TRANSPORTATION ENERGY INSTITUTE

E-fuels:

Evaluating the Viability of Commercially Deploying E-fuels in Road Transport

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Contents

Executive Summary

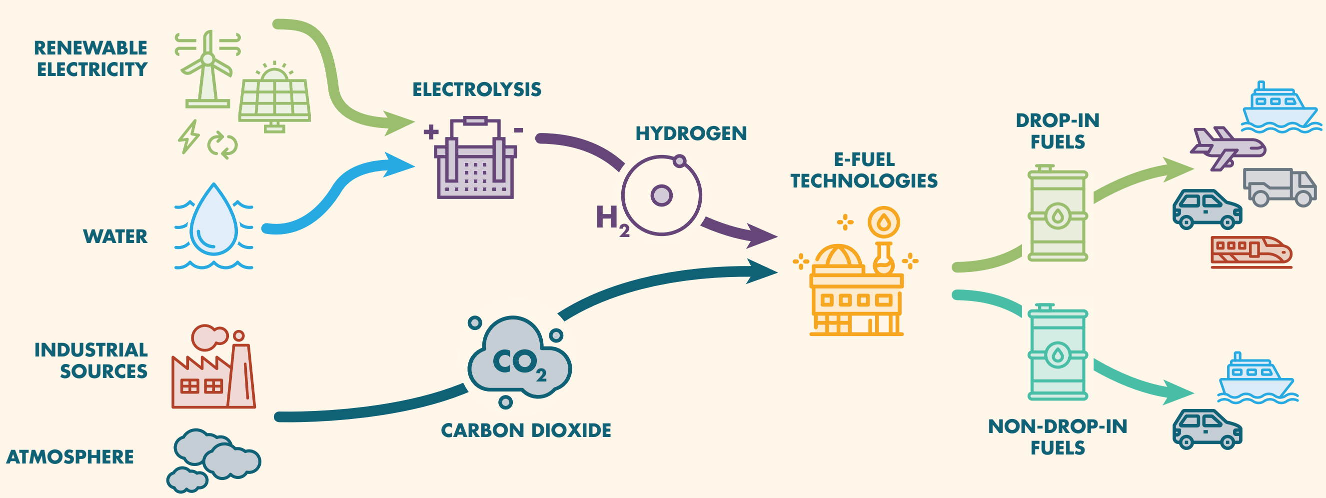
Evaluating the Viability of Commercially Deploying E-fuels in Road Transport

The United States road transport sector accounts for 22% of US greenhouse gas (GHG) emissions. Policies have been put in place to reduce emissions in the road transport sector – both on a federal and state level in the U.S., as well as around the globe. Many decarbonization technologies are available and are being incentivized under such policies, each facing a unique set of challenges as they are deployed commercially. Amongst these options, e-fuels (or synthetic fuels) are a renewable technology that can be used in existing and new vehicles while potentially yielding near-zero emissions.

WHAT ARE E-FUELS?

E-fuels are renewable fuels produced from water, renewable electricity and carbon dioxide (CO_2) via chemical or biochemical processes, which can be used to decarbonize the road, aviation, maritime, and rail sectors.

FIGURE ES-1. E-FUEL PRODUCTION PROCESS

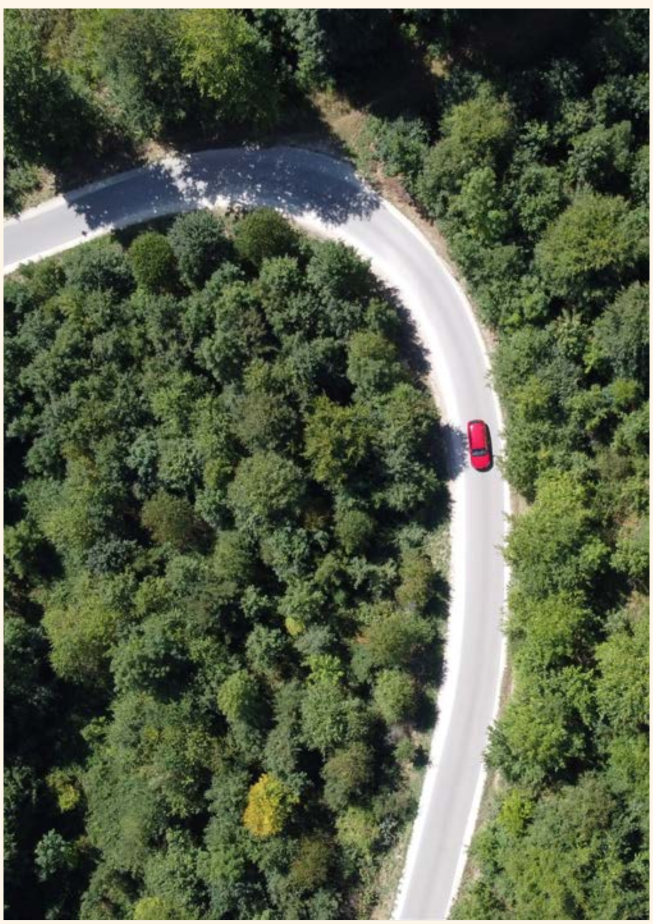


WHY IS THERE GROWING INTEREST IN E-FUELS?

E-fuels can achieve up to 75-99% GHG savings compared with fossil fuels, when made from additional renewable electricity (i.e. renewable electricity which meets incrementality, deliverability and temporal correlation requirements).

They are highly compatible with existing infrastructure and vehicles in the road, aviation, shipping and rail sectors.

E-fuels are produced from renewable electricity, carbon dioxide, and water which are **highly abundant resources globally.**



However, most e-fuels technologies are at a low level of technological and commercial development today. Key challenges are the technical risks associated with production processes, high costs, and limited policy support to bridge the cost gap with fossil fuels.

To contribute meaningfully to decarbonization across the transport sector, e-fuels will have to become commercially available and be deployed at large scale. This will depend on technical progress, feedstock availability in particular locations, availability of funding, strong policy support, and the speed in which other transport decarbonization options ramp up.

This report evaluates the viability of e-fuels in the U.S., based on their current technical suitability, emission reduction potential, scalability, and economic competitiveness, and how this could change by 2040. It focuses on e-fuels' potential contribution to the sustainable transition of the road sector and other transport energy sectors.

WILL E-FUELS BE NEEDED TO DECARBONIZE U.S. ROAD TRANSPORT?

E-fuels could close potential emission reduction gaps or accelerate emission reduction efforts in road transport in the U.S. The U.S. currently lacks a clear path for road transport decarbonization, leading to uncertainties in how quickly low carbon technologies could be adopted. Battery electric vehicles (BEVs), which are cost-effective and have high GHG savings, will play a significant role in emission reduction, but the speed at which they could replace existing internal combustion engine vehicles (ICEVs) is uncertain due to the technical and infrastructure challenges they currently face, and a lack of policy certainty. As a result, it is expected that ICEVs will continue to be on the road into the 2040s. E-fuels could be deployed to achieve higher emission reductions from existing vehicles, particularly if the supply of sustainable biofuels is slow to ramp up.

The strongest demand signals for e-fuels come from the aviation sector but e-fuels could be supplied for both aviation and road transport.

HOW COULD DEMAND FROM OTHER TRANSPORT SECTORS INTERACT WITH E-FUELS SUPPLY FOR ROAD VEHICLES?

Whether e-fuels will be supplied to the road transport sector in the U.S. will be largely influenced by policy. E-fuel production capacity in the U.S. could grow significantly between now to 2040. We estimate that they could be scaled up significantly to achieve an annual production capacity of 6-14 million tonnes (approximately 2-5 billion gallons) by 2040, but this volume is small (around 6-14%) compared to projected demand for low carbon fuels in transport overall. Currently, e-fuels are much more costly to produce than fossil fuels and biofuels, and while costs could come down in future, they are unlikely to reach cost parity. Because of this, policy support plays a key role in bridging the cost gap, but also in determining in which transport sectors e-fuels could be deployed.

Current policy landscape could result in e-fuel producers favoring markets outside of the U.S. Today, Inflation Reduction Act (IRA) tax credits (TC) in the U.S. could help bring down e-fuel production costs but the lack of widespread blending mandates for e-fuels means there is currently no guaranteed market demand for e-fuels. In contrast, fuel policies in the EU and UK include sub-targets for e-fuels and penalties for non-compliance, which create clearer and stronger demand signals, particularly in the aviation sector. Under this policy environment, e-fuels are likely to be produced in the U.S. but sold to the EU/UK markets, so that producers can capitalize on financial support from both supply and demand policies in the U.S. and Europe (including the UK).

The strongest demand signals for e-fuels come from the aviation sector but e-fuels could be supplied for both aviation and road transport. E-fuel producers may tune production capacity to maximize e-sustainable aviation fuel (e-SAF) volumes over road fuels due to the higher policy premium being available through ReFuelEU Aviation, the UK SAF Mandate, and the premium offered to SAF under the 45Z Clean Fuel Production TC, and interest from the aviation industry and customers. However, most e-SAF pathways produce diesel and naphtha as co-products, and so their ramp-up will also provide additional fuel for the road sector. High willingness to pay (WTP) from the aviation industry could potentially also help to support road e-fuel prices.

KEY ACTIONS NEEDED TO SUPPORT E-FUEL UPTAKE

E-fuels are (and will continue to be) more expensive to produce than their fossil counterparts, making policy support critical for projects to be economically viable. Today, the production cost of e-fuels is 2.5-4 times more than fossil fuels when using low-cost renewable electricity. Despite policy support being available, it could still be challenging for most early e-fuel plants to be economically viable in the near future. The cost gap could fall to 1.5-3 times current fossil fuel prices by 2040 [1], [2]. Policy support in the U.S. could help close this price gap in the future - however this relies on the availability of TCs and the ability to stack them.

Further policy drivers are needed to provide additional confidence for investments in e-fuels and to support their uptake. Without a guaranteed market, e-fuel uptake will also be highly unpredictable in the road transport sector given that cheaper alternatives are already commercially available. Given this highly uncertain outlook, enabling the uptake of e-fuels requires a multifaceted approach across technology, sustainability, policy, and market development. If U.S. policymakers are keen to further incentivize e-fuel uptake in the transport sector, some recommendations they could consider include the following:

RECOMMENDATION 1: Set Clearer Transport Decarbonization Pathways, Targets and E-fuels Road Map

- **Develop a knowledge base on U.S. transport decarbonization, including all decarbonization options:** There is currently very little detailed analysis and scenarios that show the role of all transport decarbonization options in all modes in the U.S.

- **Set clear emission reduction targets for the transport sector, including by mode:** Allow market to anticipate what types of low emission transport solutions (including e-fuels) will be needed in road transport decarbonization.
- **Develop a U.S. roadmap for e-fuels production and use:** Include the demands of the road, aviation, maritime and rail transport sectors, so that the production plants, infrastructure and policy for these can be developed together, rather than being seen as competing markets.

RECOMMENDATION 2: Set Requirements to Ensure E-fuels are Developed Sustainably

- **Standardize lifecycle assessment methodologies:** The U.S. currently does not have an agreed and published methodology for calculating the GHG emissions of e-fuels, including the treatment of renewable electricity used. Because some policies set GHG thresholds to determine eligibility or provide higher support for options that provide greater GHG emissions reductions, developing standardized methodologies that account for the benefits of e-fuels will allow stakeholders to evaluate the environmental performance quantitatively to make informed decisions about prioritization.

1 The reference prices for 2023 for gasoline is 3.50 U.S.$/gal (930 U.S.$/tonne).

2 EIA (2024): Short-term Energy Outlook. Available from: [Link]

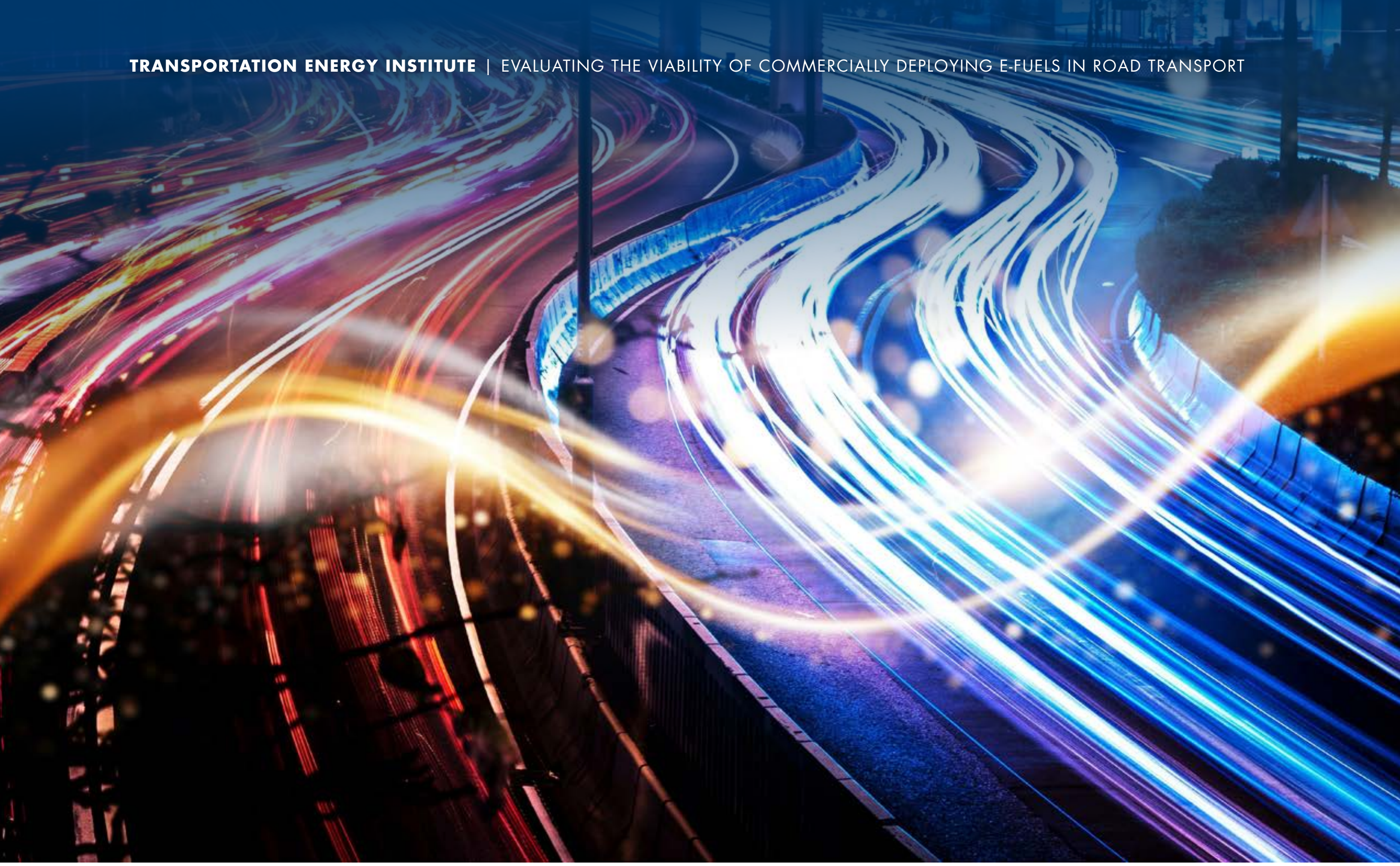
RECOMMENDATION 3: Implement Policies to Further Incentivize Market Development

- **Guarantee markets for e-fuel producers:** The U.S. e-fuel policy landscape currently lacks demand-side policy support to promote the uptake of e-fuel. Policy makers could consider mandating a minimum share of e-fuel use in the road transport sector. Unlike the technology-neutral approach taken by the Low Carbon Fuel Standard (LCFS), an e-fuel sub-target is the most direct way to facilitate market access and provide market certainty to e-fuel developers and investors. The cellulosic sub-target within the Renewable Fuel Standard 2 (RFS2) is an example of this. This could be designed to ensure that e-fuels plants in the U.S., which will receive production-side support, prioritize domestic demand instead of being drawn away to the UK/EU with mandated markets. Some have argued that a technology neutral carbon intensity (CI)-based target is more appropriate for meeting GHG reduction goals, however guaranteed markets for emerging technologies can help to give confidence in markets and so secure investment.

RECOMMENDATION 4: Create Funding Opportunities for E-fuels

- **Increase public funding for e-fuel projects**: E-fuel production is capital intensive with capital expense (CAPEX) contributing 17-24% of the levelized production costs. It is challenging to secure private investment for early development technologies due to large risks associated with low maturity plants. Having access to public funding to secure capital costs for early plants could help promote e-fuel plant roll-out in the U.S., like the Advanced Fuels Fund (AFF)[3] in the UK. While funding programs for biofuel and hydrogen projects are available in the U.S., none to our knowledge exist which targets e-fuels. Securing public funds can also provide confidence to investors and unlock additional private investment to projects as well.

3 For more information on the AFF, see [Link]



Introduction

The need to tackle climate change will require deep emissions reduction in all sectors of the economy. The U.S road sector accounts for 80% of emissions arising from the transport sector (excluding all off-road applications), and 22% of overall US GHG emissions,[4] while at a global level it accounts for approximately 12% of total anthropogenic emissions.[5] Increasingly stringent regulations have been put in place to reduce emissions in the U.S. road sector, both at a federal and state level, as well as around the globe. Many decarbonization technologies are available and are being incentivized under such policies, each facing a unique set of challenges as they are commercially deployed.

4 EPA (2022), Fast Facts on Transportation Greenhouse Gas Emissions. Available from: [Link]

5 EPA (2024), Global Greenhouse Gas Overview. Available from: [Link]

One decarbonization option is e-fuels, a type of renewable fuel produced synthetically from electrolytic hydrogen and captured carbon dioxide (CO_2). E-fuels represent a promising opportunity because they:

- **Can achieve high lifecycle GHG savings** compared with fossil fuels. Section 3 looks at this in detail.
- **Are compatible with existing infrastructure and vehicles** in the road, aviation, shipping and rail sectors as "drop-in" fuels as shown in Section 2.
- **E-fuels are produced from** renewable electricity, carbon dioxide, and water which are **highly abundant resources globally**. Feedstock availability in the U.S. is explored further in Section 3.

Given their potential scalability, e-fuels could strongly contribute towards ambitious decarbonization targets across all transport sectors. However, their production is in the early stages of technology development today, with key challenges including:

- **Technology risks**, as many e-fuels production technologies are yet to demonstrate commercial operation. This is explored in detail in Section 1.
- **High costs**, driven by the high energy consumption of producing green hydrogen and fuels processing, and the high capital investment costs of e-fuels plants. Section 5 compares this to current fossil fuel prices.
- **Competition with other uses of renewable electricity, and between end-use sectors**, meaning that consideration is needed of impacts on the energy system, and the options available to different transport sectors, which will change over time. This is discussed further in Section 3.
- **Limited policy support**, which is yet to bridge the cost gap between e-fuels and conventional fossil fuels or biofuels and provide clarity around GHG accounting methodologies. A policy analysis is carried out in Section 6.

To contribute meaningfully to decarbonization across the transport sector, e-fuels will have to become commercially available and be deployed at large scale. This will depend on several factors, such as technical progress, feedstock availability, availability of funding, strong policy support, and successful competition with other transportation decarbonization options. Despite these challenges, they could be an important way to decarbonize transportation sectors with limited alternative options. This report evaluates the viability of e-fuels in the U.S., with a specific focus on road transport sector, based on their emission reduction potential, scalability, and economic competitiveness.

KEY QUESTIONS

- **What are e-fuels and how are they produced?**
- **How can e-fuels be used in the transport sector and what alternative options are there?**
- **How can e-fuels reduce GHG emissions and how does this compare to other options?**
- **How much e-fuels production capacity could there be?**
- **What are the costs of producing and using e-fuels?**
- **What policy support is available for e-fuels?**

SECTION 1.

What are E-fuels?

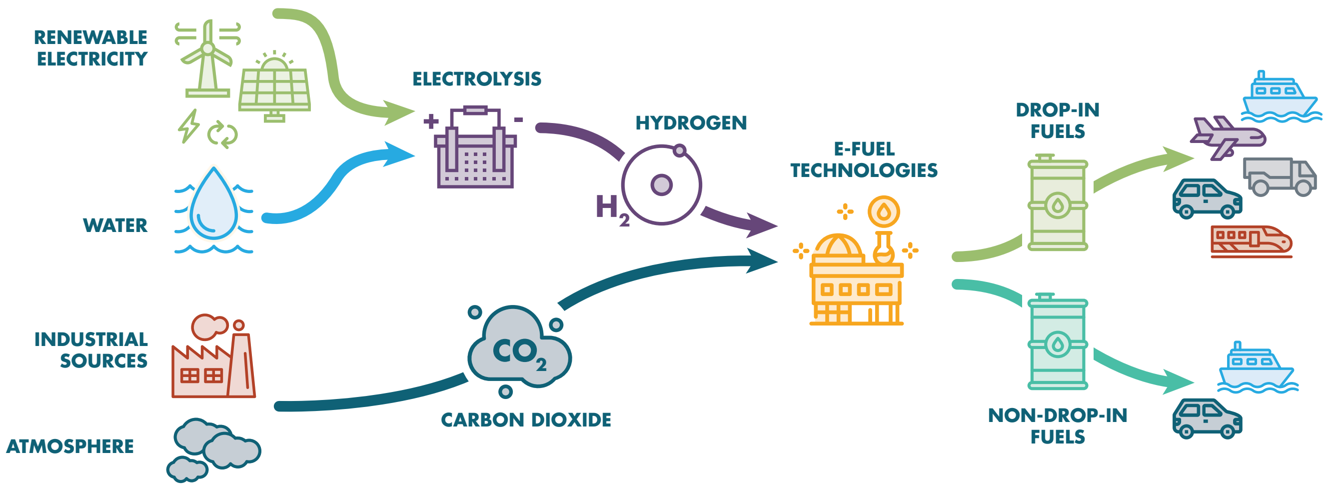
Many low carbon fuel equivalents to the fossil fuels used in road transport vehicles today can be produced from alternative sources such as biomass, or, in the case of e-fuels, synthetically from renewable electricity, water and captured CO_2. There are many e-fuels technology pathways that can produce a range of products, but generally they are all at early stages of development today, though some production technologies are already nearing commercialization.

This section defines e-fuels and introduces the main production technologies that will be discussed in this report.

SECTION 1: KEY QUESTIONS

- How are e-fuels produced?
- How mature are e-fuel technologies and what are the key technical challenges?

FIGURE 1-1. E-FUEL PRODUCTION PROCESS



1.1 HOW ARE E-FUELS PRODUCED?

Feedstocks

E-fuels are a type of low carbon fuel produced from water, renewable electricity and CO_2 feedstocks via a range of production technologies using chemical or biochemical processes as summarized in Figure 1-1. Renewable electricity is used as a primary energy source for the electrolysis of water to create green hydrogen, which can then be combined with CO_2 captured from biogenic or existing industrial point sources such as bioenergy plants and cement plants respectively, or directly from the atmosphere through direct air capture (DAC). Green hydrogen and its derivatives, such as e-ammonia, are also considered to be e-fuels, but are not discussed in detail in this report as their production and use differs from other e-fuel pathways involving captured CO_2.

Products

E-fuel technologies can produce a range of products that can be used to decarbonize the transport sectors, including vehicles used in road, aviation and shipping, as well as the chemical sector. They can produce fuels that have very similar chemical properties to fossil fuels, such as gasoline, diesel

or jet fuel, and are free of sulfur content. These are often referred to as 'drop-in-fuels', which can be blended in at high levels and used directly in existing ICEs and infrastructure without any major modifications (some can also be used to improve the property of fuels such as density, aromatics contents, and lubricity) – this can include both liquid and gaseous fuels.

E-fuel technologies can also produce fuels that are 'non-drop-ins', such as alcohols (i.e. ethanol and methanol). These are fuels that can only be blended and used in conventional gasoline vehicles up to a blend limit but require vehicle modifications to enable their use at higher blends. Alcohols can also be further processed into 'drop-in' fuel products.

E-fuel production technologies

There are many methods of producing e-fuels. This report covers the following five main technologies.

TABLE 1. E-FUEL PRODUCTION PATHWAYS IN THIS STUDY

PRODUCTION TECHNOLOGY	FUEL PRODUCTS
Fischer Tropsch (FT) based routes	Jet fuel, diesel, gasoline (from naphtha upgrading)
E-methanol synthesis	Methanol
Ethanol via partial reverse water gas shift (pRWGS) and fermentation	Ethanol
Alcohol-to-hydrocarbons • E-methanol-to-jet/gasoline (e-MTJ/e-MTG) • E-ethanol-to-jet (e-ETJ)	Jet fuel, diesel, gasoline
E-methane via methanation	Compressed or liquified methane (i.e. CNG or LNG)

PRODUCT SLATE

Many e-fuel pathways can produce a range of products in varying percentages, known as a product slate, that can be used to decarbonize the road, aviation and shipping transport sectors. Product slates are largely determined by the chemical reaction of each processing technology but can be altered to a certain degree through reconfiguring operating conditions, similar to the way in which conventional crude oil refineries can vary the proportion of gasoline and diesel output. Typical product slate ranges referenced in literature and producer data are shown for the technologies in Section 1.2. These references can be found in Appendix A.

1.2 HOW MATURE ARE E-FUEL TECHNOLOGIES AND WHAT ARE THE KEY TECHNICAL CHALLENGES?

Most e-fuel production pathways are at low stages of technological development today. Pilot and demonstration projects have only recently entered operation in the last 1-2 years. Notably, e-fuels developer Highly Innovative Fuels (HIF) opened a demonstration plant producing drop-in e-gasoline in Chile at the end of 2022, with the fuel transported to the UK for use by Porsche. More on this can be seen in Section 4 through a case study on HIF.

Most e-fuels production processes are at a Technology Readiness Level (TRL) of 7 or below, which is a system of measurement used to evaluate and compare the maturity of a technology as illustrated in Figure 1-2. However, there are plans to implement larger demonstration and first-of-a-kind (FOAK) commercial e-fuels projects in the next 2-3 years, particularly in the U.S. and the EU, which would move many of the technologies to TRL 7 and 8. More information is provided about project development timelines, future plant capacities and supply scalability in Section 4.[6]

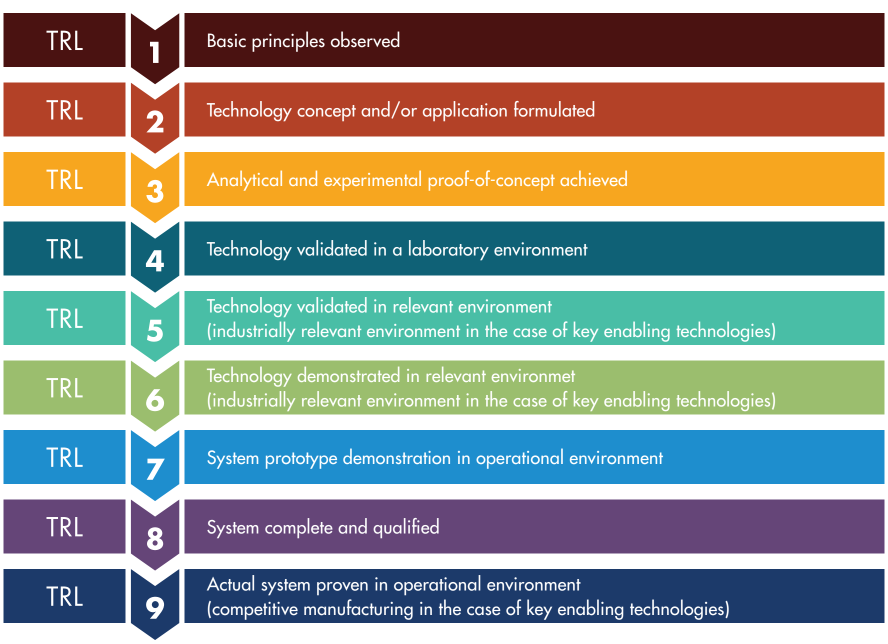
The following section provides an overview of the five main e-fuels pathways, including a brief explanation of the technology processes and maturity. Each technology pathways are scored a TRL based on their progress against the criteria in Figure 1-2, followed by a discussion of their key technical challenges.

1.2.1 FEEDSTOCK PRODUCTION

E-fuel synthesis begins with the production of its chemical building blocks: electrolytic hydrogen and CO_2, which are relatively mature.

- **Green hydrogen**, or electrolytic hydrogen, is produced from water and renewable electricity using an electrolyzer. There are many types of electrolyzer technologies available today - polymer exchange membrane (PEM) and alkaline (ALK) are the main technologies and are at TRL 9,[7] with many commercial projects operating today. Across all e-fuel pathways, electrolysis

FIGURE 1-2. THE TECHNOLOGY READINESS LEVEL SYSTEM OF MEASUREMENT[6]



6 NASA (n.d.), Technology Readiness Level Definitions. Available from: [Link]

7 IEA (n.d.), Electrolyzers. Available from: [Link]

requires the highest electricity input, typically representing 60-70% of total energy requirements for e-fuel production.

- CO_2 capture from industrial point sources, such as power stations and cement plants, is also at TRL 9. CO_2 could also be captured directly from the atmosphere via DAC, but this is at a lower maturity (TRL 7).[8]

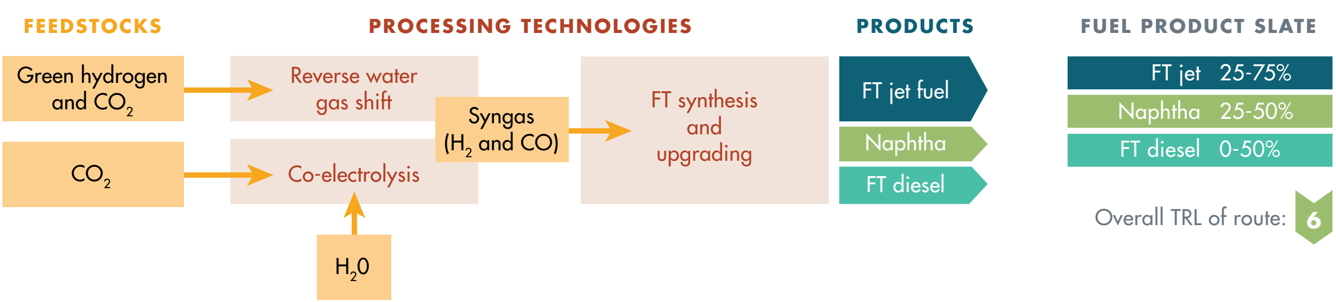
1.2.2 FISCHER TROPSCH (FT) SYNTHESIS ROUTES

The FT synthesis process begins with the production of syngas, which is a mixture of hydrogen and carbon monoxide (CO). The two main syngas production technologies are co-electrolysis and reverse water gas shift (RWGS), both of which are at an early stage of development (TRL 6) with a handful of small pilot systems in operation today.

- **Reverse water-gas shift –** This is a chemical reaction that uses hydrogen to convert CO_2 to CO at very high temperatures and pressures.
- The challenges are the very high energy consumption and maintaining a stable reaction to produce the required amount of syngas.
- **Co-electrolysis –** This is an electrochemical reaction which converts CO_2 into CO using electricity. Key challenges include the high electricity consumption and the low lifetime of membranes used in the electrolyzer.

This syngas is then chemically converted via the FTprocess into drop-in products such as jet fuel and diesel, as well as naphtha and hydrocarbon waxes. These can also be upgraded further into gasoline products and other drop-ins. FT is a commercial process (TRL 9) used in the fossil fuel industry, with many large industry players such as Shell, Johnson Matthey and Sasol aiming to license their technology to e-fuels demonstration projects in the next 2-3 years. Although FT is commercial, the overall TRL of integrated FT synthesis and upgrading routes is TRL 6, because this is limited by the low TRL of co-electrolysis and RWGS.

FIGURE 1-3. FT SYNTHESIS-BASED PATHWAYS



8 ADI Analytics, (n.d), Going Blue: A review of direct air capture. Available from [link]

1.2.3 E-METHANOL SYNTHESIS

E-methanol can be produced through the reaction of hydrogen with CO_2 at high temperatures and pressures using a metal catalyst. There are few technical challenges with this conversion process and it is already a commercial technology (TRL 8-9) but most operational projects today use fossil hydrogen and CO_2. The first commercial e-methanol projects using green hydrogen and captured CO_2 are slated to enter operation this year[9], which would move the technology from TRL 7 to TRL 8. Though the technology risk remains low as the process is highly similar to the already commercialized fossil process.

FIGURE 1-4. METHANOL SYNTHESIS PATHWAY

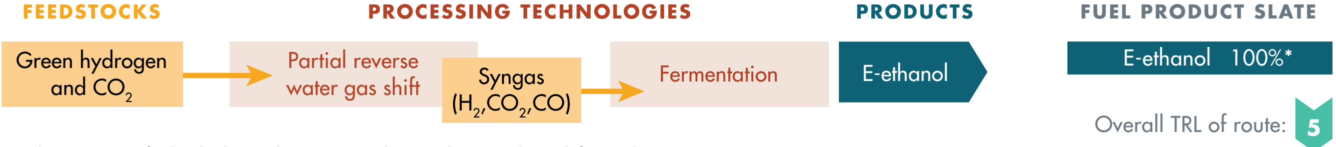
1.2.4 ETHANOL VIA PARTIAL RWGS AND FERMENTATION

E-ethanol routes also involve the use of syngas but using a different process from FT synthesis. There are two main steps in these routes:

- **Partial RWGS (pRWGS) –** This is a chemical reaction that produces syngas from hydrogen and CO_2. The syngas composition required for further processing into ethanol is different to FT and therefore lower temperatures and pressures than the full RWGS reaction are needed. This technology is at TRL 5.
- **Fermentation –** The resulting syngas is then fermented in a biochemical reaction using micro-organisms to produce ethanol and other organic compounds.

The fermentation process is at TRL 8, with five demonstrations and first commercial projects operated today by Lanzatech, who are the only player actively pursuing this technology. However, these facilities use waste fossil gases from industrial facilities rather than green hydrogen, which are not categorized as e-fuel pathways. As such, the integrated e-fuel pathway is only at TRL 5 as the pRWGS step is yet to be demonstrated. Additionally, the fermentation step faces challenges with low yield of ethanol due to the slower reaction rate of the biological processes compared to thermal/chemical routes.

FIGURE 1-5. ETHANOL VIA PRWGS AND FERMENTATION PATHWAY



*Other types of alcohols and compounds can be produced from this process, depending on the use of the microbes and reactio conditions

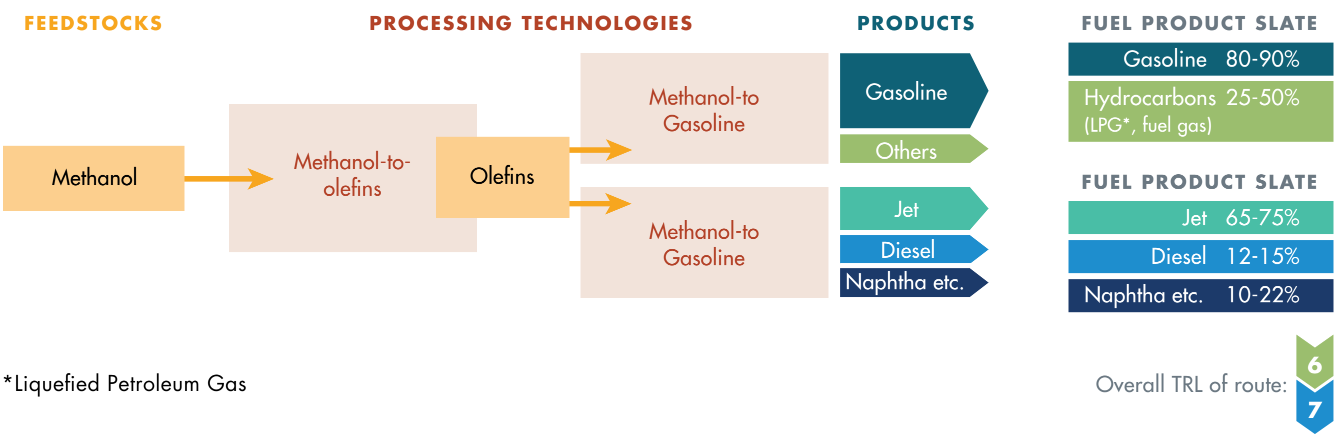
9 Mitsu & Co (2023), Mitsui Invests in the World's Frist e-Methanol Production & Sales Business in Denmark. Available from: [Link]

1.2.5 ALCOHOL-TO-HYDROCARBONS

Methanol and ethanol are not drop-in fuels but can be converted to drop-in gasoline, diesel or jet fuel. To achieve this, they are first converted to olefins such as ethylene and propylene, which are more easily reacted into the desired hydrocarbon products. For methanol-based routes, this is via a chemical reaction called methanol-to-olefins (MTO). For ethanol, this is through a dehydration reaction using heat and catalysts. A range of further processing steps then convert the olefins into transport fuels using a small amount of additional hydrogen.

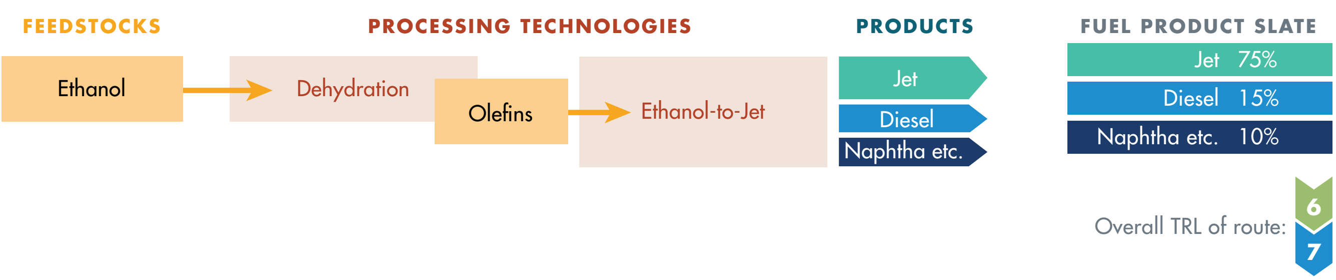
- Methanol can be converted to drop-in fuels through **Methanol-to-gasoline (MTG) or Methanol-to-jet (MTJ)**.
  - This process was developed in the 1980s but has typically used methanol from fossil sources. The first demonstration plant producing e-MTG was commissioned by HIF in 2022, bringing the technology to TRL 7. The MTJ process is less mature at TRL 6.
  - There are generally low technical risks in the individual processing steps but there has been limited development to date of the entire e-MTJ/G production process including use of green hydrogen and captured CO_2.
- **Ethanol** can also be converted to jet fuel, with drop-in diesel as a by-product. This pathway is referred to as **Ethanol-to-jet (ETJ)**.
  - This technology is currently at TRL 7, but several large demonstrations and first commercial plants are planned in the next 1-2 years which would move it to TRL 8. While the majority of individual processing technology steps in alcohol-to-hydrocarbon routes have been demonstrated, the main technical challenge may be in integrating multiple steps together to achieve efficient e-fuels production.

FIGURE 1-6. METHANOL-TO-GASOLINE/JET PATHWAYS



*Liquefied Petroleum Gas

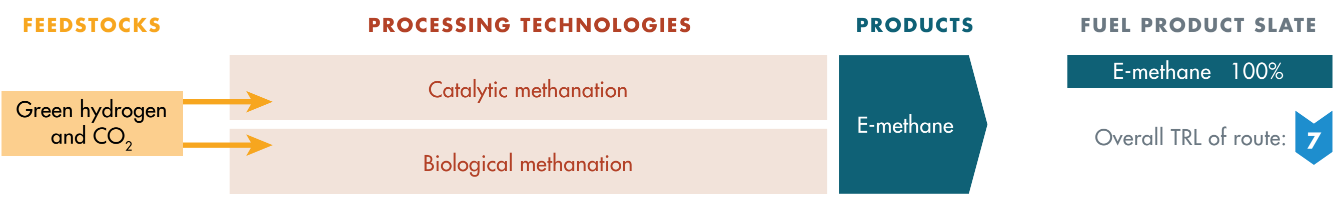
FIGURE 1-7. ETHANOL-TO-JET PATHWAY



1.2.6 E-METHANE VIA METHANATION

E-methane is a drop-in alternative to natural gas, which can be compressed or liquified and used in natural gas vehicles (NGVs) or liquefied natural gas (LNG) vessels. E-methane can be produced via a catalytic methanation reaction of CO_2 and hydrogen using metal catalysts or biological micro-organisms. The former process has been used since the 1980s using CO_2 and hydrogen from fossil sources, but biological routes are currently at demonstration stage (TRL 7). The main challenge is the relatively low yield of e-methane due to a slow biological reaction.

