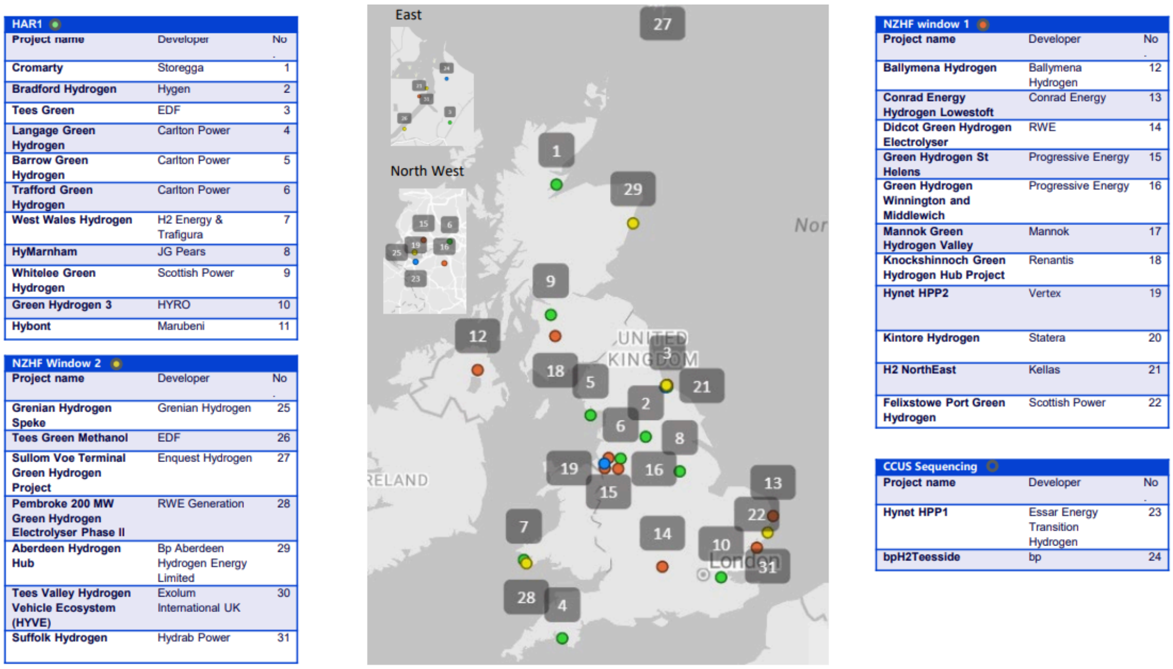
		Heavy Fuel	**GreenH2/BioCO2**	**GridH2/BioCO2**	**BlueH2/BioCO2**
Price	**£/fuel**	880	1,861	1,264	925
Normalised price	**£/kWh**	74	300	204	149
Additional cost	**%**	-	406%	276%	202%
Carbon Footprint	**kgCO2/fuel**	3,580	122	1,718	275
Normalised Carbon footprint	**kgCO2/kWh**	301	20	277	44
Emission reduction	**%**	-	-93.47%	-7.87%	-85.26%

To produce a low-emission e-methanol product with competitive pricing, the green hydrogen price needs to be reduced to around £3/kg. Stepwise introduction of a smart grid system, battery storage and local renewables may achieve this however short-term revenue support will be required.

		Green Hydrogen (£3/kg) / BioCO2
Price	**£/fuel**	886
Normalised price	**£/kWh**	140
Additional cost	**%**	189%
Carbon Footprint	**kgCO2/fuel**	122
Normalised Carbon footprint	**kgCO2/kWh**	20

Emission reduction	%	-93.47

Enabling Green Hydrogen produced under HAR subsidy in fuel creation could be an enabling mechanism to support the development of e-fuels. There are currently no hydrogen projects supported in the Solent region.



HAR1 ●

Project name	Developer	No.
Cromarty	Storegga	1
Bradford Hydrogen	Hygen	2
Tees Green	EDF	3
Langage Green Hydrogen	Carlton Power	4
Barrow Green Hydrogen	Carlton Power	5
Trafford Green Hydrogen	Carlton Power	6
West Wales Hydrogen	H2 Energy & Trafigura	7
HyMarnham	JG Pears	8
Whitelee Green Hydrogen	Scottish Power	9
Green Hydrogen 3	HYRO	10
Hybont	Marubeni	11

