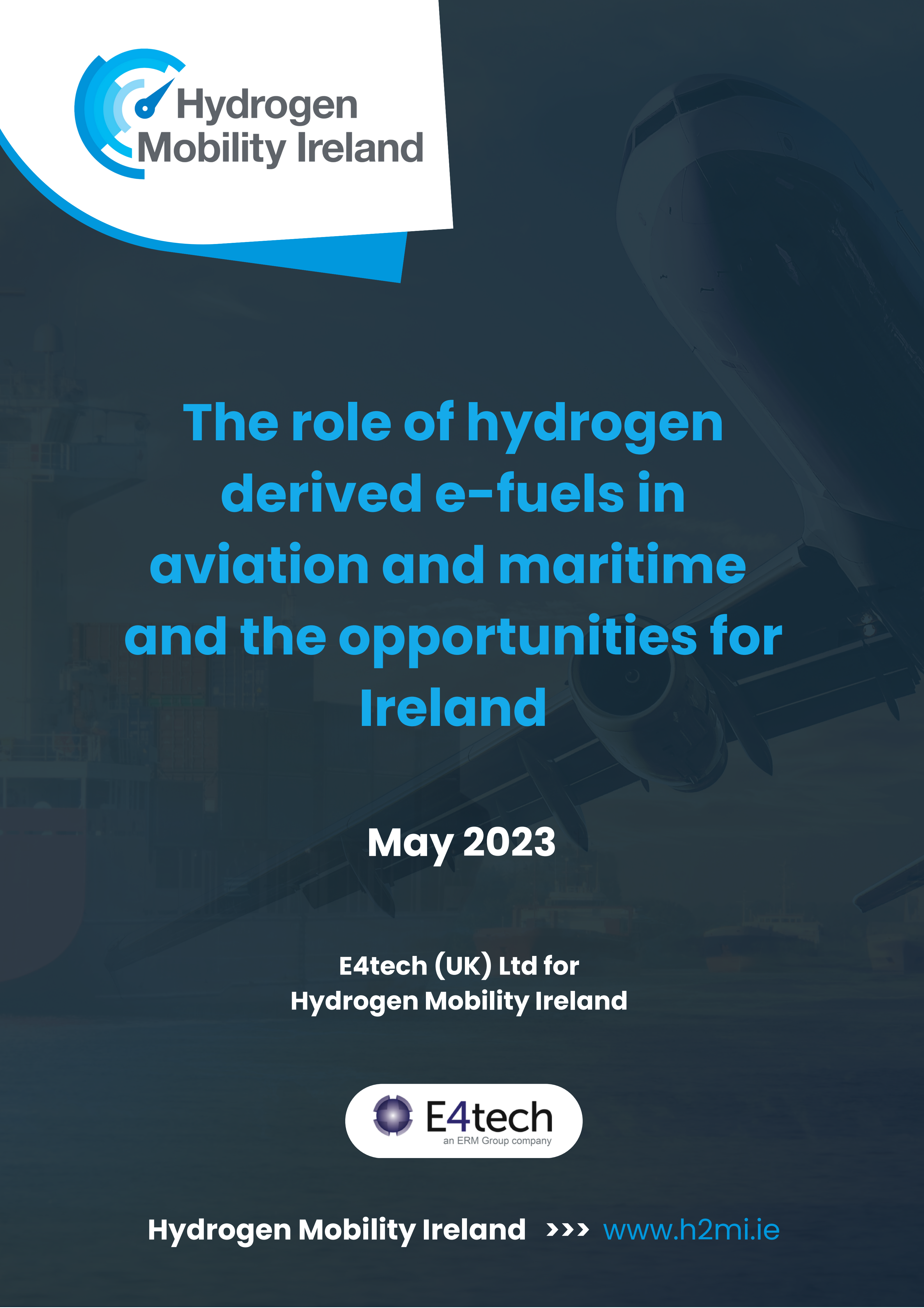


Hydrogen Mobility Ireland

The role of hydrogen derived e-fuels in aviation and maritime and the opportunities for Ireland

May 2023

E4tech (UK) Ltd for
Hydrogen Mobility Ireland

E4tech
an ERM Group company

Authors

This report was authored by E4tech, an ERM Group Company.

E4tech is a strategy consulting firm focused on sustainable energy with vast experience of managing and leading complex programmes of work for government and private sector clients. Since 1997, E4tech has completed several hundred projects related to low carbon fuels, hydrogen, renewable electricity, and sustainability.

Study Authors

Anisha Harris, Ausilio Bauen, Chris Sim, Nathan Nguyen, Stefano Dell’Orco

Contents

E4tech (UK) Ltd
2nd Floor Exchequer Court
33 St Mary Axe
London EC3A 8AA
United Kingdom

Tel: +44 20 3206 5200

Incorporated in England and Wales

Company no. 4142898

Registered address:
2nd Floor Exchequer Court,
33 St Mary Axe, London EC3A 8AA
United Kingdom

www.e4tech.com

1 Executive summary

Decarbonisation of the transport sector will rely on a range of technologies. Some transport modes, namely aviation and shipping, are expected to primarily rely on liquid fuels, thus biofuels, recycled carbon fuels and e-fuels are expected to play a major role in decarbonisation.

E-fuels, produced from hydrogen and captured CO_2, can produce drop-in fuels chemically identical to fossil fuels, with fewer constraints on feedstock availability and supply chains compared to biofuels. There are several possible routes for producing e-fuels for the aviation and shipping markets, i.e. e-SAF and e-methanol respectively. To date, three major pathways for e-SAF are being developed, via alcohol or syngas production, two of which are already ASTM D7566 certified and therefore can be blended directly with fossil jet fuel (e.g. Jet A-1) at up to 50% blend ratio by volume. Today, the production of e-methanol is at commercial scale, while e-kerosene production is at pilot scale.

The role of e-fuels within policy is growing, particularly in Europe where proposed amendments to the Renewable Energy Directive and new policy measures in aviation (RefuelEU Aviation mandate) and maritime (FuelEU Maritime) set specific sub-targets for renewable fuels of non-biological origin (RFNBOs), under which e-fuels fall. The final legislation sends strong signals that the EU sees e-fuels contributing significantly to the decarbonisation of the aviation and shipping sectors. For example, under RefuelEU Aviation, there is a 1.2% e-SAF target for 2030, increasing to 35% in 2050 (on a volume basis).Under FuelEU Maritime, there is an e-fuels sub-target of 2% in shipping fuels for 2034.

Ireland will have to transpose the RED(III) and set mandates which could open up significant opportunities for the nation associated with domestic production. In Ireland, the required e-kerosene to satisfy the target would be 12 kt e-SAF in 2030 and 388 kt e-SAF in 2050. Assuming e-methanol is used to satisfy the RFNBO maritime target, this would require 4-6 kt e-methanol in 2030 and 178-308 kt e-methanol in 2050. Developing the Irish hydrogen economy and its expansion to e-fuels, could result in a Gross Value Added (GVA) of €11m/year in 2030 up to €300m/year in 2050, with 10,500 associated jobs by 2050.

The ability and success of establishing an e-fuels sector in Ireland relies on three key factors:

- **Feedstock security:** If Ireland aims to produce e-fuels domestically, significant renewable power for electrolysis (~4 GW in 2050) and CO_2 (2,300 kt in 2050) will be required. Ireland has significant potential to develop renewable power through onshore and offshore wind, and the e-fuels sector would require approximately 110 MW renewable electricity by 2030, compared to the targeted 13 GW installed capacity in 2030. A strong renewables development policy and framework is needed for e-fuels.
- **Technology de-risking:** e-fuels are currently at a low level of maturity which means that investments in e-fuels facilities can represent a significant financial risk to investors. De-risking technologies and investments is likely to require supply-side support (e.g. capex support, tax credits, loan guarantees). Public funding is likely to be required in the short-term.
- **Revenue certainty:** The production cost of e-fuels is much higher than trading prices of other commercial alternative fuels (e.g. based on biomass or vegetable oil and fats) and fossil fuels. The cost of e-fuels is strongly linked to the cost of hydrogen and carbon capture, which are expected to fall substantially in the longer-term, in part as a result of access to cheaper

renewable electricity. However, there is need for support in bridging the gap between the costs of e-fuels and alternatives and for long-term certainty in revenues from e-fuels. This requires clear policy signals from government on e-fuels demand (e.g. mandates, price support).

2 Introduction

Alternative liquid fuels, electrification and gaseous fuels (e.g. direct use of hydrogen in fuel cells) will all play roles in the full decarbonisation of the transport sector, as illustrated in Figure 1. Transport modes such as aviation and shipping will rely primarily on alternative liquid fuels because batteries and gaseous fuels do not provide sufficient energy density. Alternative liquid fuels are either biofuels/recycled carbon fuels (RCF)[1] or e-fuels. Both routes can produce drop-in fuels chemically identical to fossil fuels, allowing them to be blended up to a limit in existing fossil mixes. Biofuels are produced from biomass, which is limited by land availability, supply chain and competing demand factors. E-fuels are produced from hydrogen and carbon dioxide, which face fewer physical constraints on feedstock availability. CO_2 is released when these fuels are used, but because CO_2 is captured and used in the creation of both fuels, they are carbon neutral. However, in term of current industrial status, some biofuel routes, e.g. HVO/HEFA production, are more mature than e-fuel routes.