FIGURE 1-8. E-METHANE PATHWAYS VIA METHANATION

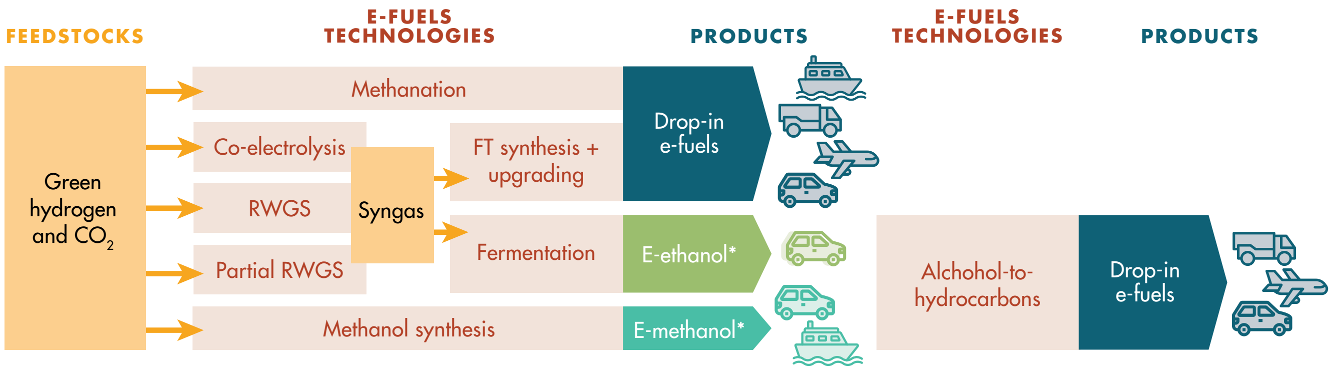


1.3 SUMMARY

How are e-fuels produced?

E-fuels are a type of low carbon fuel produced from combining hydrogen (produced via electrolysis of water using renewable electricity) with captured CO_2 from industrial processes or from the air. There are many e-fuel production technologies being developed today which can produce a range of 'drop-in' and 'non-drop-in' fuels that can be used to replace fossil fuels consumed in ICEs.

FIGURE 1-9. E-FUEL PRODUCTION TECHNOLOGIES AND PRODUCTS



*E-ethanol and e-methanol are not drop-in fuels but can be further converted into drop-ins

How mature are e-fuel technologies and what are the key technical challenges?

E-fuel technologies are currently at early stages of development, generally having TRLs of 6 or lower, with the exception of e-methanol synthesis and methanation. Several of the key processing steps are still only at the pilot stage today, but several developers are planning first commercial facilities in the next few years which could help overcome key technical challenges.

TABLE 2. SUMMARY OF E-FUEL PRODUCTION TECHNOLOGIES

PRODUCTION TECHNOLOGY	TRL	PRODUCTS	KEY TECHNICAL CHALLENGES
FT synthesis- based routes	6	Jet fuel, gasoline (from naphtha upgrading), diesel	• High energy and/or electricity consumption to produce required syngas • Maintaining stable reactions • Low lifetime of reaction catalysts
E-methanol synthesis	7	Methanol	• Few major technical challenges but high energy consumption required for hydrogenation reaction
Ethanol via pRWGS and fermentation	5	Ethanol	• Limited development of pRWGS • Relatively low ethanol yields due to slow rate of biological reaction
Alcohol-to-hydrocarbons	6-7	Jet fuel, diesel, gasoline	• Integration of multiple processing technologies for efficient and stable e-fuels production
E-methane via methanation	7	Methane	• Few major technical challenges but low e-methane yields for biological methanation

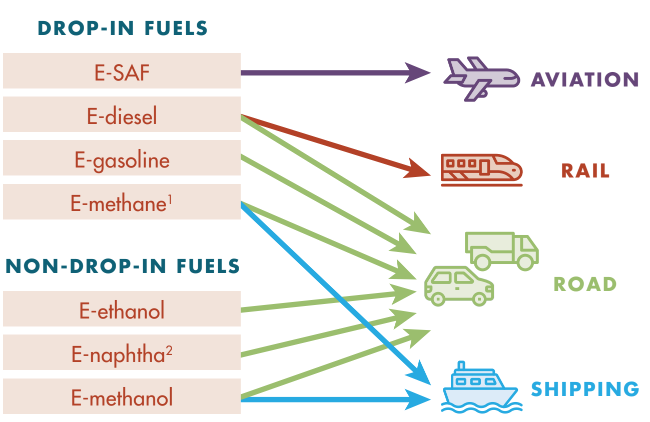
SECTION 2.

How can e-fuels be used in transport? What alternative options are there?

E-fuels can be used to decarbonize a range of transport sectors and vehicles. Drop-in e-fuels are chemically similar to their fossil counterparts and are compatible with today's ICEs, powering vehicles, aircraft and vessels. Non-drop-in e-fuels can be blended up to a limit in some of these vehicles but beyond this, modifications to engines and infrastructure are required. There also alternative technologies and powertrains that could compete with e-fuels to decarbonize the road transport sector, each with different technical characteristics, end-use infrastructure requirements and technological maturities. Some of these options are in commercial use on-road today, such as BEVs.

Outside of the road sector, e-fuels can also be used to decarbonize other transport modes including rail, shipping and aviation. Their reliance on e-fuels as a decarbonization option could impact supply availability to the road sector.

FIGURE 2-1. E-FUELS CAN DECARBONIZE MULTIPLE TRANSPORT SECTORS



[1] E-methane is considered a drop-in fuel as it is chemically similar to natural gas, but its use is limited by the availability of NGVs and fueling infrastructure.

[2] Naphtha is a hydrocarbon molecule, which can be further processed into gasoline for use in ICEVs.

This chapter evaluates the technical suitability of e-fuels, and alternative decarbonization options across vehicle types in the road sector, as well as in aviation, shipping and rail. Broader infrastructure needs are also discussed to identify challenges users may face with technology adoption.

SECTION 2: KEY QUESTIONS

- Which road transport vehicles can use e-fuels?
- How do e-fuels compare to other decarbonization options in road transport?
- How could the uptake of alternative technologies affect e-fuel demand in road transport?
- What other transport modes can use e-fuels?

2.1 WHICH ROAD TRANSPORT VEHICLES CAN USE E-FUELS?

The U.S. road sector can be categorized into three vehicle fleets, light, medium and heavy-duty vehicles, each with different technical and fuel requirements shown in Table 3.[10,11,12]

Drop-in fuels such as e-gasoline, e-diesel and e-methane are suitable for LDVs, MDVs and HDVs. These fuels can be used by themselves or as blends with fossil fuel with no modifications to engines, fuel tanks or fueling infrastructure, provided that their production pathways and the fuels themselves meet ASTM International fuel standards. They can be used directly in U.S. LDV fleets which are primarily gasoline ICE vehicles, and diesel and compressed natural gas (CNG) vehicles that are more commonly seen in medium and heavy-duty vehicle fleets.

Non-drop-in e-fuels can be used directly in gasoline ICEVs up to a certain volume but limited by a blend wall seen below and are suitable for LDVs. At high blends, significant modifications are

TABLE 3. DEFINITIONS AND CHARACTERISTICS OF ROAD TRANSPORT VEHICLE FLEETS

VEHICLE CATEGORY	DEFINITION[10]	VEHICLE TYPES	TECHNICAL AND FUEL REQUIREMENTS
Light-duty vehicle (LDV)	Maximum weight under 10,000 lbs (Class 1-2)	Most passenger cars, vans and pickups, motorbikes.	• Lowest annual mileage,[11] most used for short trips (<30 mi),[12] • Mostly use gasoline blended with ethanol.
Medium-duty vehicle (MDV)	Maximum weight between 10,001-26,000 lbs (Class 3-6)	Heavy pickups and vans, ight commercial trucks, small buses.	• Annual mileage is typically like LDVs[11], though may be significantly higher for buses. • Mostly use diesel, though some passenger pickups use gasoline.
Heavy-duty vehicle (HDV)	Maximum weight above 26,001 lbs (Class 7-8)	Medium and heavy commercial trucks, semi-trucks, large buses, trash collection trucks.	• Highest annual mileage, especially for semi-trucks and transit buses[11]. • Mostly use diesel, though NG-powered buses and trash vehicles are also used.

10 (DOE) (2012), Vehicle Weight Classes & Categories. Available from: [link]

11 DOE (2024), Average Annual Vehicle Miles traveled by Major Vehicle Category. Available from: [link]

12 Federal Highway Administration (2022), National Household Travel Survey. Available from: [link]

required to the design and materials of engines, fuel tanks, pumps, and pipelines to handle the corrosive properties of ethanol and methanol at higher blends.

- E-ethanol can be used in conventional gasoline ICEVs at up to 10% volume (E10), or up to 15% volume (E15) in LDVs of model year 2001 and newer in the U.S.[13] Flexible fuel vehicles (FFVs) are commercially available and can accept higher ethanol blends of up to 85% vol.
- E-methanol is limited in the U.S. to a blend level of 0.3% vol. in gasoline.

Ethanol and methanol are less suitable in the MDV and HDV fleet as their chemical properties differ significantly from diesel. This means they cannot generally be blended in with diesel without modifications to materials and additives in engines and tanks, even at low levels. There has been limited development of testing and standards for ethanol- and methanol-diesel blending to date.

2.2 HOW DO E-FUELS COMPARE TO OTHER DECARBONIZATION OPTIONS IN ROAD TRANSPORT?

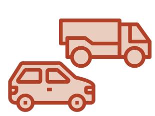
E-fuels are compatible with today's ICEVs and fuel distribution infrastructure. However, alternative decarbonization technologies and powertrain options are already available for the road sector today. E-fuels are likely to be most technically suitable for transport modes where alternative options cannot be utilized effectively. Therefore, this section carries out a comparative assessment of the technical suitability of e-fuels against biofuels that can also be used in existing ICEVs, and alternative powertrains on-road.

2.2.1 BIOFUEL IN ICEVS

Like e-fuels, biofuels can also be used directly in ICEVs across road transport vehicles, both as drop-in and non-drop in fuels, with similar technical considerations. As such, biofuels could compete with e-fuels to reduce the greenhouse gas (GHG) emission of existing road ICEVs fleets, or in other transport sectors where low carbon fuels have been identified as key decarbonization solutions.

The key difference between biofuels and e-fuels are their feedstocks and the fuel conversion technologies, though some processing steps are similar. Biofuels are produced from plant biomass and are generally categorized based on their feedstock type: crop (also known as conventional) biofuels, waste oil or animal fat-based biofuels, and cellulosic biofuels.[14]

TABLE 4. TECHNICAL SUITABILITY OF E-FUELS IN ROAD TRANSPORT

FUELS		SUITABLE VEHICLES	COMMENTS
Drop-in Fuels	E-gasoline E-diesel E-CNG/LNG		Can be used by themselves or as blends with fossil fuel with no modifications to engines, fuel tanks or fueling infrastructure, provided that their production pathways and the fuels themselves meet ASTM International fuel standards.
Non-drop-in fuels	E-alcohol		Non-drop-in fuels are used directly in gasoline ICEVs up to a certain volume but limited by a blend wall. At higher blends, significant modifications are required to vehicle engines and fuel distribution infrastructure. Not suitable for other ICEs.

13 DOE, Alternative Fuels Date Center: E15. Available from: [link]

14 Note that policies categorize biofuels in different ways, this approach is used here for simplicity.

Many biofuel production technologies are more mature than e-fuels – for example, bio-ethanol production from the hydrolysis and fermentation of corn is widely established in the U.S. However, biofuels face different challenges from e-fuels which could impact their uptake as seen in Table 5. Biofuel supply could shift to focus on waste and cellulosic base feedstocks in the future, and it is estimated that the U.S. has the potential to produce enough non-food biomass resources to support up to 50 billion gallons of biofuels annually by 2040 given supply chain and feedstock accessibility challenges can be resolved.[15] In contrast, while e-fuel production may face competing demands for renewable electricity and CO_2, their supply is not technically constrained as that of biomass.

TABLE 5. CHALLENGES AND CONSIDERATIONS IN THE UPSTREAM SUPPLY OF BIOFUELS

CHALLENGE / CONSIDERATION	CROP-BASED BIOFUELS	WASTE OIL BIOFUELS	CELLULOSIC BIOFUELS
Feedstock	• Produced from feedstocks such as corn, wheat, soy, and rapeseed.	• Oily wastes such as animal fats and used cooking oils.	• Lignocellulosic biomass, such as wastes and residues from the processing of crops and other agricultural products.
Production technology maturity	• Commercial (TRL 9) for technologies producing ethanol from e.g. corn and biodiesel/renewable diesel/jet fuel from oilseed crops .	• Commercial (TRL 9) for biodiesel and renewable diesel/jet fuel .	• More challenges associated with treating and processing feedstocks, requiring different technologies. • Some technologies reaching commercialization (e.g. gasification); others still at pilot demo stage.
Land availability	• Physical land is an inherent constraint on primary biomass feedstock supply. • The land requirements to deliver the equivalent amount of energy is estimated at 10x higher for conventional biofuels versus e-fuels.[16]	• Waste materials such as used cooking oil and animal fat with no direct land demand. • However, concerns that increased demand for some waste fats could draw more crop-oils into the market, with indirect land use effects.	• Feedstocks are largely wastes and residues such as forest residues and corn stover requiring no additional land. • However, there is also interest in cellulosic crops such as switchgrass.
Competing feedstock demand	• Competing uses for feedstocks from human/animal feed, chemicals, which could impact feedstock prices. • Displacement of feedstocks from these uses in biofuels can lead to indirect land use change (ILUC), where further expansion of cropland to support market demand leads to an unintended increase in GHG emissions.	• Some competition from other applications, e.g. animal feed, chemicals manufacturing.	• Waste and residue feedstocks face fewer competing demands as many have no alternative economic value.
Supply chains and feedstock accessibility	• Mature domestic supply chains; established methods for growth and transportation of feedstocks such as corn for bio-ethanol production.	• Mature supply chains in some regions, but remaining potential in others where feedstock is not collected today.	• Largely immature supply chains for feedstock collection and transportation. Can be challenges in securing sufficient supply if feedstock sources are dispersed.

15 DOE (2016), 2016 Billion-Ton Report, Available from: [link]

16 Boter (2023), Bio-SAF vs. e-SAF: land-use efficiency of conversion routes for sustainable aviation fuel production in the EU. Available from: [link]

2.2.2 ALTERNATIVE POWERTRAINS

Alongside using low carbon fuels like e-fuels and biofuels in ICEs, alterative powertrains (Table 6) that use other energy sources can also be used to reduce GHG emissions from road transport in the U.S. Their uptake may complement or compete with the use of e-fuels. This section provides an overview of the technical and practical challenges that could impact their uptake rates, which have direct impacts on how crucial e-fuels will be to decarbonizing the road transport sector.

TABLE 6. POWERTRAIN TECHNOLOGIES AVAILABLE

TECHNOLOGY (ABBREVIATION USED)	ENERGY SOURCES	DESCRIPTION
Conventional ICEV and Flexible fuel vehicle (FFV)	Gasoline/diesel Biofuels E-fuels	ICEVs are most vehicles on the road today. These currently run on gasoline, diesel, and blends with some biofuel or e-fuels (the extent of blending dependent on the biofuel/e-fuel used). Most gasoline vehicles currently run on E10. FFVs are a type of ICEV which are modified to run on higher blends of non-drop-in fuels such as ethanol or methanol.
Hybrid electric vehicle (HEV)	Gasoline/diesel Biofuels E-fuels	Hybrid vehicles include an electric motor as well as an ICE propulsion system. HEVs contain a relatively small battery used mainly for energy recovery upon braking, to increase the efficiency of an ICE vehicle. They cannot be plugged in to charge and have limited (or no) electric-only range.
Plug-in hybrid electric vehicle (PHEV)	Gasoline/diesel Biofuels E-fuels Electricity	PHEVs are like HEVs but have a larger battery that can be charged by an electrical supply, with all-electric ranges up to 61 miles on some new models.[17]
Battery electric vehicle (BEV)	Electricity	Powered by electricity, which is supplied from an on-board battery. The vehicle is plugged into an electrical supply to recharge.
Hydrogen fuel cell electric vehicle (FCEV)	Hydrogen	Powered by hydrogen, energy is converted to electricity via a fuel cell to power the electric motor of the vehicle. They are fueled with pure hydrogen gas stored in a tank within the vehicle. [18]
Natural gas vehicle (NGV)	Natural gas (from fossil, bio or synthetic sources)	NGVs operate similarly to conventional vehicles by combustion of the fuel. The majority of NGVs are MDVs or HDVs, and the gas can either be stored as CNG or LNG.[19]

17 EVAdoption (2023), PHEV Models Currently Available in the U.S. Available from: [link]

18 DOE, Alternative Fuels Data Center: Fuel Cell Electric Vehicles. Available from: [link]

19 DOE, Alternative Fuels Data Center: Natural Gas Vehicles. Available from: [link]

Table 7 shows the main pros and cons for each powertrain in an average use case, to give a high-level comparison between these powertrains. Key themes (such as practical considerations, relative emissions reductions and cost of use) are covered in more detail later in the report, which investigate the trends and nuances in these themes in further detail than shown in this table.

TABLE 7. HIGH-LEVEL PROS AND CONS OF POWERTRAIN TECHNOLOGIES

POWERTRAIN	PROS	CONS
Conventional ICEV and flexible fuel vehicle (FFV)	• Established technology. • Refueling infrastructure already exists. • Vehicles can have long ranges between refueling. • FFVs: reduced GHG emissions when using high ethanol blends.	• Higher GHG emissions when using fossil fuels (gasoline, diesel), but can be reduced by using low carbon fuels. • Contribute to local air and noise pollution. • FFVs: slightly reduced vehicle range when using high ethanol blends, limited number of models available and limited availability of E85 fuel.
Hybrid electric vehicle (HEV)	• Better fuel economy than conventional ICEV, reduced fuel costs and emissions. Fuel economy is improved most for stop-start, urban driving. • No operational changes needed compared to conventional ICEVs. • Could achieve approximately 29% lifecycle GHG emissions reductions alone.[20] Biofuels/e-fuels required to further reduce GHG emissions.	• Some cost premiums compared to conventional ICEVs, and fewer brands/models available. • Minimal fuel economy benefits for constant speed operation (i.e. highway driving).
Plug-in hybrid electric vehicle (PHEV)	• Potential for significant emissions reductions without the range anxiety of BEVs. • Electric-only modes can maximize cost savings and reduce local air pollution.	• Higher purchase cost than conventional ICE or HEV. • Minimal emissions and cost savings if rarely plugged in. • Higher production emissions associated with batteries (but quickly outweighed by reduced operational emissions). • Some concerns about mining practices for cobalt and nickel, but the road transport industry could transition to different battery types which avoid the use of these metals.
Battery electric vehicle (BEV)	• Lower "fuel" costs than conventional ICEVs. • Significantly reduced air and noise pollution. • Zero tailpipe emissions. • Highest availability of models for alternative powertrains.	• Limited driving range, requires en-route charging for long-distance travel. • Longer recharging times compared to ICEV refueling. • Currently higher upfront costs than conventional ICEV. • Higher production emissions associated with batteries (but quickly outweighed by reduced operational emissions). • Some concerns about mining practices for cobalt and nickel, but the road transport industry could transition to different battery types which avoid the use of these metals.
Hydrogen fuel cell electric vehicle (FCEV)	• Significantly reduced air and noise pollution. • Vehicle range between refueling could be like ICEVs. • Zero tailpipe emissions. • Refueling time potentially similar to ICEV refueling time	• Limited current availability of models. • Higher upfront cost and fuel costs. • No public refueling stations on the U.S. mainland outside of CA.
Natural gas vehicle (NGV)	• Lower fuel costs than conventional ICEV. • Historically strong market share compared to other alternative powertrains. • Emissions can be very low (or even negative) depending on the source of the biomethane used. • Reduced air pollution. • Fuel can be transmitted through the gas network where available.	• Tailpipe GHG emissions are only reduced up to 20%[21] when using fossil natural gas, meaning biomethane or e-methane is required for significant emissions reduction. • Separate refueling network required compared to gasoline. • Almost exclusively used currently in commercial vehicles.

20 Transportation Energy Institute (2022), Life Cycle Analysis Comparison: Electric and Internal Combustion Engine Vehicles. Available from: [Link]

21 Environmental Protection Agency (EPA) (2023), Learn About Green Vehicles - Compressed Natural Gas. Available from: [link]

TECHNICAL CHARACTERISTICS

Alternative vehicle options covered in this section have reached technical maturity but have different efficiency and range characteristics, driven by the fundamental difference in power sources and powertrain technology, as can be seen in Table 8.

- **From an energy efficiency point of view, alternative powertrains could outperform ICEVs, with BEVs being the most efficient.** This means more overall energy is required to run vehicles powered by e-fuels, than directly from electricity in BEVs. This will reduce overall energy demand and emissions through energy efficiency.
- **However, ICEVs have the highest range between refueling.** Reduced ranges are seen for BEVs, FCEVs and NGVs, which could impact their uptake in the MDV and HDV segments, though these may increase into the future as technologies improve. A high range between refueling may not needed for all consumers, particularly in LDVs, but range anxiety is a common concern consumers may have towards switching to BEVs.

TABLE 8. SUMMARY OF TECHNICAL CHARACTERISTICS OF POWERTRAINS IN ROAD TRANSPORT
(SEE MORE DETAILS IN APPENDIX A)

POWERTRAIN	CURRENT TYPICAL POWERTRAIN EFFICIENCY[1,2]	CURRENT MAXIMUM RANGE FOR CARS[3] (miles)	CURRENT MAXIMUM RANGE FOR M/HDV[3] (miles)
ICEV - Gasoline	~ 25%	~ 500	~ 1000
ICEV - Diesel	~ 35%		
FFV	~ 30%	~ 300	~ 500
HEV	~ 35%	~ 500	n/a
PHEV - Gasoline & Electric	~ 35%	~ 500	n/a
PHEV - Electric only	~ 80%	~ 50	n/a
BEV	~ 80%	~ 350	~ 400
FCEV	~ 55%	~ 400	~ 500
NGV	~ 35%	n/a	~ 700

[1] **Powertrain efficiency:** This measures the proportion of energy from the fuel that is converted into vehicle motion. For example, if 10 MJ of fuel is required to provide 1 MJ of energy for the vehicle's motion, the powertrain will have an efficiency of 1/10 = 10%. A higher efficiency means less fuel is required, meaning better fuel economy.

[2] **Powertrain efficiency:** Represents the average of the best-case efficiency across a drive cycle. Actual efficiency (and range) in use can be lower depending on driving style and external factors (e.g. weather, road quality, gradient, etc.).

[3] **Maximum range of current models (LDV and MDV/HDV):** This is the current maximum range quoted between refueling or recharging stops. These ranges will vary between both vehicles and driving styles. These ranges provide a high-level comparison between the current technological capabilities, rather than stating that this range is achievable for all vehicles and driving styles.

(See more details in Appendix A)

PRACTICAL CONSIDERATIONS

Practical factors, such as operational capabilities, are also important considerations for consumers or businesses who will be deciding between purchasing vehicles with these different powertrains. As shown in Table 9 the infrastructure supporting alternative drivetrains is less mature compared to existing diesel and gasoline distribution supply chain, though this could change for some in the near future as detailed in this section.

For ICEVs, FFVs, HEVs and PHEVs, the main infrastructure required is gas stations, which have been widely available in the U.S. for decades. PHEVs can also use slow electric chargers (usually up to 7 kW) to charge the on-board battery. This can be done whilst the vehicle is at home or at its destination but is not required to use the vehicle. The supply of PHEVs may be limited in the near term as production capacity and supply chains for battery materials are developed. There is an increased interest in FFVs, PHEVs and HEVs in recent years, though it is currently unclear how large of a role they will play in the future. In addition, these powertrains can run on e-fuels, so even mass adoption is unlikely to significantly affect the demand for e-fuels.

For BEVs, the main practical considerations are vehicle range, access to charging, charging speeds and vehicle supply. For most consumers which have access to a designated overnight parking area (e.g. driveway, designated parking spot, depots), BEVs can be charged overnight either from domestic sockets or with an installed EV charger. This is likely to be sufficient for most users if they don't drive more than the vehicle's range in a single day (over 250-350 miles), as they can recharge each night. For consumers without access to overnight charging and for journeys which are beyond the range of the BEV, public charging will be required. In 2023, there are 40,000 publicly available rapid EV chargers (>50 kW) in the US, with a further 120,000 public slow chargers (up to 7 kW). For HDVs, the operational impact of lower ranges could be more severe than for LDVs and MDVs, given their higher energy requirement, higher mileages and fewer available public rapid charging points. Whilst the number of BEVs in the U.S. is currently relatively small, this is expected to grow over time and affect the long-term potential demand for e-fuels in road transport.

FCEVs have the potential to be used in a similar way to ICEVs, with comparable range and refueling speeds. However, whilst there are 145,000 gas stations across the U.S., there are only 54 publicly available HRSs, 53 of which are in California (this number has recently declined due to recent closures of several Shell HRSs in California).[22] Outside of California, large logistics hubs might be able to create enough hydrogen demand to have hydrogen delivered directly to the depot. This would be most suitable for repetitive routes as there currently would be no alternative locations to refuel outside of the depot. This option would not be accessible to smaller hubs or private consumers, who would need to wait for the development of a public refueling network. FCEV uptake is currently very low and is not expected to significantly impact the potential demand of e-fuels before 2040 at earliest.

22 Hydrogen Insights (2024), Shell to permanently close all of its hydrogen refueling stations for cars in California. Available from: [link]

NGVs can be used in a similar manner to ICEVs, with comparable range and refueling speeds. Whilst there are only 1,400 NG refueling stations in the U.S. (down from nearly 1,600 in 2019), large depots can also compress NG from the gas network to refuel the depot fleet. However, this is not an option for smaller depots or private users, who will need to rely on the public refueling network. This is highlighted by the significant uptake of NGVs for buses and trash trucks in the U.S., which have predictable operations and operate from a depot, and negligible uptake for private cars. As the number of refueling stations is decreasing rather than increasing, it is unlikely that the deployment of NGVs will increase sufficiently to impact potential demand for e-fuels before 2040 at earliest.

TABLE 9. COMPARISON OF PRACTICAL CONSIDERATIONS FOR POWERTRAINS

POWER-TRAIN	REQUIRED INFRA-STRUCTURE	CURRENT INFRASTRUCTURE	REFUELING/ RECHARGING TIME	VEHICLE/FUEL SUPPLY	FIT WITH USER NEEDS
Conventional ICEV & HEV	Gas/diesel refueling stations	Over 145,000 gas stations.[23]	< 5 minutes	Widely available.	
FFV	Stations with E15 or E85 pumps	Over 4,200 E85 stations. [24]			
PHEV	Slow charge points (up to 7 kW). Gas/diesel refueling stations	Over 145,000 gas stations. Recharging can be done at homes with a garage or driveway.	< 5 minutes (gasoline) 2-10 hours for battery charging	Vehicle supply could be limited by production capacity battery supply.	Can be used as an ICEV, plug in at home to reduce emissions.
BEV	Slow charge points (up to 7 kW) for general use Rapid charge points (50-150 kW) for en-route charging. Higher power for MDVs and HDVs	Slow charging can be done at homes with a garage/ driveway, or depot for commercial vehicles. 120,000 slow public chargers and 40,000 rapid chargers in the U.S., quarter of which are in CA.[25]	5-10 hours (slow charging) 30-60 minutes from 10% to 80% charge (fast charging)	Electricity is widely available. Vehicle supply to the U.S. is currently limited, but is growing rapidly in both the U.S. and globally.	For many uses, can fit user requirements with no changes. For long-haul uses, extra stops to recharge will be required.
FCEV	Hydrogen refueling stations	53 of 54 public HRS are in CA.25	Up to 15 minutes	Hydrogen supply is currently limited. Vehicle supply limited by production capacity.	Usage could be like ICEV, but required infrastructure is lacking beyond CA.
NGV	Natural gas refueling stations	1,400 NG refueling stations in the U.S.,25 vehicles can also be refueled at depots with delivered gas or through the gas network.	Rapid refueling possible under 15 minutes	NG is widely available. Significant vehicle supply is limited to certain vehicles (e.g. buses, trash trucks).	Similar performance to ICEV.

23 American Petroleum Institute (2024), Service Station FAQs. Available from: [link]

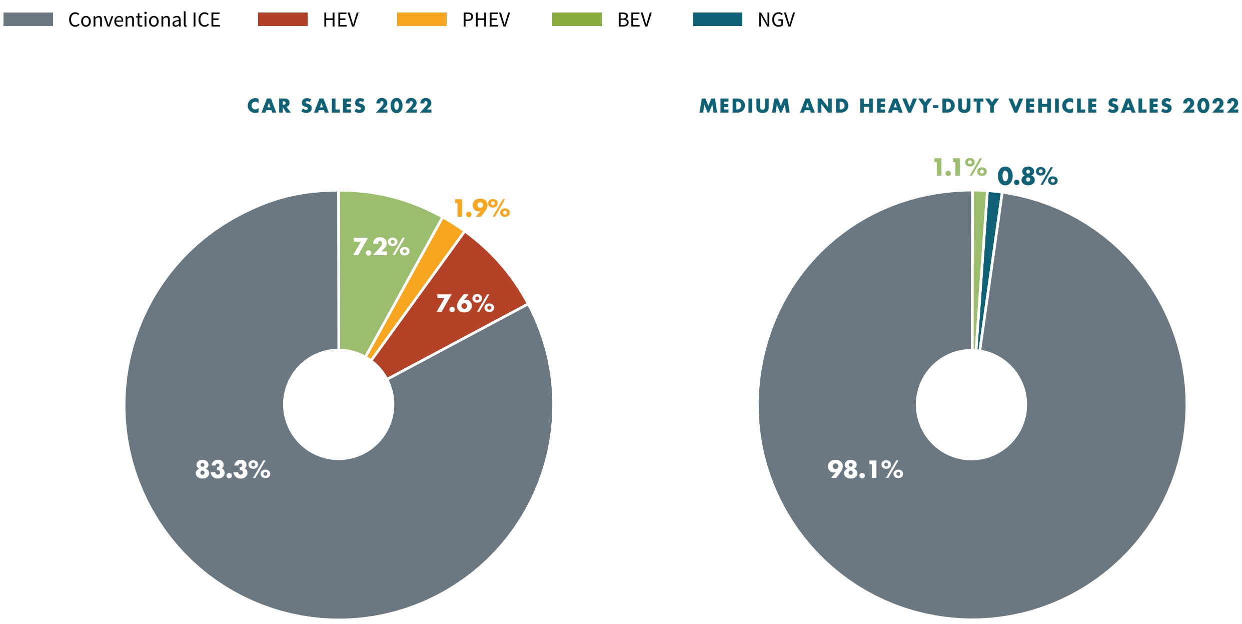
24 DOE, Alternative Fuels Data Center: E85 (Flex Fuel). Available from: [link]

25 DOE, Alternative Fuels Data Center: Alternative Fueling Station Counts by State. Available from: [link]

2.3 HOW COULD THE UPTAKE OF ALTERNATIVE TECHNOLOGIES AFFECT E-FUEL DEMAND IN THE ROAD TRANSPORT SECTOR?

New sales of vehicles in the U.S. are currently dominated by conventional ICEVs for both cars and MDV/HDVs, as shown in Figure 2-2. The proportion of sales of non-ICE vehicles is expected to increase in coming decades, but given the current average vehicle is 12.2 years old,[26] it is likely there will still be many ICE vehicles still on the road into the 2030s and 2040s. Some powertrains had negligible sales in certain road transport segments in 2022, for example NGV for passenger cars, HEV and PHEV for medium and heavy-duty vehicle. Whilst these technologies are technically suitable, there has been minimal sustained interest from manufacturers to develop and sell these vehicles.

FIGURE 2-2. U.S. CAR[27] AND HDV[28] SALES IN 2022 BY POWERTRAIN



Note: powertrains that are not shown had <0.1% sales in 2022.

Although ambitions have been set in the U.S. to achieve 50% EV sales by 2030,[29] the ability to achieve this non-legally binding goal is highly uncertain given the technical and infrastructure challenges which could impact uptake rate across all road transport segments. This uncertainty is reflected by the large range of vehicle stock forecasts in the U.S. Across all scenarios, light-duty ICEVs are expected to continue to play a role in road transport in 2040 (Figure 2-3). This means that there could be a role for e-fuels as a decarbonization solution in road transport, given their flexibility to be used in ICEVs as other options ramp up, as well as in other modes.

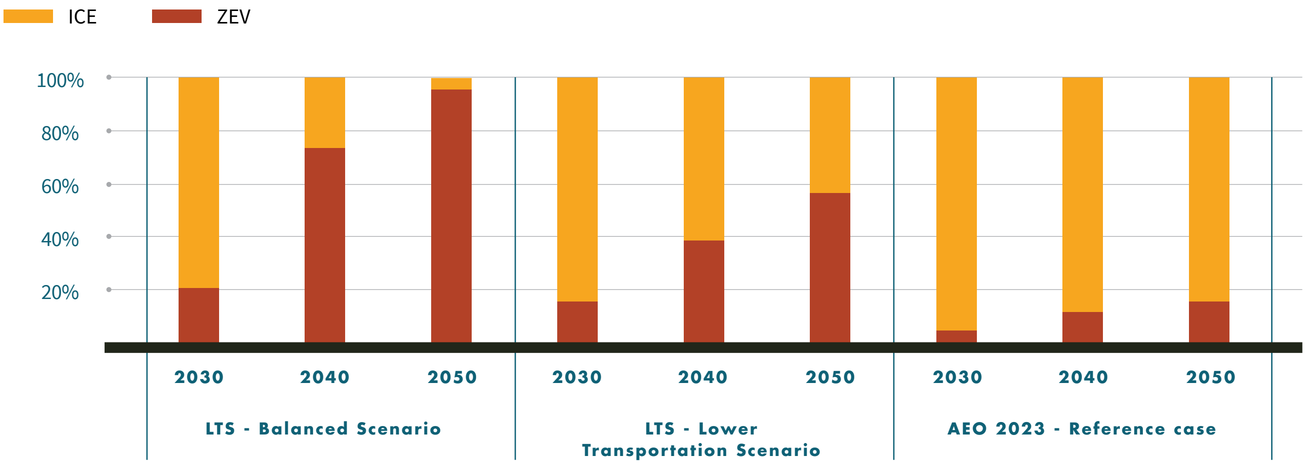
26 S&P Global Mobility (2022), Average Age of Vehicles in the U.S. increases to 12.2 years, according to S&P Global Mobility. Available from: [link]

27 National Automobile Dealers Association (2023), NADA Market Beat: 2023 New Light-Vehicle Sales Reach 15.46 Million Units. Available from: [link]

28 S&P Global Mobility (2023), Fuel for Thought: The commercial vehicle fleet accelerates toward ZEV (zero emission vehicles) adoption. Available from: [link]

29 The White House (2023), FACT SHEET: Biden-Harris Administration Announces New Private and Public Sector Investments for Affordable Electric Vehicles, Available from: [link]

FIGURE 2-3. U.S. LDV STOCK FORECAST IN THE LONG-TERM STRATEGY (LTS)[30,31] AND BY THE ANNUAL ENERGY OUTLOOK (AEO).[32]



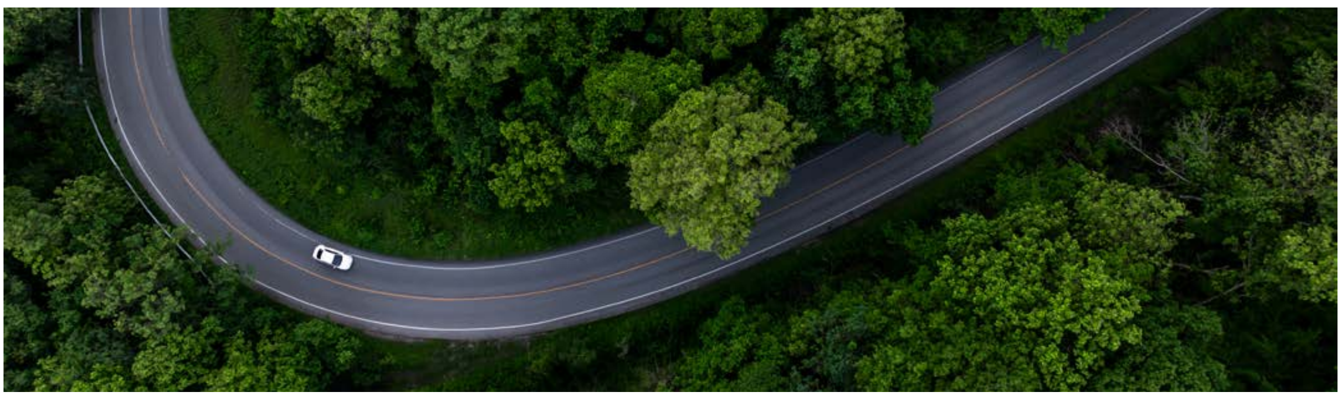


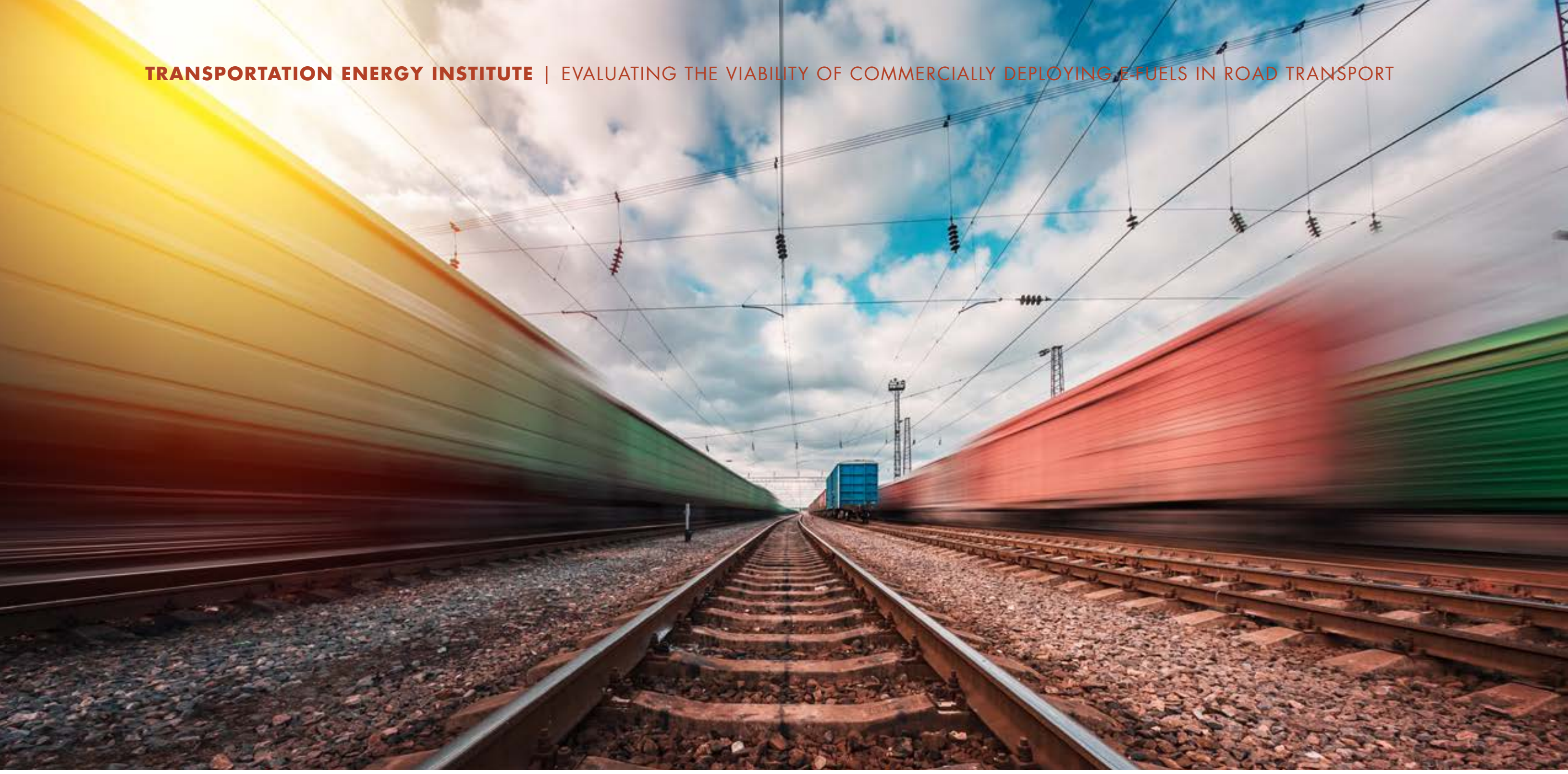
TABLE 10. SCENARIO DESCRIPTIONS AND ASSUMPTIONS FOR LDV STOCK FORECAST

FORECAST	FORECAST DESCRIPTION	EV SALE ASSUMPTIONS FOR LDV
U.S. Long-Term Strategy (LTS)	Published by the U.S. Department of State and the U.S Executive Office of the President, Washington DC. November 2021. Projection driven by alignment with delivering U.S. 2030 Nationally Determined Contribution (50% reduction in 2030), and net zero in 2050.	Varies based on scenarios below
LTS - Balanced advanced scenario	Represents a scenario with few technological and political barriers to GHG mitigation.	2030: >50% 2050: 100%
LTS - Lower transportation scenario	Represents a scenario in which decarbonization challenges emerge in the transport sector.	2030: >30% 2050: 70%
Annual Energy Outlook (AEO) 2023	Projection using a market-based approach, while subject to regulation and standards. It accounts for economic competition across the various energy fuels and sources.	2030: 7% 2050: 18%

30 U.S. Department of State and the U.S. Executive Office of the President (2021), The Long-Term Strategy of the U.S., Available from: [link]

31 R. Horowitz, et al. (2022), The energy system transformation needed to achieve the U.S. long-term strategy, Available from: [link]

32 EIA (2023), AEO 2023, Available from: [link]



2.4 WHAT OTHER TRANSPORT MODES CAN USE E-FUELS?

The rail, shipping and aviation industry also face the need to decarbonize, and all could also use low carbon fuels. The role that e-fuels will play in each of these will depend on the specific technical requirements of the transport modes, the maturity of alternative decarbonization technologies, and the availability of other low carbon fuel options such as biofuels. Given that the production capacity of e-fuel could be limited in the near future, e-fuel supply for the road sector could also be impacted by demand for e-fuels in these other transportation sectors. This is discussed in more details in Section 4.