NZHF Window 2 ●

Project name	Developer	No.
Grenian Hydrogen Speke	Grenian Hydrogen	25
Tees Green Methanol	EDF	26
Sullom Voe Terminal Green Hydrogen Project	Enquest Hydrogen	27
Pembroke 200 MW Green Hydrogen Electrolyser Phase II	RWE Generation	28
Aberdeen Hydrogen Hub	Bp Aberdeen Hydrogen Energy Limited	29
Tees Valley Hydrogen Vehicle Ecosystem (HYVE)	Exolum International UK	30
Suffolk Hydrogen	Hydrab Power	31

NZHF window 1 ●

Project name	Developer	No.
Ballymena Hydrogen	Ballymena Hydrogen	12
Conrad Energy Hydrogen Lowestoft	Conrad Energy	13
Didcot Green Hydrogen Electrolyser	RWE	14
Green Hydrogen St Helens	Progressive Energy	15
Green Hydrogen Winnington and Middlewich	Progressive Energy	16
Mannok Green Hydrogen Valley	Mannok	17
Knockshinnoch Green Hydrogen Hub Project	Renantis	18
Hynet HPP2	Vertex	19
Kintore Hydrogen	Statera	20
H2 NorthEast	Kellas	21
Felixstowe Port Green Hydrogen	Scottish Power	22

CCUS Sequencing ○

Project name	Developer	No.
Hynet HPP1	Essar Energy Transition Hydrogen	23
bpH2Teesside	bp	24

Projects offered support through windows 1 and 2 of the NZHF and HAR 1, and the CCUS enabled hydrogen projects in the latest stage of the Track-1 cluster sequencing process

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Annex 2: Feasibility

>> E-METHANOL PROJECTS AROUND THE WORLD

Company	Projects	Role	Country	Start-up year	Capacity	Feedstock	Link
Carbon Recycling International	MefCO2 - demo	Emissions to Liquids technology	Germany	2019	1 t/d	CO2 from the thermal plant of RWE	[52]
	Free - demo		Sweden	2020		CO2 from a steel furnace	[52]
	Goerge Olah - industrial scale		Iceland	2012	1,300-4,000 t/y	CO2 from geothermal power plant	[52]
	Finnfjord - commercial		Norway	In design	100,000 t/y	CO2 from ferrosilicon plant	[52]
	Shunli - commercial		China	2022	110,000 t/y	CO2 from a coke-oven facility	[52]
	Sailboat - commercial		China	2023	100,000 t/y	CO_2 sourced from ethylene oxide production facility	[52]
Mitsubishi	MefCO2 - demo	EPC	Germany	2019	1 t/d	CO2 from the thermal plant of RWE	[53]
	Clean Plaza Fujimi		Japan	2022		CO2 from the incineration of MSW	[54]
	Selected for green ammonia project/ Involved in conventional methanol projects						
Johnson Matthey	ABEL Energy Bell Bay Power Fuels Project	Technology catalyst	Australia	2028	300,000 t/y	Syngas from wood fibres	[55]
	Project Air in Stenungsund	Methanol licence and engineering services	Sweden	2026			[56]
	Agreements with HIF Global, world’s leading company in SAF						[57]

Thyssenkrupp Uhde Swiss	ABEL Energy Bell Bay Power Fuels Project	Technology Electrolysis	Australia	2028	300,000 t/y	Syngas from wood fibres	[55]
	Enowa and Armco - demo	EPC and Uhde green methanol process	Saudi Arabia				[58]
	Carbon2Chem - demo	Proof-of-concept for methanol production	Germany	2020		Still mill gases	[59]
BASF/Bse energy	The collaboration announced in 2024 with China's Envision Energy	Catalyst technology			8,200-16,400 t/y		[60]
Haldor Topsoe	FlagshipONE (developed by Liquid Wind but acquired by Orsted)	Catalyst technology	Sweden	2025	50,000 t/y	CO2 from a CHP	[61]

Table A2.1: Different technological supplier and their involvement in green methanol projects