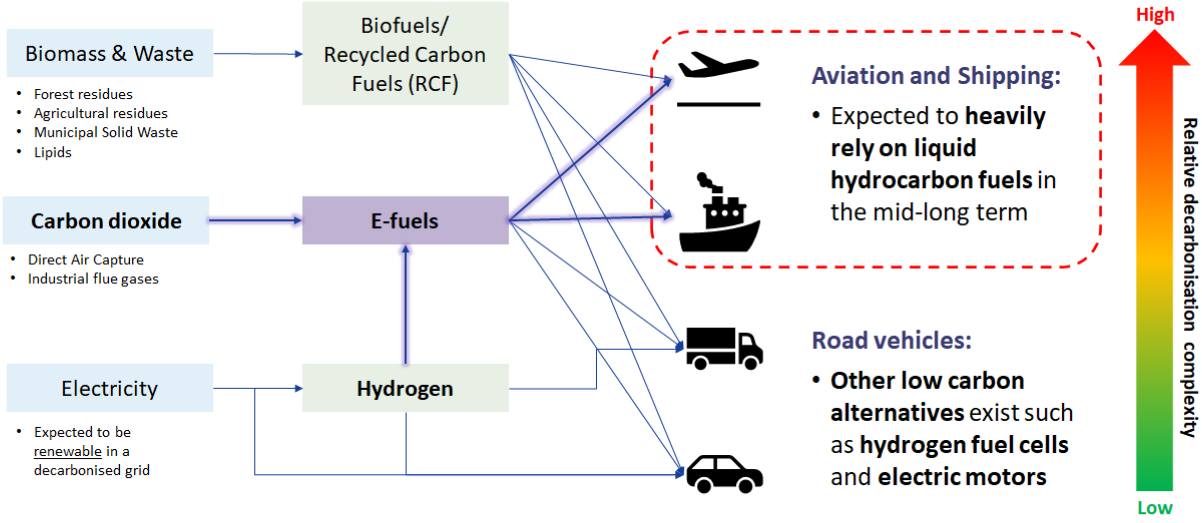


Figure 1. Options for decarbonisation of the transport sector by fuel and mode

Road

Battery electrification continues to emerge as the key decarbonisation option for the light duty vehicle fleet. However, future battery supply chain shortages and increased grid electricity demand for charging may mean biofuels and e-fuels will still have an important role, as both can be directly blended into existing fossil fuel mixes. Hydrogen fuel cells may be important for long-haul, heavy-duty and frequent-cycle operation, allowing further range, faster refuelling and higher payloads than electrification. However, high costs and limited supporting infrastructure make hydrogen viable in the long-term only, with biofuels and e-fuels having a potential stronger role in the short and medium-term, especially regarding the decarbonisation of the existing internal combustion engines fleet.

---

[1] Renewable Energy Directive 2018/2001/EU – Article 2, (35) *'recycled carbon fuels' means liquid and gaseous fuels that are produced from liquid or solid waste streams of non-renewable origin which are not suitable for material recovery in accordance with Article 4 of Directive 2008/98/EC, or from waste processing gas and exhaust gas of non-renewable origin which are produced as an unavoidable and unintentional consequence of the production process in industrial installations*

E-fuels in Maritime

For smaller vessels and short voyages, options include battery electrification, hydrogen fuel cells and hydrogen ICEs. For larger vessels and longer voyages, where the energy density of batteries and hydrogen make them less attractive, e-fuels, such as methanol and ammonia, are expected to be better solutions. International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code) and International Maritime Organization guidelines already allow methanol to be used as a marine fuel, making it a potentially attractive short- to medium-term solution. Ammonia releases no carbon when combusted but ammonia combustion engines are yet to be commercialised, and IGF and IMO guidelines do not yet approve the use of ammonia as marine fuel.[2] Therefore, e-ammonia is not further considered in this report.

E-fuels in Aviation

Energy density limitations may only allow battery electrification and hydrogen use in small aircraft for regional flights (several hundred-kilometre ranges). Companies including Airbus, ZeroAvia and Linde are in the early stages of developing electric or hydrogen airframes, propulsion systems and fuelling infrastructure, which could help the technologies reach meaningful scales by the 2040s. Due to strict regulations on jet fuels and the need to maximise energy density, alternative liquid hydrocarbons with similar chemical compositions as fossil jet (kerosene range) will be the only viable options in the short- to mid-term for decarbonising medium to long haul, and frequent-cycle aviation. Aviation biofuels and e-fuels, collectively referred to as sustainable aviation fuels (SAF), can both be blended at up to 50% by volume with existing fossil mixes and are already commercial (e.g. Hydroprocessed Esters and Fatty Acids, or HEFA for short), or at pilot stage (e-SAF).

---

[2] https://www.ics-shipping.org/wp-content/uploads/2021/07/MSC-104-15-9-Development-of-non-mandatory-guidelines-for-safety-of-ships-using-ammonia-as-fuel-Japan-Singapore-ICS-and....pdf

3 E-fuel pathways

In the context of this study, e-fuels cover a wide range of technology pathways and are produced by reacting **CO_2 and electrolytic hydrogen** to generate oxygenated (ethanol or methanol) or hydrocarbon liquids through chemical/biochemical synthesis as summarised in Figure 2[3] The CO_2 can be captured from industrial processes, such as cement production or waste-to-energy plants or directly from atmosphere through Direct Air Capture (DAC), while hydrogen is produced through electrolysis of water using renewable electricity as primary energy source.[4,5]

All e-fuel routes combine the CO_2 and hydrogen to first produce either methanol directly or a mixture of CO and H_2 called syngas. The methanol produced can be used either as a marine fuel, or it can be further processed into jet fuel via the methanol-to-jet process. Syngas can be further processed to produce jet fuel through:

- Reverse Water Gas Shift (RWGS) / Co-electrolysis + Fischer-Tropsch (FT) synthesis
- Partial RWGS followed by syngas fermentation to ethanol and ethanol-to-jet synthesis.

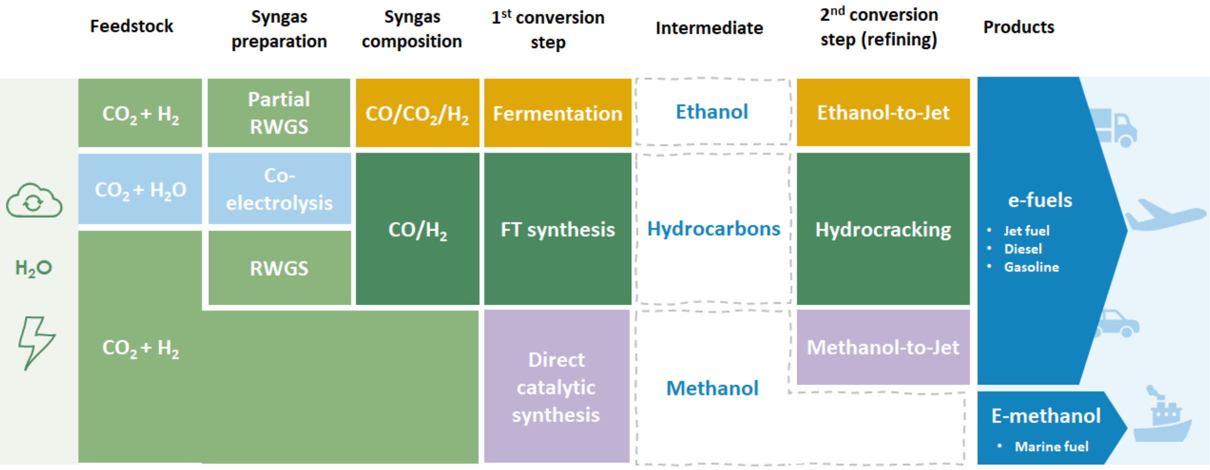


Figure 2: Schematic e-fuels production summary

The e-SAF produced can then be blended directly with fossil jet fuel (e.g. Jet A-1) at up to 10 to 50% blend ratio by volume. Only those approved by the Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons (ASTM D7566) can be blended and combusted in aircraft engines. The only e-SAF routes currently ASTM approved are the Alcohol-To-Jet Synthetic Paraffinic Kerosene (ATJ-SPK) and Fischer-Tropsch Hydroprocessed Synthesized Paraffinic Kerosine (FT-SPK) that produce jet fuel via ethanol and FT synthesis respectively.[6] Overall, the production of hydrocarbon fuels is currently at pilot scale, corresponding to a Technology Readiness Level (TRL)[7] of 5-6 (for e-SAF); it is not yet clear which (if any) technology will have the competitive advantage. E-methanol production is already at commercial scale (TRL 8). TRL is a measurement system used to assess the maturity of a

---

[3] Yugo et al. *Concawe Review* **2019,** 1, 28 https://www.concawe.eu/wp-content/uploads/E-fuels-article.pdf

[4] S. Brynolf et al., *Renew. Sustain. Energy Rev.* **2018**, 1887–1905, https://doi.org/10.1016/j.rser.2017.05.288

[5] C. Malins, **2017**, report for *Transport and Environment* and funded with the support of the *European Climate Foundation*

[6] https://www.icao.int/environmental-protection/GFAAF/Pages/Conversion-processes.aspx

[7] TRL NASA, https://www.nasa.gov/directorates/heo/scan/engineering/technology/technology_readiness_level

technology. Technologies are evaluated on their progress against the criteria detailed in Figure 5 and assigned a TRL rating.