2.4.1 RAIL SECTOR

Most passenger and freight trains are powered by diesel in the U.S., with direct electrification installed on less than 1% of all rail tracks, compared to 30-40% globally [33].

- **Low carbon fuel options –** Low carbon diesel is an alternative that could be used in rail transportation. As with MDVs and HDVs, other low carbon fuels are less suited to replace diesel as engine modifications are required to accommodate blends including ethanol or methanol.
- **Alternative powertrains options –** The most common alternative to diesel trains is direct line electrification, where the train is directly powered by overhead wires or an electrified third rail. Development of alternative powertrains that use hydrogen is underway, though they will face range challenges for long-distance routes as they require large and heavy energy storage.

RAIL SECTOR
ROLE OF E-FUELS

Without significant investments into line electrification, the use of liquid fuels for rail transportation is likely to continue in the U.S., which may be a potential market for e-diesel.

33 Environmental and Energy Study Institute (2018), Electrification of U.S. Railways: Pie in the Sky, or Realistic Goal? Available from: [link]

2.4.2 AVIATION SECTOR

Today's aircraft fleet relies on liquid fossil jet fuel, which has a high energy density and allows for fast refueling.

- **Low carbon fuel options –** Sustainable aviation fuels (SAF), can be blended with fossil jet as drop-in liquid jet fuels due to having similar chemical properties and energy density to fossil jet. SAF can be produced from biomass, or from renewable electricity, e-SAF using production pathways very similar to the ones for producing road e-fuels (e.g. FT synthesis), some with additional processing steps (i.e. alcohol-to-jet via ethanol or methanol).
  - Today, there are two e-SAF routes (FT synthesis and alcohol-to-jet via ethanol) are currently qualified by ASTM International for use in existing aircraft engines and fueling infrastructure up to a blend limit of 50% by volume.
- **Alternative powertrain options –** For aviation, alternative powertrains using hydrogen and electricity are technically challenging. This is because aircraft are both highly size and weight sensitive, so the use of heavier or larger energy storage systems is likely to be limited to smaller, short-range aircraft.

AVIATION SECTOR
ROLE OF E-FUELS

There is likely to be significant use of low carbon fuels over the next 30 years in aviation because alternative technologies for aviation such as hydrogen and electricity have much lower energy density, which could limit their use in aviation to short-haul flights only. In addition, a long aircraft lifetime and fleet turnover time will mean the aviation sector continues to rely on liquid fuels compatible with existing engines and infrastructure, therefore making e-fuels and other low carbon fuels critical for decarbonization. As a result, many planned commercial e-fuels are configured to maximize e-SAF production (see Section 4), with a smaller portion of road fuels produced as co-products. This could impact e-fuel's supply to the road sector before e-fuel production capacities become more widely available. This dynamic is assessed further within the context of policy in Section 6.

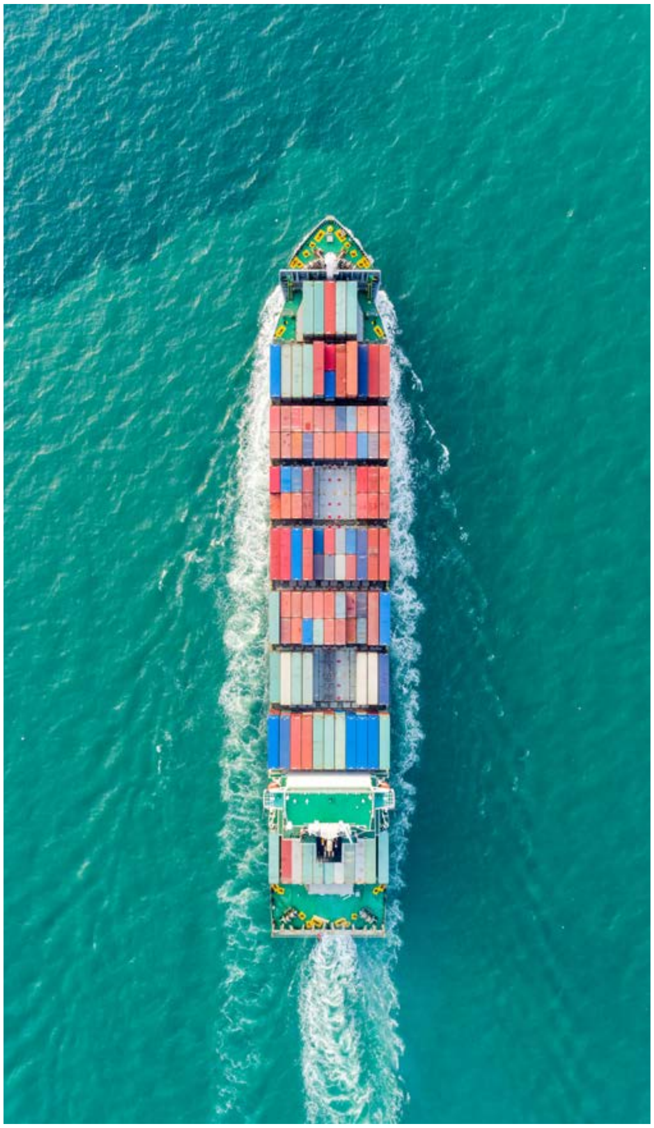
2.4.3 SHIPPING SECTOR

Like aircraft, vessels also require fuels with high energy density, with most using heavy fuel oil (HFO).

- **Low carbon fuel –** The main alternative fuel options for shipping being explored:
  - Liquefied methane or LNG, which is a drop-in fuel that can be used in existing LNG vessels and bunkering infrastructure with no major modifications or impacts on range.
  - Methanol, which is a liquid fuel that can be used in pure methanol vessels or dual fuel vessels compatible with methanol.
  - Green hydrogen and ammonia, which are also produced from renewable electricity and would be used as liquid fuels in new vessel types. These have not been considered in this study because they are not produced from captured CO¬2 as other e-fuels.
  - All of these fuels require different engines, vessels, bunkering infrastructure, and safety standards to existing HFO vessels, which are currently limited, particularly for methanol. However, LNG and methanol vessels represent over 70% of the global vessel order book as of 2023 and there is growing interest from ports and regulatory bodies in developing infrastructure and standards 34.
- **Alternative powertrain options –** For shipping, the technical potential of alternative powertrains depends on the range required. For short trips (e.g. local ferries, river vessels), hydrogen or battery electric could be options. However, range could be limited for electric boats and cost for hydrogen fuel cell ships could be less competitive compared to other liquid fuel options such as ammonia due to high storage costs, thus limiting their ability as decarbonization options for deep-sea shipping.

SHIPPING SECTOR
ROLE OF E-FUELS

Though hydrogen and electric boats are viable decarbonization options for short trips, liquid fuels are likely to be used in deep-sea shipping for many more decades due to their high energy density, which could represent a key market for e-fuels. Despite infrastructure challenges, there could still be strong growth in demand for liquid fuels and e-fuels in the shipping sector. In addition to biofuels, this demand could also be met with liquid hydrogen and ammonia produced via renewable electricity, which are not used in road ICEVs fleets.



34 DNV (2023), Alternative Fuels Insight. Available from: [link]

2.5 SUMMARY

Which road transport vehicles can use e-fuels?

E-fuels are highly compatible with existing ICEVs and hybrid vehicles across all vehicle categories (i.e. LDVs, MDVs, and HDVs). Drop-in fuels such as e-gasoline, e-diesel and e-methane can be used directly at high blends in existing engines and fuel distribution infrastructure with no modifications. Non-drop-in fuels can be similarly used, but only up to a low blend wall. Higher blends of e-ethanol and e-methanol can be used in FFVs, but these require different distribution and fueling infrastructure, which could limit their uptake.

How do e-fuels compare to alternative technologies and powertrains in the road transport sector?

In road transport, there are a variety of technically suitable powertrains which are already commercially available. Other powertrain types are being developed in all transport sectors, though the level of suitability between road transport segments depends on the energy storage requirements on the vehicle as well as other technical requirements of the vehicle and supporting infrastructure.

Like e-fuels, biofuel technologies can produce drop-in and non-drop-in fuels for transport. There are no differences in the vehicle and infrastructure modifications required for a given fuel type produced from biomass or e-fuel feedstocks. However, biofuels face upstream supply challenges due to feedstock availability, potential sustainability concerns for some feedstocks, and in some cases immature supply chains. It is estimated that non-food biofuel production could reach 50 billion gallons by 2040.

Electrification of LDVs via BEVs is a popular decarbonization solution as they not only meet the driving needs of an average user from a range perspective, but are also significantly more efficient than ICEVs, which could reduce overall energy demand. However, the charging infrastructure required to support electrification is less developed compared to e-fuels, which can use existing liquid fuel distribution supply chains. This limits current uptake, though is rapidly improving.

There are no differences in the vehicle and infrastructure modifications required for a given fuel type produced from biomass or e-fuel feedstocks.

Comparatively, fewer alternative powertrain options are available for MDVs and HDVs due to requirements for range and charging efficiency. BEVs are currently available for short-range use, whilst long-range options are currently limited but could be available within five years. Similarly, FCEV options are also limited at present with more development expected in the near future. NGVs are already in use in commercial vehicles but face infrastructure challenges as the number of CNG refueling stations for NGVs has declined over the past decade. Growth of infrastructure has also been slow for hydrogen refueling in recent years.

BEVs could be widely adopted in road transport in the future, along with some niche uses of FCEVs, which could reduce long-term demand for e-fuels. Uptake of hybrid vehicles will likely be constrained to LDVs and NGVs to MDV and HDVs but will complement e-fuel demands. There is potential for HEVs and NGVs in the short term, however, it is expected that they have limited potential in the long-term as zero-emission technology capabilities improve and reduce in price.

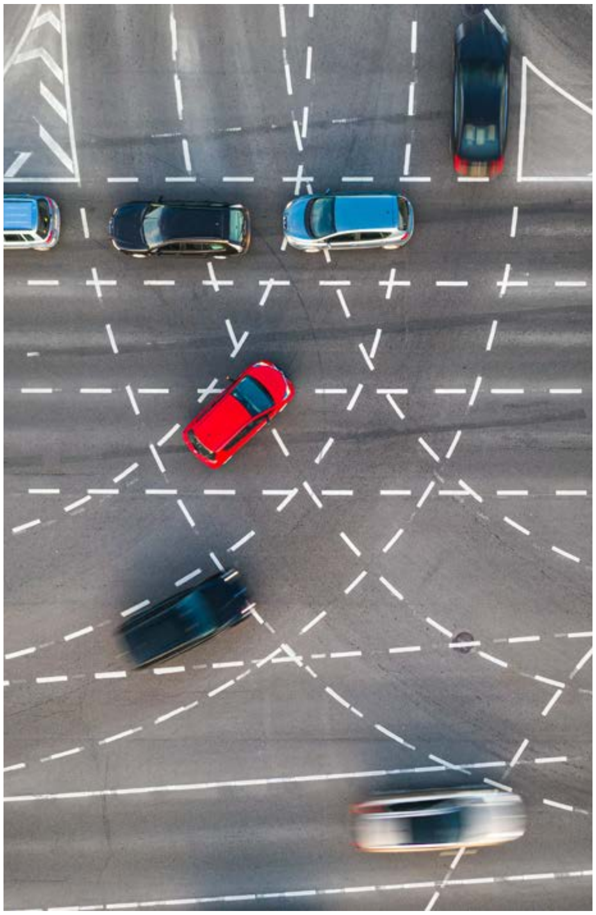


TABLE 11. AVAILABILITY OF ALTERNATIVE POWERTRAINS ACROSS ROAD TRANSPORT SEGMENTS

POWERTRAINS	CAN USE E-FUELS?	LDVS	MDV/HDVS	
Conventional ICEV	✓	Dominant powertrain technology today.	Dominant powertrain technology today.	
Flexible fuel vehicle(FFV)	✓	Commercially available.	Minimal interest from manufacturers.	
Hybrid electric vehicle(HEV)	✓	Widely commercially available.	**Buses:** Commercially available, but limited market share.	**Other MDV/HDVs:** Minimal interest from manufacturers.
Plug-in hybrid electric vehicle(PHEV)	✓	Widely commercially available.	Minimal interest from manufacturers.	
Battery electric (BEV)	✗	Widely commercially available.	**MDV:** Commercially available, with the number of models expected to increase.	**HDV:** Available for shorter range use. Long range options currently limited but could be available within 5 years
Hydrogen fuel cell electric (FCEV)	✗	Some commercial options, but less developed than alternatives.	Commercial options possible within 5 years, especially for high-intensity, long-range use.	
Natural gas vehicle(NGV)	✓	Minimal commercial availability or development.	Widely used in some sectors.	

How could the uptake of alternative technologies affect e-fuel demand in the road transport sector?

Conventional ICEVs dominate current sales in both LDV, MDV and HDV sectors. Many of these vehicles are likely to still be on the roads at least into the 2030s and early 2040s.

The decarbonization pathway for road transport in the U.S. is highly uncertain, but most vehicle stock projections expect that ICEVs will continue to be available in 2040, making low carbon fuels including e-fuels, potentially important decarbonization options.

What other transport modes can use e-fuels?

Outside of road transport, low carbon fuels are identified as the main decarbonization solution in rail, shipping and aviation in the U.S. due to infrastructure and/or technology limitations shown in Table 12. This could drive policymakers to prioritize low carbon fuel supply for these hard-to-abate sectors as seen in later chapters on policy (Section 6), thus reducing availability for road.

TABLE 12. TECHNICAL SUITABILITY OF POWERTRAINS IN OTHER TRANSPORT SECTORS

POWERTRAIN AND FUELS	CAN USE E-FUELS?	RAIL	SHIPPING	AVIATION
Low carbon fuels	✓			
Electricity	✗	Line electrification is most common alternative power source. Batteries could bridge sections which aren't electrified.	Examples of use for short trips in Europe (up to 25 nautical miles). Very unlikely to be used for deep-sea shipping.	Battery electric aircraft limited in size and range.
Hydrogen	✗	Hydrogen could bridge sections which aren't electrified or operate on non-electrified routes.	Possible for short trips, though significant storage space needed for deep-sea shipping.	Possible, but range limited by the volume and weight of hydrogen storage needed.
CNG or LNG	✓	Technically possible, but no significant current use or development.	LNG regularly used in shipping, requires non-fossil LNG to significantly reduce GHG emissions.	Possible, but range limited by the volume and weight of natural gas storage needed.

SECTION 3.

What are the GHG benefits of e-fuels and how do they compare to other options?

The environmental performance of low carbon fuels is a critical factor considered in policies focused on transport decarbonization. A fuel's lifecycle greenhouse gas (GHG) emission is a key element of this, representing the total GHG emissions generated along the whole fuel supply chain expressed on a CO_2 or CO_2e (CO_2 equivalent) basis. In some markets, this figure, often called the carbon intensity (CI), drives a fuel's eligibility for policy support and market value. E-fuels, when used in LDVs, has the potential to achieve up to 75% GHG emissions reduction and 92% reduction when used in HDVs as CNG or compressed e-methane in the near-future. This could be further increased to reach 99% in the future.

In addition to the GHG emissions, this section also assesses other environmental impacts of e-fuel production and use. The lifecycle GHG emissions are then compared with other low carbon transportation options to understand which have the highest decarbonization potential.

SECTION 3: KEY QUESTIONS

- How do e-fuels lead to GHG savings?
- What are the well-to-wheel GHG savings of e-fuels now and in the future?
- How does the well-to wheel GHG savings of e-fuels compare to alternative technologies and drivetrains?
- What are the other environmental impacts of e-fuels production and use?

GHG emissions shown in this analysis reference the Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) model developed by Argonne National Laboratory as far as possible. At the time of the report, given there is no agreed and published methodology for calculating the GHG emissions of e-fuels in the U.S., and GREET has not been updated to include all the e-fuel pathways considered in this report, an internal ERM GHG model was used to calculate the well-to-wheel emissions for all the production pathways considered in this report, using an energy allocation approach across all fuel products. This model aligns closely with e-fuel GHG calculation methodologies established under relevant policies in Europe like the Renewable Energy Directive (RED) and the Renewable Transport Fuel Obligation (RTFO), which include emissions arising from feedstock, fuel processing, fuel transport and distribution, and fuel combustion. They do not account for emissions that arise from the construction of infrastructures (e.g. solar panels, wind farms) as this emission is expected to be negligible when amortized across a project's lifetime.

3.1 HOW DO E-FUELS LEAD TO GHG SAVINGS?

The lifecycle GHG emissions of a fuel, or its well-to-wheel emissions, represent emissions that occur during the entire value chain of fuel production, distribution and use. (Figure 3-1)

The combustion of e-fuels does not generate net positive emissions

Unlike fossil fuels, the combustion emissions of e-fuels are considered to be zero. This is because:

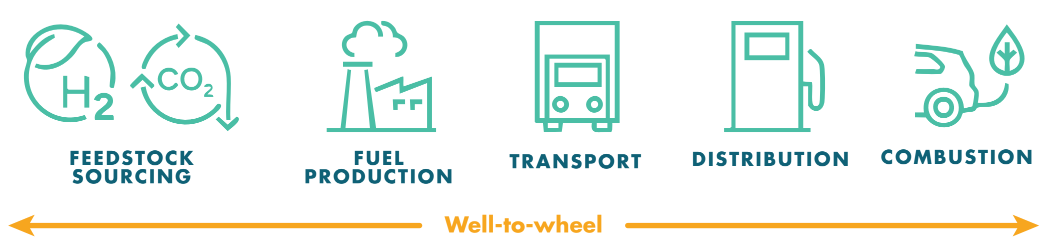
- When using **CO_2 captured from existing industrial sources**, it is assumed that this would have been released to the atmosphere anyway. Using this CO_2 in e-fuel production effectively recycles this CO_2, which is ultimately released at the tailpipe.
- With **DAC**, the CO_2 is taken directly from the atmosphere, which is released again at the tailpipe. This does not create any additional CO_2 emissions.

Note that from a carbon accounting perspective, this assumes that the point source CO_2 emitters have not claimed any emissions reductions as a result of the CO_2 capture as part of any policy compliance programs, such as with emissions trading schemes. However, there are currently no rules in place in the U.S. specifying this requirement. In Europe, carbon accounting rules under the EU Emissions Trading Scheme state that the point source emitter must continue to count, and pay for these emissions, as they will ultimately be released to the atmosphere.

E-fuel value chains do not have zero emissions

Nevertheless, the well-to-wheel GHG emissions of e-fuels are not zero because emissions can arise from the fuel production process, stemming from the following value chain steps. (Table 13)

FIGURE 3-1. LIFECYCLE/WELL-TO-WHEEL GHG EMISSIONS OF E-FUELS



E-fuels produced using renewable electricity could achieve significant GHG savings as their energy content will come from nearly zero emission sources such as wind or solar.

TABLE 13: SOURCES OF EMISSIONS FROM THE LIFECYCLE OF E-FUELS

PRODUCTION VALUE CHAIN	SOURCES OF EMISSIONS
Electricity for e-fuel production	The GHG impact is only negligible if e-fuel is produced from renewable electricity meeting incrementality, deliverability and temporal correlation (see below). Grid electricity could be used to supplement for hours where renewable electricity is not available. However, this would impact the GHG emissions of the final fuel.
CO_2 capture	Energy is expended to capture, condition and transport CO2 feedstocks, which can come from fossil or renewable sources.
Energy (heat & electricity) sources for fuel processing	E-fuel synthesis processes often take place under high temperature and pressure conditions. The energy requirements for this could be met by fossil or renewable sources.
Fuel transportation and distribution	The transport of e-fuels to their final users can be carried out via pipelines or trucks, which could generate GHG emissions if using fossil fuels.

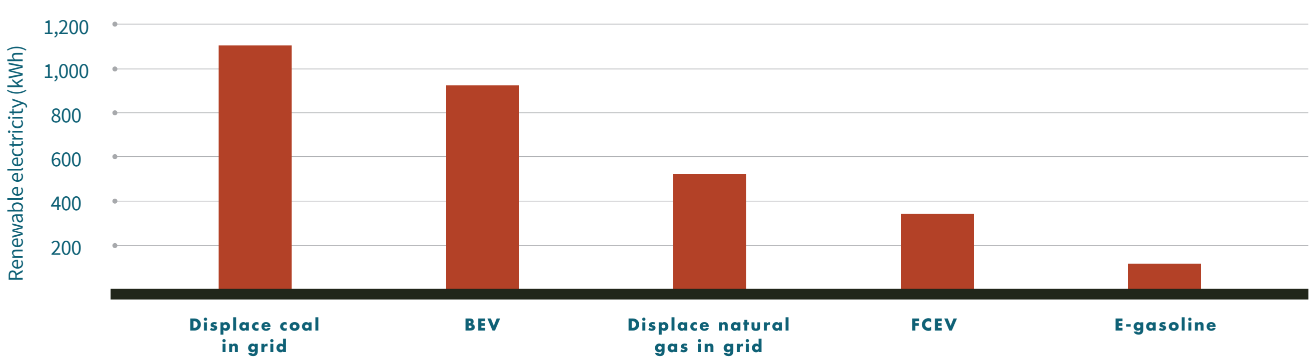
E-fuels achieve the highest GHG savings when produced using additional renewable electricity

E-fuels produced using renewable electricity could achieve significant GHG savings as their energy content will come from nearly zero emission sources such as wind or solar. However, concerns over the significant renewable electricity generation capacity required to enable production of e-fuels has raised concerns over the role of e-fuels in decarbonizing the transport industry.

Concern 1: E-fuel's demand for renewable electricity could **divert it from existing uses**. This is a problem because increasing electricity demand overall could lead to a net increase in GHG emissions across the economy, if fossil fuel is used to meet this additional demand.

Concern 2: E-fuels are a **less efficient way to decarbonize the transport sector** as renewable electricity can be used directly in BEVs with fewer energy losses in the supply chain. This is shown in Figure 3-2, which compares potential uses of renewable electricity and the emissions reduced per kWh, calculated on a lifecycle basis for displaced fuels, not including embodied emissions in infrastructure. A higher value signifies more emissions savings per unit of renewable electricity used. Of the applications shown, the highest emissions reductions in the U.S. result from displacing coal electricity generation, followed by powering BEVs, followed by displacing natural gas electricity generation, then FCEVs, then e-fuels produced using renewable energies (i.e. for both hydrogen and fuel production).

FIGURE 3-2. LIFECYCLE EMISSIONS AVOIDED USING RENEWABLE ELECTRICITY



See Appendix B for assumptions.

However, as discussed in Section 2, technical and infrastructure requirements could limit which vehicles can be electrified and how quickly BEVs or other solutions are adopted. BEVs are the highest efficiency route from renewable electricity to miles travelled, but there is likely to be continued demand for liquid fuels while BEVs are rolled out, and in sectors harder to electrify.

More broadly, these concerns stem from the view that renewable electricity is a limited resource, for which e-fuels production could compete with other important end uses. In practice, the technical potential of renewable electricity is unlikely to be a constraint (this is covered in more detail in Section 4-3). The more important question relates to diversion of the limited renewable electricity generation capacity already in place (concern 1).

As a result, policymakers in the U.S. and EU are aiming to implement rules to ensure e-fuels projects a re developed from additional renewable electricity capacity, to avoid negative impacts on the wider electricity system.

KEY CONSIDERATIONS TO ENSURE SUSTAINABLE DEVELOPMENT OF E-FUELS

To minimize the risk of e-fuels generating negative impacts on the wider electricity system, hydrogen and e-fuel policies, including very recently the Clean Hydrogen Production TC (45V), require renewable electricity used in green hydrogen production to meet 3 sustainability criteria: incrementality, deliverability and temporal correlation.

These 3 pillars are designed to ensure the renewable electricity to produce hydrogen comes from additional capacity, rather than from existing capacity with competing demand. This includes preventing claims that renewable electricity is being used for hydrogen production in hours or locations when renewable electricity is not available.

1. **Incrementality:** Clean power generators that began commercial operations within three years of a hydrogen facility being placed into service are considered new sources of clean power. Generation resulting from a generator's newly added capacity ("uprates") are also considered new sources of clean power.
2. **Deliverability:** Clean power must be sourced from the same region as the hydrogen producer, as derived from Department of Energy (DOE)'s 2023 National Transmission Needs Study.[35]
3. **Temporal Correlation:** New, deliverable clean power will generally need to be matched to production on an hourly basis – meaning that the claimed generation must occur within the same hour that the electrolyzer is operating. The proposed rules allow annual matching until 2028 when hourly tracking systems are expected to be more widely available.

Renewable electricity meeting these sustainability criteria could be directly supplied to hydrogen plants through co-location or sourced from Power Purchase Agreements or other purchasing schemes.

35 DOE (2023), National Transmission Needs Study. Available from: [link]

E-fuels producers relying on tax credits (TCs) for hydrogen production will be required to meet these rules. However, these criteria are not currently included within the rules for the 45Z Clean Fuels Production credit, for which no specific guidance currently exists for the calculation of e-fuels GHG emissions in the U.S. This means that an e-fuels producer not claiming hydrogen TCs would not necessarily need to meet these important criteria.

3.2 WHAT ARE THE WELL-TO-WHEEL GHG SAVINGS OF E-FUELS NOW AND IN THE FUTURE?

The lifecycle GHG emissions of e-fuels are largely determined by the amount of energy required for fuel production, which is dictated by the processing chemistry of production pathways. Production plant configuration for key technology blocks such as carbon capture, electrolyzer, etc. can also significantly impact fuel emissions. This includes design choices such as the source of CO_2 and energy (i.e. electricity and heat) used, which could be influenced by policy requirements and commercial viability.

This section assesses the lifecycle (i.e. well-to-wheel) GHG emissions of e-fuel pathways covered in Section 1 and discusses key differences across the technologies under three scenarios and operating parameters as defined in Table 14.

TABLE 14. GHG EMISSION ASSESSMENT SCENARIO PARAMETERS

PARAMETERS	DESCRIPTION	ELECTRICITY FOR H_2 PRODUCTION	CO_2 SOURCE	ELECTRICITY FOR FUEL PROCESSING	HEAT FOR FUEL PROCESSING
Base case	Additional renewable energy sources that meet incrementality, deliverability and temporal correlation requirements are costly, so this type of renewable electricity is only used for hydrogen production. Other processes use grid electricity (using 2022 U.S. electricity generation CI)[36] and natural gas where heat is required. This scenario is representative of e-fuels production configuration in the near future, if policy does not put requirements on other electricity use in the production process.	Renewable electricity	Point source CO_2 from cement plants **Heat:** Heat integration from fuel processing, supplemented with natural gas **Electricity:** Grid electricity	Grid electricity	Natural gas
Low GHG emissions case	Renewable energy is competitive with grid electricity and natural gas, or is required by policy, and so is used for all operations. This scenario shows the maximum GHG saving potential of e-fuels.	Renewable electricity	DAC using renewable electricity **Heat:** Heat integration from fuel processing, supplemented with natural gas **Electricity:** Renewable electricity	Renewable electricity	Renewable energy (Electricity or hydrogen)
Grid electricity case	Supplying uninterrupted additional renewable electricity could be costly, therefore, it is likely that e-fuel plants will supplement with other grid electricity for part of the time to ensure continuous fuel production. This will have an impact on GHG emission of the fuel. This scenario is used to evaluates what the maximum CI the average electricity can be in order to produce e-fuels that meet the 50 kgCO_2e/mmBTU (or 47.4gCO_2e/MJ) threshold set under the 45Z Clean Fuel Production TC.	Partial grid electricity	Point source CO_2 from cement plants **Heat:** Heat integration from fuel processing, supplemented with natural gas **Electricity:** Grid electricity	Grid electricity	Natural gas

36 EIA: AEO, (2023), U.S. Energy-Related Carbon Dioxide Emissions (2022). Available from: [link]

3.2.1 BASE CASE EMISSIONS

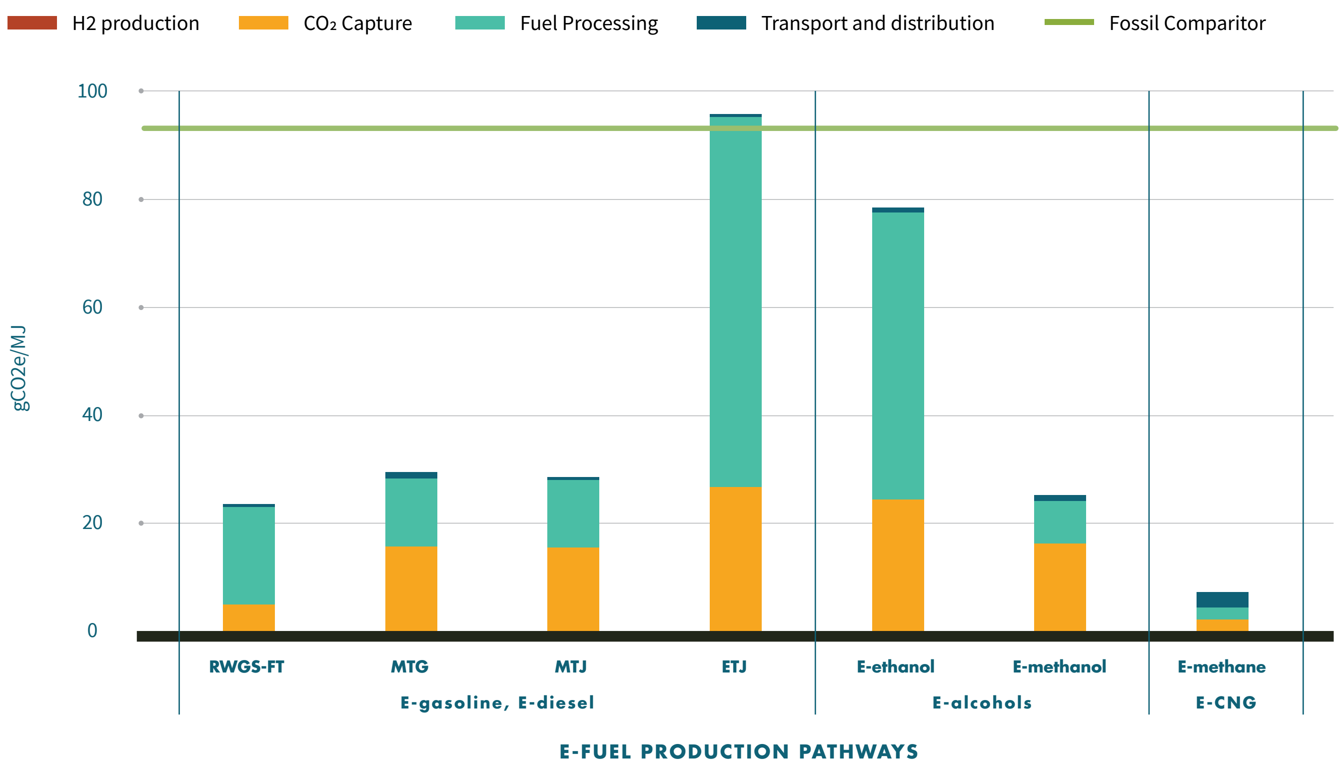
In the base case, most e-fuels suitable for road transport can generate GHG emission savings when additional renewable electricity is used only for hydrogen production. This is representative of early e-fuels plants, which are likely to rely on natural gas and grid electricity for process energy.

Aside from the ETJ pathway, all pathways produce e-fuels with well-to-wheel emissions that are lower than the fossil fuel baseline emissions of gasoline of 93 gCO_2e/MJ (Figure 3-3).

- The most GHG reduction potential is seen with e-methane, which could potentially achieve more than 90% GHG savings when used in CNG vehicles.
- Drop-in fuels produced through RWGS + FT, methanol to gasoline or jet pathways could achieve the highest GHG savings of around 70-75%. However, under a conservative carbon yield assumption (the carbon yield of converting CO_2 to ethanol via pRWGS and syngas fermentation steps is assumed to be 75% for this study. Some developers claim it to be as high as 90%, but this has yet to be proven), e-fuels produced via ETJ exceeds the GHG emissions of its fossil comparator in the base case mainly due to its reliance on natural gas as a heat source.
- For alcohols, e-methanol in the base case could generate about 75% GHG savings whereas e-ethanol is shown to only achieve around 15% GHG savings.

An internal GHG assessment model to calculate the lifecycle emissions saving potential of each fuel pathway following key assumptions stated above under each scenario. The GHG emissions for each pathway are broken into four categories: hydrogen production, CO_2 capture, fuel synthesis and fuel transport and distribution.

FIGURE 3-3. WELL-TO-WHEEL GHG EMISSIONS FOR E-FUEL PATHWAYS FOR NEAR-FUTURE PRODUCTION CONFIGURATIONS.



Hydrogen production

Hydrogen production is assumed to have negligible GHG emissions when renewable electricity that meets incrementality, deliverability and temporal correlation is used.

Fuel processing

Downstream from hydrogen production, fuel processing also consumes energy which is used to sustain e-fuel synthesis processes that take place under high temperature and pressure conditions, and to support auxiliary operations throughout the plant. In the base case, the energy demand from fuels synthesis is assumed to be met by natural gas and grid electricity. Some pathways generate waste heat, such as RWGS + FT and methanol synthesis which are exothermic reactions. This waste heat is reused to reduce natural gas demand.

Conversely, the ethanol and ethanol to jet pathways have the highest natural gas demand and no waste heat is produced during fuel synthesis, resulting in high emissions.

CO_2 capture

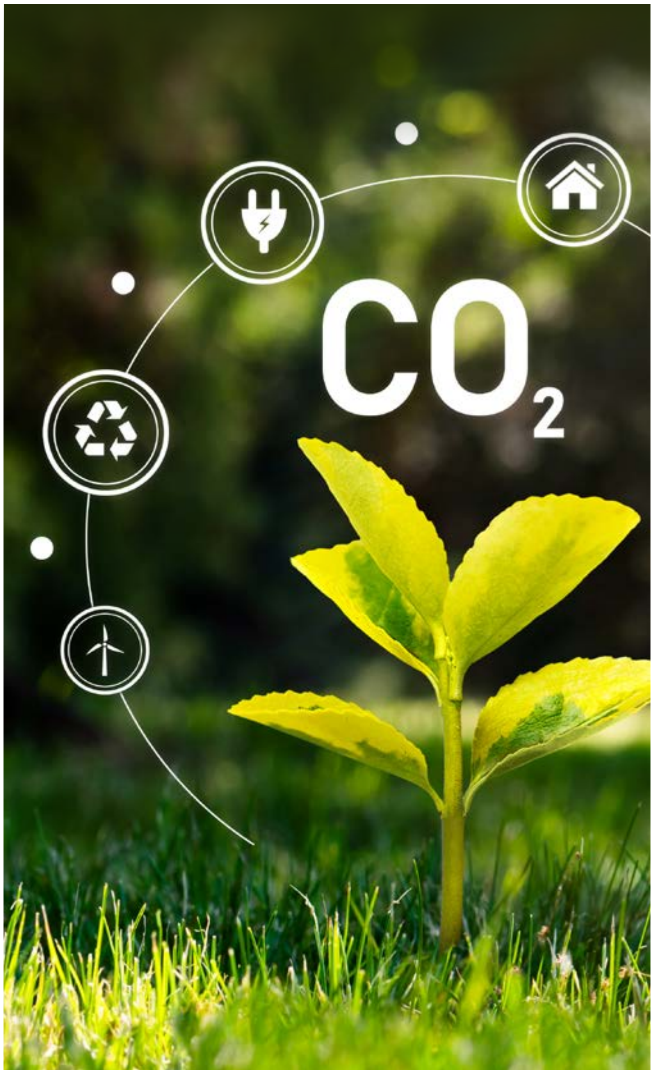
The base case assumes CO_2 is captured from industrial or biogenic point source waste gas streams with low CO_2 concentrations, such as flue gas from cement plants. Emissions associated with CO_2 capture is related to the level of heat integration available to each pathway and its CO_2 requirements.

Separation of CO_2 from low concentration streams requires heat, which is assumed to come from downstream e-fuel production if excess heat is available from fuel synthesis. This is achieved through the co-location of CO_2 source and the e-fuel production plant. In pathways where excess heat is unavailable, natural gas is used to meet head demand, which leads to additional emissions. This results in the RWGS + FT pathway having the lowest emissions associated with CO_2 capture, assuming waste heat can be utilized for this process.

Energy required for CO_2 capture is also determined by the pathways' CO_2 requirements. Comparatively, ethanol pathways require approximately 40% more CO_2 than RWGS + FT and methanol pathways.

Transport and distribution supply chain

The transport and distribution logistics vary by production pathway and fuel properties. Liquid fuels can be transported via trucks or pipelines, whereas gaseous fuels (e-methane) require additional compression before being delivered to refueling stations. This contributes to higher GHG emissions in e-methane pathways. For all other pathways, transport and distribution emissions account for a negligible part of lifecycle GHG emissions compared to CO_2 capture and fuels processing.



3.2.2 LOW GHG EMISSIONS CASE

In the low case all energy used during fuel production comes from renewable sources. It is assumed that DAC will be used to source CO_2 and that it will also use renewable electricity. Similar to hydrogen production, these renewable sources should also come from additional capacities to minimize system wide negative GHG impacts. However, without a GHG methodology, it is currently not known whether this will be required. This scenario also assumes that fossil natural gas consumption is replaced by renewable heat sources such as green hydrogen or renewable natural gas.