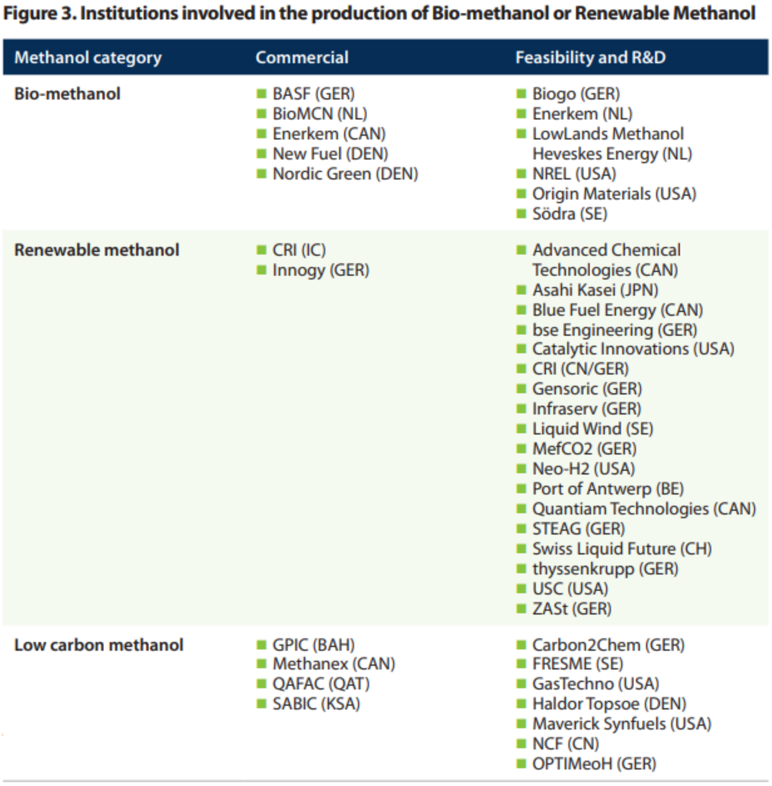


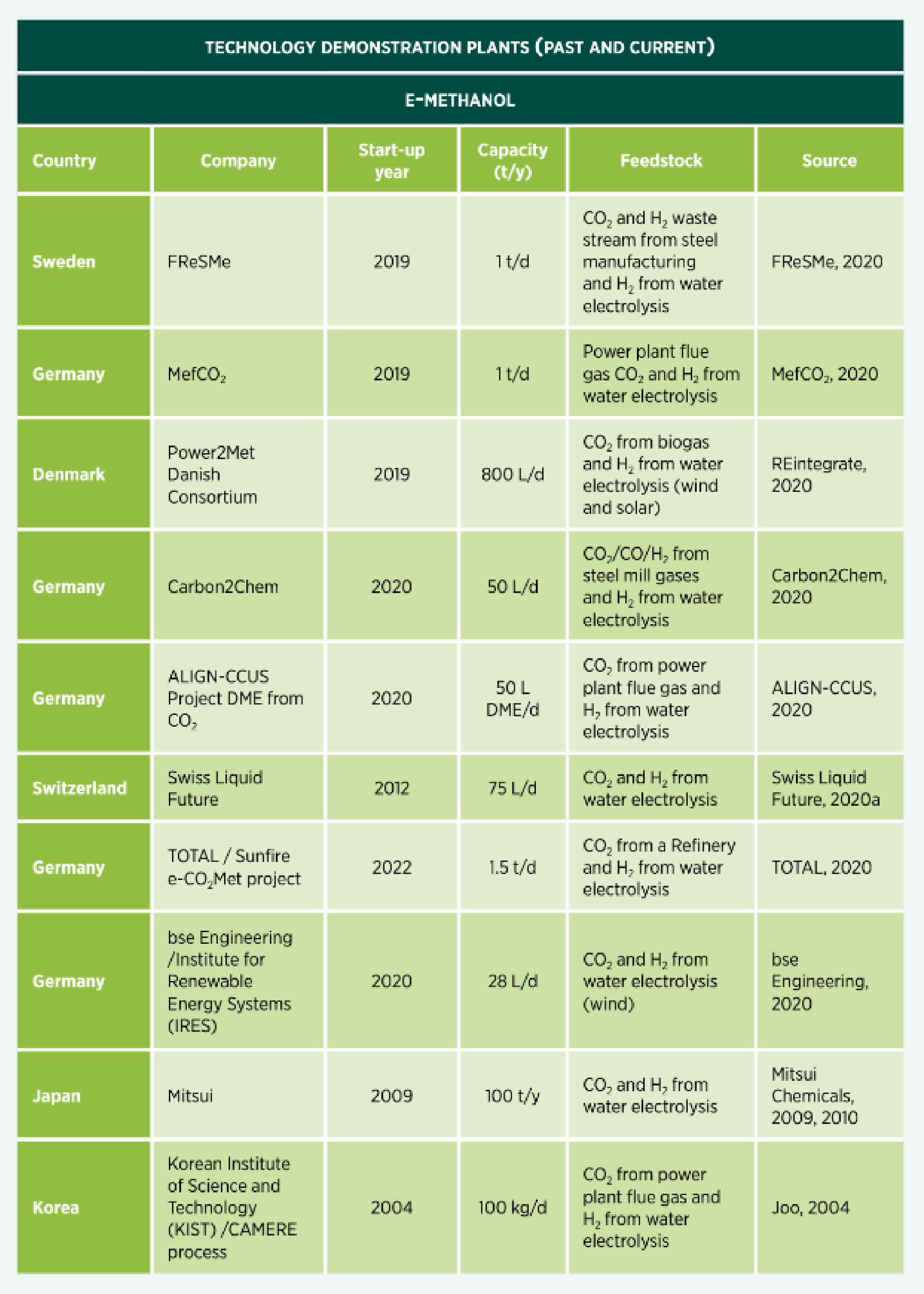
Figure 3. Institutions involved in the production of Bio-methanol or Renewable Methanol