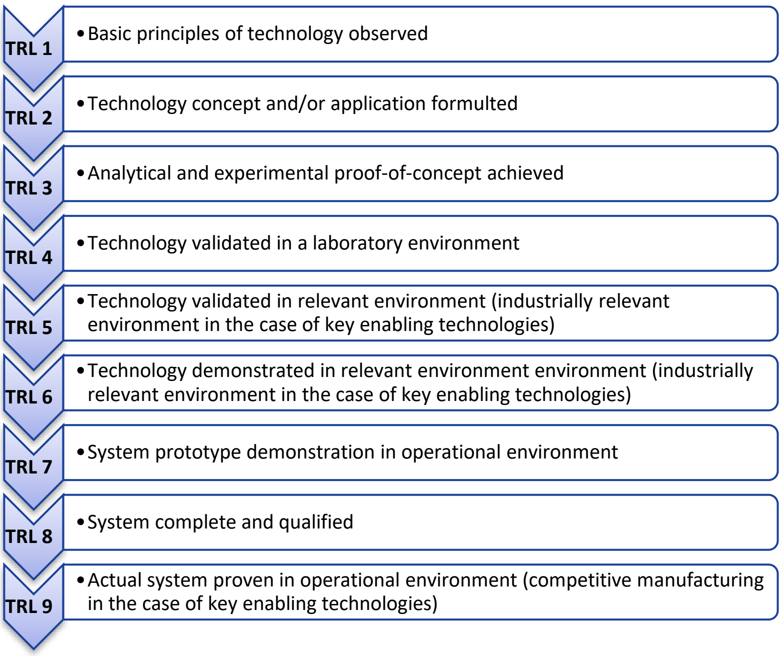


Figure 3: Technology Readiness Level (TRL) ratings and criteria

3.1 Description, industrial status and indicative cost of production

3.1.1 CO_2+H_2 > e-methanol / methanol-to-jet

Methanol is produced through the direct reaction of hydrogen with CO_2 via catalytic synthesis: this process is relatively mature (TRL 8) with several credible technology licensors, Johnson Matthey, Air Liquide and Haldor Topsøe.

The methanol produced can be used directly as a marine fuel or as a precursor for e-SAF, using the methanol-to-jet (MTJ) process that produce hydrocarbon in the kerosene-range. There is limited public information available for this pathway, but it will likely be using some components of commercial technologies (e.g. ExxonMobil is developing the MTJ after developing a methanol to gasoline process in the last decades, that is currently commercial). There are three main conversion steps in the MTJ process:

1. **Methanol-to-Olefins (MTO) or Methanol-to-Propylene (MTP):** mature technologies (TRL 9) which are widely commercialised in China, producing ethylene and propylene. The leading technology suppliers are: UOP/TotalEnergies (MTO), Air Liquide (MTP) and Dalian Institute of Chemical Physics-DICP (MTO).
2. **Oligomerisation:** is a commercial process, forming straight chain paraffinic hydrocarbons.
3. **Refining:** to extract jet fuel cuts (and co-products such as gasoline and diesel).

The above steps are commercial individually but have not been integrated at scale. The jet fuel produced through MTJ is currently not certified in the ASTM D7566, though there are no foreseen issues due to the process similarities between MTJ and ATJ, the latter being already certified.

3.1.2 CO_2+H_2 > RWGS or Co-electrolysis > Fischer Tropsch (FT)

FT synthesis requires hydrogen and CO as feedstock to synthetise hydrocarbons, at a ratio of 2:1, which can be obtained one of two ways, both of which are still at early stage of development (see Figure 5):

1. **RWGS reaction**, converting CO_2 and H_2 from electrolysis to CO and water, to produce syngas (mix of H_2, CO_2 and CO). Haldor Topsøe has a licensable version of the technology, despite a lack of demonstration units.
2. **Co-electrolysis** of H_2O and CO_2 to produce syngas.

The H_2 and CO is then synthesised to produce paraffinic waxes through **FT synthesis,** a commercially mature process (licensors include big industry players such as Johnson Matthey, Shell, Sasol). The waxes are then refined into lighter hydrocarbons to meet the desired output profile, using additional H_2.

Reverse Water Gas Shift	Co-electrolysis
• High temperatures required (~900°C) to achieve high CO_2 conversion, needs alternative nickel-based catalysts. • Current industry practice involves WGS reactions at lower temperatures (~250 – 300°C) • RWGS catalytic process generates methane but this can be minimised by operating above 700°C and constantly removing water • **A major barrier to scale up is that the catalyst lifetime remains unknown**	• Requires the use of high-temperature solid oxide electrolysis cells (SOECs) instead of standard electrolysers. • Surplus steam from the FT process could be used to feed the SOEC to improve energy efficiency • Steam electrolysis to hydrogen is TRL 6 (Sunfire) but co-electrolysis remains slightly less developed at TRL 5.

Figure 4: Description of the processes that can be used to produce hydrogen and CO for FT synthesis [8,9],

The jet fuel produced through FT is already certified in the ASTM D7566 as FT-SPK and can be used in blends up to 50% by volume. FT waxes can also be co-processed in existing refinery units – co-processing up to 5% (by volume) is included in ASTM D1655. Even though FT is already commercial (TRL 9), overall, the integrated pathway is currently at TRL 5, limited by the earlier stage of RWGS.

3.1.3 CO_2+H_2 > Partial RWGS > syngas fermentation > ethanol-to-Jet

This pathway involves the use of hydrogen and CO_2 to produce ethanol, through syngas fermentation, that can be converted to e-SAF through ethanol-to-jet (ETJ) technology. Fermentation requires a mixture of $CO/CO_2/H_2$[8], therefore, a preliminary step is needed to convert CO_2 into reactive CO; **"partial" RWGS** is being explored by interested parties as means of achieving this. Partial RWGS could be carried out at a lower temperature to RWGS, but the technology is still at research level, therefore there remains uncertainty surrounding the performance of this technology at scale, particularly regarding the catalysts and overall yields/efficiencies.[9]

---

[8] Molitor et al., *Bioresour. Technol*. **2016**, 215, 386–396

[9] Li et al. *Cell Reports Physical Science* **2022**, https://doi.org/10.1016/j.xcrp.2022.101021

The **syngas fermentation** step uses anaerobic micro-organisms to produce ethanol, acetic acid and other organic compounds. This step is at TRL 5. The ethanol can be separated from the fermentation broth using distillation and/or more novel techniques (e.g. molecular sieves), which can be energy intensive. The final **ETJ** step involves the dehydration of ethanol to ethylene, then oligomerisation reactions, followed by hydrogenation, isomerisation and distillation.. ETJ was first developed at the Pacific Northwest National Laboratory in US and then developed commercially by Lanzajet, who has operated a pilot plant and has demonstration scale plants currently planned (TRL 6). ETJ is already ASTM D7566 certified (ATJ-SPK[10]) and the fuel can be blended up to 50% by volume with fossil jet fuel.

3.1.4 Cost of production and comparison with biofuels and fossil fuels

To date, the minimum selling price of e-fuels (i.e. the fuel production cost) is higher than trading prices of other commercial alternative fuels (e.g. HEFA SPK) and fossil fuels, as summarised in the Table 1.

Table 1: Production costs ranges for e-fuels compared to fossil fuels and advanced biofuels

Fuel type	Production cost, $/t	Comparator	Market price, $/t
e-methanol	1,000-1,400[11]	Fossil methanol	308-374[12]
		Bio-methanol from biomass gasification	250-750[13]
e-SAF*	2,000-6,000[11]	Fossil Jet A-1	600-1,110[14]
		HEFA SPK	2,000-3,500[15]

*Range covers all the e-SAF pathways described above

Although the current cost disadvantage of e-fuels might not facilitate fast development and deployment, the production costs range is substantial and there is potential for improvement. Hydrogen and carbon capture costs are the main component of the overall production cost, followed by CAPEX and OPEX for fuel production. Hydrogen and carbon capture costs are expected to dramatically reduce in the future, with falling renewable electricity costs and as industrialisation advances. Capturing CO_2 from industrial off-gases is more cost competitive than DAC due to a higher carbon concentration in the stream, and low-cost hydrogen can be obtained using lower cost renewable electricity with higher capacity factors (e.g. off-shore wind farms) as well as expected electrolyser CAPEX/OPEX reduction due to learning factors. For instance, producing e-SAF at lower cost (c. 2000 $/t) would require a hydrogen cost of 2.5 $/kg and using CO_2 from industrial off-gases, while a hydrogen cost of 6.5 $/kg and CO_2 from atmosphere (DAC) drives the cost up to about 6000 $/t. In

---

[10] Note under ATJ-SPK, isobutanol can also be used as feedstock for jet fuel production through the same steps

[11] Internal E4tech analysis, varying hydrogen price in the range 2.5 to 6.5 $/kg and considering different range of carbon capture costs (direct air capture and point source carbon capture from industrial flue gases)

[12] Methanol Institute, https://www.methanol.org/methanol-price-supply-demand/, range from average 2021 to most recent spot price available (Aug 22)

[13] IEA **2020**, https://www.ieabioenergy.com/wp-content/uploads/2020/02/T41_CostReductionBiofuels-11_02_19-final.pdf

[14] Fossil Jet A-1 spot price in Rotterdam, range from average 2021 to current 08/09/2022 spot price, https://www.iata.org/en/publications/economics/fuel-monitor/

[15] Hydroprocessed Esters and Fatty Acids. (HEFA), price from Argus Biofuels (2021) and E4tech estimation for 2022 using current feedstock (UCO) price

addition, policies can play a fundamental role in supporting hydrogen and its use as feedstock, as demonstrated in Section 2, which can make these fuel pathways competitive.