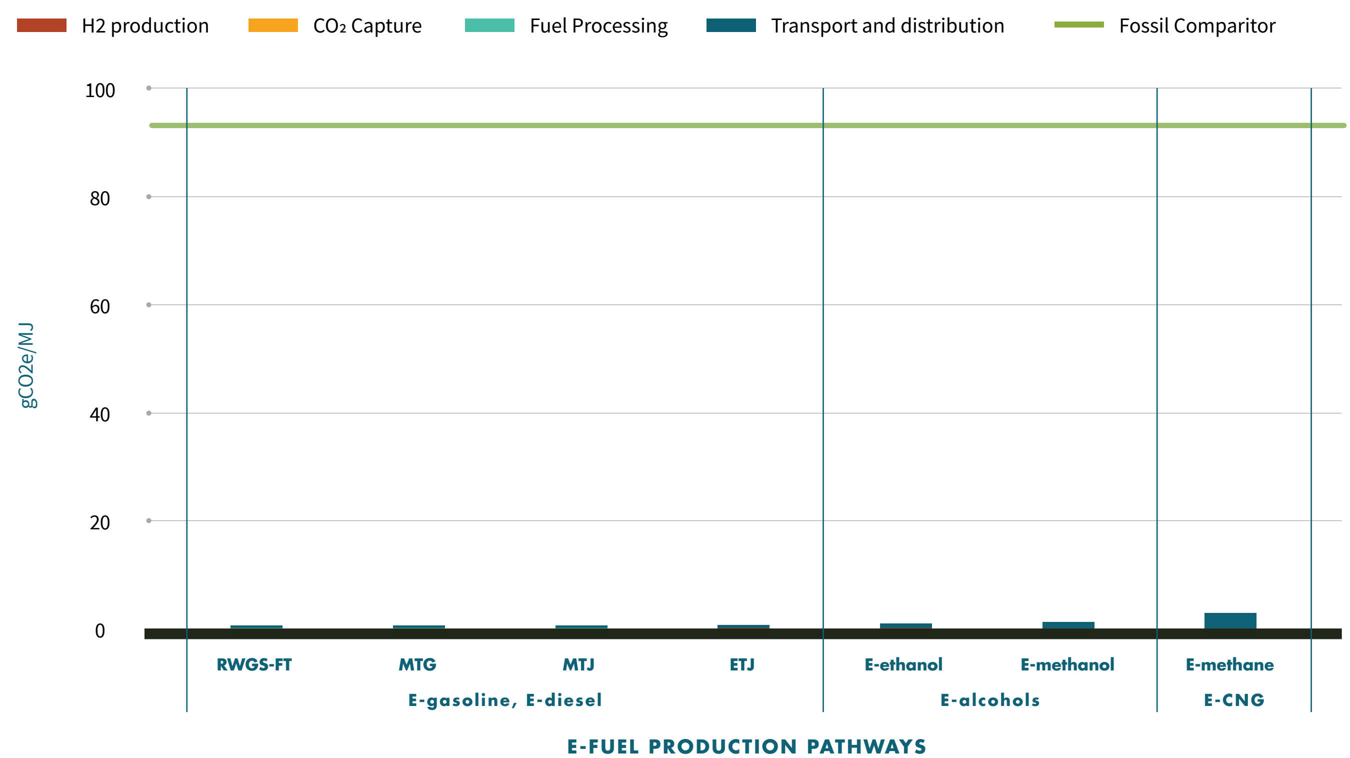
E-fuel pathways under this low emission scenario generates 97 to 99% GHG savings compared with fossil fuels (Figure 3-4). Here, the main source of emission arises from fossil fuel consumed in the downstream transport and distribution of fuels, which can be reduced further as the fleets decarbonize. This emission for CNG is higher as additional energy is required to compress this fuel. The ability to achieve this GHG reduction potential is dependent on renewable energy availability and affordability.

Renewable energy availability and affordability

Renewable electricity and heat sources such as green hydrogen or renewable natural gas are currently supply constrained.

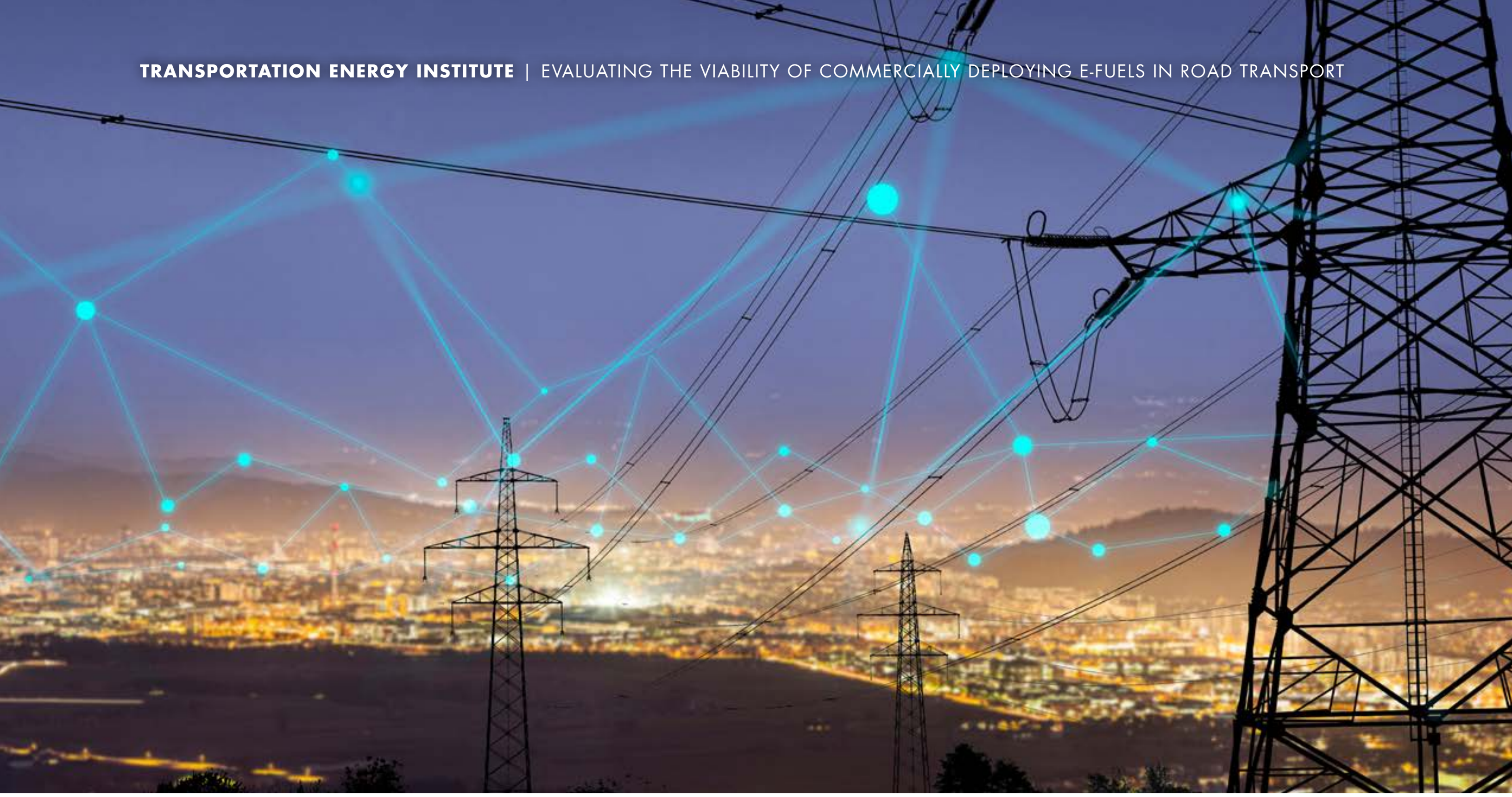
In terms of renewable electricity, supply is projected to grow significantly from the 890 TWh that is available today.[37,38] This electricity could support the production capacity of green hydrogen which can be used as a clean heat source for e-fuel production. Competition for this supply, however, will dictate its price. This price, together with the product value, will determine whether it will be economically viable to use renewable energy for all processes.

FIGURE 3-4. WELL-TO-WHEEL GHG EMISSIONS FOR E-FUEL PATHWAYS REPRESENTING FUTURE PRODUCTION CONFIGURATIONS.



37 EIA (2023), Electricity: Total Electricity Generation by Fuel: Renewable Sources. Available from: [link]

38 International Renewable Energy Agency (2023), Country Rankings. Available at: [link]



Currently, policy is the main driver to reduce the GHG emissions of fuels. As explained in detail in Section 6, most policies set GHG thresholds to determine the eligibility of fuels and some policies offer additional support for fuels with high GHG emission savings. This means that e-fuel producers could be motivated to source renewable energy for fuel processing to meet the aforementioned GHG threshold, in order to benefit from certain clean fuel policies. This could be desirable to pathways with poor GHG emission performances such as e-ethanol or e-ethanol-to-jet as shown in the base case scenario.

However, the willingness to purchase additional renewable energy beyond what is required (i.e. renewable electricity for hydrogen) is highly influenced by the economics of sourcing cost and additional policy support. The interaction between the two will be investigated further in Section 6.

3.2.3 PARTIAL GRID ELECTRICITY CASE

At the time of this report, the definition of e-fuels and the GHG methodology to be used for them has not been established under any fuel policies in the U.S., such as the 45Z Clean Fuel Production TCs or California LCFS. Therefore, it is unclear how sourcing grid electricity would impact the GHG emissions of the resulting e-fuels.

If the average U.S. electricity emission factor is used to calculate the lifecycle emissions of e-fuels, its CI must be below approximately 36 gCO_2e/kWh to meet the GHG threshold for drop-in fuels set under the 45Z Clean Fuel Production TC (50 $kgCO_2e/mmBTU$ or 47.4 gCO_2e/MJ. [39] In other words, around 10% of the electricity used in electrolyzers in e-fuels production could come from the grid today, while still meeting the definition of low carbon fuels. This could be different if alternative GHG calculation methodologies are implemented.

39 This analysis builds off the assumptions of the base case scenario and assumes the energy sources for fuel production come from natural gas and grid electricity, and is applicable to the RWGS + FT, and methanol-to-gasoline and -jet (MTG/J) pathways.

3.3 HOW DO THE WELL-TO-WHEEL GHG EMISSIONS OF E-FUELS COMPARE TO ALTERNATIVE TECHNOLOGIES?

Using the above GHG emissions analysis, this section compares the current and 2040 well-to-wheel emissions per mile travelled for e-fuels, biofuels and other vehicle powertrains introduced in Section 2.2. Emissions associated with vehicle manufacturing are not considered here because they are considered to be insignificant relative to emissions from fuel use – see Appendix E for further details. The emissions factors used in this section are listed in Table 15.

TABLE 15. CURRENT AND 2040 GREENHOUSE GAS EMISSIONS FACTORS FOR ENERGY SOURCES

FUEL TYPE	CURRENT EMISSIONS FACTOR (gCO2e/kWh)	EMISSIONS FACTOR IN 2040 (gCO2e/kWh)	SOURCE/ASSUMPTION
Gasoline and Diesel	335.1	335.1	Renewable Fuel Standard fossil comparator
E-gasoline and E-diesel	High: 345.0 Average: 159.8 Low: 84.9	High: 2.5 Average: 2.3 Low: 2.3	Values from pathways in Section 3.2. Average taken as average for the four diesel/gasoline pathways.
Bio-gasoline	High: 218.7 Average: 165.2 Low: 85.1	High: 218.7 Average: 165.2 Low: 85.1	Renewable gasoline made from forestry residues or vegetable oil (pathways approved by the California Low Carbon Fuel Standard (CA LCFS), 2023)
Renewable Diesel	High: 214.3 Average: 141.2 Low: 53.2	High: 214.3 Average: 141.2 Low: 53.2	Renewable diesel made from waste oil or vegetable oil (pathways approved by the CA LCFS, 2023)
Grid electricity	High: 722.1 Average: 362.1 Low: 106.1	High: 303.4 Average: 152.2 Low: 44.6	EPA eGrid data for 2023, EIA AEO 2023 for 2040 average, with high and low reduced proportionally from 2023 (reference case) [link]
Renewable electricity	0	0	Production emissions of solar panels/wind turbines not considered
Hydrogen	High: 120.0 Average: 60.0 Low: 0	High: 120.0 Average: 60.0 Low: 0	2023: Range of emissions intensity of hydrogen to be classed as "clean hydrogen". (DOE) [link]
Methane	284.4	284.4	As reported by the CA LCFS (2023)
E-methane	High: 28.7 Average: 26.1 Low: 23.5	High: 11.6 Average: 10.5 Low: 9.5	Average value from Section 3.2. High and low values 10% higher/lower than average.
Landfill Biogas	High: 83.0 Average: 53.0 Low: 30.0	High: 83.0 Average: 53.0 Low: 30.0	Emissions intensity of biogas from landfill (pathways approved by the CA LCFS, 2023)
Manure Biogas	High: -543 Average: -1127 Low: -1919	High: -543 Average: -1127 Low: -1919	Emissions intensity of biogas from manure (pathways approved by the CA LCFS, 2023)

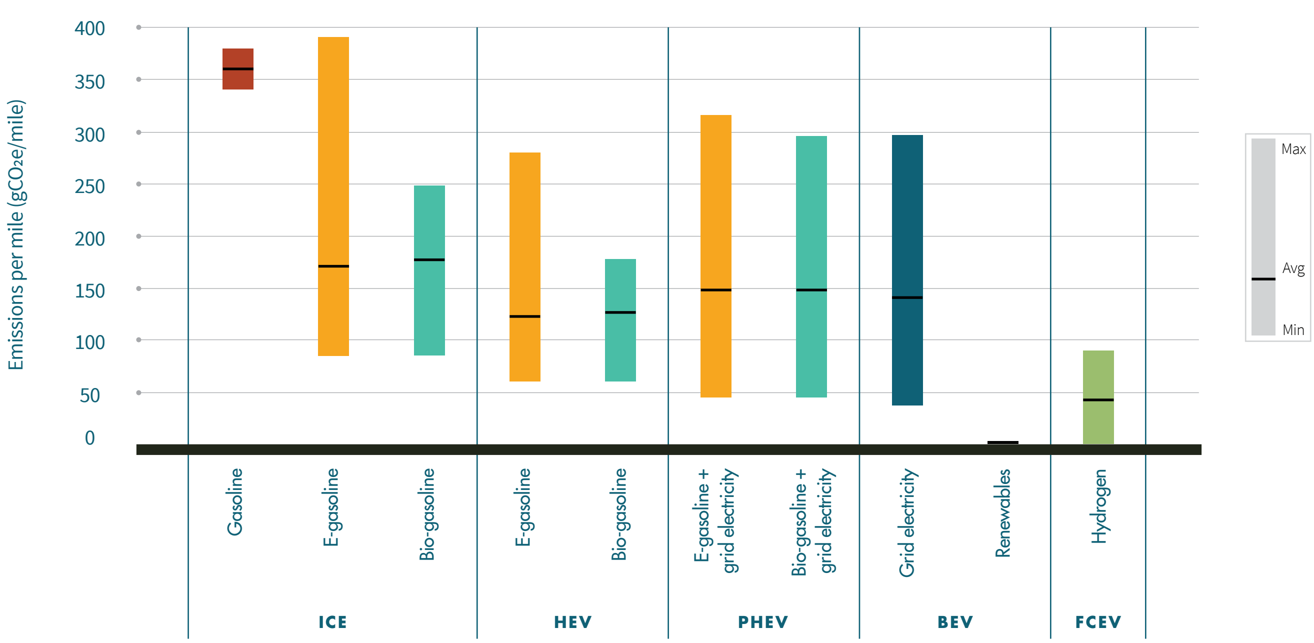
3.3.1 HOW DO EMISSIONS PER MILE COMPARE TODAY?

Emission in LDVs

The GHG performance of vehicles can vary significantly as seen in Figure 3-5. Here, the range represents the varying degree of GHG savings that could be achieved by different production methods and/or feedstocks. For example, the top-end of e-gasoline represents e-fuels produced via e-ETJ pathways, and the bottom-end refers to GHG savings that could be achieve via RWGS + FT routes. The line within each box represents the average emissions across the different production pathways and/or energy sources considered for e-fuels and the other energy sources. The key observations are summarized below.

- E-gasoline from most production pathways could achieve significant GHG savings (i.e. up to 75% lower GHG emissions per mile compared to fossil gasoline) when produced using additional renewable electricity. Some pathways may lead to a net increase in emissions given likely plant configuration in the near future.
- E-gasoline in a HEV can generate further savings of up to 85% of GHG emissions compared to a gasoline ICE car (75% less compared to fossil gasoline in a HEV), due to the increased fuel economy of HEVs combined.
- E-gasoline could yield better GHG savings compared to biofuels in the near future. This is because a high share of biofuels currently used in the U.S. are produced from crop-based feedstocks such as corn, vegetable oil, etc. The lower end of the emission range for biofuels represents those produced from waste and cellulosic feedstocks, but these bio-gasoline pathways are less mature at present.
- Of all the options, a BEV running on renewable electricity and a FCEV with low carbon hydrogen could result in the lowest level of GHGs emitted per mile. However, emissions of BEVs would be higher if grid electricity is used due to fossil intensive

FIGURE 3-5. WELL-TO-WHEEL GHG EMISSIONS PER MILE TRAVELLED CURRENTLY FOR A CAR BY POWERTRAIN AND FUEL TYPE.



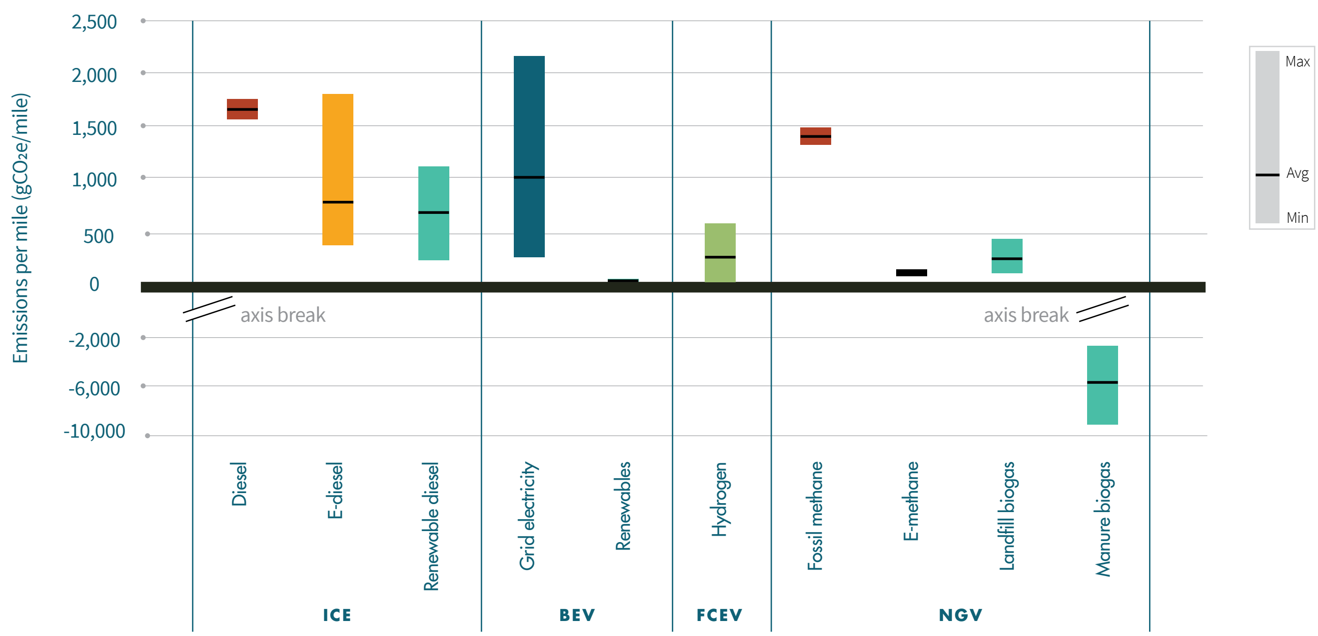
grids in parts of the U.S. (though still below gasoline cars), whilst using high-carbon hydrogen (e.g. unabated natural gas) in an FCEV result in a net increase in emissions (not shown in graph).

Emission in M/HDVs

Use of e-fuels (i.e. e-diesel and e-methane) in M/HDVs could also provide significant GHG emissions savings per mile. (Figure 3-6) It can be seen that:

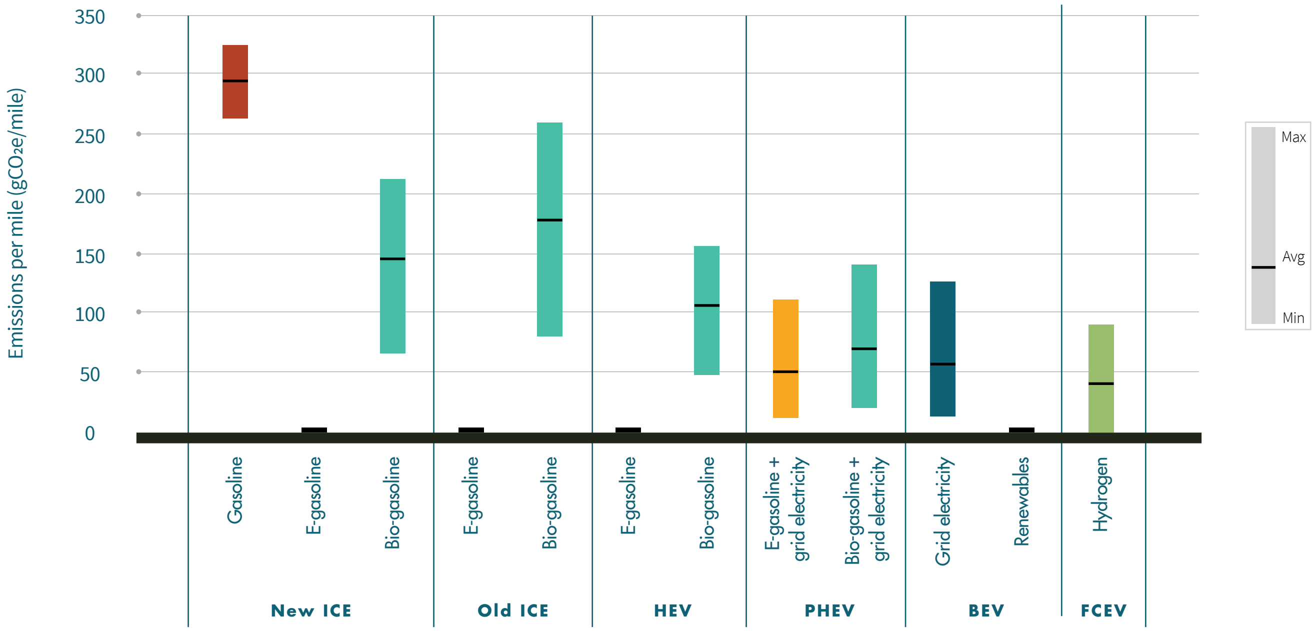
- E-diesel can save up to 80% GHG emissions compared to a diesel ICE. The level of emissions saving depends on the production pathway used to produce the e-diesel, as discussed in Section 3.2.1.
- Of all the options, NGVs using biogas produced from manure could result in the lowest GHG emissions per mile, as the current GHG methodology (i.e. LCFS in California) allows it to generate net-negative well-to-wheel emissions due to avoided methane emissions.[40]
- In addition to BEVs using renewable electricity and FCEVs using low-carbon hydrogen, biofuels could also generate higher GHG savings compared to e-diesel. This is because waste based HVO and biomethane production technologies are mature. These fuels are already commercially available and are readily used in U.S. road transport today. The higher end of the emission range represents biodiesel produced from vegetable oil, which will have emissions from land-use change.
- As for cars, the production method and energy source are crucial in determining the potential emissions savings. Using e-fuels produced from the ETJ pathway, electricity from fossil fuel dominated grids in a BEV, or high-carbon hydrogen (from unabated natural gas) in a FCEV can result in a net increase in emissions.

FIGURE 3-6. WELL-TO-WHEEL GHG EMISSIONS PER MILE TRAVELLED CURRENTLY FOR A M/HDV BY POWERTRAIN AND FUEL TYPE.



40 Using manure biogas is considered to have negative emissions because if the methane was not collected for use in an NGV, it would be released directly to the atmosphere. As methane is a more potent GHG than CO_2, burning the methane in an NGV and releasing the CO_2 produced has a lower GHG emissions impact than releasing the original methane directly into the atmosphere.

FIGURE 3-7. WELL-TO-WHEEL GHG EMISSIONS PER MILE TRAVELLED FOR A CAR IN 2040 BY POWERTRAIN AND FUEL TYPE.



3.3.2 HOW COULD EMISSIONS PER MILE COMPARE IN 2040?

Emission in LDVs

Between now and 2040, emissions per mile fall for most options as a result of maximizing renewable energy for e-fuel production, decarbonization of the electricity grid, and the improved energy efficiency of vehicles. The same GHG emissions have been used for biofuels from the previous section as

modelling GHG emissions from biofuels is out of the scope of this project. However, it is expected that their GHG emissions would move towards the lower end of the bar, which represents waste and cellulosic based biofuels, as their supply ramps up. There will also be opportunities to use more renewable energy and deploy carbon capture and storage technologies for some biofuels options, which could reduce emissions further. This shows that:

- E-gasoline in 2040 could offer up to 99% well-to-wheel emissions reduction per mile compared to standard gasoline, closely matching BEVs running on renewable electricity and FCEVs on green hydrogen.
- The potential emissions reductions from crop-based bio-gasoline and BEVs using grid electricity are less than for e-gasoline. This is limited by land-use emissions related to crop feedstocks and the rate of grid decarbonization in the U.S. In 2023, the EIA projected that the grid CI will reduce by 40% in 2040 compared to today.[41]

41 EIA (2023), AEO (2023) - Electricity (reference case), Available from: [link]

Emission in M/HDVs

Trends are similar for M/HDVs in 2040, with all technologies benefitting from lower emissions per mile due to reductions in fuel CI and/or improved fuel economy (Figure 3-8):

- E-diesel in 2040 could offer up to 99% emissions reduction compared to fossil diesel, closely matching BEVs running on renewable electricity and FCEVs on green hydrogen.
- Manure biogas in an NGV remains the option with the highest emissions reduction per mile on a well-to-wheel basis, assuming the avoided methane emission mechanism is still applicable.
- Biodiesel could also achieve higher levels of GHG savings if production shifts away from vegetable oil feedstocks to waste-base ones, and if renewable energy is used to meet their energy demands.
- The extent of GHG savings achieved by BEV charged using grid electricity will be determined by the grid's CI in 2040.

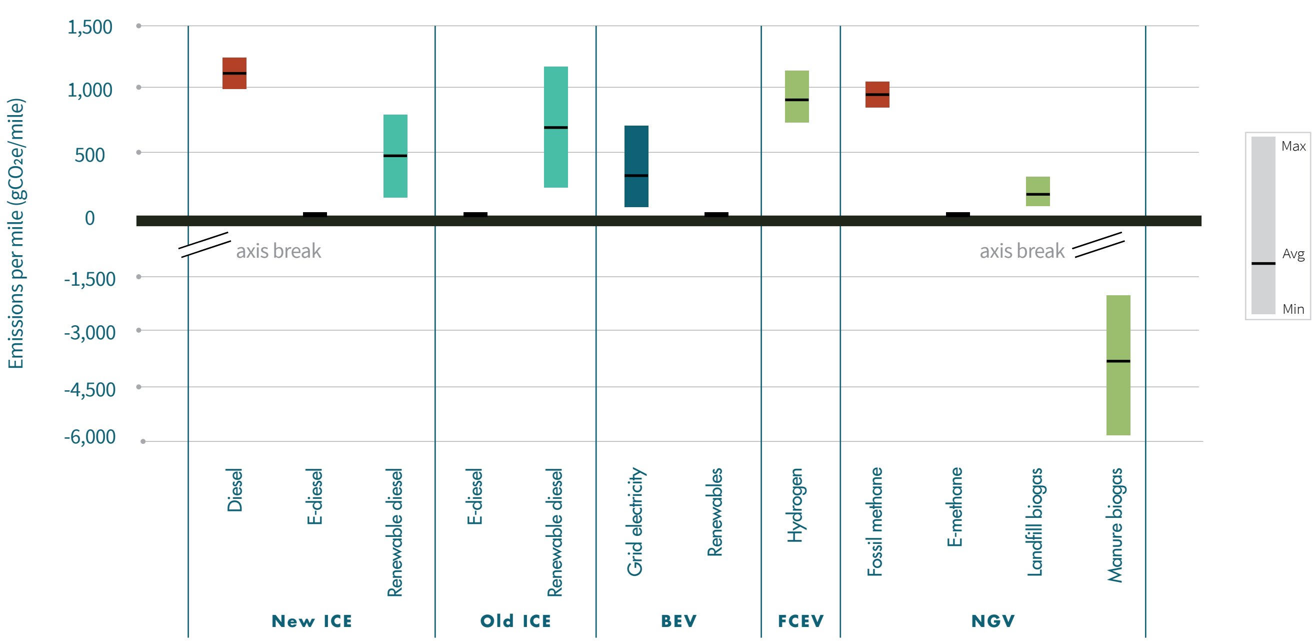
3.4 WHAT ARE THE OTHER ENVIRONMENTAL IMPACTS OF E-FUEL PRODUCTION AND USE?

This section provides a high-level assessment of the potential environmental impacts for e-fuel pathways relating to their production (water demand, land use and use of mined resources) as well as their use (air quality).

3.4.1 WATER DEMAND

Water scarcity is a growing issue in some regions of the world. The production of e-fuels requires water, and there is therefore concern that this could add further stress to fresh water availability given important existing uses such as human

FIGURE 3-8. WELL-TO-WHEEL GHG EMISSIONS PER MILE TRAVELLED FOR A M/HDV IN 2040 BY POWERTRAIN AND FUEL TYPE.

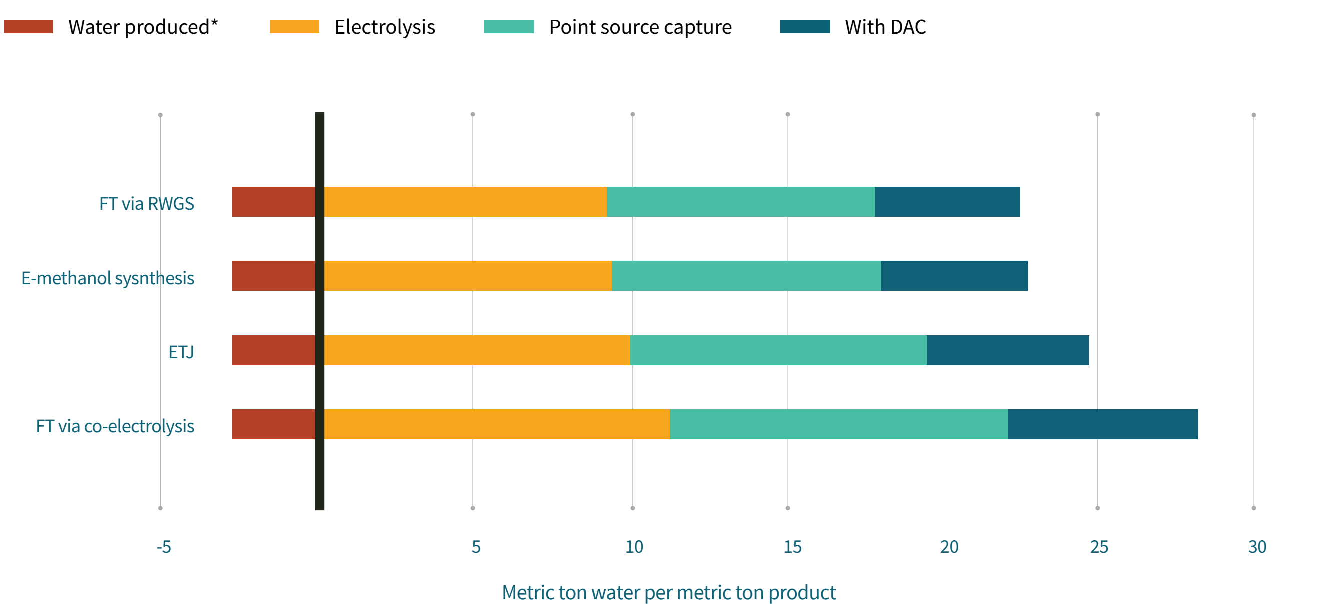


consumption, agricultural irrigation and other industrial applications. Water demand for e-fuels production is primarily for hydrogen production, CO_2 capture and e-fuel synthesis:

- **Hydrogen production –** The minimum amount of water required for electrolysis is 9 metric tons per ton of hydrogen produced. However, in practice, this is around 20 tons of water per ton of hydrogen (or 2.4 gallon of water per lb of hydrogen) due to water treatment requirements for electrolysis and other losses.[42]
- **CO_2 capture –** Water is required during the capture process for cooling and to obtain high-concentration CO_2 gas from flue gas streams. Point source CO_2 capture at a natural gas power plant requires around 2.6 tons of water per ton of CO_2, while DAC has a higher footprint of 4 tons per ton of CO_2.[43]
- **E-fuel synthesis –** Water footprint will vary by conversion technologies and is driven by the inputs of hydrogen and CO_2 needed for the specific pathway.

The water requirements for e-fuels range on average from 18-22 metric tons water per ton of product when using point source capture and 23-28 tons water per ton product when using DAC as seen in Figure 3-9. However, water that's produced as a by-product from e-fuel processing could slightly reduce demand. Majority of the water demand from the carbon capture processes are to support the cooling system, which can be recycled, though some makeup volume is required to compensate for evaporation. This recycled volume is not reflected in the graph below as it can vary significantly based on plant design. For comparison, the water footprint from e-fuels is much higher than bioethanol

FIGURE 3-9. WATER FOOTPRINT FOR E-FUELS

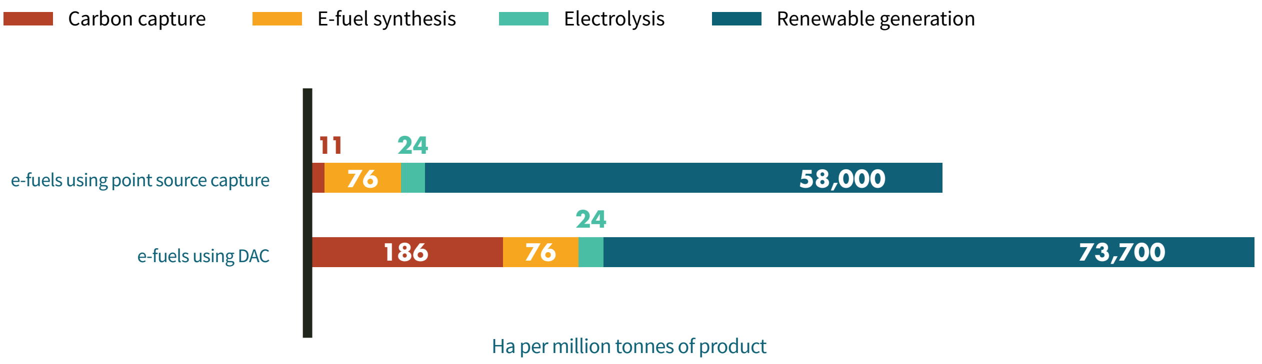


**Water produced is approximated based on the average from the FT and e-methanol processes.*

42 Element Energy (ERM Group) (2018), Hydrogen supply chain evidence base. Available from: [link]

43 Renewable and Sustainable Energy Reviews (2021), The water footprint of carbon capture and storage technologies. Available from: [link]

FIGURE 3-10. LAND AREA REQUIREMENTS FOR E-FUELS PRODUCTION



Bars are not to scale

production when considering the refining steps only (e.g. 1-5 metric tons per ton ethanol). However, this increases significantly (e.g. up to 1,000 tons water per ton ethanol) when considering the requirement upstream growth and irrigation of crops like corn.[44]

On a global scale, water availability is unlikely to constrain e-fuels production, given the vast seawater and wastewater resources available. However, utilizing these sources will add further desalination, water treatment costs and other challenges which are outside the scope of this project. Local freshwater resources could be used to reduce treatment costs, but this will come with location-specific water scarcity risks that must be considered during planning and design of projects.

3.4.2 LAND USE

Significant land area is required to develop e-fuels production. This is an important consideration as land area is physically constrained and already faces competing uses for agricultural activity, urban development, or protection of ecosystems and indigenous communities. Based on average footprints for infrastructure, this section estimates the high-level land requirements for siting the CO_2 capture facility (point-source or DAC), the renewable electricity generation (assuming an equal mix of solar photo-voltaic (PV) and wind generation), the electrolyzer, and the e-fuels synthesis plant. Land requirements are estimated at 110-290 hectares (or 270-700 acres) per million metric tons of product as seen in Figure 3-10. The direct land usage of e-fuels production can be almost twice the size of petroleum refineries. This increases to up to 73,700 hectares (180,000 acres) when considering the renewable electricity generation.

- Renewable **electricity generation** by far accounts for the largest land requirements of the e-fuels value chain, representing over 99% total area:
  - Greater land area is required for renewable electricity when using DAC due to the higher electricity consumption of this process versus point source capture.
  - It is important to note that this area includes the entire wind and solar farm, but not all the ground area is used. Wind turbine bases and access roads would require around 1% of the total ground area, while the rest could in theory be used for other activities such as agriculture or grazing.[45]

44 University of Michigan Centre for Sustainable Systems (2023), Biofuels Factsheet. Available from: [link]

45 Haroon Kamal, Muhammad Ahmad Mudassir, Shazia Kousar, Mohammad Amin Makarem, Muhammad Adnan Bodlah, Shahzad Murtaza (2023), Wind energy investment analysis: design, parts, installation, and land costs. Available from: [link]

- **Carbon** capture accounts for a larger area when using DAC, as units must be spaced out to avoid drawing in air that has already been depleted of CO_2. Point source capture requires relatively little additional area as this typically involves the retrofit of capture units to existing facilities.
- **Electrolysis and e-fuels synthesis** land footprint varies by electrolyzer and e-fuel technology, but overall represents a much smaller part of total area requirements versus renewable electricity or DAC.

Given the vast areas required for renewable electricity generation, land use considerations are significant for e-fuels requiring new-build generation. However, land use competition will not be an issue that only the e-fuels sector will face, but also any sector that requires new renewable electricity. Furthermore, as mentioned in Section 2.2.1, e-fuels technologies require on average 10 times less land area to deliver the same amount of energy as crop-based biofuels.

3.4.3 USE OF MINED RESOURCES

Critical resources, such as rare earth metals and other mined materials, are important for the manufacturing of carbon capture, renewable electricity, electrolysis and other clean energy technologies. Given limited supply for some of these resources, and growing competition for use, there are concerns around the sustainable mining of reserves and the use and disposal of metals.

- **Carbon capture technologies –** Most commercial carbon capture techniques currently use solvents made from common earth materials, generally considered to have a low environmental risk associated with their mining, use and disposal.
- **Renewable energy –**wind farms require significantly more mineral resources (mainly copper, zinc, manganese, and chromium) than fossil counterfactuals.[46] Offshore wind turbines use rare earth metals in generators. Growing demand for renewable energy will require a scale-up in generation capacity, and the associated growing demand for these resources.
- **Electrolyzers –** Alkaline (ALK) electrolyzers typically rely on more common earth materials such as zinc and copper. However, polymer exchange membrane (PEM) electrolyzers require rare metals such as platinum and iridium as reaction catalysts.

Due to the nature of their deposits and low concentrations in ores, many rare earth metals require highly energy-intensive processes to mine, separate and refine. Significant volumes of toxic leachate, wastewater and gas are also generated during this process (e.g. up to 2,000 tons of toxic products per ton of rare earth metal), requiring appropriate treatment to avoid serious environmental and health impacts.

Growing demand for rare metals and other mined resources to support scale-up of clean energy

46 IEA (2021), The role of critical minerals in clean energy transitions. Available from: [link]

technologies may result in expansion of mining operations. Ensuring this is underpinned by robust environmental, social and broader sustainability regulation will be crucial to mitigating any adverse environmental impacts. Improving mining practices to achieve higher material recovery, or advancing metal/material recycling approaches, may also reduce the need for new mineral extraction and associated environmental impacts.

3.4.4 AIR QUALITY

While water demand, land use and use of mined resources relate to the production of e-fuels, air quality impacts result from their use. EVs and FCEVs running on electricity and hydrogen are associated with zero tailpipe emissions, and therefore do not result in air quality impacts. However, for e-fuels and other liquid fuels, air quality impacts generally result from incomplete combustion of fuels that lead to emission of sulfur oxides (SOx), nitrogen oxides (NOx), particulate matter (PM) and soot. This has serious implications for the climate and human health, for example, SOx and soot emissions are linked with risk of acid rain. Exposure to PM is associated with risk of cancer and respiratory and cardiovascular diseases.