Methanol category	Commercial	Feasibility and R&D
Bio-methanol	■ BASF (GER) ■ BioMCN (NL) ■ Enerkem (CAN) ■ New Fuel (DEN) ■ Nordic Green (DEN)	■ Biogo (GER) ■ Enerkem (NL) ■ LowLands Methanol Heveskes Energy (NL) ■ NREL (USA) ■ Origin Materials (USA) ■ Södra (SE)
Renewable methanol	■ CRI (IC) ■ Innogy (GER)	■ Advanced Chemical Technologies (CAN) ■ Asahi Kasei (JPN) ■ Blue Fuel Energy (CAN) ■ bse Engineering (GER) ■ Catalytic Innovations (USA) ■ CRI (CN/GER) ■ Gensoric (GER) ■ Infraserv (GER) ■ Liquid Wind (SE) ■ MefCO2 (GER) ■ Neo-H2 (USA) ■ Port of Antwerp (BE) ■ Quantiam Technologies (CAN) ■ STEAG (GER) ■ Swiss Liquid Future (CH) ■ thyssenkrupp (GER) ■ USC (USA) ■ ZASt (GER)
Low carbon methanol	■ GPIC (BAH) ■ Methanex (CAN) ■ QAFAC (QAT) ■ SABIC (KSA)	■ Carbon2Chem (GER) ■ FRESME (SE) ■ GasTechno (USA) ■ Haldor Topsoe (DEN) ■ Maverick Synfuels (USA) ■ NCF (CN) ■ OPTIMeoH (GER)

Table A2.2: Institutions involved in the production of green methanol (Methanol Report, [62])

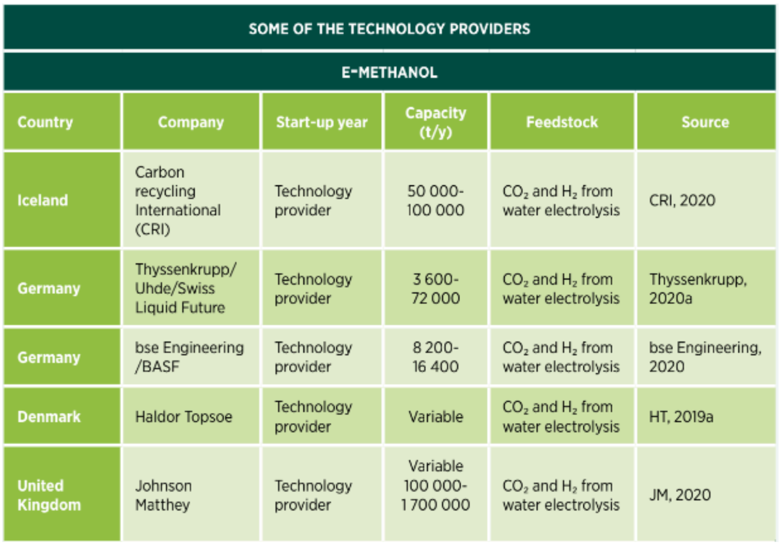
PLANTS (EXISTING AND PROJECTED)					
E-METHANOL					
Country	**Company**	**Start-up year**	**Capacity (t/y)**	**Feedstock**	**Source**
Iceland	Carbon Recycling International (CRI)	2011	4 000	Geothermal CO_2 and H_2 from water electrolysis	CRI, 2020 Product sold under the name "Vulcanol"
China	Dalian Institute of Chemical Physics	2020	1 000	CO_2 and H_2 from water electrolysis (PV)	AAAS, 2020
Sweden	Liquid Wind	2023 (plan for 6 facilities by 2030)	45 000	Upcycled industrial CO_2 and H_2 from water electrolysis	Liquid Wind, 2020
Australia (Tasmania)	ABEL	2023	60 000	Biogenic CO_2 and H_2 from water electrolysis	ABEL Energy, 2020
China	Henan Shuncheng Group / CRI	2022	110 000	CO_2 from limekiln and H_2 from coke oven gas	CRI, 2020
Norway	Swiss Liquid Future / Thyssenkrupp	n/k	80 000	CO_2 from ferrosilicon plant and H_2 from water electrolysis (hydro)	Swiss Liquid Future, 2020a, Swiss Liquid Future, 2020b
Norway	Joint Venture/CRI	2024	100 000	CO_2 and H_2 from water electrolysis	Stefánsson, 2019
Canada	Renewable Hydrogen Canada (RH_2C)	n/k	120 000	CO_2 and H_2 from water electrolysis (hydro)	RH_2C, 2020
Belgium	Consortium at the port of Antwerp	n/k	8 000	CO_2 and H_2 from water electrolysis	INOVYN, 2020
Belgium	Consortium at the port of Ghent	n/k	46 000-180 000	Industrial CO_2 and H_2 from water electrolysis	aet, 2019
The Netherlands	Consortium Nouryon/Gasunie/ BioMCN/3 others	n/k	15 000	CO_2 and H_2 from water electrolysis	Nouryon, 2020
Germany	Dow	n/k	- 200 000	CO_2 and H_2 from water electrolysis	Schmidt, 2020
Denmark	Consortium of companies	2023-2030	n/k	CO_2 from MSW and biomass. H_2 from water electrolysis (offshore wind). Up to 1.3 GW electrolyser capacity by 2030	Maersk, 2020
Germany	Consortium	n/k	n/k	CO_2 from cement plant and H_2 from water electrolysis (wind)	Westküste 100, 2020