3.1.5 Industrial deployment status

Currently most of the operational and planned plants are focusing on methanol production, as summarised in Figure 5. Most of the operational and planned e-fuels projects are in Europe: there are several operational projects in Germany, with planned projects in additional countries including Norway, Denmark, France and Belgium.

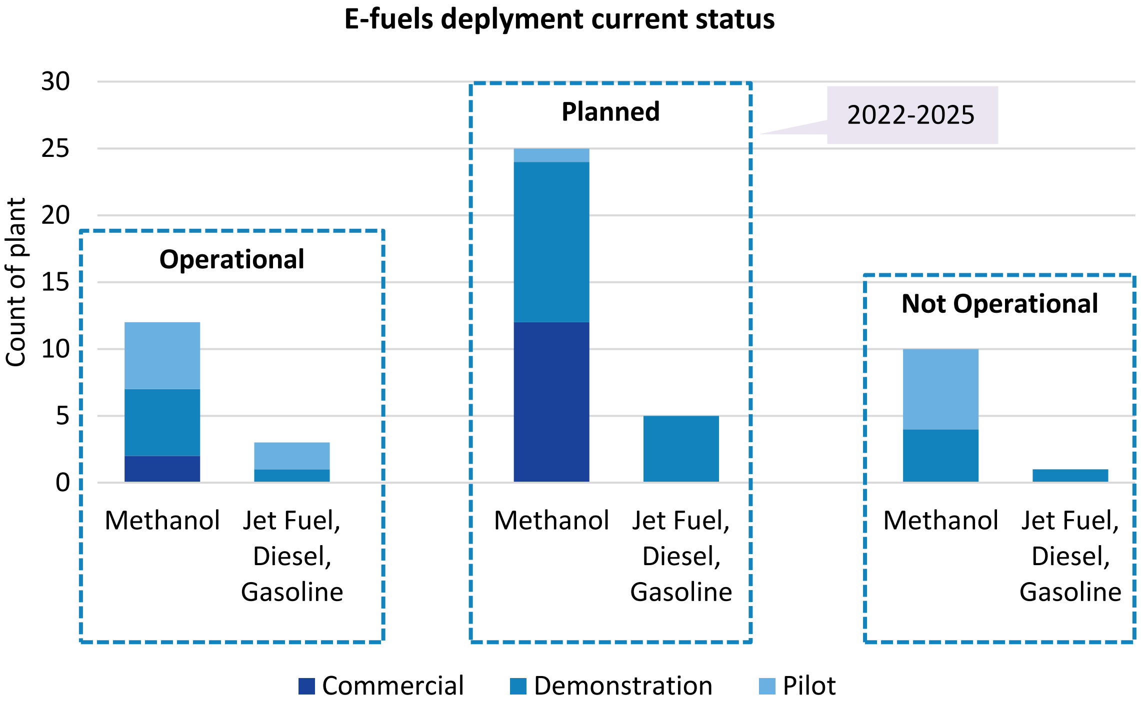


Figure 5: E-fuels deployment status in term of number of plants operational, planned and shut down

E-methanol has a higher TRL and by virtue of having less process steps than e-SAF (e.g., methanol-to-jet), commercial activities in this field are more advanced. It is more efficient, due to less process steps being required and consequently it is lower cost. In addition, e-methanol also has the advantage that it is an intermediate product (with lower initial CAPEX compared to hydrocarbons) with multiple end markets, making it a potentially attractive pathway for e-fuel producers, for direct use in shipping, additional processing to hydrocarbon fuel (MTJ) or for use in the chemical industry.

4 Policy landscape for e-fuels

The policy landscape for transport is rapidly evolving with increased ambition and more rapid decarbonisation trajectories expected at both an international and regional level across all transport modes. At an international level, the International Civil Aviation Organization's (ICAO) Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) is the leading aviation decarbonisation policy, whilst the International Maritime Organisation (IMO), the regulator for the international shipping industry, is set to announce its new decarbonisation strategy in 2023.

The role of e-fuels within policy is growing, particularly in Europe. The Renewable Energy Directive (REDII) is an EU **Directive** which set frameworks and targets that all Member States have to transpose into national law. Therefore, Directives are binding but MS can choose how to achieve the targets and it may take a few years before they are transposed. RED II defines Renewable Fuels of Non-Biological Origin (RFNBO) as "liquid or gaseous fuels which are used in the transport sector, the energy content of which is derived from renewable sources other than biomass". Thus, effectively RFNBOs are either hydrogen used in fuel cells, or e-fuels, derived from hydrogen.

Currently, RED II does not have a specific RFNBO target, but the revision of Directive, RED III, agreed by European Parliament and Council on 30 March 2023 sets RFNBO targets for transport and industry. RED III sets a combined sub-target of 5.5 vol % by 2030 for advanced biofuels and RFNBOs in final energy consumption in transport. Furthermore, it introduces a RFNBO-specific sub-target of 1.1 vol % by 2030. The RFNBO industry target is less relevant to e-fuels because it specifically aims to drive green hydrogen uptake in industry, but it requires 42% of hydrogen use in industry to come from RFNBOs by 2030 and 60% by 2035. The transport targets in RED III cover all modes of transport, while RED II excluded aviation and maritime from the obligations. Furthermore, the EU is also driving the uptake of e-fuels specifically in aviation and maritime through separate policy initiatives.

Aviation – EU policy signals

In July 2021, the European Commission proposed **ReFuelEU Aviation**[16], a SAF blending **regulation** from 2025 to 2050 across all EU Member States (MS). Parliament and Council negotiators agreed on a final text on 25 April 2023[17], which now has to pass through both institutions for formal adoption. The final agreement sets ambitious targets for total SAF supply (70% in 2050) and for e-fuels, starting at 1.2% in 2030, increasing to 35% in 2050, as shown in Figure 5.

The definition of SAF initially only included SAF included **advanced biofuels** (those in Annex IX parts A & B of the RED), and **green synthetic fuels (e-fuels)** but was expanded to allow **further fuels to contribute to the overall target**, extending to all biofuels that comply with RED II sustainability and GHG savings criteria (except for food and feed, palm or soy-based fuels), hydrogen, recycled carbon fuels and synthetic low-carbon fuels, i.e. nuclear derived e-fuels. However, given the separate sub-target for synthetic fuels, this wider definition will not result in more competition for e-fuels. As of 25

---

[16] European Commission (2021) Proposal for a Regulation of the European Parliament and of the Council on ensuring a level playing field for sustainable air transport. Available at: https://ec.europa.eu/info/sites/default/files/refueleu_aviation_-_sustainable_aviation_fuels.pdf

[17] European Parliament (2023), Fit for 55: Parliament and Council reach deal on greener aviation fuels https://www.europarl.europa.eu/news/en/press-room/20230424IPR82023/fit-for-55-parliament-and-council-reach-deal-on-greener-aviation-fuels

April 2023, the EU institutions have published a press release on the ReFuelEU agreement but the full final text will be under technical for the coming weeks before it is published.

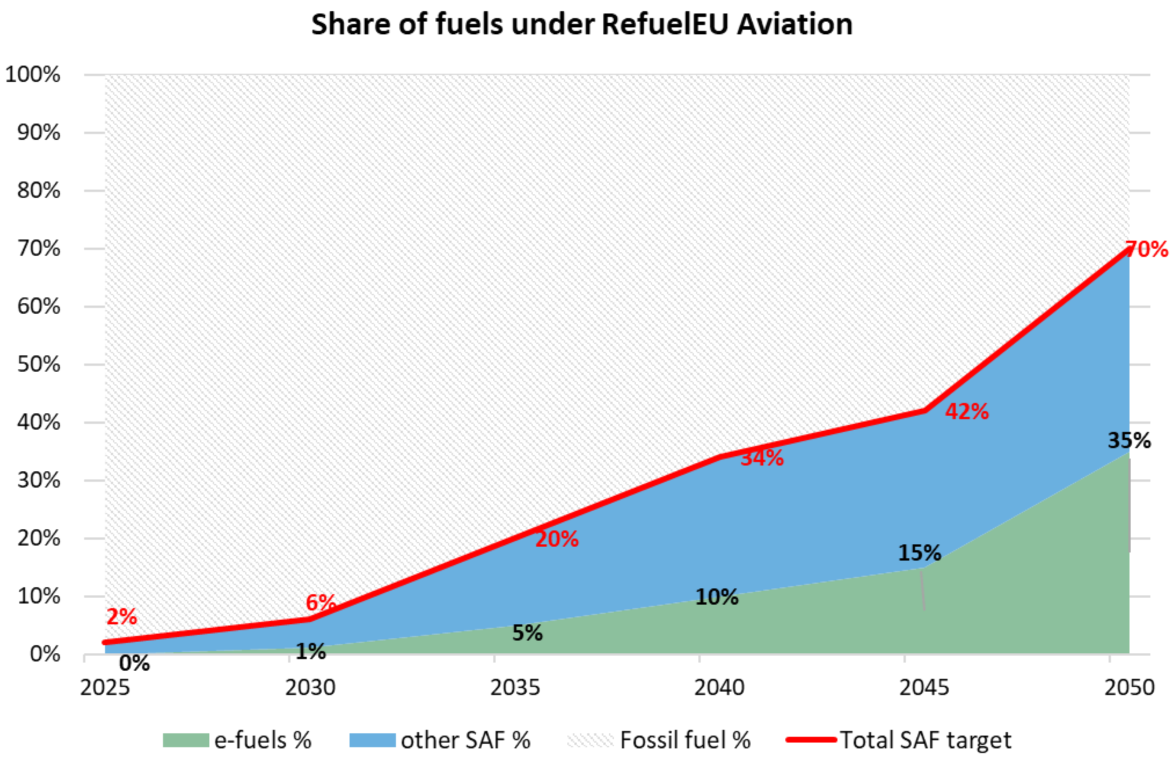


Figure 6: Share of fuels under the European Parliament position of RefuelEU, volume basis (September 2022)