The impact of using e-fuels on air quality varies by fuel properties and blend levels. Use of oxygenates like e-ethanol and e-methanol can significantly reduce emissions of pollutants, for example, by up to 40% on E10 versus full gasoline.[47] However, there is less certainty on the extent to which liquid hydrocarbons such as e-gasoline and e-diesel reduce emissions of pollutants. Current U.S. fuel standards require gasoline to contain 25% aromatics by volume,[48] which have a higher susceptibility to incomplete combustion. This is higher than the requirements for e-gasoline, which could result in a reduction in particulate emissions.

However, use of e-gasoline may not result in reduced NOx emissions, and there is generally likely to be a lower reduction of pollutants overall for e-gasoline and e-diesel because they are more molecularly and chemically similar to fossil fuels compared to oxygenates. Air quality impacts therefore remain an important environmental and health consideration for use of some e-fuels.

47 Transport and Environment (2021), Magic green fuels: why synthetic fuels in cars will not solve Europe's pollution problems. Available from: [link]

48 TransportPolicy.net (2018), U.S.: Fuels: Diesel and Gasoline. Available from [link]

3.5 SUMMARY

How do e-fuels achieve GHG savings?

E-fuels achieve GHG savings due to two main principles:

- The energy content of e-fuels (i.e. the hydrogen) is derived from renewable electricity sources, which are associated with near-zero GHG emissions. It is critical that this renewable electricity comes from sources that meet incrementality, deliverability and temporal correlation to avoid negative impacts on the wider electricity system. It is crucial that e-fuel production does not displace existing uses of renewable electricity.
- E-fuels release CO_2 when they are combusted, but this CO_2 either would have been emitted to the atmosphere anyway or is captured from the atmosphere.

However, emissions can still arise from the production process and can vary considerably.

What are the well-to-wheel GHG savings e-fuels achieve now and in the future?

The well-tank GHG savings that e-fuels can achieve depend on the production pathway and processing chemistry, source of CO_2, source of energy used in carbon capture and fuels production, and the transport and distribution steps considered in the supply chain. The highest savings are achieved when using renewable electricity for all fuel production processes. The GHG savings of all e-fuels pathways improves between now and 2040 (Table 16). It is assumed that renewable electricity sourced in these scenarios come from additional sources that meet sustainability criteria above.

How do the well-to-wheel GHG emissions of e-fuels compare to other technologies?

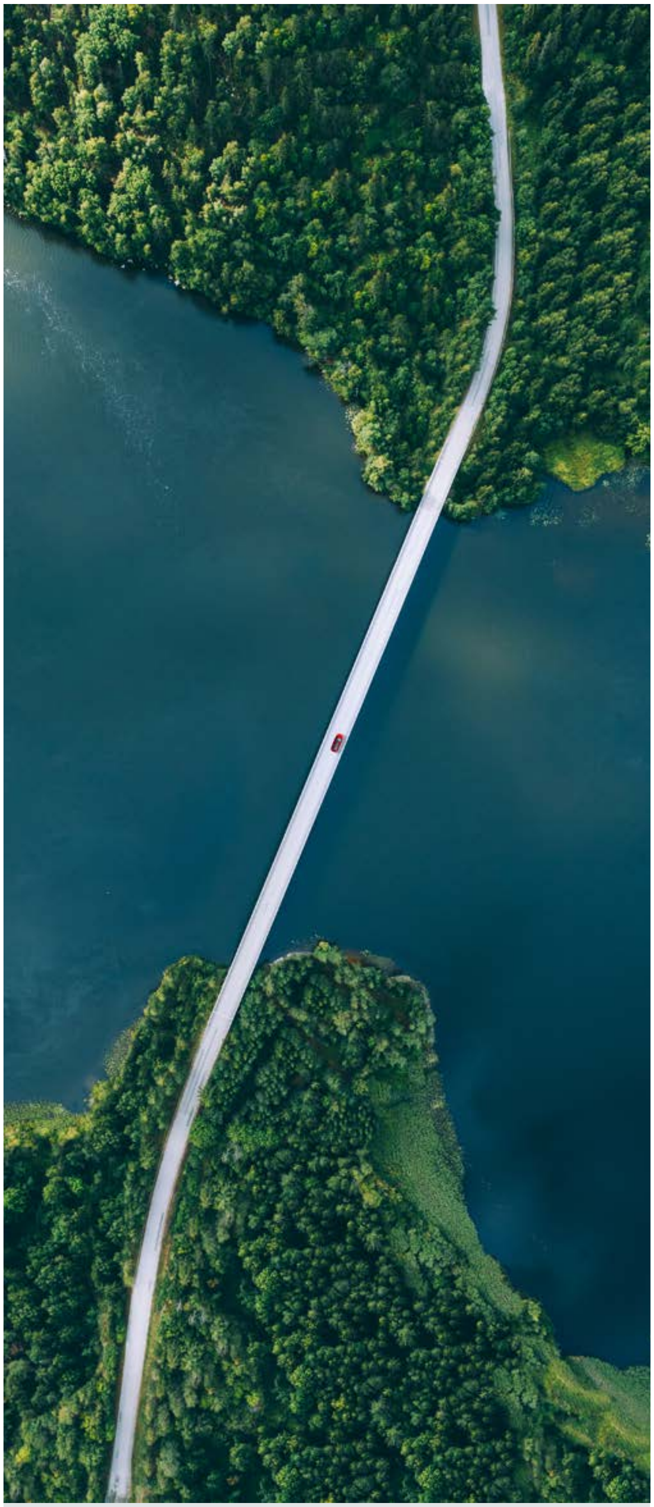
E-gasoline and e-diesel can currently offer around 80% GHG savings per mile when used in conventional gasoline or diesel ICEVs. However, BEVs running on renewable electricity and FCEVs running on green hydrogen are currently the options with the lowest well-to-wheel GHG emissions for cars versus fossil fuels (e.g. as low as zero gCO_2e per mile travelled). For HDVs, these options in addition to NGVs using biomethane from manure have the lowest emissions. Emissions could increase substantially for BEVs and FCEVs when using grid electricity, and this can vary significantly by where recharging and hydrogen production occurs.

In future, the optimization of e-fuel production to reduce emissions, decarbonization of the electricity

TABLE 16. WELL-TO-WHEEL GHG REDUCTION OF E-FUELS

FUELS	FUEL PATHWAY	WELL-TO-WHEEL GHG SAVINGS (% reduction on fossil baseline)	
		Base case (current)	Low case (2040)
Fossil baseline		93 gCO_2e/MJ	
E-FUEL PATHWAY			
CNG	e-methane	92%	97%
E-gasoline, e-diesel	RWGS + FT	75%	99%
	e-MTG	68%	99%
	e-MTJ	69%	99%
	e-ETJ	-3%	99%
Alcohols	e-ethanol	16%	99%
	e-methanol	73%	99%

grid, and improved vehicle fuel economy will result in the GHG savings of all options improving. By 2040, e-fuels like e-gasoline and e-diesel could be one of the options with highest GHG savings, and in the range of BEVs and FCEVs running on renewable electricity and green hydrogen.



What are the other environmental impacts of e-fuels?

The production and use of e-fuels has other important environmental considerations aside from their GHG performance. None of these are likely to be a cause for significant concern when managed appropriately, and impacts will generally be less severe than for fossil fuel and biofuel value chains.

- **Water demand –** Demand for e-fuels could reach 23-28 tons water per ton product when using DAC. This could be a concern in water-strained regions, but using desalinated seawater and treated wastewater may reduce these burdens (though it could add challenges such as cost and potential concerns that are beyond the scope of this project). The overall water demand for e-fuels is much lower than for biofuels when including the growth of feedstock and refining steps.
- **Land use –** Land area required for e-fuels production is driven by the renewable energy generation, which accounts for over 99% of footprint. E-fuels will face competing demand for land area with agricultural activities, urban development, and protection of ecosystems. However, biofuels require much more land area per fuel output (primarily for growth of feedstocks) than e-fuels.
- **Use of mined resources –** Development of renewable energy, CO_2 capture and electrolysis supply chains may require further demand for raw materials and rare earth metals, some of which involve intensive mining practices.
- **Air quality –** BEVs and FCEVs are not associated with air quality impacts as they are zero-emission technologies at the tailpipe. E-fuels can also reduce these impacts but still emit some pollutants due to incomplete fuel combustion. Of the e-fuels considered, e-ethanol and e-methanol are likely to reduce air quality impacts the most compared to fossil fuels.

SECTION 4.

How much e-fuels production capacity could there be?

E-fuels are at early stages of development today, resulting in limited production capacities. However, several first commercial plants may come online in the next 1-2 years and many more over the next decade.

Based on this, we estimate that e-fuels production capacity could scale from today's low levels to around 0.9 million metric tons per year (Mt/year) in the U.S. and 4.3 Mt/year globally. This is approximately 0.3 billion gallons/year in the U.S. and 1.4 billion gallons/year globally.[49] By 2040, this could reach around 6-14 Mt/year (2.0-4.7 billion gallons/year) in the U.S. and 34-82 Mt/year (11.4-27.5 billion gallons/year) globally. Note that this is not a projection of supply or of demand; instead, it represents how fast e-fuels plant might be able to be built.

Achieving these production capacities by 2030 and 2040 will require significant investment and overcoming the technical challenges identified in Section 1. E-fuels plants must also have sufficient and secure access to CO_2 and renewable electricity. They will also need a viable business case for the price available to cover the production costs and margins, which is likely to rely on a policy driver.

49 Approximated using a conversion value of 335 gallon/tonne, based on an average density of liquid fuels.

This section assesses trends in e-fuels production capacity to 2030 based on publicly announced projects as of January 2024. A scenario to 2040 is also provided based on ERM's in-house ramp-up model, which represents an estimate of how fast production capacity could scale if there was significant demand and supply was profitable. This is compared to the availability of CO_2 and renewable electricity in the U.S. to understand potential constraints on e-fuels supply.

SECTION 4: KEY QUESTIONS

- **What are the development trends of announced e-fuel projects?**
- **How much e-fuel production capacity could be available in the U.S.?**
- **Is there enough renewable electricity and CO2 in the U.S. to support e-fuels scale-up?**

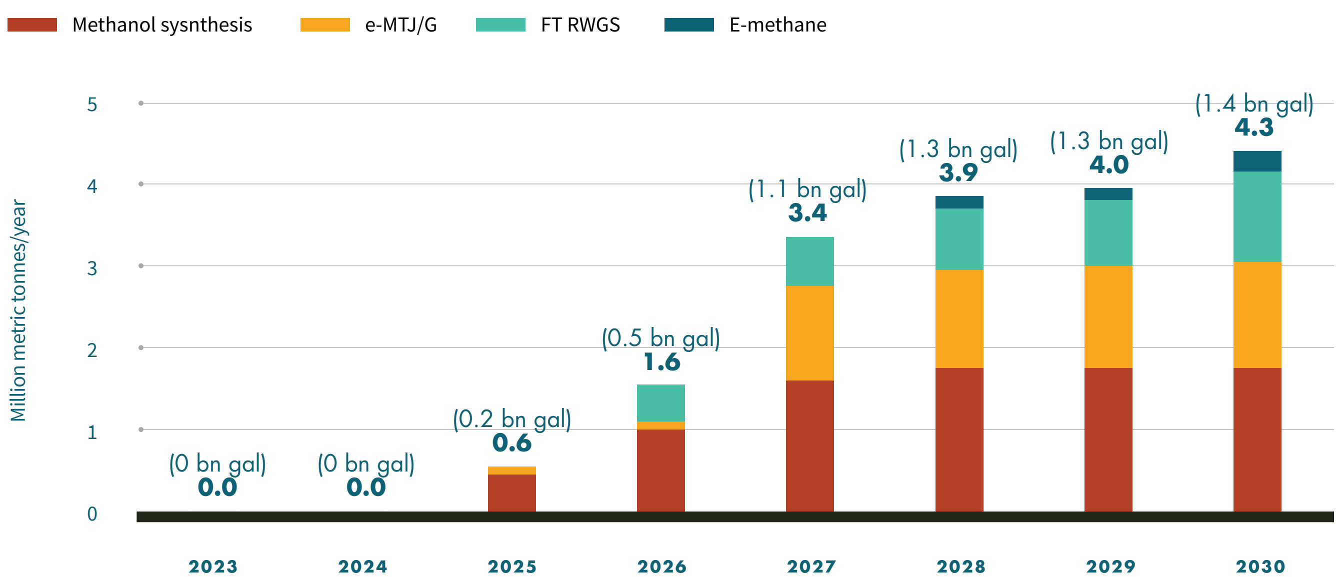
4.1 WHAT ARE THE DEVELOPMENT TRENDS OF ANNOUNCED E-FUEL PROJECTS?

Today, only a few pilot and demonstration e-fuels projects are in operation with the aim of demonstrating successful operation and integration of e-fuel technologies. However, as the technologies mature, many first commercial (TRL 8) and commercial scale (TRL 9) projects are expected to start over the next decade. Drawing on ERM's global database, this section shows current and planned e-fuel production capacity and assesses high-level trends in production technologies and locations, target products, development priorities and major players.

4.1.1 TRENDS IN E-FUEL PRODUCTION TECHNOLOGIES

Based on project announcements, Figure 4-1 shows that 4.5 million tons per year (1.4 billion gallons/ year) of e-fuel production capacity could be built globally by 2030, growing from very small volumes today. This is based on current and planned e-fuel production capacity, including all plants for which a start-date and capacity has been announced.

FIGURE 4-1. GLOBAL PLANNED E-FUELS PRODUCTION CAPACITY BY TECHNOLOGY



While the ramp-up rate is fast, the expected capacity in 2030 is still lower than U.S. biodiesel production, at around 6.7 million tons per year (2 billion gallons/year).[50]

The annual growth in capacity in Figure 4-1 indicates that there could be a large contribution from methanol synthesis, alcohol-to-hydrocarbons (particularly MTJ/G) and FT synthesis routes by 2030.

- E-methanol is set to be the first e-fuels technology to reach commercialization, with the first commercial e-methanol plant expected to be commissioned in 2024 in Denmark. There is a growing number of developers pursuing this pathway.
- Several upcoming commercial projects and developers are implementing FT synthesis. Pilots and demonstrations are nearing commissioning today, and the first commercial plant is expected to start in 2026.
- There are currently fewer e-MTJ/G plants planned, however, planned production capacities are very large as most planned projects aim to be co-located with new large renewable energy assets. A demo plant is in operation today (see Section 4.1.4), with the first commercial plant expected to start in 2025.

For new technologies, the transition from a pilot to a full commercial-scale facility can take many years. Based on evidence of projects in the field, this is around 5-8 years for e-fuels. For example, e-fuels technology and project developer Re:Integrate began operating an e-methanol pilot plant (TRL 6) in 2018. The company was since acquired by European Energy, who is expected to commission a first commercial facility (TRL 8) this year. Once technologies have reached commercial scale and proven successful operations, development times may decrease.

Other e-fuel technologies remain further behind in development status due to a lack of active developers. For example, LanzaTech is also the only developer actively pursuing ethanol via pRWGS and fermentation. There are two planned commercial plants aiming to use this to produce jet fuel via the e-ETJ pathway.

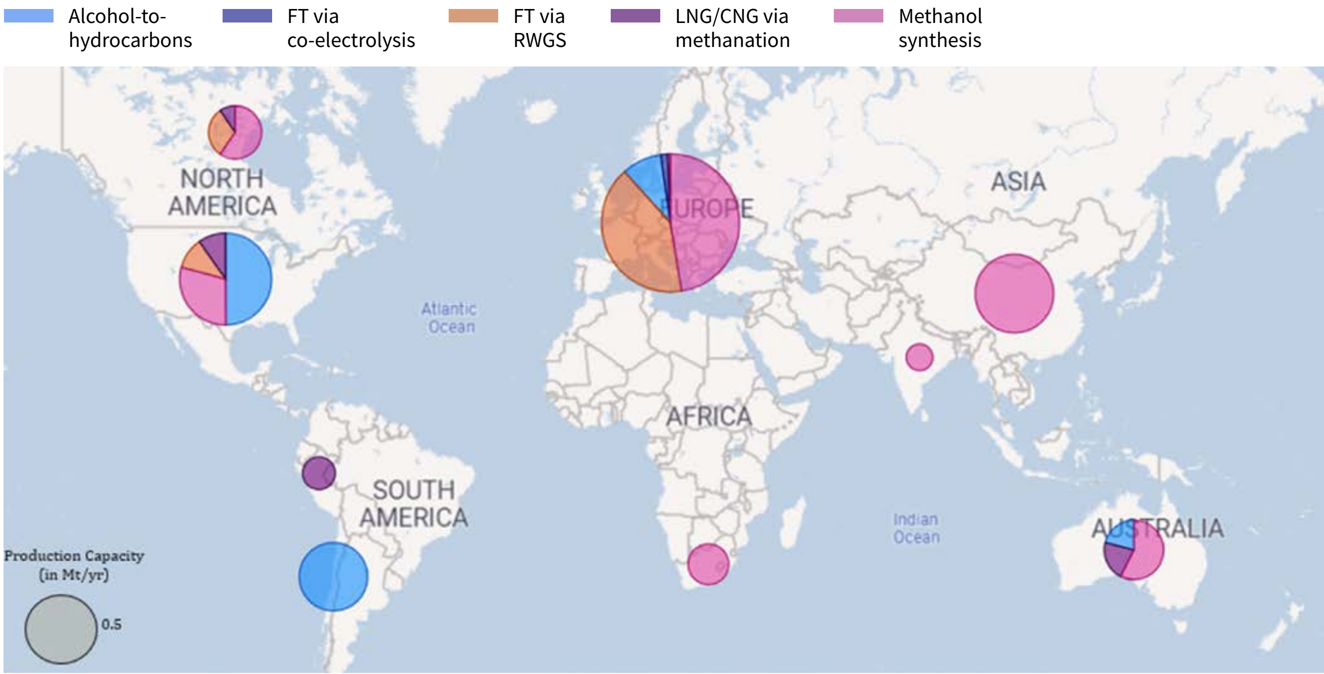
4.1.2 TRENDS IN PRODUCTS

Many planned plants are focused on production of two fuel types: jet fuels and methanol. However, it is important to note that there is uncertainty in the specific fuel types plants will choose to produce. This is because many technologies can yield a range of fuel products in varying percentages, and the exact makeup will depend on the economics of production, and demand for fuels, both of which are heavily influenced by policy support.

- **Jet fuel –** As there are few decarbonization options available for the aviation sector, there is growing policy focus on supporting production and deployment of SAF. These drivers are expected to create a large market for SAF in the future, which e-fuels developers are hoping to access. In the EU, there are specific targets for e-SAF. Policy drivers for the uptake of low carbon options in transport are assessed in more detail in Section 6.
- **Methanol –** Methanol has fewer processing steps than other e-fuels routes and can be directly blended at low levels into gasoline, used as a marine fuel in methanol vessels, or further converted into drop-in jet fuel, diesel or gasoline. It also has applications in the chemical industry. The relative ease of production and flexibility in end-use applications may be one reason many developers are pursuing this fuel, in addition to the expected demand growth for low carbon marine fuel and SAF.

50 EIA (2024), U.S. Biodiesel Plant Production Capacity. Available at: [link]

FIGURE 4-2. MAP SHOWCASING ANNOUNCED COMMERCIAL E-FUEL PLANTS GLOBALLY



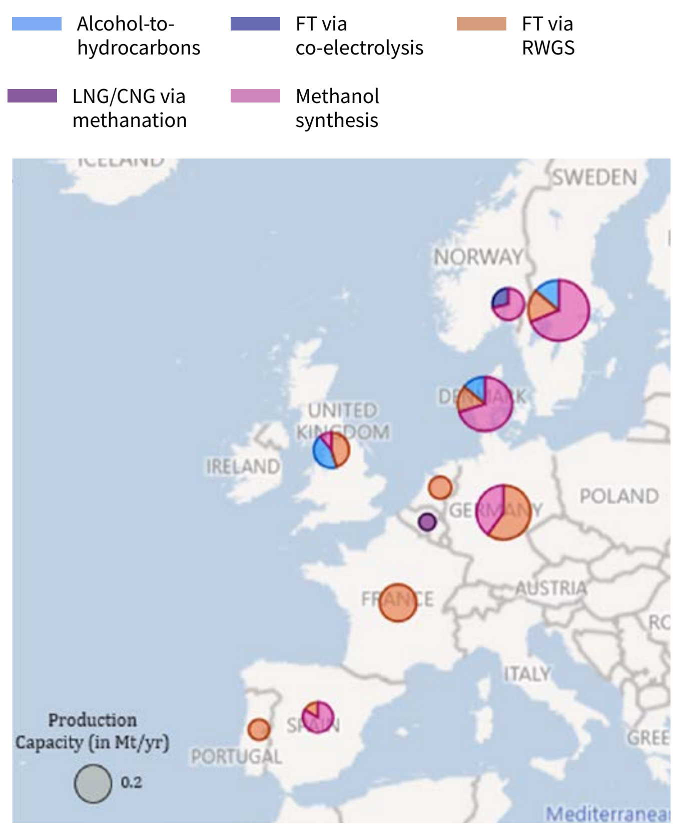
4.1.3 TRENDS IN PROJECT LOCATIONS

Figure 4-2 and Figure 4-3 shows the geographical distribution and scale of current and planned e-fuel commercial plants, globally and in Europe, derived from ERM's e-fuels database.

Planned e-fuels projects are predominately located in the U.S. and Europe, with 5 and 48 planned commercial projects respectively. Large projects are also planned in Chile and Australia. Within Europe, the UK, Denmark and Sweden have the largest pipeline. This is likely related to:

- **Proximity to technology development –** most interest and technology development effort in these pathways has been in the EU and the U.S., and developers are often keen to build first plants near to their technology development teams.
- **Policy support –** In the short to mid-term, low carbon fuel demand is expected to be strongest in the EU and the U.S. where policy support is most mature. Many developers are planning projects

FIGURE 4-3. MAP SHOWCASING ANNOUNCED COMMERCIAL E-FUEL IN EUROPE



in these markets where there is an economic incentive to produce the fuel, or there are strong prospects for offtake.

- **Feedstock availability –** Secure access to cheap renewable electricity and CO_2 will be crucial to the success of e-fuels projects. Developers are seeking to build projects in areas with abundant renewable energy potential, such as the U.S. Gulf Coast, and parts of Chile and Australia. In many cases, these projects aim to utilize energy from new, co-located GW-scale renewable electricity assets, which is reflected in the large production capacities being planned.
- **Access to funding –** E-fuels projects currently represent a significant upfront capital investment, therefore, raising public and private funding is critical to successfully developing projects. Many countries in Europe, notably the UK, Denmark and Germany, have made grant funding available for developers. This has contributed to pilot and demonstrations being developed and first commercial facilities being planned in these countries.

4.1.4 MAJOR PLAYERS

There are a range of companies involved in the e-fuels value chain. In some cases, companies act as more than one of the roles below:

- **Project developers -** These companies are responsible for designing, coordinating, and operating e-fuels projects, including sourcing the feedstock and selling the products. Some of these companies are start-ups founded in the last 3-4 years as spin-offs from larger technology companies or academic research institutions. Large industry players from the oil and gas, chemicals, and utility sectors are also entering the market. Project developers generally do not develop and license e-fuels technologies themselves, although there is an increasing number of start-ups who are seeking to both develop their own technology and operate plants using it. Examples: Arcadia eFuels, Highly Innovative Fuels, Infinium.
- **Technology licensors –** These companies are engaged in developing the technologies required for e-fuels and own the patents for components such as electrolyzers, catalysts and reactors. They are often large technology and manufacturing companies and license their technologies to developers for use in e-fuels plants. Examples: Johnson Matthey, Topsoe, HoneywellUOP.
- **Engineering, Procurement and Construction (EPCs) –** These companies work closely with the developers and technology licensors to prepare the site and construct the projects. Examples: Technip Energies, Bechtel, KBR.

E-FUEL DEVELOPER CASE STUDIES

E-fuels technologies are still associated with technical risks resulting from the uncertainty in being able to operate technologies effectively at large scale. This means that investments in e-fuels plants can represent a financial risk, as technologies may not operate as well as expected, particularly in the first few years. It is therefore critical for e-fuel projects to receive sufficient funding to support high up-front capital investments and enable successful operation of plants, which de-risks the technologies for further investments. Public funding is seen as crucial in the short term while the industry matures to unlock further private investment. The following section includes high-level case studies on two e-fuels developers who have recently raised funding from public and private sources, which could help scale up their projects. Information is provided on the company backgrounds, their development status and planned projects, and key partners and sources of finance to showcase some of the success stories in e-fuel projects so far.

E-FUEL DEVELOPER CASE STUDIES

Arcadia eFuels

Role: e-fuels project developer
Headquarters: Copenhagen, Denmark
Founded: 2021
E-fuels technology: FT synthesis via RWGS

Number of employees: N/A
Operating plants: 0
Announced plants: 2 (as of January 2024)
Planned production capacity: 150 kt/year

PROJECTS

Arcadia has announced two e-fuels projects in Denmark and the UK, with start dates of 2026 2028 respectively. The projects currently focus on production of e-SAF and e-diesel. Whilst still several years from start-up, there has been progress in recent months – Arcadia announced a recent investment in the Denmark project from a new clean energy fund led by German investor KGAL[51] and signed an agreement with U.S. electrolyzer manufacturer Plug Power.[52] The project is currently in the Front-End Engineering Design (FEED) phase, which typically involves activities such as preliminary design of the plant. The final investment decision (FID) is expected in mid-2024, after which the project will enter the detailed engineering design and construction phase.

The UK project is at an earlier stage of development but recently won funding from the UK Department for Transport under the £165m Advanced Fuels Fund (AFF) competition. The AFF awards developers grant funding to support the construction of SAF projects in the UK, with the aim of providing a signal for raising further investment to commercialize projects.[53] Arcadia is seeking to develop a standardized and modular e-fuels plant design, which could allow the company to replicate plants in other locations and quickly scale-up production capacity.

KEY PARTNERS

The company has received investment from several financiers and has established partnerships with technology licensors and EPCs to develop projects. Notably, Topsoe and Sasol will license RWGS + FT technology respectively for the Denmark project; the two companies benefit from several years of developing fuels production technologies, both separately and in collaboration. Arcadia has letters of intent in place with Sunclass Airlines and DCC Shell Aviation for supply of e-SAF from the Denmark problem.

KEY INVESTORS	TECHNOLOGY LICENSORS	EPCS
SWEN Capital Partners	PLUG POWER	T.EN TECHNIP ENERGIES
KGAL	TOPSOE	
	sasol	

51 Arcadia eFuels (2023), New Green Hydrogen fund KGAL ESPF 6 invests in Arcadia eFuels climate-neutral e-kerosene production facility. Available from: [link]

52 Plug Power (2023), Arcadia eFuels Taps Plug Power for 280 MW Electrolyzer System. Available from: [link]

53 UK Government (2024), AFF competition winners. Available from: [link]

E-FUEL DEVELOPER CASE STUDIES

Highly Innovative Fuels (HIF) Global

Role: e-fuels project developer
Headquarters: Houston TX, USA
Founded: 2016, by Andes Mining & Energy (AME)
E-fuels technology: E-methanol synthesis, Methanol-to-Jet/Gasoline (MTJ/G)

Number of employees: around 160
Operating plants: 1
Announced plants: 3 (as of 2024)
Planned production capacity: >1,000 kt/year

PROJECTS

HIF Global commissioned an e-fuels demonstration projects in December 2022 in the Magallanes region of Chile. The Haru Oni demonstration project is currently producing e-gasoline from renewable hydrogen made from wind energy and CO_2 captured from the atmosphere via the MTG pathway. March 2023 saw the first shipment of e-gasoline for use in Porsche's test and race circuits in the UK,[54] and a further 25,000 liters (around 6,600 gallons or 31 tons) was delivered in 2023. HIF has plans to significantly scale-up the Haru Oni project from the current capacity of 0.13 million liters per year to 550 million liters per year (around 145 million gallons or 400 kt per year) by the late 2020s.[55]

The company is planning several plants with similar capacities across Chile, USA and Australia from the late 2020s. These projects are currently focused on production of methanol, gasoline and jet fuel. HIF is working closely with renewable energy project developers, equipment suppliers, and technology licensors to progress their projects, and has been engaging with potential offtakers for supply of fuels, such as Japanese oil and gas player Idemitsu Kosan.[56]

KEY PARTNERS

HIF Global is backed by investors including Porsche, AME and Baker Hughes. HIF is partnered with Siemens for the electrolysis and e-methanol synthesis section of the Haru Oni plant and with ExxonMobil for the MTG section. Other technology licensors have been engaged for future projects, including Topsoe (e-methanol synthesis) and HoneywellUOP (MTJ) for the planned plant in Matagorda TX, USA.

KEY INVESTORS

PORSCHE
AME
Baker Hughes
EIG GLOBAL ENERGY PARTNERS

TECHNOLOGY LICENSORS

SIEMENS
ExxonMobil
TOPSOE
Honeywell UOP

EPCS

Honeywell UOP
BECHTEL

54 Renewables Now (2023), HIF Global sends commercial shipment of e-fuels to Porsche in UK. Available from: [link]

55 Porsche AG (2022), eFuels pilot plant in Chile officially opened. Available from: [link]

56 Idemitsu Kosan (2023), MOU with HIF Global for Strategic Partnership in the Field of e-fuels. Available from: [link]

4.2 HOW MUCH E-FUEL PRODUCTION CAPACITY WILL BE AVAILABLE IN THE U.S.?

Due to technological advancements and increasing demand, e-fuels production capacity is expected to scale up considerably by 2040. However, project developers generally only announce new plants progressively as they move from the demonstration stage into commercial phase. The aim of this section is to estimate how fast e-fuels production capacity could scale based on estimates of project development rates.

4.2.1 RAMP-UP METHODOLOGY

The model uses ERM's in-house ramp-up model with inputs from our advanced fuels database to forecast the e-fuels production capacity in a bottom-up approach with two phases:

- **Development phase –** this consists of "real" capacity based on planned and operational capacity for each technology developer, as well as "forecasted" capacity based on assumptions about the pace of technology development, construction timelines and success rates based on industry knowledge.
- **Growth phase –** this assumes that the fuel pathway is mature and so future "forecasted" expansion is modelled based on historic trends. Average future commercial plant sizes for each technology are based on historic trends and academic studies.

Note that this is **not a projection of supply or of demand**, which will depend on production economics and policy support. Instead, the scenarios represent **how fast e-fuels plants could be built** based on current and potential level of developer activity and project development rates.

4.2.2 SCENARIO ASSUMPTIONS

A central and low scenario were developed, with the central scenario showing an ambitious but potentially realistic trajectory of production capacity based on historic trends, and the low scenario using a more conservative approach. A high scenario is not developed as a higher growth rate than the central scenario has generally not been observed in the renewable fuels industry. Key differences between these are:

- **Initiation rate**, which is the number of commercial projects that start construction per year, per developer, is more optimistic in the central scenario. This aligns with a scenario where there is increased investment and confidence in e-fuel projects, driven by government support, market demand, or advancements in technology.
- The **launch point** defines when the next technology stage (e.g. pilot, demonstration or commercial) is likely to start. In the low scenario, the start dates for the next technology stage are projected to be further in the future compared to the central scenario due to technological challenges or limited funding.
- The **success rate of a plant** is higher in the central scenario than in the low scenario, which accounts for challenges in starting up and reliably operating plants.

E-fuels capacity in the U.S. is modelled assuming it achieves a share of global capacity that is proportional to GDP per capita projections from OECD long-term forecasts. This is to represent a high-level link between economic growth and interest in investment and advancement of clean energy projects. However, in practice, the selection of e-fuel plant locations is influenced by other factors such as proximity to technology development, policy support, and feedstock availability, as detailed in Section 4.1.4.

4.2.3 PRODUCTION CAPACITY POTENTIAL IN 2030 AND 2040

The ramp-up model shows that e-fuels production capacity in the low and central scenario in 2030 could exceed current planned production capacity, as they account for any new e-fuels facilities that could be announced in the coming years with a start-up date in 2030 or before. By 2040, provided there was demand for e-fuels and supply was profitable, global production capacity could grow by 6-7 times in the low scenario to reach around 34 Mt/year (11.4 billion gallons/year)[57] and by 15-16 times in the central scenario to almost 82 Mt/year (27.5 billion gallons/year). In the U.S., capacity could reach 5.8 Mt/year (1.9 billion gallons/year) and 14 Mt/year (4.7 billion gallons/year) in the low and central scenario respectively by 2040, representing 22% of global production. For comparison, U.S. gasoline demand was around 376 Mt in 2022 (136 billion gallons) and this demand could decrease to between 300-165 Mt in 2040 (110-60 billion gallons) depending on different forecast scenarios.[30, 31, 32,58]

E-methanol synthesis, alcohol-to-hydrocarbon and e-FT synthesis technologies all play a strong role across both scenarios:

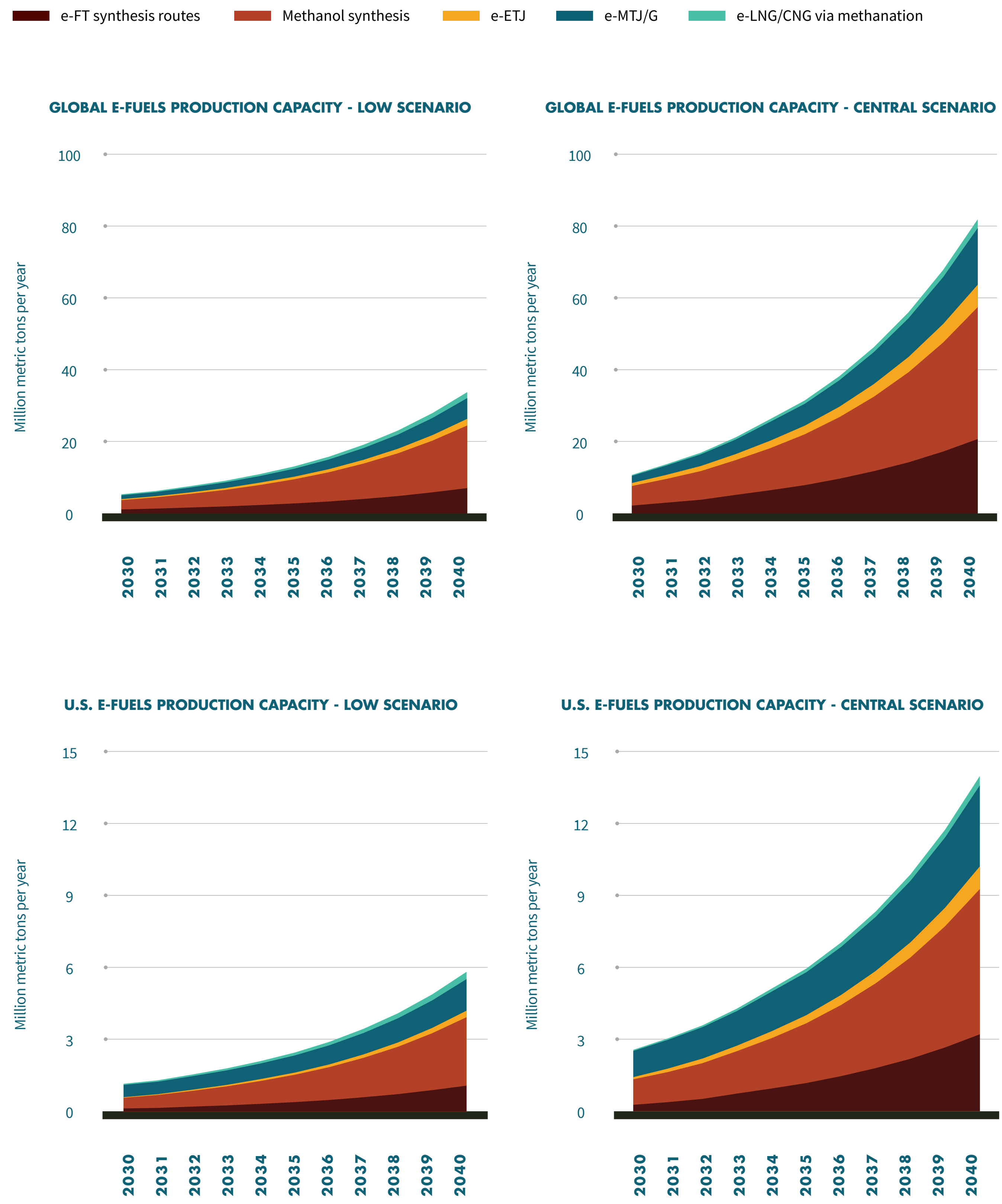
- **E-methanol synthesis** is projected to increase in production capacity to reach 33-38% of U.S. production capacity by 2040. This is driven by growing plant development activity today in response to the potential role of methanol in the transport sector for road, maritime, aviation (through conversion to jet fuel via MTJ) and chemicals, as identified in Section 4.1.2.
- **Alcohol-to-hydrocarbons** (principally e-methanol-to-jet/gasoline, MTJ/G) MTJ/G could account for 23% of U.S. production capacity by 2040, assuming further large projects such as HIF's are announced and reach start-up. However, given the limited number of developers pursuing e-ETJ today, there may be limited production capacity of this technology in future.
- **E-FT synthesis** production capacity could reach 15-18% of the mix by 2040 in the U.S.Many FT developers are likely to focus on production of jet fuel given growing SAF policy, particularly in the EU and UK.

While these production capacities reflect the potential of the industry to scale, policy support will have a significant influence on how much capacity will actually be built. Furthermore, the strength of policy driven decarbonization signals in specific transport modes (i.e. road, rail, shipping and aviation) will have impacts on which e-fuel production technologies will be selected, as well as the products that will be targeted. This impact will be further discussed in Section 6. (Figure 4-4)

57 Approximated using a conversion value of 335 gallon/tonne, based on an average density of liquid fuels.

58 EIA, (2022), U.S. gasoline demand. Available from: [link]

FIGURE 4-4. E-FUELS PRODUCTION CAPACITY GLOBALLY AND IN THE U.S.



IMPACTS FROM PRODUCT SLATE ON E-FUEL SUPPLY

As discussed in Section 1.4, e-fuel technologies often produce a range of products in varying percentages in varying amounts. This product slate could be altered to a certain extent to maximize the production volume of specific fuels, based on processing chemistry of e-fuel technologies, as well as plant design.

For example, in a jet optimized configuration, up to 75% of the output from a FT synthesis plant could be jet fuel with a smaller proportion of road fuels (e.g. diesel, naphtha). In a road fuel optimized configuration, over 90% of an MTG/J plant output could be gasoline. There is therefore a large range in the potential product output from future e-fuel facilities (Table 19). However, it is expected that some road fuels will be produced even in the jet fuel optimized configurations.

This product slate selection is mostly determined by plant economics, such as production cost and product revenue, as well as the level of demand for different e-fuels. This will be heavily influenced by how much policy support is available in each transport mode. The flexibility to change this product slate could enable project developers to better adapt to changing policy climates, allowing e-fuels plants to target transport sectors with the strongest markets signals.

TABLE 17. POTENTIAL RANGES IN E-FUEL PRODUCT OUTPUTS FROM FUTURE PLANTS

FUEL TYPE	2040 PRODUCTION CAPACITY – CENTRAL SCENARIO (Mt/year)			
	Road fuel optimized		Jet fuel optimized	
	(Mt/year)	(Billion gal/year)[59]	(Mt/year)	(Billion gal/year)
Road fuels (e-diesel, e-gasoline)	7.0	2.3	1.9	0.6
Jet fuel	0.6	0.2	5.6	1.9
Other (e-methanol, e-methane)	6.1	2.0	6.1	2.0

59 Approximated using a conversion value of 335 gallon/tonne, based on an average density of liquid fuels.

4.3 WILL THERE BE ENOUGH RENEWABLE ELECTRICITY AND CARBON DIOXIDE IN THE U.S. TO SUPPORT E-FUELS SCALE-UP?

The production of e-fuels requires considerable amounts of CO_2 and renewable electricity (RE). Whilst CO_2 (e.g. from the atmosphere) and renewable energy resources are theoretically unconstrained, they face constraints in practice due to market factors. For example, there are competing demands for renewable electricity to decarbonize the grid and there is growing interest in capturing CO_2 for geological storage, as storing the CO_2 will result in lower net emissions than recycling it to produce a combustible fuel.