Table A2.3: Plants existing or projected for the production of e-methanol (IRENA and Methanol Institute, Annex 4, [42])



TECHNOLOGY DEMONSTRATION PLANTS (PAST AND CURRENT)					
E-METHANOL					
Country	**Company**	**Start-up year**	**Capacity (t/y)**	**Feedstock**	**Source**
Sweden	FReSMe	2019	1 t/d	CO_2 and H_2 waste stream from steel manufacturing and H_2 from water electrolysis	FReSMe, 2020
Germany	MefCO_2	2019	1 t/d	Power plant flue gas CO_2 and H_2 from water electrolysis	MefCO_2, 2020
Denmark	Power2Met Danish Consortium	2019	800 L/d	CO_2 from biogas and H_2 from water electrolysis (wind and solar)	REintegrate, 2020
Germany	Carbon2Chem	2020	50 L/d	CO_2/CO/H_2 from steel mill gases and H_2 from water electrolysis	Carbon2Chem, 2020
Germany	ALIGN-CCUS Project DME from CO_2	2020	50 L DME/d	CO_2 from power plant flue gas and H_2 from water electrolysis	ALIGN-CCUS, 2020
Switzerland	Swiss Liquid Future	2012	75 L/d	CO_2 and H_2 from water electrolysis	Swiss Liquid Future, 2020a
Germany	TOTAL / Sunfire e-CO_2Met project	2022	1.5 t/d	CO_2 from a Refinery and H_2 from water electrolysis	TOTAL, 2020
Germany	bse Engineering /Institute for Renewable Energy Systems (IRES)	2020	28 L/d	CO_2 and H_2 from water electrolysis (wind)	bse Engineering, 2020
Japan	Mitsui	2009	100 t/y	CO_2 and H_2 from water electrolysis	Mitsui Chemicals, 2009, 2010
Korea	Korean Institute of Science and Technology (KIST) /CAMERE process	2004	100 kg/d	CO_2 from power plant flue gas and H_2 from water electrolysis	Joo, 2004

Table A2.4: Demonstration plants for the production of e-methanol (IRENA and Methanol Institute, Annex 4, [42])



SOME OF THE TECHNOLOGY PROVIDERS

E-METHANOL

Country	Company	Start-up year	Capacity (t/y)	Feedstock	Source
Iceland	Carbon recycling International (CRI)	Technology provider	50 000-100 000	CO_2 and H_2 from water electrolysis	CRI, 2020
Germany	Thyssenkrupp/ Uhde/Swiss Liquid Future	Technology provider	3 600-72 000	CO_2 and H_2 from water electrolysis	Thyssenkrupp, 2020a
Germany	bse Engineering /BASF	Technology provider	8 200-16 400	CO_2 and H_2 from water electrolysis	bse Engineering, 2020
Denmark	Haldor Topsoe	Technology provider	Variable	CO_2 and H_2 from water electrolysis	HT, 2019a
United Kingdom	Johnson Matthey	Technology provider	Variable 100 000-1 700 000	CO_2 and H_2 from water electrolysis	JM, 2020

Table A2.5: Technological supplier for e-methanol (IRENA and Methanol Institute, Annex 4, [42])