Maritime

The European Parliament and Council agreed on the final text of **FuelEU Maritime** on 23 March 2023, the EU's law that requires vessels trading within and to the EU to meet **GHG emissions reduction targets starting in 2025**. Fuel EU Maritime is intended to accelerate decarbonisation through the adoption of renewable and low carbon fuels and technologies in maritime transport with a goal-based approach. It sets a reduction target for the GHG intensity of energy used, with 2020 as the reference year and a reduction of 2% in 2025, increasing in steps to 80% by 2050. The regulation will apply to all vessels > 5,000 gross tonnage (GT) calling at EU ports[18] and covers all energy used for intra EU voyages, whilst at port in EU, as well as half of the energy used for voyages that start or end in the EU. Figure 7 presents the GHG emissions reduction targets.

The final legislation also includes a **specific sub-target for e-fuels**, requiring that hydrogen-derived synthetic fuels make up at least 2% of the EU's shipping fuels by 2034. Furthermore, the use of **e-fuels in shipping will be counted twice** against the overall GHG reduction target until 2035, thereby doubling the incentive for the use of e-fuels in the shipping sector.

---

[18] excluding inland vessels, fishing, naval and government vessels

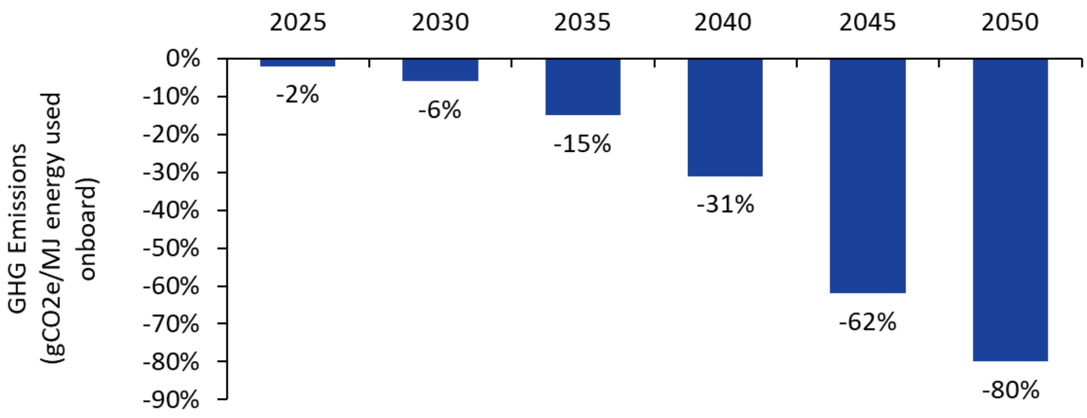


Figure 7: FuelEU Maritime GHG reduction target

5 Implications for Ireland

This section seeks to quantify what role e-fuels could play in Ireland and the economic and social benefits this could bring.

5.1 Aviation

The Sustainable Energy Authority of Ireland (SEAI) estimated jet fuel demand of 1,116 ktoe (1,062 kt) for international and domestic flights in 2019. Following the European Parliament's final position on **ReFuelEU Aviation** sub-targets for e-fuels – 1.2% vol.% in 2030, 10% in 2040 and 35% in 2050 – and assuming demand remains constant, Ireland's e-SAF demand would be 12 kt in 2030, increasing to 103 kt in 2040 and 388 kt by 2050, as depicted in **Error! Reference source not found.**.

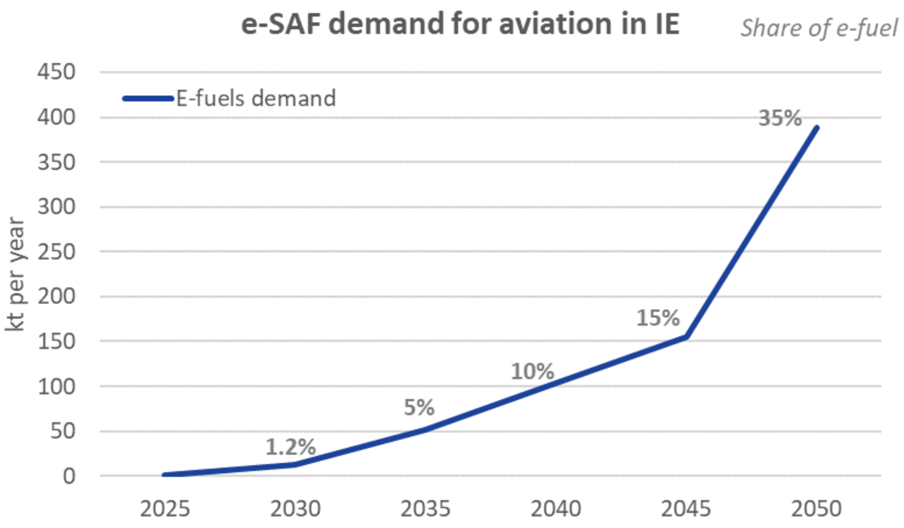
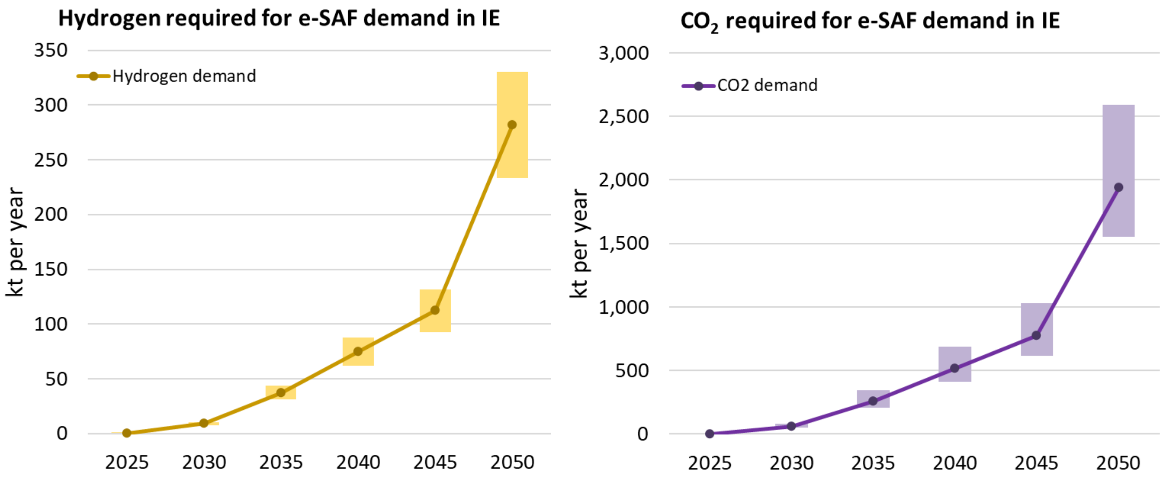


Figure 8: e-SAF demand ramp-up in IE, based on ReFuelEU Aviation targets and IE 2019 international and domestic jet fuel demand (SEAI data)

To meet this demand, Ireland could import e-fuels and/or start domestic production. To cover the overall demand domestically, there is the need for relatively large amounts of CO_2 and electrolytic H_2



(Figure 9): the amount of each required will in part depend on the e-fuel route(s) pursued, as efficiencies differ across the different pathways.