This section estimates the renewable electricity, renewable hydrogen, and CO_2 feedstock requirements to achieve the current and planned e-fuels production capacities in the U.S. and globally. This is compared to the current and technical potential of renewable electricity and CO_2 in the U.S. to understand potential e-fuels supply constraints.

4.3.1 RENEWABLE ELECTRICITY

The electricity required for e-fuels is very small, less than 1%, compared with U.S. renewable electricity generation today. Operating the five planned facilities in the U.S. at full capacity could require around 470 GWh/year renewable electricity and 0.4 Mt/year renewable hydrogen by 2030. If e-fuels production capacity could ramp up to 6-14 Mt/year

FIGURE 4-5. OPERATING UTILITY-SCALE ELECTRICITY GENERATION FACILITIES IN THE U.S., AND RENEWABLE ENERGY RESOURCE POTENTIAL[62,63]

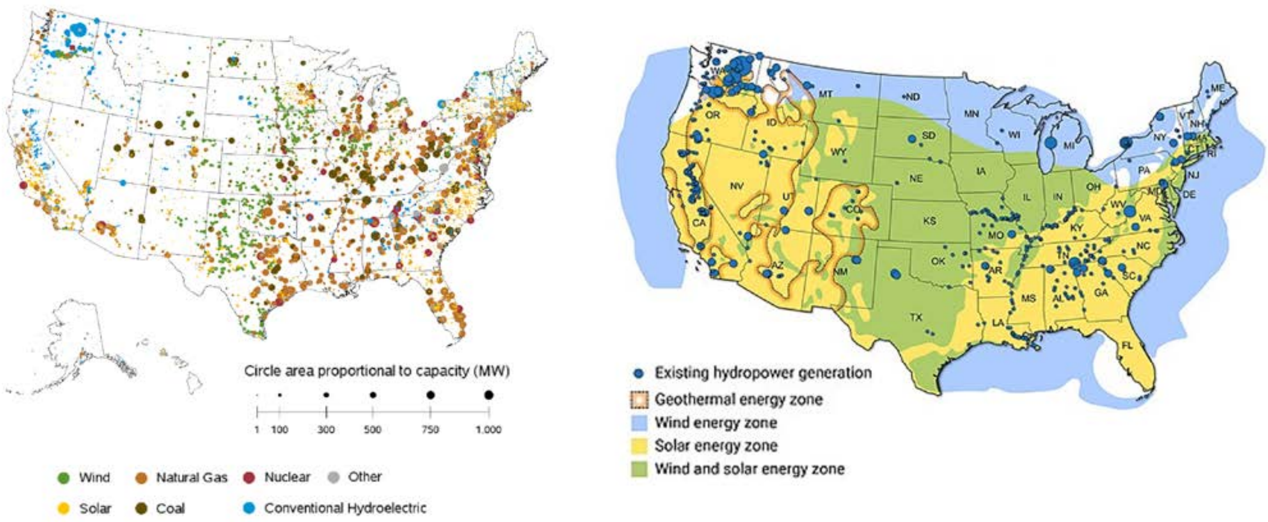


TABLE 18. RENEWABLE ELECTRICITY GENERATION BY TOP 5 U.S. STATES[64]

STATE	RENEWABLE ELECTRICITY GENERATION (GWh/year)	MAJOR RENEWABLE ENERGY SOURCES
TX	157,000	Wind, solar
IL	117,000	Hydro
CA	97,400	Solar, wind
WA	90,800	Hydro
PA	83,800	Wind, hydro
All U.S. states	890,000	

as in our model, this would require 3,600-9,900 GWh/year renewable electricity and 3-7 Mt/year hydrogen. U.S. renewable generation is currently around 890,000 GWh,[60] with wind, hydropower and solar representing 48%, 29% and 16% respectively.[61] Figure 4-5 below shows the geographical distribution of operating utility-scale (at least 1 MW) electricity installations in the U.S. as of November 2023, compared with a map of renewable energy 'zones' in the contiguous U.S. Wind and solar projects are generally located in zones with high wind and solar potential, and new capacity continues to be announced in these zones. Texas and California lead on solar and wind capacity respectively, having connected a further 19 GW cumulatively in 2023. They are currently in the top three of U.S. states for renewable energy generation as seen in Table 18, alongside Illinois.[62, 63, 64]

60 International Renewable Energy Agency (2023), Country Rankings. Available from: [link]

61 EIA (2023), Electricity generation, capacity, and sales in the U.S. Available from: [link]

62 EIA (2023), Preliminary Monthly Electric Generator Inventory. Available from: [link]

63 U.S. National Renewable Energy Laboratory (2022), Renewable Energy Resource Assessment Information for the U.S. Available from: [link]

64 EIA (2022), Historical State Data. Available from: [link]

TABLE 19. TECHNICAL RENEWABLE ENERGY POTENTIAL IN THE U.S.

RE SOURCE	TECHNICAL POTENTIAL (GWh/year)	COMMENTS
Solar	386,646,000	Includes solar photovoltaic (PV), concentrated solar power (CSP) and distributed PV
Wind	48,464,000	Includes onshore and offshore wind
Geothermal	24,818,000	-
All sources	463,395,000	Includes hydropower, tidal power, and biomass energy

The 3,300-9,900 GWh/year required by 2030 for e-fuels is an even smaller percentage of estimated U.S. renewable electricity generation in 2030, which is over 6,000,000 GWh/year under EIA AEO scenarios. The U.S. has an even higher technical renewable energy potential, which represents the resource that is effectively available based on factors such as average wind speeds and solar radiance, as well as topographic, environmental or land-use constraints. A report by the U.S. National Renewable Energy Laboratory (NREL) summarizes the results of 30 studies on the technical renewable potential in the U.S. (Table 19). This shows that existing and future renewable electricity generation capacity is a fraction of the potential availability, leaving significant opportunities for additional renewable energy development.

Similarly, the electricity required for e-fuels production in the U.S. is a small fraction of both current renewable generation and the total technical potential. Therefore, the physical availability of renewable energy resources will not constrain e-fuels capacity. Instead, it will be economic and market factors that influence both the ability to develop additional renewables projects and the amount available for e-fuels:

- **Costs –** The reduction in levelized cost of renewable energy (LCOE) has been a key driver for growth over the past 10-15 years.
  - The LCOE of solar and wind is already competitive with fossil fuels like natural gas in parts of the U.S. when considering tax incentives[65], which will lead to further growth in future. The AEO expects renewable generation to grow to 44% of the mix by 2050.
  - However, in the short-term, factors such as inflation and supply chain constraints (e.g. availability of materials for building solar plants and wind farms) can limit the rate of project development.
- **Supply chain constraints –** Availability of the raw materials required for renewable energy projects, such as rare earth metals in wind turbines, may face constraints due to limited supply and competing demand from other sectors. Supply of electricity transmission components and infrastructure may also limit how much

65 EIA (2022), Levelized Costs of New Generation Resources in the AEO (2022). Available from: [link]

renewable energy can be connected to the grid or directly to e-fuels projects.

- **Policy and regulation –** Policy support, such as investment and production TCs, have contributed significantly to the reduction in renewables production costs and continues to be a key driver of uptake. As discussed in Section 3, requirements such as incrementality, deliverability and temporal correlation could further incentivize the development of renewable hydrogen projects, including those for e-fuels production.
- **Competing demand –** E-fuels production must compete with other end-uses for both new renewable electricity generation and renewable hydrogen.
  - EIA AEO scenarios expect demand for RE to grow most significantly in the transport sector and in the residential and commercial sectors.
  - Demand for renewable hydrogen is also expected to grow in the transport and industrial sector for use as energy and feedstock. Clean hydrogen production (including via renewable electrolysis, and steam methane reforming with carbon capture and storage (CCS), also known as blue hydrogen) could reach 20 million metric tons per year (Mt/year) by 2040 based on a DOE outlook.[66] E-fuels would account for 33% of this in the central scenario.

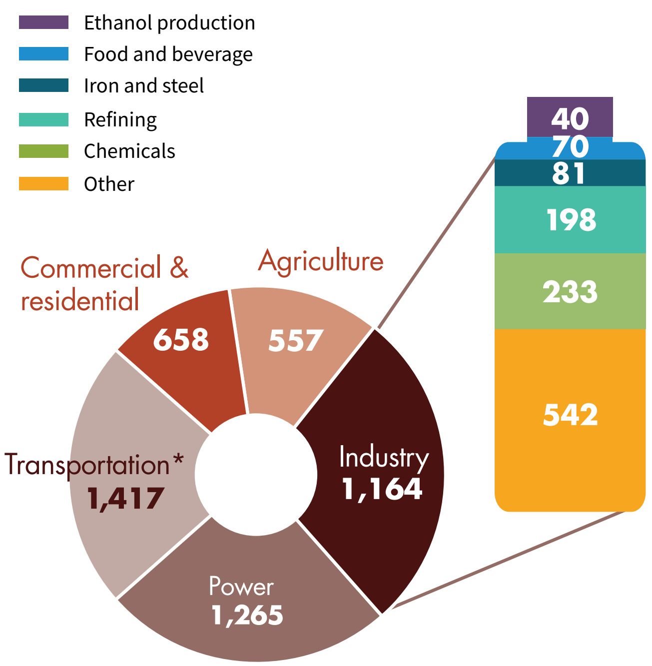
There is high uncertainty in how these factors could constrain the growth of renewable energy, and whether this will limit e-fuels production.[67] However, it is important to note that renewable energy is not a finite resource and significant demand for e-fuels under stronger policy support could drive the development of additional renewables.

4.3.2 CO_2

E-fuels require a source of CO_2, which can be captured from the waste gas streams of industrial point sources or directly from the atmosphere via DAC. Point sources with high concentrations of CO_2 have the lowest capture costs, such as from ethanol plants. Achieving the planned e-fuels production capacity by 2030 would require around 3 Mt/year CO_2. By 2040, the CO_2 requirements could grow to 18-47 Mt/year.

U.S. CO_2 emissions were around 5,000 Mt/year in 2022,[68] of which the industrial and power sectors cumulatively represent 48% of emissions (around 2,400 Mt/year) as shown in Figure 4-6.[69] The chemicals, fuels refining, iron and steel sectors together represent 44% of industrial emissions.[70]

FIGURE 4-6. U.S CARBON DIOXIDE EMISSIONS BY SECTOR IN 2022.



Million metric tonnes per year

**Emmisions from international aviation and shipping are excluded*

66 DOE (2023), Clean Hydrogen Outlook and Roadmap. Available from: [link]

67 Mærsk McKinney Møller Center for Zero Carbon Shipping (2023), Will renewable electricity availability limit e-fuels in the maritime industry? Available from: [link]

68 Friedlingstein et al. (2023), Global Carbon Budget. Available at: [link]

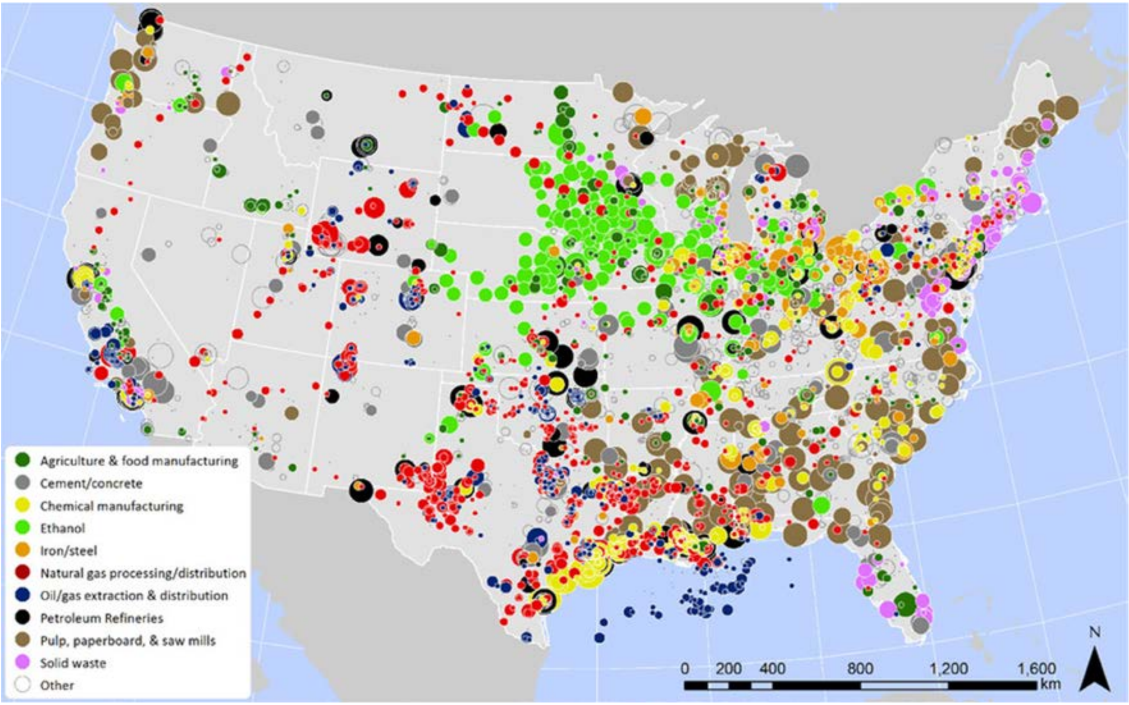
69 EPA (2022), Sources of Greenhouse Gas Emissions. Available at: [link]

70 EIA (2022), AEO (2022). Available at: [link]

Current annual CO_2 emissions from the industrial and power sectors are more than sufficient to meet the CO_2 required for e-fuels production in the U.S. in 2030 and 2040, representing 0.13% and 0.6-1.6% respectively. However, the amount of CO_2 that can be economically accessed will be much lower in practice than the total amount emitted, and depends on several factors:

- **The wide geographical distribution** of industrial and power sector point sources across the country. There are many sources of industrial CO_2 emissions in the U.S., with concentrated areas of high industrial emissions in parts of the Gulf Coast and Southern California (Figure 4-7).[71]

FIGURE 4-7. MAJOR INDUSTRIAL POINT SOURCES IN THE U.S.



- **Availability of capture and transport infrastructure** affects the amount of CO_2 that can physically be delivered to e-fuels plants.
  - Capture technologies are in commercial operation today, with many technology developers active in this space. There are 15 operational CCS facilities in the U.S. currently. The barriers to further development of capture infrastructure are largely commercial in nature rather than technical.
  - Further development is required in processing and pipeline infrastructure to ensure CO_2 can be effectively accessed. The cancellation of Navigator's planned Heartland Greenway pipeline is one setback to the security of CO_2 supply for the U.S. e-fuels industry, including developer Infinium who have a Memorandum of Understanding with Navigator for supply of up to 0.6 Mt/year CO_2. Many developers are seeking to establish CO_2 supply agreements directly with industrial players at sites to make use of existing infrastructure.

71 Los Alamos National Laboratory (2018). Available from: [link]

- Competing **demands** for CO_2 from other end uses may limit the availability of CO_2 for e-fuels production.
  - CO_2 demand in North America is estimated at around 68 Mt/year, of which fertilizer production, enhanced oil recovery (EOR) and the food and beverage industry represent the largest uses.[72,73] Global CO_2 demand is expected to grow by around 1.7% per year with increasing demand from EOR and chemicals manufacturing.
  - CCS to decarbonize existing power generation or industrial processes is another competing 'end use' to e-fuels production. There is growing interest in storage, with almost 100 planned CCS plants in the U.S., with a higher level of support under 45Q TCs than CO_2 utilization.
- **Policy and regulation** also play an important role in determining the overall availability of CO_2 as well as from which feedstocks e-fuels can be economically produced.
  - Decarbonization targets are likely to drive a reduction in point source CO_2 emissions from the industrial and power sectors, such as through support for CCS, energy efficiency measures, or renewable energy use. Power sector emissions have already been decreasing steadily since 2007 due to the phaseout of fossil power stations and the addition of renewable electricity generation.
  - There are currently no requirements on the source of CO_2 required for e-fuels to receive policy support in the U.S., so it is unclear which source of CO_2 can be used. For example, in the EU, e-fuels must be produced using sustainable biogenic CO_2 (such as from qualifying bioethanol plants) or atmospheric CO_2 in order to qualify for policy support after 2041. More information on this is provided in Section 6.

Atmospheric CO_2 is an alternative source of CO_2 for e-fuels production, meaning there is growing interest in developing DAC technology. One benefit is that DAC plants can be developed in any location, provided there are sufficient land and energy resources, allowing greater flexibility in where e-fuels plants can be developed. However, DAC is only at TRL 6-7 with a handful pilot or demonstration facilities in operation today, which are too small to support commercial e-fuels production. DAC still faces key technical and commercial barriers to scale-up, which add further costs and risks to e-fuels production (see Section 5.3.2). If DAC matures it could play an increasingly important role in e-fuels production from the 2030s onwards, provided the renewable electricity used to power it meets the criteria discussed in Section 3.1.

72 IEA (2019), Putting CO_2 to Use. Available from: [link]

73 S&P Global (2021), Carbon Dioxide Market Research. Available from: [link]

4.4 SUMMARY

What are the development trends of announced e-fuel projects?

There is currently a large focus on developing methanol synthesis, due to the relative ease of production (only one processing step), and the range of potential markets available for methanol or methanol derivatives. Drop-in fuels produced from alcohol-to-hydrocarbon and FT technologies are also being targeted, with a particular focus on SAF due to growing policy support.

The U.S. and Europe, particularly the UK, Denmark and Sweden, currently lead on number of planned commercial projects. Large projects are also planned in Chile and Australia. Proximity to technology development teams/HQs, policy support for low carbon fuels, access to cheap renewable electricity, and availability of funding support while the industry matures are the key factors that will determine project locations.

How much e-fuel production capacity will be available in the U.S.?

E-fuels production capacity is very small today as the majority of facilities are only at pilot or demonstration scale. However, based on announced commercial plants as of January 2024, e-fuels production capacity could grow to reach 0.9 million metric tons per year (Mt/year) in the U.S. and 4.3 Mt/year globally by 2030 (Table 20). ERM's ramp up model estimates that production capacity could continue to ramp up to potentially reach 6-14 Mt/year in the U.S. and 34-82 Mt/year, provided there was significant demand for e-fuels and supply is profitable for developers given policy support.

TABLE 20. E-FUELS PRODUCTION CAPACITY

E-FUELS TECHNOLOGY	PRODUCTION CAPACITY[1] (million metric tons per year)			
	2030[3] (based on announced plants)		2040 (based on ERM ramp-up model)	
	USA	GLOBAL	USA	GLOBAL
All e-fuels[2]	0.9 (0.3 billion gallon/year)	4.3 (1.4 billion gallon/year)	6-14 2-4.7 billion gallon/year)	34-82 (11.4-27.5 billion gallon/year)
e-Methanol synthesis	0.3	1.8	3-6	17-37
e-MTJ/G	0.5	1.2	1-3	6-16
e-ETJ/G	0.0	0.2	0.3-0.9	2-6
FT synthesis routes	N/A3	0.9	1-3	7-21
Methanation	0.1	0.3	0.3-0.4	~2
Fermentation + pRWGS	0.0	0.0	0.0	0

[1] Only includes plants with a publicly announced start-date, location, and production capacity.

[2] Total e-fuels production may not equal sum of individual technologies due to rounding.

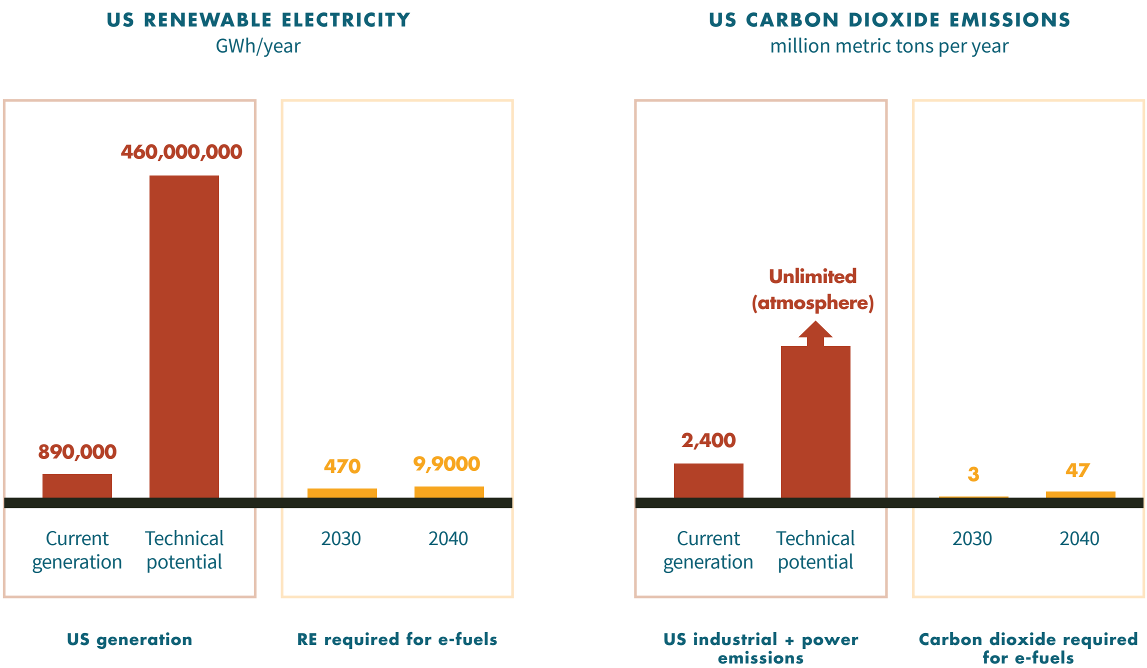
[3] Infinium's Roadrunnner facility planned for 2026 is yet to publicly announce production capacity.

Is there enough renewable electricity and CO_2 in the U.S. to support e-fuels scale-up?

Renewable electricity and CO_2 requirements to support planned U.S. e-fuels production are far lower than the current and technical renewable energy generation and CO_2 potential (Figure 4-8). E-fuels are therefore unlikely to face physical constraints on the availability of feedstocks, unlike biofuels.

However, other factors may affect the ability to develop additional renewable electricity capacity and affect the access to secure and economic sources of CO_2. Supply chain constraints could constrain growth of additional renewable generation, whilst policy requirements and demand from other sectors mean e-fuels must compete for generation. However, strong policy support and demand for e-fuels may drive the development of new renewables. For CO_2, DAC technology must also overcome significant commercial barriers before sufficient volumes of CO_2 can be captured cheaply to support e-fuels production.

FIGURE 4-8. U.S. RENEWABLE ELECTRICITY GENERATION AND CARBON DIOXIDE EMISSIONS AND REQUIREMENTS



Bars are not to scale

SECTION 5.

How much do e-fuels cost to produce and use?

Most e-fuel pathways are at early stages of development with commercial production not yet demonstrated. This means that the current and near-term production costs of e-fuels will be higher than fossil fuels and biofuels. It is crucial to assess the cost gap between e-fuels and conventional fuels to understand the economic feasibility of using them, to which production costs and policy premiums (discussed in Section 6.2) are key contributors.

This section gives projected production costs for different e-fuel pathways at different stages of their technical development. Uncertainties that impact these costs are factored in, and their impact on the overall cost of production is assessed. We also estimate future production costs, as technologies mature and become commercial. Finally, the cost of different e-fuels is put in the context of road transport decarbonization and compared against existing technologies.

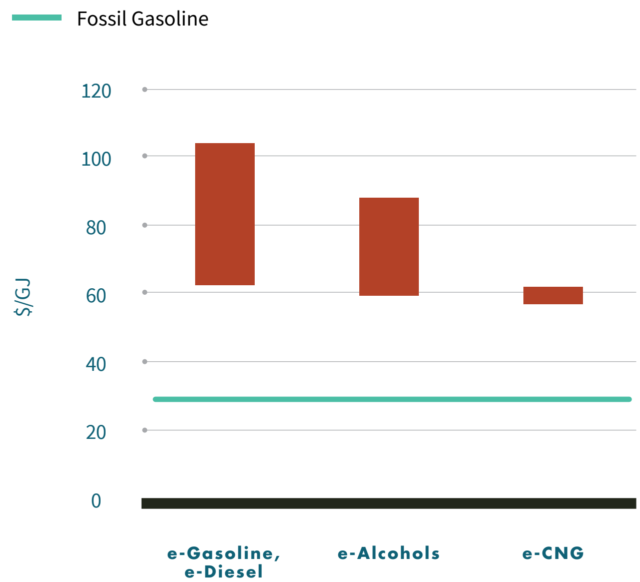
SECTION 5: KEY QUESTIONS

- What is the current production cost of e-fuel technologies?
- What affects e-fuels production costs?
- How much could costs come down in future?
- How much do e-fuels plants cost to build?
- What are the cheapest decarbonization options for the road transport sector?

5.1 WHAT IS THE CURRENT PRODUCTION COST OF E-FUEL TECHNOLOGIES?

The cost of producing e-fuels currently far exceeds that of producing fossil fuels. Compared to fossil gasoline, liquid e-fuels such as e-gasoline or e-diesel can cost 2.5-4 times more on an energy basis, whilst alcohols such as e-methanol or e-ethanol can cost 2.5-3.5 times more. These high costs are largely

FIGURE 5-1. NET LEVELIZED COST OF E-FUEL PATHWAYS



driven by the costs for producing hydrogen using renewable electricity, CO_2 capture costs, and the energy required for fuel processing. (Figure 5-1)

E-fuel technologies often produce more than one product which have different prices and levels of policy support, and all of which bring revenue to the plant. As a result, the production costs for e-fuels in this report are presented on a per GJ basis,[74] including those co-products. This represents the levelized cost, which is the total cost of building and operating the plant, per unit of e-fuel produced over an assumed lifetime.

In this section, costs are given for the FOAK plants for each technology, which represents the first commercial plant that demonstrates large-scale production. FOAK plants cost more than future commercial plants due to limited learnings, higher risks, and larger financing costs. For each technology, the planned FOAK plant can be found in the planned projects list in Appendix A, with all pathways estimated to open the FOAK plant between 2026-2028.

5.1.1 COST ASSUMPTIONS

The production costs in this analysis have been estimated through ERM modelling and literature data using the following key assumptions:

- **CO_2** captured near the plant and accounted for as a feedstock cost. For the scenarios, point-source CO_2 from cement production is assumed unless otherwise specified, with an additional DAC scenario assessed in the sensitivity analysis.
- **Hydrogen production** via PEM electrolysis onsite with costs shown respectively under capital expense (CAPEX), operational expense (OPEX), and feedstock (electricity). Hydrogen is assumed to be produced with renewable electricity via PPAs meeting additionality rules (i.e. Incrementality, deliverability and temporal correlation – see Section 3.1 for more details).
- **Electricity** for fuel processing is assumed to be grid electricity. These costs are accounted for in OPEX.
- **Heat** for fuel processing is assumed to be natural gas with industrial prices and is accounted for in OPEX.

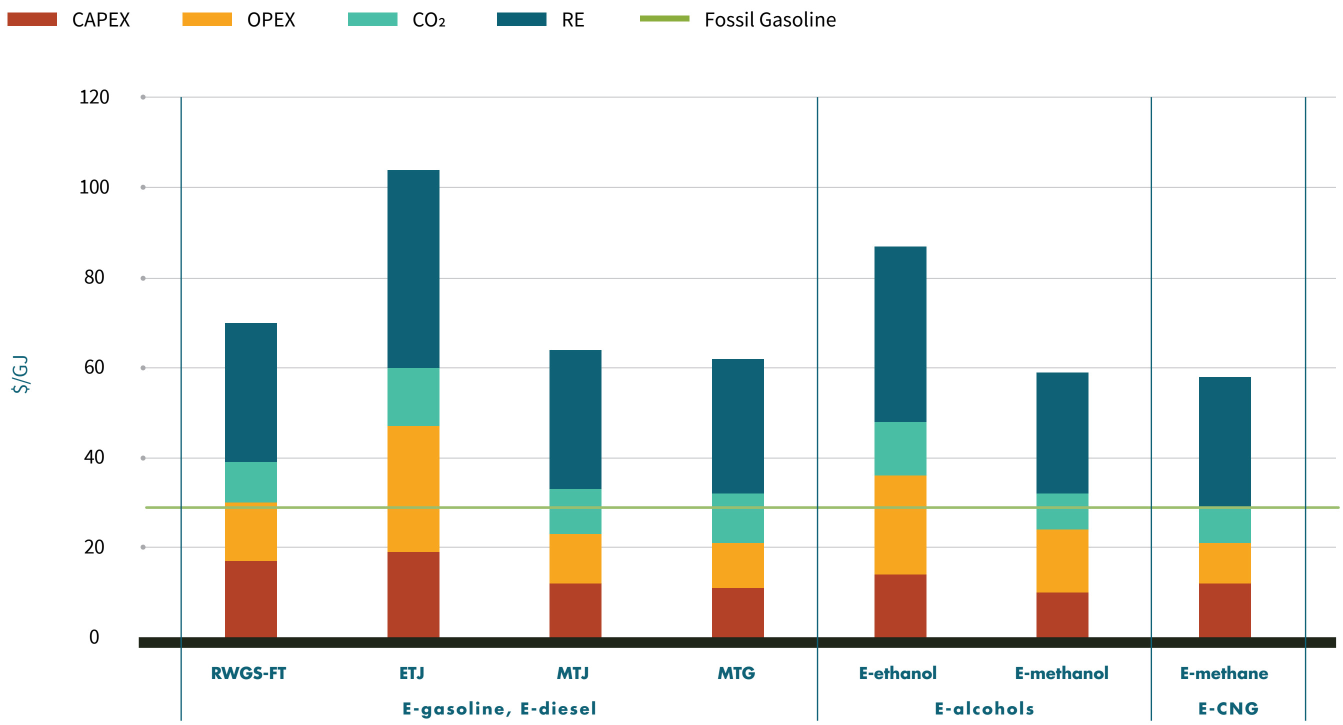
Detailed assumptions and sources are given in Appendix D.

74 Divide value by 0.16 to achieve cost per barrel.

5.1.2 E-FUEL PRODUCTION COST PER PATHWAY

For all e-fuel pathways, renewable electricity is the largest contribution to production costs. The variations between pathways are largely dependent on the amount of feedstock needed and the heat requirements. Pathways with more conversion steps generally have higher costs. (Figure 5-2)

FIGURE 5-2. NET LEVELIZED PRODUCTION COST PER GJ OF ALL FUELS PER PATHWAY AT FOAK



RWGS + FT

FT via RWGS can be at the lower end of the cost range for liquid fuels if heat integration is implemented. RWGS requires extremely high temperatures which can be costly in terms of external heat requirements, but this can be reduced through using heat from the FT synthesis step. FT produces wax that requires hydrocracking to convert to fuels, which adds additional capital expense (CAPEX) and hydrogen needs.

e-ethanol and e-ETJ

E-ethanol has higher costs than other pathways due to low yields of syngas fermentation, resulting in greater feedstock requirements. Syngas fermentation requires high energy inputs for processing due to the heat requirements of partial RWGS, which also leads to higher OPEX. Both e-ethanol and e-ETJ have relatively low TRLs and developer activity compared to the other routes, making it difficult to estimate potential costs. The costs involved with the final step of the ETJ process are similar to that of MTJ/G, but e-ethanol is the main driver for a higher overall cost for the integrated ETJ process.

e-methanol and e-MTJ/MTG

Methanol synthesis has low requirements for additional heat input, and a higher yield compared to ethanol synthesis, resulting in a lower cost jet and gasoline product through MTJ/MTG.

e-Methane

Methane production requires the most hydrogen per ton of fuel output of the technologies discussed. However, it does not require external heat sources and can potentially utilize its waste heat as well.

Another key factor driving cost difference between the production pathways is OPEX, or more specifically the natural gas consumption to provide heat for industrial processes within the plant. The amount of natural gas demanded by each pathway varies as some can reuse waste heat from some processes to use in others. Pathways with high degrees of heat integration such as RWGS + FT have a lower OPEX than pathways that do not, such as ETJ. This is discussed in more detail in Section 3.2.1.

5.2 WHAT AFFECTS E-FUELS PRODUCTION COSTS?

The main feedstock for e-fuel production is renewable electricity. This can be procured from a third-party at a fixed price or produced on-site. As feedstocks account for the majority of production costs, securing cheap supply is key to producing competitive e-fuels.

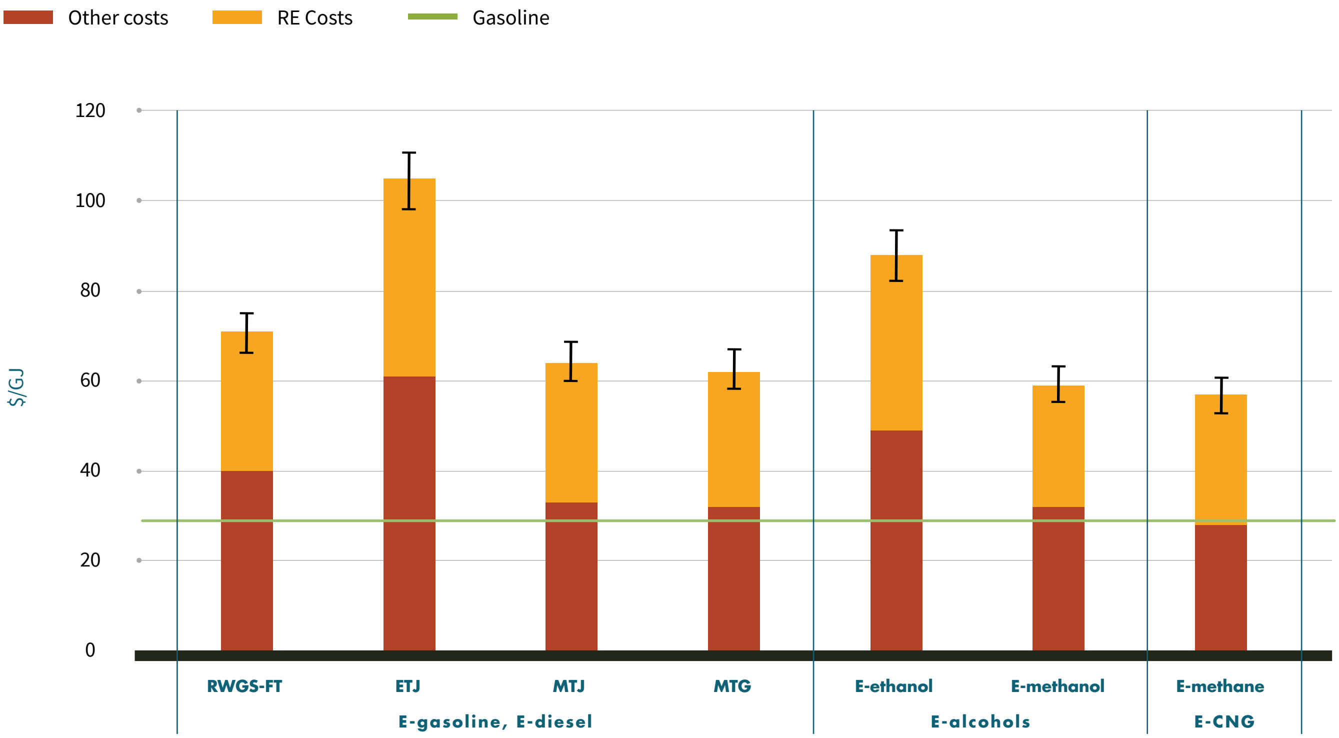
5.2.1 HYDROGEN AND RENEWABLE ELECTRICITY

The cost of green hydrogen is highly dependent on the cost of renewable electricity, as electrolysis is highly energy intensive. We analyzed several scenarios to understand the impact of different renewable electricity prices and availability on the levelized cost of e-fuels. Texas was chosen as a representative location of the e-fuels plants due to its availability of cheap renewable electricity. The electricity prices chosen in the scenarios reflect power purchase agreement (PPA) prices from the various grids that service Texas. We also varied the electrolyzer and plant utilization rates, explained further below.

TABLE 21. PRODUCTION COST SCENARIOS

SCENARIO	ELECTRICITY SOURCE	ELECTRICITY COST	ELECTROLYZER UTILIZATION RATE	PLANT UTILIZATION RATE	ONSITE HYDROGEN STORAGE
Low cost case	ERCOT average wind and solar	\$43/MWh \$12/GJ	85%	85%	No
Base cost case	Midpoint between low and high	\$49/MWh \$ 14/GJ	85%	85%	No
High cost case	MISO solar	\$55/MWh \$15/GJ	85%	85%	No
Partial utilization	ERCOT average wind and solar	\$43/MWh \$12/GJ	45% (based on offshore wind)	85%	Yes

FIGURE 5-3. E-FUEL PRODUCTION COST AT FOAK VARIATION IN LOW AND HIGH ELECTRICITY COST SCENARIOS



The FOAK production costs are 10-15% higher in the high-cost electricity scenario than in the low-cost electricity scenario. Pathways with high use of hydrogen per GJ of fuel such as methane have higher sensitivities towards electricity prices. (Figure 5-3)

The 45V Clean Hydrogen Production Tax Credit (PTC) proposes that renewable electricity must achieve hourly matching starting in 2028, which could have additional impacts on cost that will vary from project-to-project basis and require more detailed modelling.

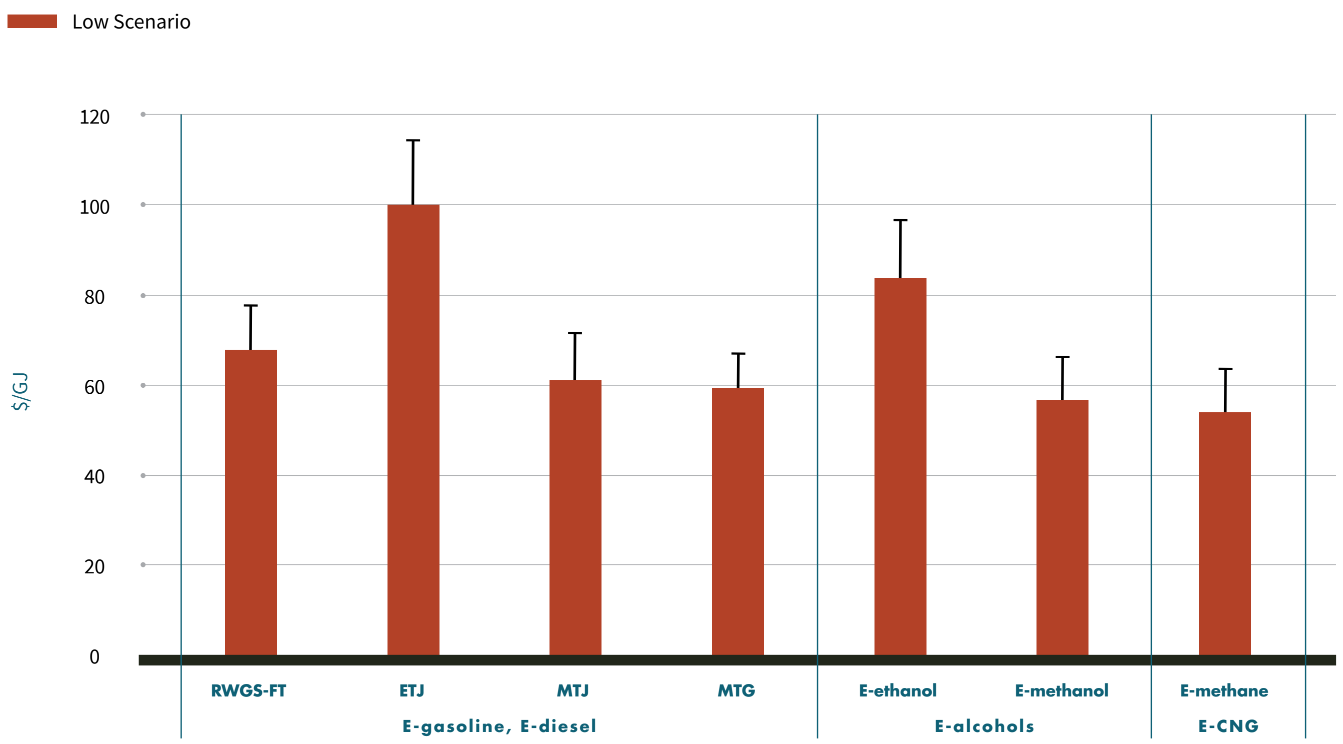
5.2.2 PLANT UTILIZATION

Plant utilization is defined as the proportion of time that the plant is running in a year. Low plant utilization means that the fixed costs of production (CAPEX and fixed OPEX) are spread out over fewer tonnes of fuel produced, and so higher levelized production costs. In the case of a non-grid connected configuration, where renewable energy is generated onsite, electrolyzers producing green hydrogen can only operate when renewable electricity is available.