Figure 9: Hydrogen (left) and CO_2 (right) expected requirements for domestic e-SAF production to cover the estimated demand under RefuelEU. Lines represent the average value and bars the possible ranges resulting from different routes.[19]

The amount of hydrogen that will be required ranges from 0.25-0.35 kt in 2025, up to 7-11 kt in 2030, finally reaching 230-330 kt in 2050. A similar trend is expected for CO_2, with requirements growing from 1.6-2.7 kt in 2025 to 50-82 kt in 2030 and reaching 1,600-2,600 kt in 2050.[19] In order to meet this electrolytic hydrogen demand, about 0.003-0.005 GW of renewable installed power will be needed in 2025, increasing to 0.10-0.13 GW in 2030 and further to 2.7-3.8 GW in 2050 (Figure 10). For reference, Ireland is forecasted to need around 9 GW of installed renewable power capacity by 2030 and 25 GW by 2050 to meet future electricity demand.[20]

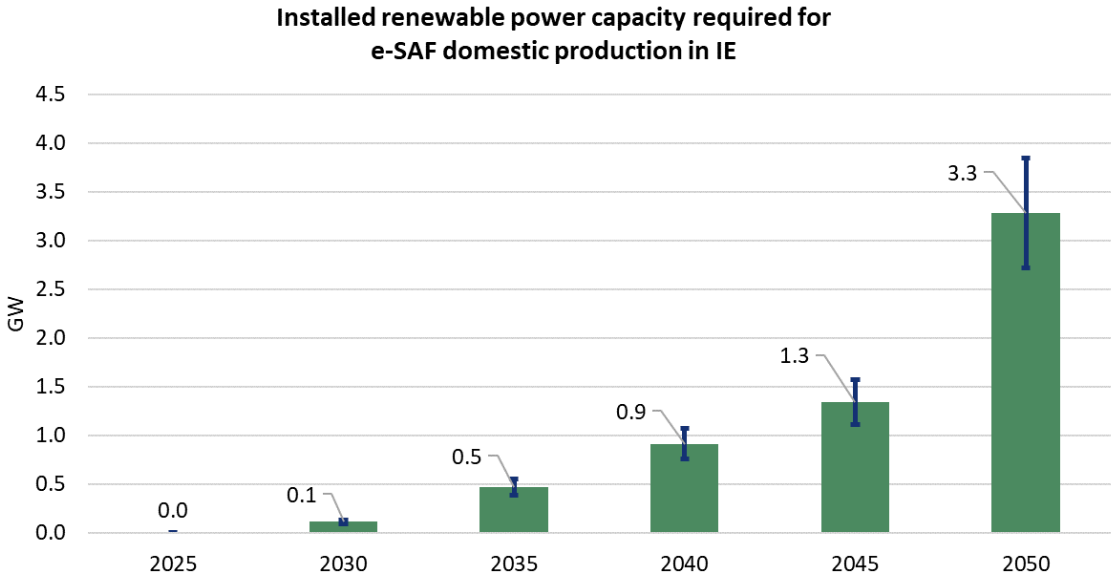


Figure 10: Installed renewable power (GW) required for domestic e-SAF production to cover the estimated demand under RefuelEU. Error bars represent the ranges resulting from different routes.

5.2 Shipping

Total international and domestic demand for marine fuel in Ireland estimated by SEAI was 293 ktoe (303 kt) in 2021, with long-range international shipping representing about 60% of the total. The final FuelEU Maritime legislation includes an e-fuels sub-target of 2% of the EU's shipping fuels by 2034. As further targets to 2050 are not included in FuelEU, this report assumes a linear trajectory to meet the 2034 target and a linear trajectory thereafter. It is also assumed that the e-fuel of choice would be methanol, though other options such as hydrogen and ammonia are possible. In order to estimate the demand of e-methanol in Ireland's shipping sector, two cases have been evaluated:

---

[19] *Internal E4tech models,* considering yields in the range: 0.6-0.85 t H_2/t SAF and 4.0-6.7 t CO_2/t SAF

[20] Centre for Marine and Renewable Energy – MaREI, https://www.marei.ie/wp-content/uploads/2021/03/Our-Climate-Neutral-Future-Zero-by-50-Skillnet-Report-March-2021-Final-2.pdf

1. E-methanol covering the overall shipping demand (international and domestic): For a RFNBO target of 2% of **all** shipping, this scenario is most appropriate.
2. E-methanol covering only long-range shipping demand (international only), assuming short-range is covered by direct electric propulsion

The resulting estimated e-methanol demand could grow from 4-6 kt in 2030 to 178-303 kt in 2050, following an increment in the share of e-fuels from 2% (2030) to 54% (2050), as depicted in

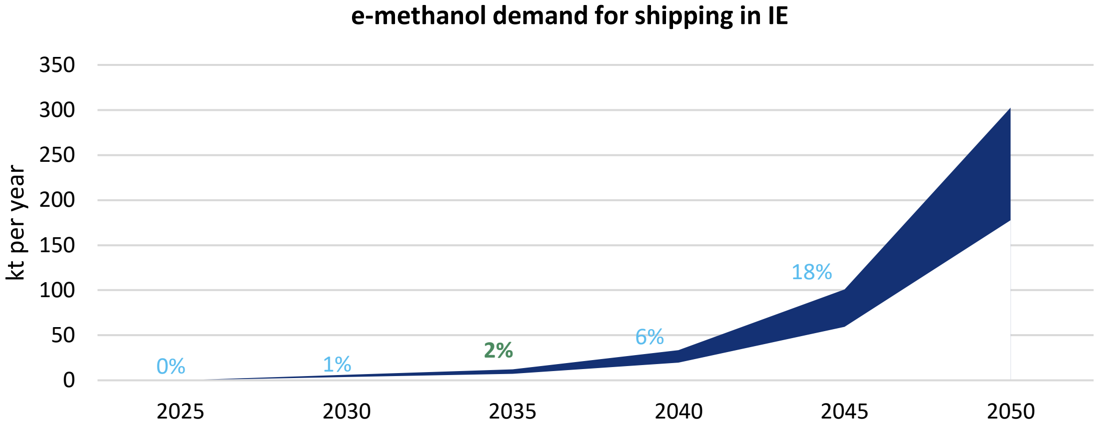


Figure 11.

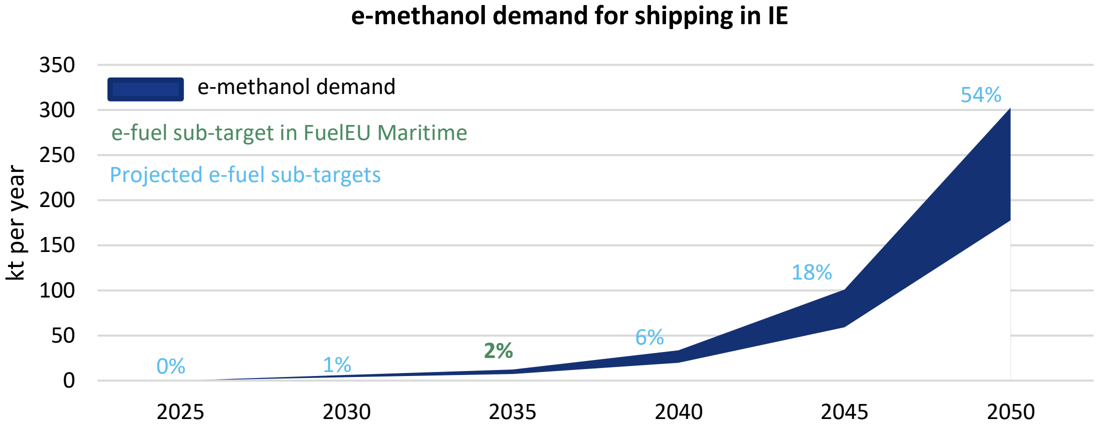


Figure 11: e-methanol demand for shipping ramp-up in IE, based on a linear trajectory using FuelEU Maritime targets and IE 2021 international (long range) and domestic (short range) marine fuel oil and gas oil demand (SEAI data).[21] Area represents the envelope of expected demand range between the two cases considered

As with e-SAF, this demand could be met by: (i) importing fuel from other locations or (ii) through domestic production. The latter case would require a hydrogen supply in 2030 ranging between 0.6-0.7 kt for only international shipping (Case 2) to 1.0-1.2 kt for both international and domestic shipping

---

[21] SEAI – Sustainable Energy Authority of Ireland, https://www.seai.ie/publications/Previous-Energy-Balances.xlsx, 2021 data were selected as benchmark (instead of 2019 as for aviation) to be more conservative due to higher reported demand in 2021 compared to 2019 and 2020.

(Case 1). This hydrogen demand would rise to 28-36 kt (Case 2) and 48-61 kt (Case 1) in 2050. Similarly, 4.5-5.2 kt (Case 2) and 7.7-8.8 kt (Case 1) of CO_2 in 2030 would be required, increasing to 222-254 kt (Case 2), up to 378-432 kt (Case 1) in 2050. This is summarised in

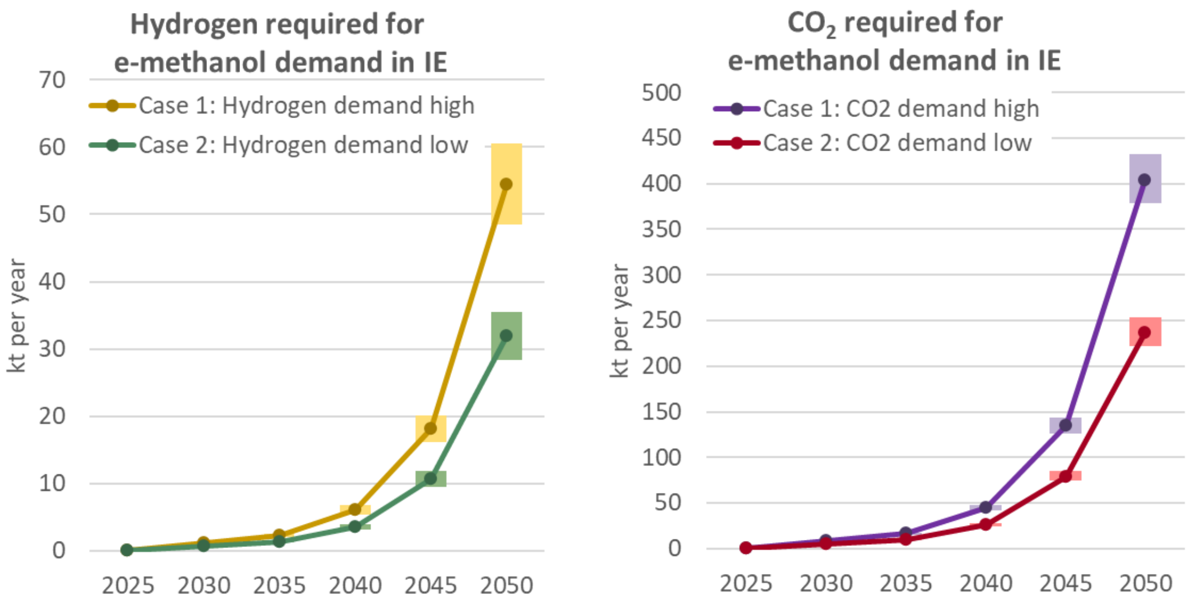


Figure 12.

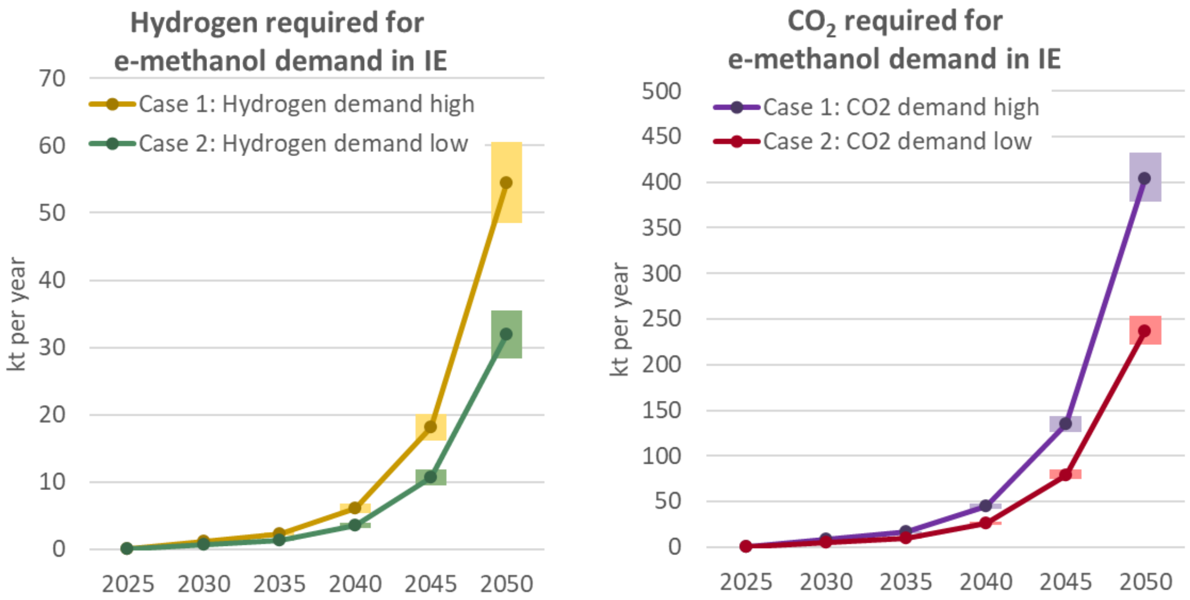


Figure 12: Hydrogen (left) and CO_2 (right) requirements for domestic e-methanol production to cover the estimated demand between 2025 and 2050. Lines represent the average value and error bars the possible ranges resulting from different routes.

The production of electrolytic hydrogen would require an installed renewable power capacity that in 2030 could range from 7 MW to 16 MW. This could increase to a demand of 330-700MW in 2050. This analysis suggests that the requirements for producing shipping e-fuels are much lower than for producing e-SAF, where the renewable installed capacity could be one order of magnitude higher (about 3 GW in 2050). This is because the shipping sector in Ireland consumes much less energy than aviation, a trend that is expected to remain similar in the long term.

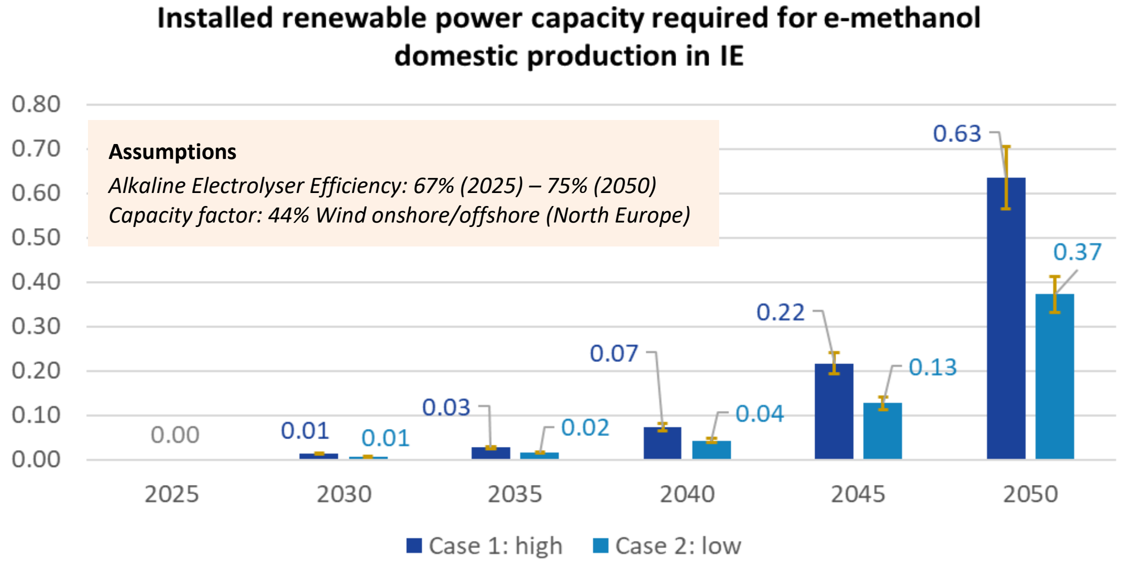


Figure 13: Installed renewable power (in GW) required for domestic e-methanol production to cover the estimated demand between 2025 and 2050. Bars represent the average value and error bars the possible ranges resulting from different routes.

5.3 Potential economic benefits and connectivity

Ireland's geography makes the country an attractive location for renewable electricity generation (both on and off-shore wind), which is the critical first step in the e-fuel supply chain. Ireland is making early steps towards developing a hydrogen economy, driven by industrial groups such as Hydrogen Mobility Ireland (which seeks to develop hydrogen for transport decarbonisation in Ireland), Hydrogen Ireland, regional, national and international partnership and early government signals of intent (such as the proposal to include hydrogen within the Biofuels Obligation Scheme and the development of a hydrogen strategy). Including domestic e-fuel production in Ireland's hydrogen economy could bring further economic and social benefits for the nation. The potential economic benefit can be quantified as gross value added (GVA)[22], a function of revenue and social benefit quantified through number of direct jobs created. The methodology for calculating GVA in this study is based on the Energy Innovation Needs Assessment work for BEIS (2019).[23]

To determine the GVA for Ireland, this study assumes the Irish e-fuel demand for aviation and shipping to be met entirely by domestic production and the revenue generated through this. Additional revenue achieved through Irish businesses accessing the global e-fuels market is also included. The IEA predicts the global market for e-SAF to be 214 PJ for aviation and 1.07 PJ for shipping in 2030, increasing to

---

[22] Gross Added Value (GVA) is the measure of the value of goods and services produced in an area, industry, or sector of an economy

[23] BEIS (2019) Energy Innovation Needs Assessments - GOV.UK (www.gov.uk)

4,490 PJ and 54 PJ respectively in 2050: Irish businesses could access a portion of the global market revenue through, for example, the export of intellectual property or services.’[24]

For the purpose of this study, a uniform fuel price has been assumed for the Irish and global market, based on existing policy mechanisms and 2022 fossil fuel prices (excluding taxes and duty).

- For e-SAF, the premium was calculated based on the support for advanced biofuels under the Irish Biofuel Obligation Scheme (BOS), which was 2x €1/litre[25]in 2022. This was added to the fossil jet fuel price.
- E-methanol is likely to benefit from the EU Emissions Trading Scheme (ETS) and FuelEU Maritime. A premium of c. €150/tonne is assumed for e-methanol under the ETS, compared to conventional shipping fuel oil – VLSFO – with a carbon price of €100 per tonne CO_2. In addition, the penalty for using VLSFO in 2030 will be €167/tonne in 2030 under Fuel EU Maritime – equivalent to a premium of €81/tonne e-methanol. This increases to €877/tonne e-methanol in 2050.[26]

Table 2 shows that by 2050, where e-SAF could represent 35% of Ireland’s aviation demand, GVA from domestic e-fuel production could reach €230 million/year, with an additional €2,100 million/year through tapping into the global market “export GVA”. Considering an average annual GVA of €234,770 per worker[27], this is equivalent to 9,900 new jobs created between now and 2050: the majority of these would come from accessing the global market and thus dependent on Ireland/Irish businesses developing IP and deploying licensing/engineering services abroad. Assuming Ireland accesses a smaller portion of the global market (1% rather than 2%) would see the total number of jobs in the e-SAF industry drop to 5,400 in 2050 and “export GVA” decrease by 50%. In shipping, GVA could reach between €45-73 million domestically and €22 million in the global market due to increased demand in e-methanol and higher premium under FuelEU Maritime, assuming Ireland accesses 2% of the global market in 2050. This would correspond to approximately 280-400 new jobs, dropping to 230-350 when assuming 1% market access Whilst e-methanol is easier to produce and requires fewer steps than e-SAF, the total demand for e-SAF is expected to be far greater – domestically and internationally – therefore the potential GVA through production of e-SAF could be significantly more than GVA generated through e-methanol. Nonetheless, the two are synergetic and should be considered as complementary. This analysis does not account for any displacement effects (e.g. loss of jobs in other sectors) nor does it consider additional job creation through indirect effects.