One way to achieve a consistent supply of green hydrogen despite having intermittent renewable electricity is to use a larger fleet of electrolyzers accompanied by hydrogen buffer storage.

To show the effects of this, we analyzed a partial-utilization scenario. This scenario used low-cost renewable electricity with a capacity factor and electrolyzer utilization rate of 45%. It also included the construction of compressed hydrogen storage that can store enough green hydrogen for up to 50 hours of continuous plant operation, and roughly doubled the electrolyzer capacity. The additional cost of this scenario compared to the low-cost electricity scenario is shown in Figure 5-4.

FIGURE 5-4. INCREASE IN E-FUEL PRODUCTION COST AT FOAK IN PARTIAL UTILIZATION SCENARIO COMPARED TO LOW SCENARIO



5.2.3 CARBON DIOXIDE

Point source CO_2 capture refers to the process in which CO_2 is separated from a plant's exhaust gas or syngas stream to produce a concentrated stream of CO_2. Conversely, DAC directly extracts CO_2 from the atmosphere at any location. DAC is significantly more expensive as the CO_2 in the atmosphere is much more dilute than in plant exhaust gases.

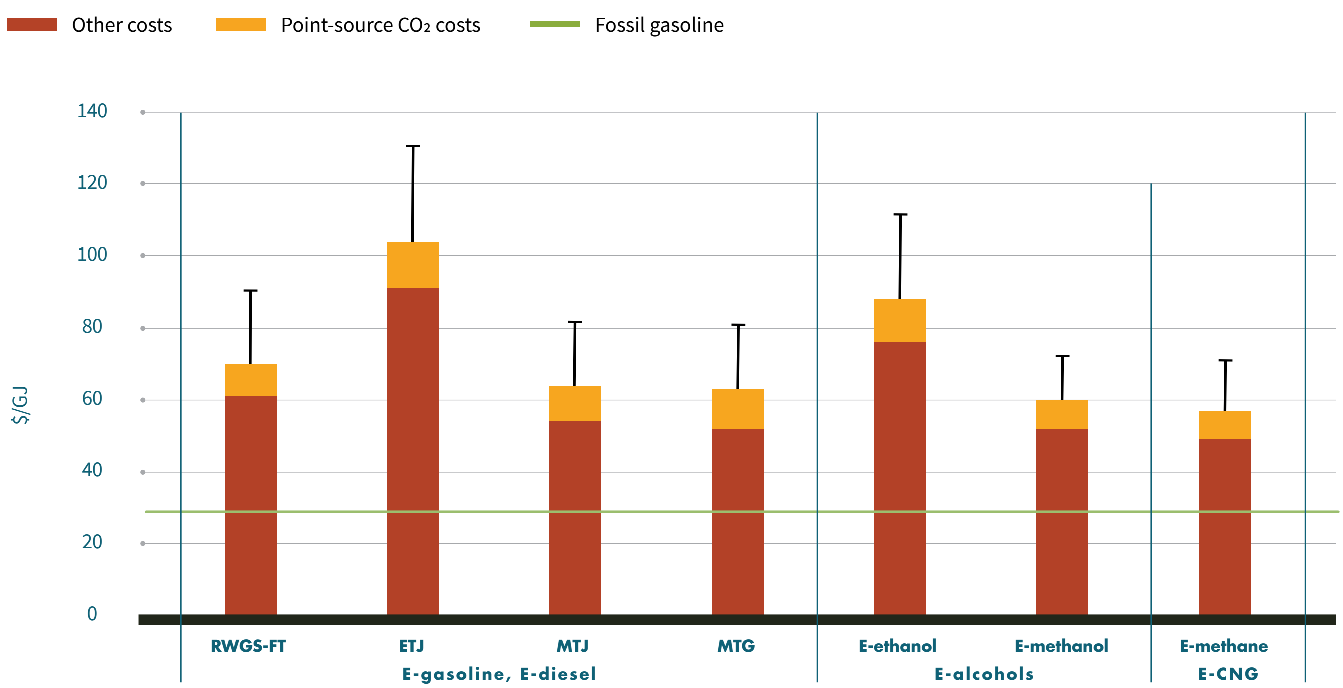
Figure 5-5 compares e-fuels produced from point-source captured CO_2 (base case) which is assumed to cost around \$120/ton CO_2 and from DAC assumed at around \$290/ton CO_2. Given the large range in CO_2 costs, net levelized costs increase by a significant 30-40% when using DAC.

5.2.4 PROCESSING ENERGY

The source of process energy has the largest impact on production costs for pathways with the highest energy needs. Natural gas is assumed in the base case, but renewable options are available but could be significantly more expensive as illustrated below. Therefore, as mentioned in Section 3.2.2, whether they will be utilized will depend on the availability of renewable electricity and green hydrogen, as well as plant economics and how much additional policy drivers are there to achieve further emission reductions.

- **Renewable electricity** could be sourced from onsite generation or via PPAs. However, electric heating technologies that could meet the high temperature demand of some e-fuel processes are relatively immature though cost could come down in the future.
- **Green hydrogen**, this could be produced on site or purchased from third parties. Green hydrogen is currently much more expensive than natural gas or renewable electricity. The cost could be \$3.5/kg in the U.S. by 2030 in an optimistic case,[75] equating to a heating cost of ~27 U.S.\$/GJ (around 3.3 times higher than natural gas heating).[76]

FIGURE 5-5. "FOAK PRODUCTION COST INCREASE WITH USE OF CO_2 FROM DAC



75 Value calculated in model.

76 The Midwest USA is assumed, prices from EIA (2024), Short term energy outlook (Natural Gas). Available from: [link]

It is unlikely that renewable electricity and green hydrogen will be readily available for FOAK e-fuel plants, as such, the cost analysis of using renewable energy for fuel processing is only carried out for e-fuel production costs in 2040.

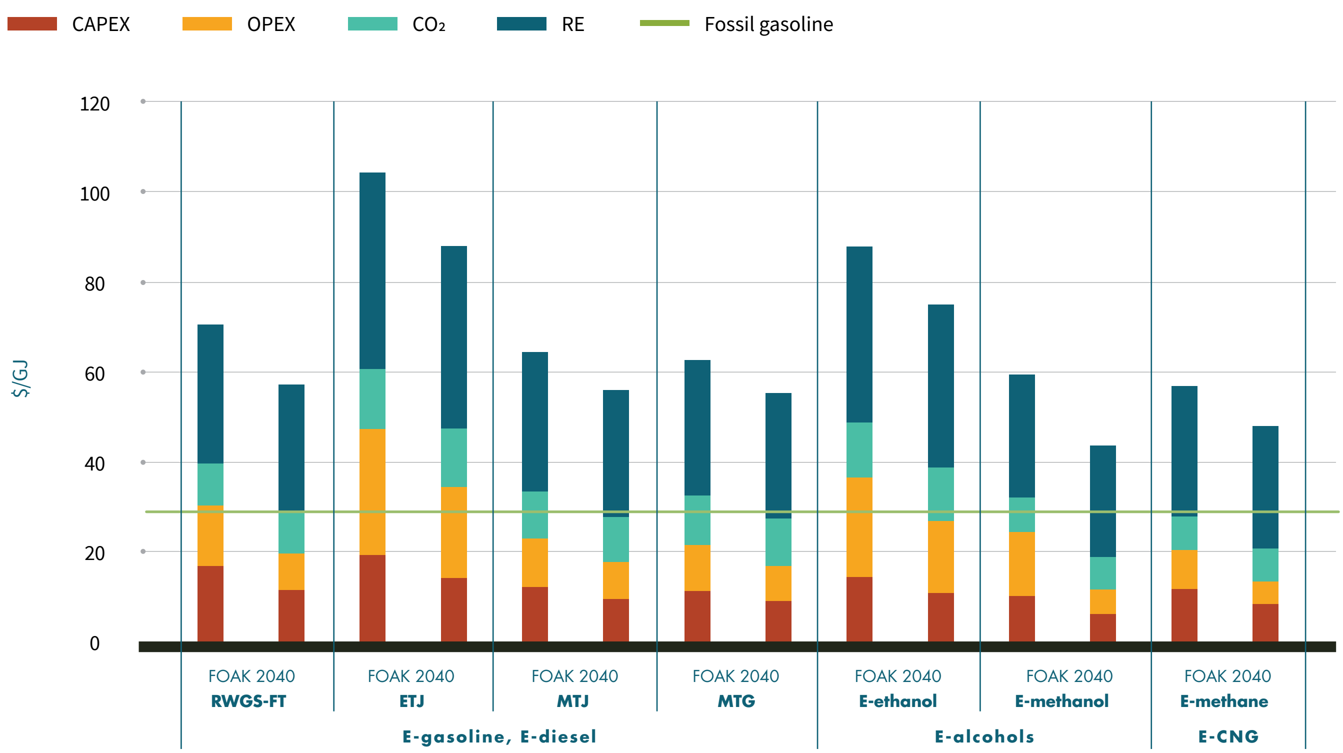
5.3 HOW MUCH COULD COSTS COME DOWN IN THE FUTURE?

As more e-fuel plants are built and the technology moves from FOAK to Nth-of-a-kind (NOAK) plant, the costs of producing e-fuels will decrease. NOAK is used to describe plants that are already technically and commercially mature, and therefore have limited scope for further cost reductions. NOAK plants are usually larger than FOAK plants and given advantages of scale, can produce fuels at a lower levelized cost. By 2040, it is assumed that all fuel production pathways have reached NOAK status. (Figure 5-6)

E-fuels production costs fall by 2040 for all pathways considered, with the largest reductions for e-methanol and RWGS + FT at 27% and 19% respectively. By 2040, e-methanol and drop-in e-fuels via RWGS + FT and MTG/J could have the lowest production costs:

- **CAPEX reduction –** Increasing the size of the plants leads to economies of scale savings, which results in lower CAPEX
  - Every additional plant built, especially during early stages of development, leads to technical learnings that result in construction and operations being optimized for improved efficiencies. Associated cost reductions also occur for carbon capture, renewable energy generation and hydrogen production, all of which contribute to e-fuel production's OPEX.
  - E-methanol sees the largest decrease in CAPEX of around one-third, due to the potentially very large future plant sizes and associated economies of scale savings. E-MTJ and e-MTG are expected to have a more modest reduction of 13% and 12% respectively.

FIGURE 5-6. NET LEVELIZED PRODUCTION COSTS REDUCTION FROM FOAK TO 2040 FOR ALL E-FUEL PATHWAYS

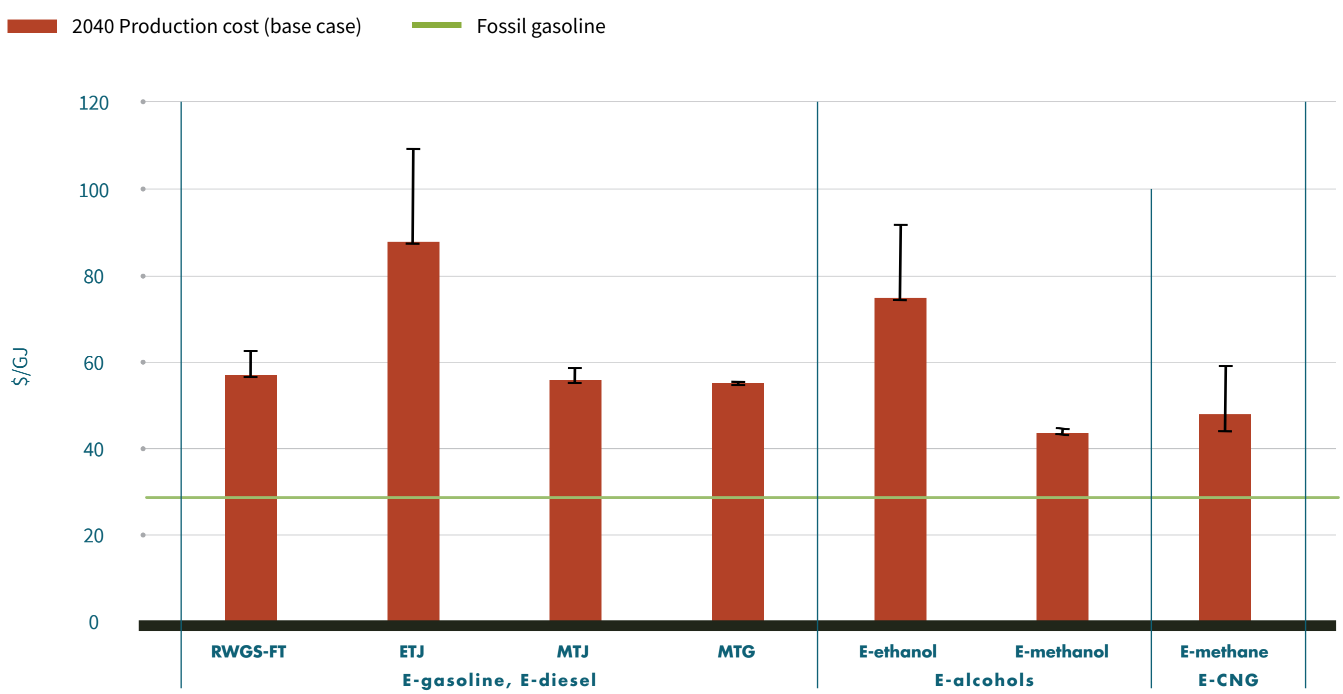


- **OPEX reductions:**
  - Savings from technical learnings and economies of scale also apply to maintenance and labor costs with increasing plant size, resulting in decreased OPEX on a levelized basis.
- **Feedstock costs reduction –** Hydrogen and CO_2 contribute significantly to levelized production costs:
  - Hydrogen production cost reduction is driven by falling electrolyzer costs due to cost savings from material innovations and economies of scale from increased manufacturing capacity.
  - CO_2 capture technologies also have scope for CAPEX and OPEX reductions. DAC sees the largest CAPEX reduction as it is still in the early stages of development. However, continued reliance on natural gas for steam requirements combined with increasing gas prices may offset OPEX reductions.

Whilst levelized costs may reduce significantly for e-fuels, all production pathways remain higher in 2040 than the current cost of fossil gasoline. Drop-in e-fuels via RWGS + FT and MTJ remain 2 times the fossil gasoline cost whereas ETJ is around 3 times. Other fuels such as e-methanol are closer to fossil gasoline but are still 1.5-2 times more expensive.

If renewable energy (i.e. renewable electricity instead of grid electricity and green hydrogen instead of natural gas) is also used for fuel processing, the NOAK costs for e-fuels can increase between 1-24% depending on the production pathway. Those with higher heat requirement, such as e-ethanol and ETJ pathways will see the largest cost impact, whereas exothermic pathways (i.e. MTG, MTJ and e-methane) will see little impact from switching to green hydrogen for heat. It is assumed that renewable electricity prices will be comparable to grid electricity given the abundant resources availability of wind and solar. Both electricity prices are assumed to remain the same in the future given high degrees of uncertainty in price forecasts. (Figure 5-7)

FIGURE 5-7. 2040 PRODUCTION COST INCREASE WITH USE OF RENEWABLE ENERGY FOR FUEL PROCESSING

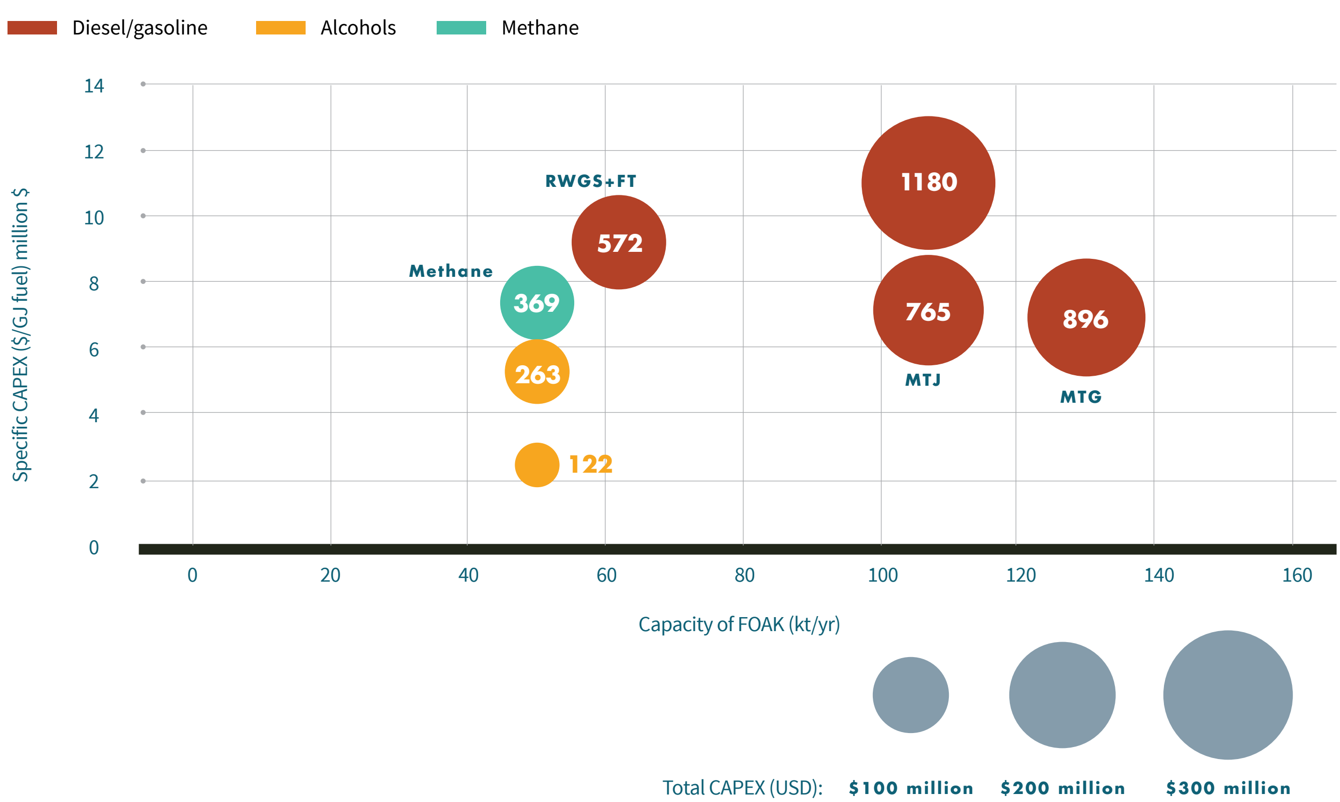


5.4 HOW MUCH DO E-FUELS PLANTS COST TO BUILD?

The levelized cost of capital investment of a commercial scale plant depends on the type of process equipment required and the typical size of the plant. FOAK levelized capital costs are in the range of $12-20/GJ all products (Figure 5 8). Pathways with fewer processing steps generally have lower CAPEX requirements:

- **E-methanol** has the lowest CAPEX requirements as this pathway only includes hydrogen production and methanol synthesis, which is cheaper than most other fuels synthesis processes (Figure 5-8).
- **E-MTJ and e-MTG** pathways have a higher specific CAPEX than e-methanol production alone as they require an additional conversion process to produce jet.
- **E-methanation** has the third lowest specific CAPEX because like methanol synthesis, it only involves one fuel synthesis process. Despite the simpler process and producing an energy-dense fuel, an e-methanation plant is around 3 times the capital cost of a methanol synthesis for the same capacity which increases its specific CAPEX to similar costs as MTJ and MTG.
- **E-ethanol and ETJ** is almost twice as expensive as an e-methanol plant. As a result, ETJ plants have the highest CAPEX requirements (around 60-70% more intensive than MTJ/G pathways).
- **FT via RWGS** has the second highest CAPEX requirements, which are mostly associated with the RWGS + FT reactors. The downstream hydrocracking process to upgrade FT waxes to drop-in fuels is a well-established petrochemical technology with a relatively minor contribution to overall CAPEX.

FIGURE 5-8. FOAK CAPACITY AND SPECIFIC CAPEX FOR EACH E-FUEL PATHWAY.
(BUBBLE SIZE AND LABEL REPRESENTS TOTAL CAPEX IN $USD MILLIONS).



5.5 WHAT ARE THE CHEAPEST DECARBONIZATION OPTIONS FOR THE ROAD TRANSPORT SECTOR?

The cost of alternative technologies is also likely to decrease over time as they become commercial. In this section, the cost of using e-fuels in cars and heavy-duty vehicles is compared against other technologies which are being developed for the road sector (See Section 2.2). The key assumptions made in this section are listed below – see Appendix C for the specific values used and the sources for these:

- Costs include fuel/electricity, vehicle purchase price and maintenance. Taxes, financing costs and residual value are not included in this analysis.
- Cost is calculated per mile, based on a typical total vehicle lifetime (200,000 miles for cars, 1,000,000 miles for HDV). By accounting for the whole vehicle life, the residual value of the vehicle is assumed to be negligible.
- Subsidies and tax rebates are not included. This includes fuel subsidies (e.g. Inflation Reduction Act (IRA) tax incentives) as well as purchase price subsidies for low emission vehicles.
- Vehicle costs and fuel consumption statistics are for a compact SUV for cars (e.g. Honda CR-V, Kia Sportage), and for a Class 8 Semi for HDVs.
- For existing ICEVs, no vehicle cost and a total mileage of half of a new ICEV are assumed.
- For new ICEVs, all new vehicles have the same lifetime mileage as current ICE vehicles, and vehicle lifetimes are assumed to not increase in the future.[77]
- Wider infrastructure costs are not included in these calculations (e.g. grid reinforcement costs, charger purchase and installation, transportation and storage of e-fuels, biofuels or natural gas).

5.5.1 COSTS FOR CARS

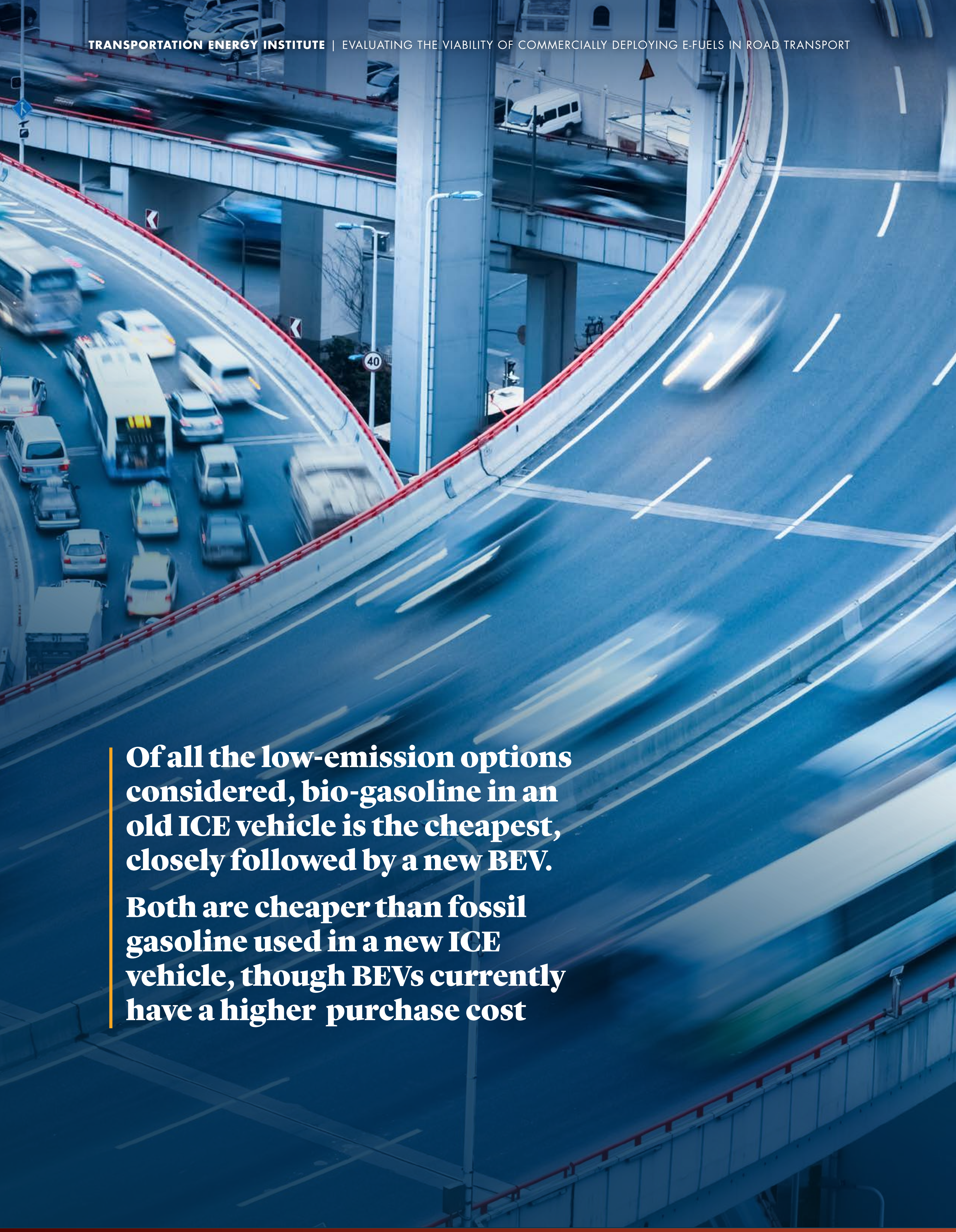
Based on production costs from a First-of-a-Kind (FOAK) plant, using e-fuels currently results in a higher cost per mile for cars compared to most of the other powertrain options, and biofuel alternatives (Figure 5-9).

- E-gasoline in a new ICE vehicle has the highest cost per mile, like a FCEV running on hydrogen, around 40% higher per mile than fossil gasoline.
- Costs are lower for e-gasoline in a HEV or PHEV (which have better fuel economy) and e-gasoline in an old ICE vehicle (which does not have a vehicle purchase cost) compared to e-gasoline in a new ICE vehicle, though all these options are still more expensive than a BEV or bio-gasoline in an old ICE vehicle.
- Of all the low-emission options considered, bio-gasoline in an old ICE vehicle is the cheapest, closely followed by a new BEV. Both are cheaper than fossil gasoline used in a new ICE vehicle, though BEVs currently have a higher purchase cost (which is then offset by lower running costs over the vehicle's lifetime).

By 2040, costs reduce for all options as new vehicles become more efficient and the price of alternative powertrains reduce. However, e-fuels remain more expensive than most options though the price gap reduces.

- E-gasoline in a new ICE vehicle remains the most expensive option, but the cost gap to a new ICE vehicle using fossil gasoline narrows to 25-30% higher.
- E-gasoline in a HEV, PHEV or old ICE is still cheaper than in a new ICE, though the cost of these three per mile is still higher than a BEV or bio-gasoline in an old ICE.

77 Vehicle lifetime may increase in the future as vehicle reliability increases and safety advancements mean fewer vehicles are scrapped prematurely. However, this is not considered in these cost calculations for simplicity.



Of all the low-emission options considered, bio-gasoline in an old ICE vehicle is the cheapest, closely followed by a new BEV.

Both are cheaper than fossil gasoline used in a new ICE vehicle, though BEVs currently have a higher purchase cost

- BEVs are now the cheapest low carbon transport option, closely followed by bio-gasoline in an old ICE vehicle.

From this comparison, it was found that for LDVs:

- From now until at least 2040, running an existing gasoline ICE car will be cheaper than switching to e-gasoline or purchasing a new vehicle of any type.
- Additional policy incentives are therefore required to incentivize consumers to either buy a new alternative powertrain vehicle or use a low carbon fuel in their existing vehicle.
- BEVs are cheaper per mile than new cars running on fossil gasoline both currently and in 2040, so policy supporting BEV uptake where possible is likely to be the cheapest option for consumers and policy makers.
- Low carbon fuels may still be useful in cars in existing ICE vehicles and in situations where BEVs are either unavailable or unsuitable. Given e-gasoline is more expensive than bio gasoline both now and in 2040, additional policy support will be needed for e-fuels compared to biofuels to be cost-competitive.

FIGURE 5-9. 2025 AND 2040 CAR COSTS PER MILE BY POWERTRAIN AND FUEL

5.5.2 COSTS FOR HDVS

Similar current cost trends are present for e-fuels compared to other options for a semi-trailer HDV (Figure 5-10):

- E-diesel is one of the more expensive options, only cheaper per mile than a FCEV running on hydrogen. The cost per mile of a new diesel ICE vehicle running on e-diesel is approximately 50-60% higher than running on fossil diesel.
- The cost per mile for e-diesel options is dominated by the price of fuel, similar to bio-diesel options and NGVs. For BEVs, the cost per mile is dominated by vehicle purchase costs, whilst FCEVs have both high vehicle purchase costs and fuel costs.
- The cheapest low emission option is an NGV with bio-CNG, closely followed by bio-diesel in an existing ICE vehicle and a BEV charging exclusively at depots. All of these low emission options have a similar cost per mile of a new ICE vehicle running on fossil diesel (from 5% cheaper for NGV and biodiesel in an existing ICE, to equal for a BEV charging at depots).

FIGURE 5-10. 2025 AND 2040 HDV COSTS PER MILE BY POWERTRAIN AND FUEL

By 2040, vehicle fuel economy improves, and the cost of e-diesel decreases as well as the purchase price of BEVs and FCEVs:

- E-diesel is still one of the more expensive options, with a new ICE with e-diesel comparable to an FCEV with hydrogen.
- Using e-diesel in a new ICE vehicle is approximately 40% more expensive per mile than diesel in an equivalent vehicle.
- Using e-diesel in a new ICE is more cost effective than in an old ICE, as fuel efficiency improvements in new vehicles reduce the amount of fuel required.

Of all the options, a BEV using depot charging is the cheapest per mile (20% cheaper than a fossil diesel ICE vehicle). A BEV using a mix of public and depot charging and an NGV using bio-CNG have similar costs per mile to a fossil diesel ICE vehicle (within 5%). These comparisons do not account for any operational changes required to meet specific duty cycles. For some technologies, changes to operations may be required to accommodate more frequent and longer charging/refueling sessions (mainly BEV), or reduced payload available (BEVs and FCEVs). These limitations may increase the cost of these technologies to the business through additional time or additional vehicles required to fulfil the same task, however, as this is highly dependent on the type of operation undertaken, these costs have not been considered or included. In general, it is expected that the negative operational impacts of BEVs or FCEVs will decrease in the future, as powertrain weights decrease, charging/refueling speeds increase and range increase.

From this comparison, it was found that for HDVs:

- From now until at least 2040, e-diesel use in HDVs will be more expensive than fossil diesel, requiring policy incentives to be competitive.
- NGVs using bio-CNG and BEVs are currently cost competitive with fossil diesel ICE vehicles over the vehicle's lifetime and are likely to become more competitive into the future.
- Policy to encourage the uptake of NGVs and BEVs where possible may be the cheapest way for policymakers to encourage lower emission options in the HDV sector.
- E-diesel may still be useful in HDVs for situations where NGVs or BEVs are either unavailable or unsuitable, such as long-distance operations in areas where installing infrastructure to accommodate the lower ranges is impractical or prohibitively expensive.

5.5.3 HOW DO DECARBONIZATION OPTIONS COMPARE ON EMISSIONS REDUCTION AND COST?

Cost and emissions reductions have been discussed separately in Sections 3 (GHG emissions) and Section 5 (costs). These results are summarized together below, giving an insight into the relative merits and disadvantages of each technology.

Cost and emissions of cars

Combining cost and emissions, the performances of all LDVs are compared in Figure 5-11, with potential for reduction in 2040 illustrated through an arrow. Both the emissions and cost of e-fuels have opportunity to decrease significantly in the future but will still remain one of the most expensive options for cars. Among the e-fuel options, the lowest cost application of e-gasoline is in existing ICEs or PHEVs, but this still could be more expensive than EVs. Fossil gasoline use in existing ICEs will remain the cheapest option.

Cost and emissions of cars are compared in Figure 5-12, and similar to cars, e-fuels have the one of the largest cost and emission reductions in the future. The lowest cost e-fuel option for HDVs could be e-methane. However, all e-fuel options will remain more expensive than fossil diesel. However, unlike LDVs, low carbon options could become cost competitive with fossil diesel used in existing ICEVs. These include BEVs and NGVs using biomethane.

FIGURE 5-11. CURRENT AND FUTURE CAR COSTS AND EMISSIONS PER MILE

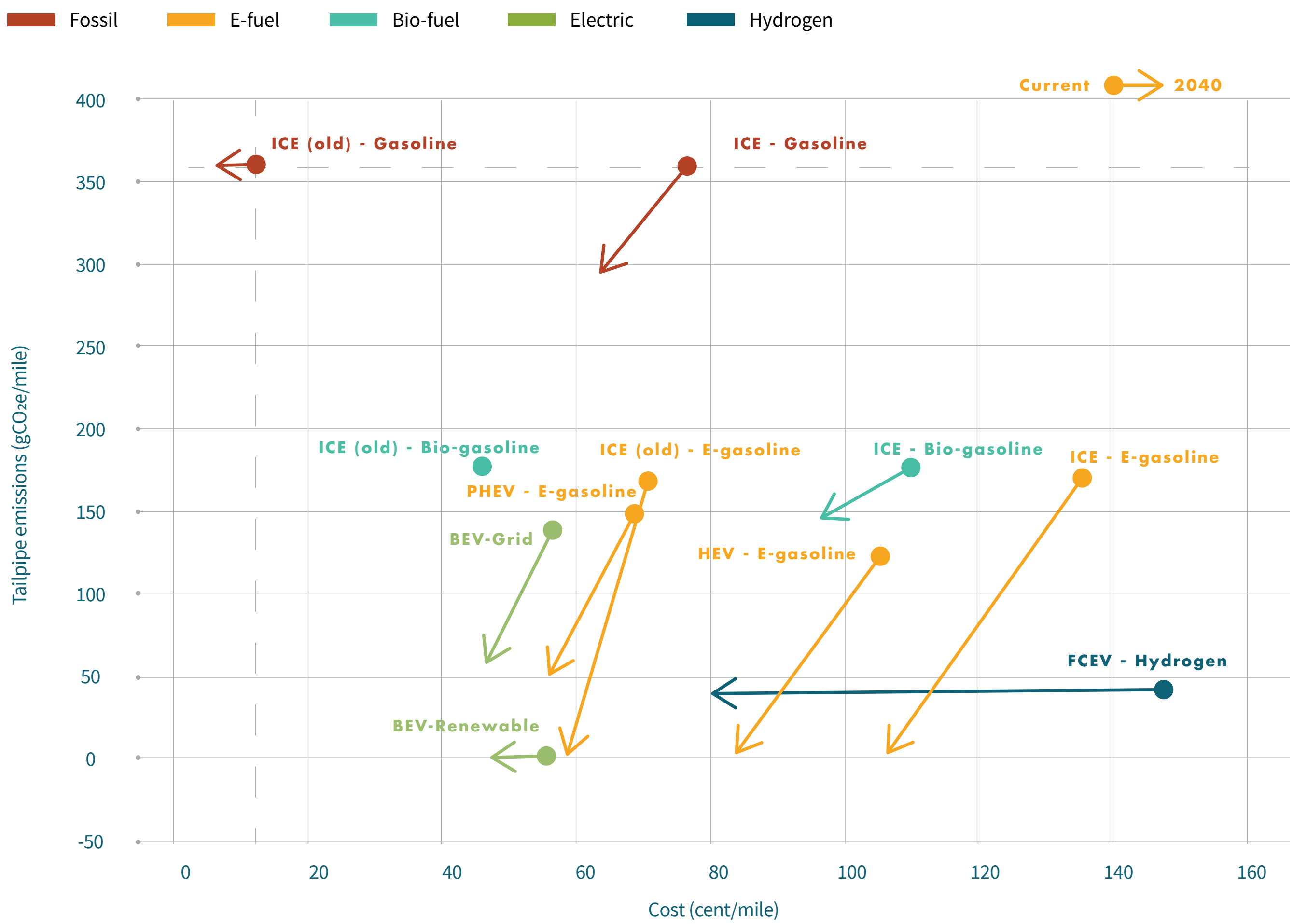
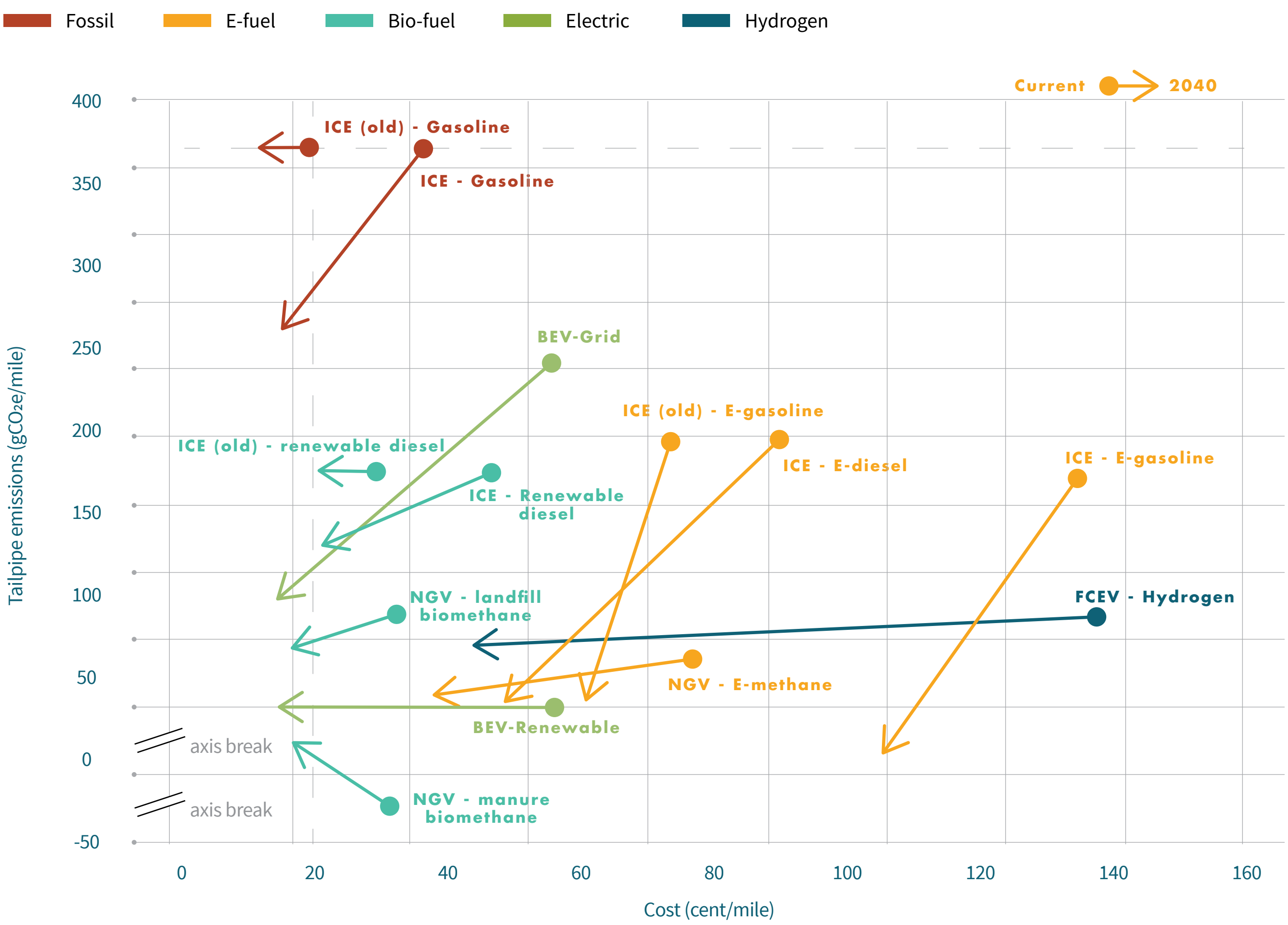


FIGURE 5-12. CURRENT AND FUTURE HDV COST AND EMISSIONS PER MILE



5.6 SUMMARY

What is the current production cost of e-fuel technologies?