Table 2: GVA and job creation through the development of an e-fuels market in 2050

	e-SAF		e-Methanol (Case 1)		e-Methanol (Case 2)	
	Domestic	Global	Domestic	Global	Domestic	Global

---

[24] Assumed Ireland can access 2% of the global market through export of services, IP etc.

[25] IEA (2020) Ireland Biofuel Obligation Scheme – Policies - IEA. Note, this has now been replaced by the Renewable Fuels Transport Obligation.

[26] Council of the European Union. (2021) https://data.consilium.europa.eu/doc/document/ST-12813-2021-REV-1/en/pdf

[27] Central Statistics Office (2021) *GVA Indicators* PIA09.20220928135212.xlsx (live.com). Figure taken based on categories A, B, D and E.

Fuel production (PJ/yr)	17	4,500	6	48	4	50
Fuel Revenue (mEUR/yr)	1,400	360,000	440	3,500	260	3,700
GVA – Irish market (mEUR/yr)	230		73		45	
GVA – Global market (mEUR/yr)		2,100		20		22
Jobs (approximate)	1,000	9,000	310	86	190	90

There are additional benefits that could be realised through the establishment of an Irish e-fuels industry which are not captured through GVA or job creation, notably the benefits of increased energy security and wider hydrogen ecosystem growth. At a time of great turmoil and volatility in the global energy markets, increasing self-sufficiency of transport fuels for an island nation could be greatly beneficial.

5.4 Establishing an e-fuels sector in Ireland

There are several e-SAF projects planned in Europe in the coming years, which will serve as important milestones in establishing the e-fuels sector. Many of these projects are planned at existing industrial hubs or ports, such as Reuze at the Port of Dunkirk in France – a first of a kind (FOAK) commercial project which will enter operation in 2026. The project will see Infinium produce 100 kt per year of synthetic jet fuel (e-SAF), diesel and naphtha via Fischer-Tropsch synthesis. In order for projects to achieve this scale and help establish the sector, there are three main considerations which Ireland should address:

- **Feedstock security:** Reuze will capture 300 ktCO_2 per year from ArcelorMittal's steel plant. While CO_2 sources for e-fuels projects are expected to be abundant aside from biogenic sources in some regions of the world, sufficient renewable electricity must also be secured to produce the hydrogen quantities required and for DAC where point source CO_2 is not available. Reuze will install a 400 MW electrolyser, one of the largest announced electrolyser systems to date in Europe, and offshore wind energy will be important for supplying electricity for electrolysis to this and other SAF plants at port clusters. Ireland is fortunate to have significant potential to develop both onshore and offshore wind energy. In 2020, Ireland had an installed wind capacity of 4.3 GW. Ireland has a target of ~ 13 GW installed grid capacity by 2030 and e-fuels (e-SAF and e-methanol) would require approximately 1 GW by 2030 to produce the required hydrogen. [28,29] The additional electricity required to secure CO_2 via DAC would be less than 1% of what is required for the hydrogen. Ireland's wind energy is expected to have high load factors of renewables will also contribute to securing the availability of hydrogen, produced when there is low-cost surplus electricity which can bring down total production costs.
- **Technology de-risking:** As this report has shown, e-fuels have potential but are currently at a lower TRL than other routes, such as HEFA. This means that investments in e-fuels facilities can represent a significant financial risk, as facilities may not operate as well as expected and production can be below nameplate capacity, particularly within the first few years when plants may face reliability issues. To de-risk the technologies and future investments, it is critical for current and planned e-fuels facilities to receive sufficient funding to enable their successful operation, particularly in supporting CAPEX expenditures. Public funding is likely required in the short-term, for example Reuze will receive financial support from the ADEME, France's environment and energy management agency, representing an investment of €500 million. The UK's current Advanced Fuels Fund also supports demonstration and first of a kind commercial SAF facilities in the UK to further unlock private investment.
- **Revenue certainty:** Project developers and private investors also need long-term certainty in the revenues the fuels will produce to commit to project execution. This requires clear and committed signals from government to provide policy support for production of e-fuels. Given the trans-national nature of the aviation sector, clear policy support and regulation that cover multiple jurisdictions, such as the EU's ReFuelEU, is also important for providing revenue certainty for the uptake of e-SAF across borders.

---

[28] SEAI (2021) Energy in Ireland 2020 Report (seai.ie)

[29] SEAI (2022) Wind Turbine Energy | Renewable Energy Technologies & Solutions| SEAI

6 Conclusions

Decarbonising the transport sector will require a multitude of technologies and fuel types. Liquid carbon fuels will continue to have a critical role in the sector, particularly in transport modes which have specific requirements that leave liquid carbon fuels as the most suitable option.

Whilst the policy landscape is evolving and important legislation is yet to be finalised, there are clear and strong signals that the EU will look to e-fuels to contribute significantly to decarbonisation efforts in both the aviation and shipping transport sectors. E-methanol is likely to serve the shipping sector, as well as becoming a key intermediate for e-SAF production, for which there are three main technology pathways being pursued.

The quantity of e-fuels required under the RefuelEU aviation and FuelEU Maritime mandates will start conservatively - starting at 1.2% in 2030 and rising substantially 35% of the aviation demand in 2050, and at 2% of marine fuel demand in 2034. In Ireland, this is equivalent to 12 kt e-SAF in 2030 and 388 kt e-SAF in 2050, as well as 4-6 kt e-methanol in 2030 and 178-303 kt e-methanol in 2050. Significant renewable power for electrolysis (~4 GW in 2050) and available CO_2 (2,300 kt in 2050) will be required to produce the required fuel volumes domestically.

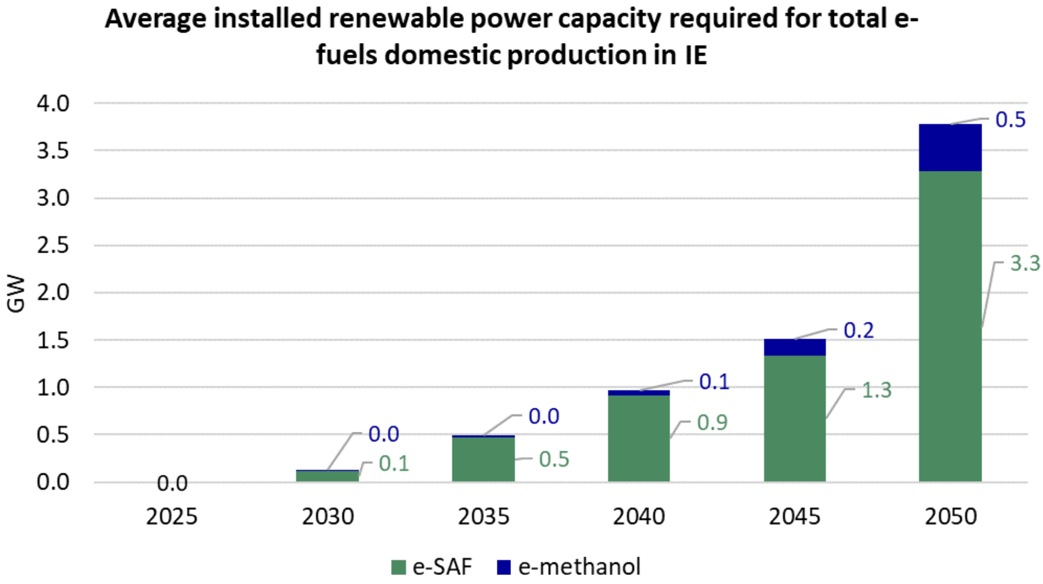


Figure 14: Average installed renewable power (GW) required for total e-fuels (e-SAF + e-methanol) domestic production to cover the estimated e-fuels demand in shipping and aviation.

Ireland is already looking to how it can develop a hydrogen economy: expanding this economy to cover e-fuels could generate a GVA of €11m / year in 2030 up to €300m / year in 2050, as well as significantly more through Irish businesses accessing a global e-fuels market. The Irish economy could see c. 10,300 e-fuels jobs by 2050.

However, e-fuels currently remain at an early development stage, limited mostly to small scale pilot and demonstration projects (e-methanol is slightly more progressed). In addition, currently e-fuels have high production costs compared to fossil fuel prices, making it financially difficult for e-fuel producers to commercialise the technologies. Therefore, there is a short-term need to facilitate the scale-up of these technologies, through concrete policy signals and financial support.

Hydrogen Mobility Ireland

E4tech (UK) Ltd for
Hydrogen Mobility Ireland

E4tech
an ERM Group company