E-fuels produced from a NOAK plant could be between 2.5 and 4 times more expensive than their fossil counterparts for a plant which is built in the U.S., where cheap renewable electricity can be sourced consistently to achieve high plant utilization rates. The most expensive e-fuel routes are via ethanol with ETJ and e-ethanol production costs, followed by RWGS + FT (72 $/GJ) and routes via methanol. E-methanol and e-methane are the lowest cost routes.

Key factors driving cost differences between pathways are hydrogen consumption rate due to conversion efficiency, natural gas consumption rate dictated by net heat demand and potential for heat integration, and CAPEX requirement which are typically lower for pathways with fewer processing steps. (Figure 5-2)

What affects e-fuels production costs?

The cost and availability of feedstocks such as renewable electricity to produce hydrogen, and CO_2 have the largest impact on the cost of e-fuels production.

Renewable electricity used to produce green hydrogen accounts for the largest share of costs for the production of e-fuels. Using a 30% increase in renewable electricity price can increase costs by between 10-15%.

Ensuring a consistent supply of renewable electricity which allows the production plant to operate at high utilization rates will also be key in achieving low production cost e-fuels. Maximizing fuel production volume enables overall fixed cost to be amortized more efficiently. A consistent supply of feedstocks (i.e. renewable electricity or hydrogen) could be achieved by purchasing PPAs for different sources of renewable electricity (i.e. a combination of solar and wind), or by adding hydrogen buffer storage.

Point-source CO_2 capture is the cost-effective option for sourcing CO_2 whereas using DAC increases overall costs by 30-40%. However, DAC is predicted to reduce in cost in the future and point-source capture is not.

How much could costs come down in future?

E-fuel production costs will decrease between 13-27% from FOAK to 2040 but will still be 1.5 to 3 times more expensive than fossil fuels. E-ethanol pathways remain to be the highest cost fuels, followed by RWGS + FT, MTJ and MTG which all have very similar production costs. E-methanol cost, however, experiences a higher cost reduction compared to e-methane, and could become the cheapest e-fuel pathway.

In 2040, technology could be more mature and operate with higher efficiencies as more plants are built. Plants scale will likely increase, allowing production costs to benefit from economies of scale. Hydrogen production costs will also reduce as the technology matures. (Figure 5-6)

How much do e-fuels plants cost to build?

E-fuel plants roughly cost between $100m to $1.1bn depending on the size and type of e-fuel production pathway. Jet producing pathways are the most expensive from a specific CAPEX view with RWGS + FT having the lowest upfront CAPEX requirement of $572m and ETJ costing $1.18bn. The ETJ plant however is significantly larger in scale compared to RWGS + FT, producing over 100 kilo tonne per year (kt/year) of fuel compared to 62 kt/year of fuel from the RWGS + FT plant. However, requiring high upfront investments could be challenging before the technology is proven.

Pathways requiring more processing steps and those with lower conversion efficiencies are generally more CAPEX intensive as they require more and larger equipment to be built. Simpler e-fuel production pathways such as e-methanol and e-ethanol that require small amounts of hydrogen have the lowest total CAPEX. Despite the high CAPEX of the MTJ and MTG pathways, they have a low specific CAPEX as they tend to have a higher capacity. (Figure 5-8)

What are the cheapest decarbonization option for the road transport sector?

By 2040, using e-gasoline in cars will still be more expensive than fossil gasoline, though reducing from 40% more expensive per mile currently to approximately 25-30% more expensive by 2040. Similarly, using e-diesel in HDVs will also be more expensive than fossil diesel, reducing from 50-60% more expensive per mile currently to approximately 40% more expensive by 2040.

For both cars and HDVs, there are other low carbon technologies that are expected to be cost-competitive or cheaper than gasoline- or diesel-powered vehicles both currently and into the future (BEVs for cars, BEVs and NGVs for HDVs).

However, a key advantage to e-fuels is that they can be made where the renewable electricity can be produced at cheaper prices, whereas EVs have to pay electricity prices at where its charged and at the time they are charged. Additionally, e-fuels can exploit where renewable electricity is abundant without having to transmit it so can help with geographical and temporal correlation of renewable electricity generation and consumption.

SECTION 6.

Are policies strong enough today to support e-fuel deployment in road transport?

As with many low carbon technologies in the transport sector, higher costs than fossil incumbents mean that policy is important in driving uptake.

As shown in Section 5, e-fuels from first-of-a-kind plants can cost 2.5-4 times more to produce than fossil counterparts, making policy for e-fuel adoption essential for widespread market deployment. In the U.S., there are currently federal and state level policies for low carbon fuels, but not all are applicable to e-fuels. Because fuels are globally traded commodities, their supply and demand are influenced by global market signals driven by both U.S. policies and international policies. Regions with mature fuel policies such as EU and the U.S. have identified e-fuels as key transportation decarbonization solutions, particularly in the aviation sector, which could generate competition for e-fuel supply.

This section provides an overview of U.S. policies that could help to close the cost gap between e-fuels and fossil fuels and assesses whether they offer enough support to deploy e-fuels in the road transport sector. The impact of global policies, and fuel policies in other transport sectors on e-fuel supply and demand in the road will also be discussed.

SECTION 6: KEY QUESTIONS

- How do U.S. policies support e-fuels today?
- Are these policies enough to support e-fuel production?
- How will global fuel policies impact e-fuel supply in the U.S.?

6.1 HOW DO U.S. POLICIES SUPPORT E-FUELS TODAY?

Low carbon fuel policies can be characterized as a technology-push (e.g. production subsidies) or market-pull (e.g. clean fuel standards) policy. Technology-push policies help drive early-stage development towards commercialization and encourage scale-up of production within the region. Market-pull policies ensure demand and a willingness to pay (WTP) for the resulting product to be used within the region. In the U.S., there is a mixture of pull and push policy instruments that are relevant to low carbon fuels, including e-fuels today which will be covered in this section.

Market-pull policies

At the federal level, the **RFS2** supports domestic demand for biofuels by setting a blending obligation for road transport fuel refiners and importers. However, the RFS2 does not cover hydrogen or e-fuels. Separately, some individual states encourage demand for low carbon fuels (including e-fuels) through state legislation such as the **California LCFS**. These are considered market-pull policies as they set carbon reduction mandates for low carbon fuels, which creates a minimum level of market demand through credit generation and trading programs. This leads to an increase in WTP from end-users as the credit market is intended to reduce the final price of the low carbon fuel.

Market-push policies

The **2022 IRA** introduced a series of PTCs aimed to support domestic production of sustainable fuels in the U.S. which e-fuels could benefit from. These TCs are technology-push policies, which will reduce production costs for fuel producers thereby attracting investments in e-fuels plants in the U.S. However, because IRA TCs are not volume mandates, they do not guarantee this fuel will be sold in the U.S.

6.1.2 THE RENEWABLE FUEL STANDARD

The Renewable Fuel Standard program was introduced under the Energy Policy Act of 2005, with a blending target for renewable fuels generally set annually on a volume basis. This mandate applies to fuels supplied in the road transport sector, but low carbon fuels used in aviation and heating oil can also benefit on an opt-in basis.

RFS2 assigns credits, or RINs (renewable identification numbers), to each gallon of renewable fuel eligible under the program. Obligated parties can meet their blending target by selling the required renewable fuel volume or purchasing RINs from other parties that exceed their requirements. Failure to meet targets results in significant financial penalties, thus generating WTP for renewable fuels.

The RFS2 only applies to renewable fuels produced via an approved pathway. Currently these are all biomass-based[78] including for conventional biofuels, advanced biofuel, cellulosic biofuel, and biodiesel. There has been no proposal for the inclusion of e-fuels. This means that, on a federal level, there is no mandate for e-fuel blending. Without this, suppliers will not have the willingness to procure e-fuels as they would with biofuels.

78 U.S. EPA (2023), Approved Pathways for Renewable Fuel. Available from: [link]

6.1.3 THE IRA

In 2022, the IRA introduced TCs to incentivize the production of low carbon fuels in the U.S. The IRA introduced the 45Z Clean Fuel Production tax credit (TC) which can be claimed by eligible low carbon fuel producers. There are also TCs for clean hydrogen production and for carbon sequestration, which could be relevant to e-fuels production (Table 22). Under the IRA, the 45V and 45Q TCs apply to both road and aviation e-fuels alike. However, SAF receives additional support under the Clean Fuel PTC (45Z) meaning overall a higher level of support for e-fuel producers to produce SAF rather than road fuels (see Section 6.2.2).

TABLE 22. SUMMARY OF IRA TAX CREDITS RELEVANT TO E-FUELS

PRODUCTION TAX CREDITS (PTCS)	AVAILABILITY	ELIGIBILITY	VALUE
45Z Clean Fuel PTC	2025-2027	Low carbon fuels with 50% GHG savings produced in the U.S.	\$0.20-1.00/gallon for road fuels and \$0.35-1.75/gallon for SAF. Incentive value increases with higher GHG savings beyond 50%.
45V Clean Hydrogen PTC	2023-2033	Low carbon hydrogen produced in the U.S.	Up to \$3/kg H_2 – would apply to the hydrogen used in e-fuel production.

There are a number of uncertainties related to these TCs that could affect investors' confidence in e-fuel projects. These will be discussed in more detail in Section 6.2.

- As seen above, most credits will expire before 2035, which create uncertainty on long-term policy support available for e-fuels.
- The ability to claim more than one credit (called 'stacking' credits) is highly debated. The full IRA bill states that the 45V Clean Hydrogen PTC cannot be claimed by a facility where the taxpayer has also claimed a 45Q and 45Z Clean Fuel PTC. However, many from industry and the IRS understand this as separate PTCs can be claimed by different companies in the same value chain, thus indirectly stacked.

45Z Clean Fuel PTC

The Clean PTC can be claimed by fuel producers for every gallon of eligible fuel (see eligibility below) produced domestically in the U.S. and sold. The credit amount is the product of the base credit amount of $0.20/gallon for road and marine fuels, and the emission reduction factor of the fuel from a baseline of 50 kgCO_2e/mmBTU. This means fuels with higher GHG saving potential will receive higher support.

SAF receives additional support through an uplifted credit value, with the base credit amount increased to $0.35/gallon. The base credit amount for all fuels increases by a multiple of 5 if the production facility meets prevailing wage and apprenticeship requirements. The credit is available from 2025-2027 for fuels that meet the following requirements:

- Produced in the U.S. by a registered producer; note that it is not yet clear what the definition of 'produced' is here, i.e. whether a fuel pathway where the final conversion step is in the U.S. is acceptable, even if the feedstock (e.g. CO_2) or an intermediate product (e.g. methanol) is imported;
- Fuel GHG below 50 kgCO_2e/mmBTU (or 47.4gCO_2e/MJ) based on GREET for road and GHG methodologies that align with CORSIA for aviation fuels. However, there are no agreed methodologies for e-fuels under this PTC, nor does it set requirements for it to be produced from additional renewable electricity to match rules proposed under the 45V Clean Hydrogen PTC.
- Not derived from co-processing with fossil fuels or other ineligible feedstocks (e.g. palm fatty acid distillates or non-biomass feedstocks like plastic).

45V Clean Hydrogen PTC

The 45V Credit for Production of Clean Hydrogen can be claimed by domestic hydrogen producers with qualified production facilities for a 10-year period, starting on the date the plant is placed into service. Construction of the facility must begin before 2033. E-fuel producers could potentially claim this TC for their hydrogen production operations.

The credit amount is determined by the lifecycle GHG emissions of hydrogen production, excluding downstream transport and distribution, shown as below. Hydrogen produced from renewable electricity (i.e. for e-fuel production) is expected to have a lifecycle GHG of less than 0.45 kgCO_2e/kg H_2. Similar to the Clean Fuel PTC, this base credit amount increases by a factor of 5 if the facility meets prevailing wage and apprenticeship requirements, giving it a maximum credit value of $3/kg H_2.

TABLE 21. PRODUCTION COST SCENARIOS

LIFECYCLE GHG (CO_2E/KG H_2)	CREDIT ($/KG H_2)	CREDIT IF FACILITY MEETS PREVAILING WAGE AND APPRENTICESHIP REQUIREMENTS ($/KG H_2)
<0.45 kg (e.g. green H_2)	$0.60	$3.00
0.45 to <1.5 kg	$0.20	$1.00
1.5 to <2.5 kg	$0.15	$0.75
2.5 to 4 kg	$0.12	$0.60
>4kg	Not eligible	Not eligible

At the end of 2023, the 45V proposed rules govern the eligibility and sustainability of hydrogen produced from renewable electricity. As mentioned in Section 4, the aim of these rules is to minimize negative impacts of high renewable electricity demand on the wider electricity system. Given no U.S. fuel policies have set specific rules or GHG guidance for e-fuels at the time of this report, it is assumed that e-fuel producers will follow the rules below set under the 45V to maximize policy support.

- **Incrementality -** the production facility may not draw from electricity generating facilities that are more than 36 months older than the hydrogen production facility
- **Temporal matching -** electricity used to make the hydrogen must be generated in the same year through 2027 and from 2028 in the same hour
- **Deliverability -** the electricity must be from the same geographic region

45Q PTC

The 45Q Carbon Sequestration TC can be claimed by industrial facilities and power plants that capture carbon from their operations when the CO_2 is used for purposes for which a commercial market exists. E-fuel producers could potentially benefit from this TC for the captured CO_2 used as feedstocks. Currently e-fuel production is not a recognized carbon capture and utilization (CCU) pathway, but it is likely that a commercial market will be able to be proven to exist.

For CO_2 captured for utilization, the base credit would be $12/tonne CO_2 for industrial source CO_2, and $26/tonne CO_2 for CO_2 from DAC. This value is higher if the captured CO_2 is sequestered instead. Similar to the other PTCs, the base credit increases by a multiplier of 5 if the facility meets prevailing wage and apprenticeship requirements. Specific eligibility rules for CO_2 utilized for fuel production are uncertain, but all qualifying facilities must be operated in the U.S. and meet annual capturing requirements shown below.

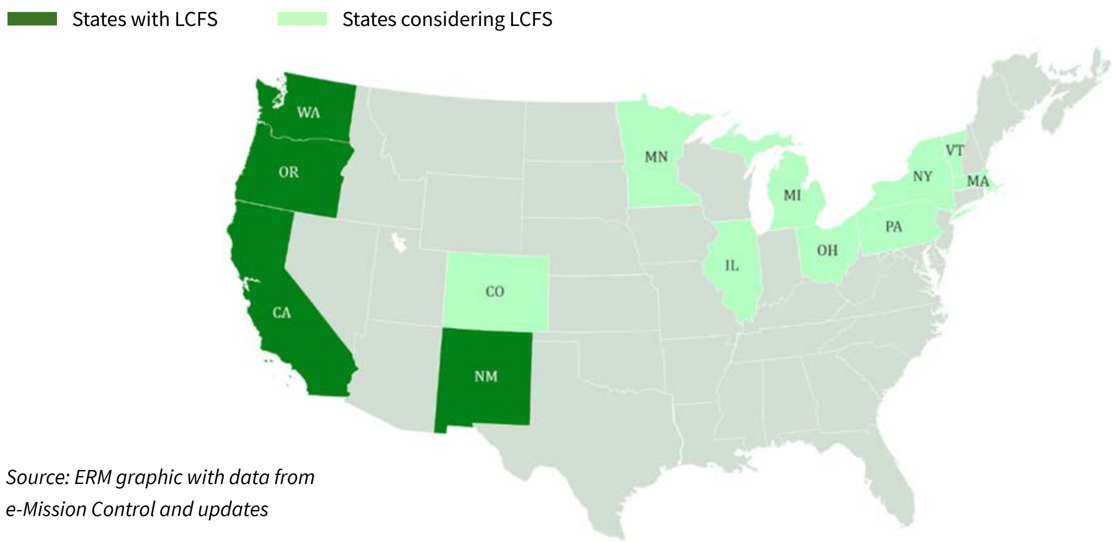
- >18,750tCO_2 for power plants
- >12,500tCO_2 for industrial facilities
- >1,000tCO_2 for DAC facilities

6.1.4 CALIFORNIA LOW CARBON FUEL STANDARD

California was the first state to adopt a LCFS in 2018 and has since encouraged other states to adopt similar programs (Figure 6-1). The California LCFS program has generated the largest market for low carbon fuels so far and will be used as a representative example of a state-level demand-pull policy.

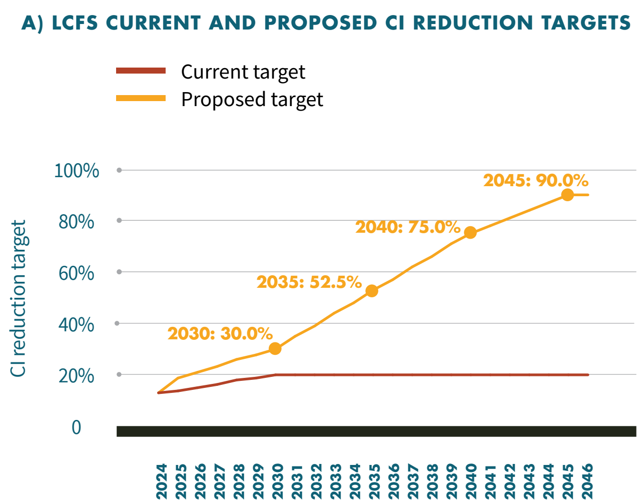
The California LCFS is designed to decrease the CI of transportation fuel sold within California. The program currently has set GHG reduction targets to 2030 (as shown in Figure 6-2) but an amendment was proposed in 2023 to extend the program to 2046 and increase the CI reduction targets. This could expand market demand for e-fuels.

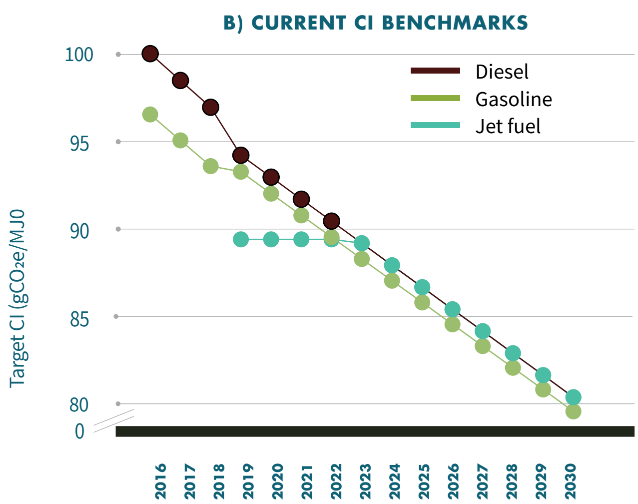
FIGURE 6-1. U.S. STATES WITH CURRENT OR PLANNED LCFS PROGRAMS[79]



Source: ERM graphic with data from e-Mission Control and updates

FIGURE 6-2. (A) LCFS CURRENT AND PROPOSED CI REDUCTION TARGETS AND (B) CURRENT CI BENCHMARKS





79 e-Mission Control (2023), States with Pending Clean Fuel Programs. Accessible from: [link]

The LCFS covers a wide scope of low-carbon transportation measures, including project-based crediting (e.g. upstream emission reduction, CCS, hydrogen) and capacity-based crediting (e.g. zero emission vehicle infrastructure), in addition to a range of lower carbon fuels. All transport fuels are eligible to generate credits if:

- their GHG intensity is below the yearly benchmark CI (as shown in Figure 6-2b), and;
- they are produced through an LCFS-approved pathway.

Fuels not meeting the annual threshold will create deficits which must be reduced via credit purchases or blending with low carbon fuels.

There are no approved e-fuel pathways currently[80] but there is no obvious barrier to this being achieved given the GHG-based nature of the program.

The credits generated by each fuel are calculated based on their CI reduction (calculated following California GREET methodology) and the LCFS credit price. This means that fuels with higher GHG savings will receive higher policy support. The LCFS acts in addition to the RFS2 and the IRA credits, which means fuels supplied in California can receive benefits from all three policies if they are eligible.

The LCFS applies to all transport fuel providers but exempts suppliers of fuel for aircraft, ocean-going vessels, locomotives etc. Nonetheless, SAF can contribute to achieve the mandates, but does not receive any additional benefits. This means that under the LCFS, e-fuels for road and aviation are currently treated the same. The proposed amendment to the LCFS suggests that the jet fuel exemption be removed, meaning that jet fuel would become obligated in the same way as road fuels[81]. However, it is unclear whether the support values will be the same between road and aviation fuels.

6.2 ARE THESE POLICIES ENOUGH TO SUPPORT E-FUEL PRODUCTION?

E-fuels will only be sold at scale in the U.S. if the gap between their high production costs and today's fossil fuels can be bridged by policy support and/or higher consumer willingness to pay (WTP). While some companies have shown an increased WTP for lower carbon fuels to meet corporate sustainability goals, this is not widespread, meaning policy support is key. This section calculated the total value of policy support in the U.S., including the benefits of production TCs in decreasing the production cost, and the increased prices that end-users are willing to pay due to market-pull (i.e. demand-side) policies.

This support is calculated for a FOAK plant and a future NOAK. In both scenarios, CO_2 is assumed to be captured from an industrial point source. The FOAK scenario is assumed to occur in 2025, such that all three IRA Production TCs are available. In 2040, e-fuel production costs will reduce but could still be higher than fossil fuels. As such, it is assumed the same policies will remain in place for the future plant scenario to help close this cost gap. Additional assumptions are provided in Appendix F.

80 California Air Resources Board (2023), Current Fuel Pathways. Accessible from: [link]

81 California Air Resources Board (2023), Low Carbon Fuel Standard Public Workshop. Available from:[link]

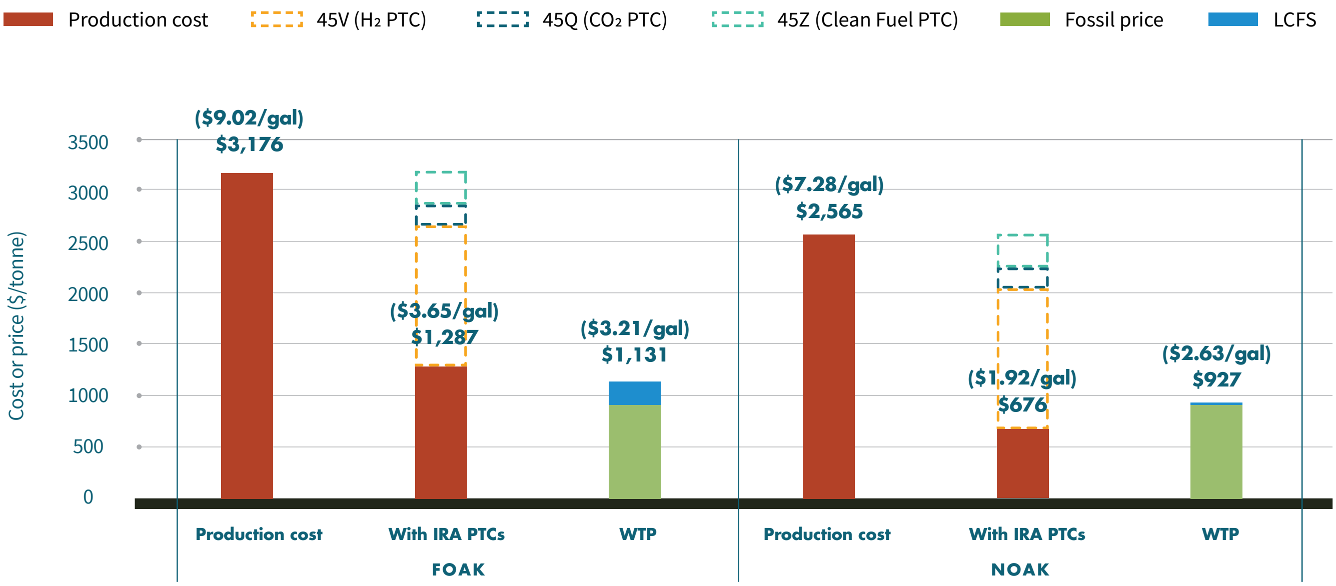
6.2.1 UNDERSTANDING POLICY SUPPORT

For each e-fuel production pathway, the total policy support per ton of product was calculated based on the product slate of a typical production facility, as different co-products receive different levels of support. Impact from policies supporting production cost and WTP are shown separately. Using Figure 6-3 as an example, which shows the total support an e-RWGS + FT plant producing SAF, diesel and naphtha (assumed to be converted to gasoline):

- The first column represents production cost without any policy support;
- The second column represents the potential production cost after receiving IRA TCs;
- The third column represents WTP in California for the average product, calculated from the fossil fuel price and the LCFS premium (calculated from average LCFS ticket prices in 2023).

This is repeated on the right to show impact of policy support in 2040. Figures for the remaining e-fuel production pathways are included in Appendix F.

FIGURE 6-3. PRODUCTION COST AND POLICY SUPPORT FOR AN E-RWGS + FT PLANT, ASSUMING A PRODUCT SLATE OF 75% SAF, 12.5% DIESEL AND 12.5% NAPHTHA.



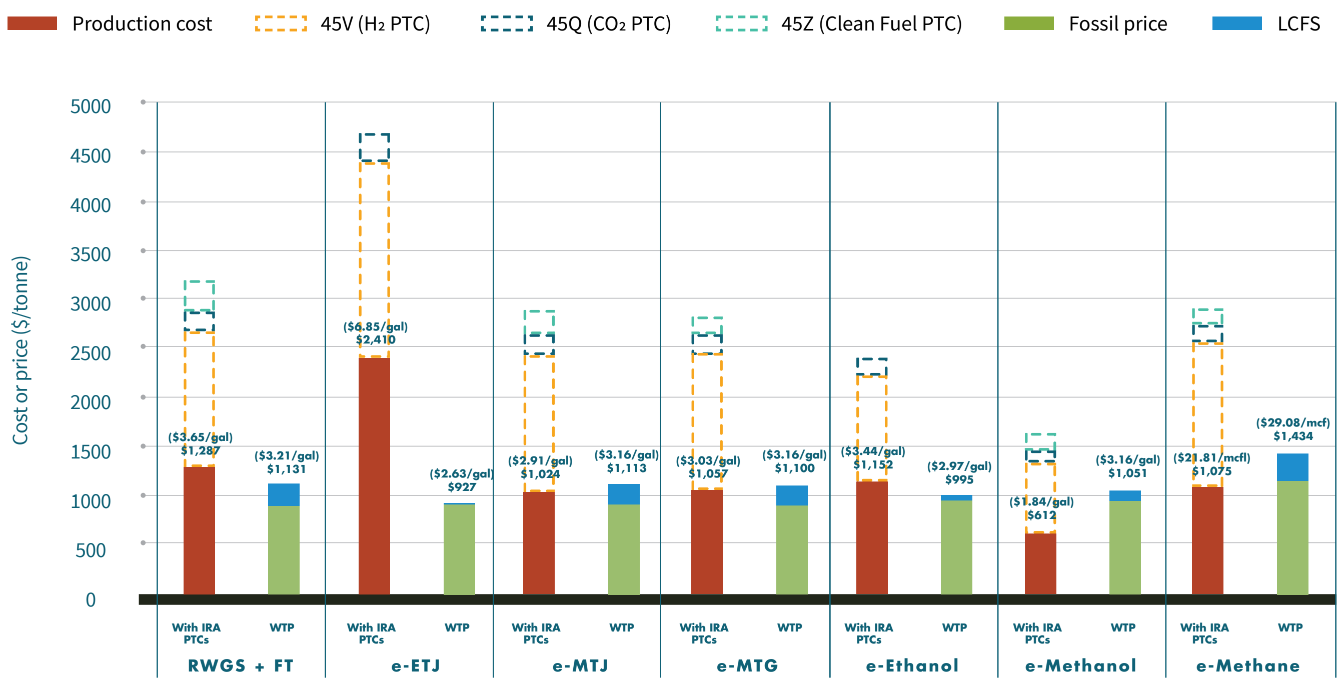
6.2.2 CURRENT POLICY SUPPORT VALUE

The results show that when e-fuel plants are built in areas with cheap renewable electricity (e.g. Texas), most pathway's production costs could be reduced via policy support to almost match the current WTP for these fuels. Crucially this is assuming that IRA TCs can be stacked, which is a key uncertainty.

E-methanol and e-methane pathway shows the highest potential to become economically viable, but the business case for e-MTJ and e-MTG pathways will be less certain given that the production costs closely match the WTP. Similarly, while RWGS + FT and e-ethanol pathways are shown to have higher production costs, the small price gap to their WTP indicates that the resulting fuel could become economic in the near-future. FOAK e-ETJ plants, however, are unlikely to become economically viable even with policy support.

The highest support comes from 45V Clean Hydrogen PTC, which could reduce the production cost of e-fuels by approximately 40% across all pathways. For the e-ethanol and e-ETJ pathways, high GHG emissions mean that an FOAK plant would not qualify for 45Z Clean Fuel PTCs.

FIGURE 6-4. PRODUCTION COSTS AND POLICY SUPPORT FOR CURRENT FOAK PLANTS
(ALL FUEL PATHWAYS)

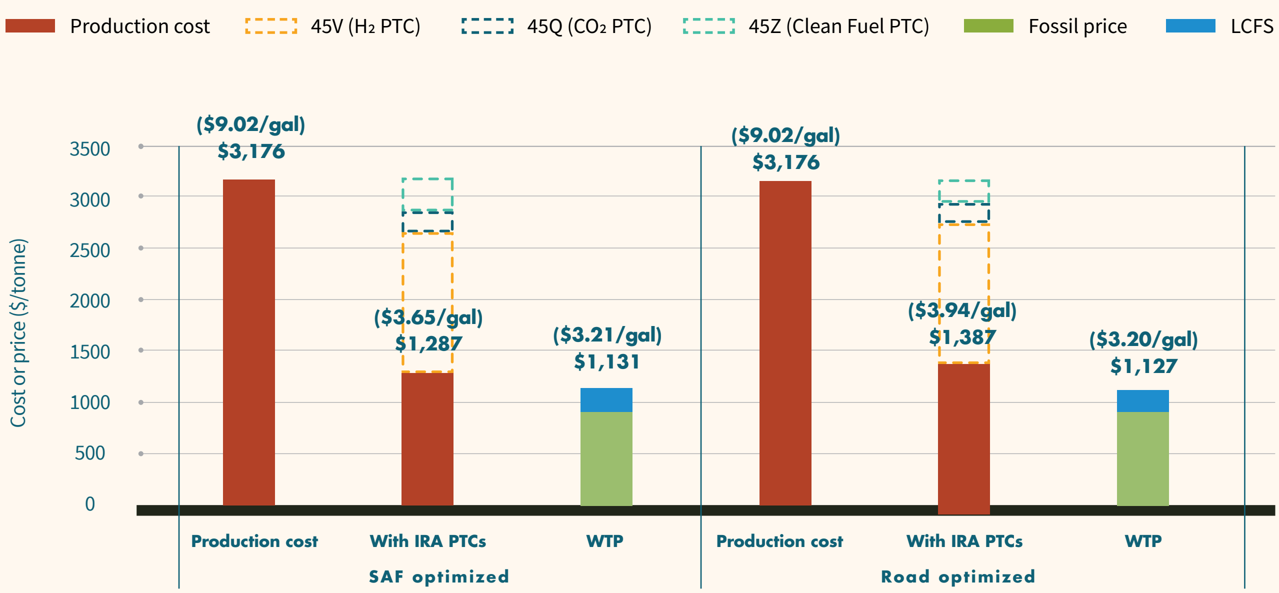


IMPACT FROM PRODUCT SLATE

In Figure 6-4, RWGS + FT and ETJ pathways are configured to optimize SAF production. This gives higher support under the 45Z Clean Fuel PTC ($1.75/gallon for SAF compared to $1.00/gallon for road fuel). The support value for a road optimized configuration is shown in Figure 6-5, where the support from the 45Z Clean Fuel PTC is $210/tonne compared to $310/tonne in the SAF optimized configuration. Support from the CA LCFS is also slightly lower due to gasoline having a lower fossil fuel baseline GHG.

When combined, the jet optimized configuration has a smaller price gap of $156/tonne, compared to the road optimized configuration of $261/tonne. This indicates that the business case is stronger for prioritizing jet fuel production. For simplicity, the production costs were assumed to be the same for both configuration, which could be different in practice.

FIGURE 6-5. PRODUCTION COST AND POLICY SUPPORT FOR A SAF OPTIMIZED VS. ROAD OPTIMIZED RWGS + FT PRODUCTION CONFIGURATION.

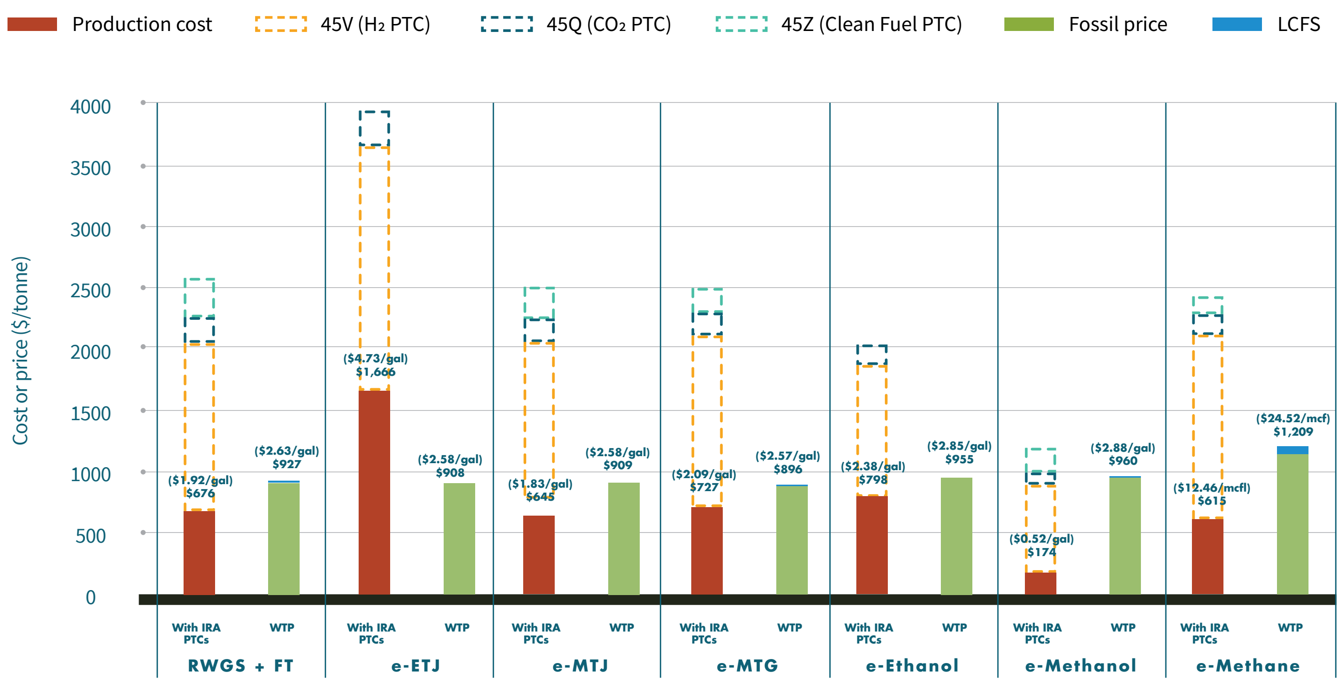


6.2.3 FUTURE POLICY SUPPORT VALUE

In the future case, almost all e-fuel production pathways in the U.S. have the potential to generate profit if TCs are still in place and can be stacked. This is mainly because production costs are expected to decrease. Only e-ETJ production costs are likely to remain greater than the WTP, on account of its high GHG emissions relative to other e-fuel pathways.

We note that in the future case, the value of the California LCFS premium for all pathways decreases compared to the present-day scenario. This occurs because the total GHG emissions of the e-fuel pathway remains the same, but the CA LCFS benchmark against which the fuel is compared decreases annually, meaning that the GHG savings of the e-fuel against the benchmark reduces. For some e-fuels pathways including e-ethanol and e-ETJ, there is no policy premium derived from the CA LCFS because the GHG

FIGURE 6-6. PRODUCTION COSTS AND POLICY SUPPORT FOR FUTURE NOAK PLANTS
(ALL FUEL PATHWAYS)



emissions of the fuel pathway is higher than the 2040 benchmark (approximately 25 gCO_2/MJ). However, this does not account for changes in future CA LCFS credit prices.

The future NOAK e-fuel facilities were modelled as using CO_2 from an industrial point source. If instead they used CO_2 from DAC powered by renewable electricity, then the total GHG emissions of the production pathway would be reduced, leading to increased policy premia under the California LCFS and the 45Z Clean Fuel PTC. A higher premium would also be achieved under the 45Q Carbon Sequestration PTC, which offers a higher base credit for CO_2 from DAC compared to a point source. For example, a facility producing e-methanol from point source CO_2 would receive policy support which would reduce the total production cost from $1,181/t to $174/t (which would generate a margin of $785/ton between production cost and WTP). In comparison, a DAC facility would receive greater policy support from 45Q on account of using DAC technology and 45Z and California LCFS from achieving greater GHG savings from the fuel product. However, given that incorporating DAC into a production facility can increase net levelized production costs by 30-40%, the margin between total production cost and WTP would be roughly $675/ton, less than using point sourced CO_2. Therefore, both point source and DAC e-fuel facilities could generate a profit, but DAC facilities may have a slightly lower profit margin than a facility using point source CO_2. (Figure 6-7)

This analysis relies on the assumption that the IRA credits will be extended to support plants in 2040, and that the three PTCs can all be claimed for the same fuel pathway. Ultimately, e-fuel producers may only be able to claim one of the PTCs for their facility. The 45V Hydrogen PTC would provide the greatest support per ton of e-fuel. If producers were to claim only the 45V credit to support production costs, most production pathways would not be profitable (Figure 6-8). Only e-methanol and e-methane producers

FIGURE 6-7. COMPARISON OF POLICY SUPPORT AND PRODUCTION COSTS FOR A FUTURE NOAK E-METHANOL PLANT USING POINT SOURCE CO_2 COMPARED TO CO_2 FROM DAC.

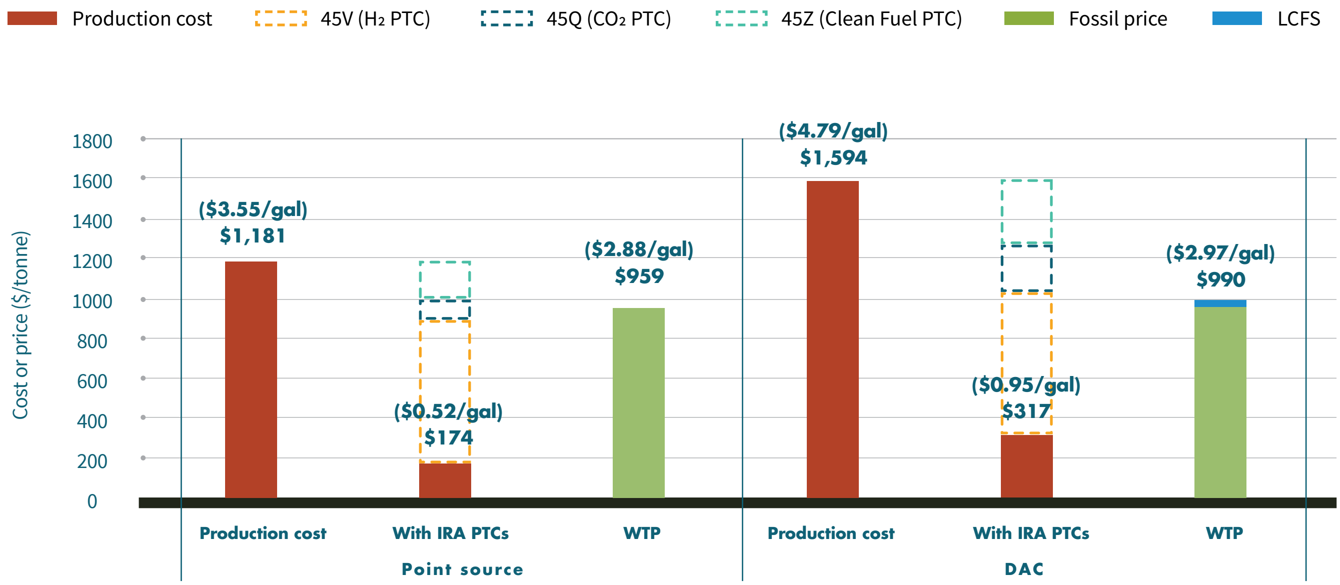
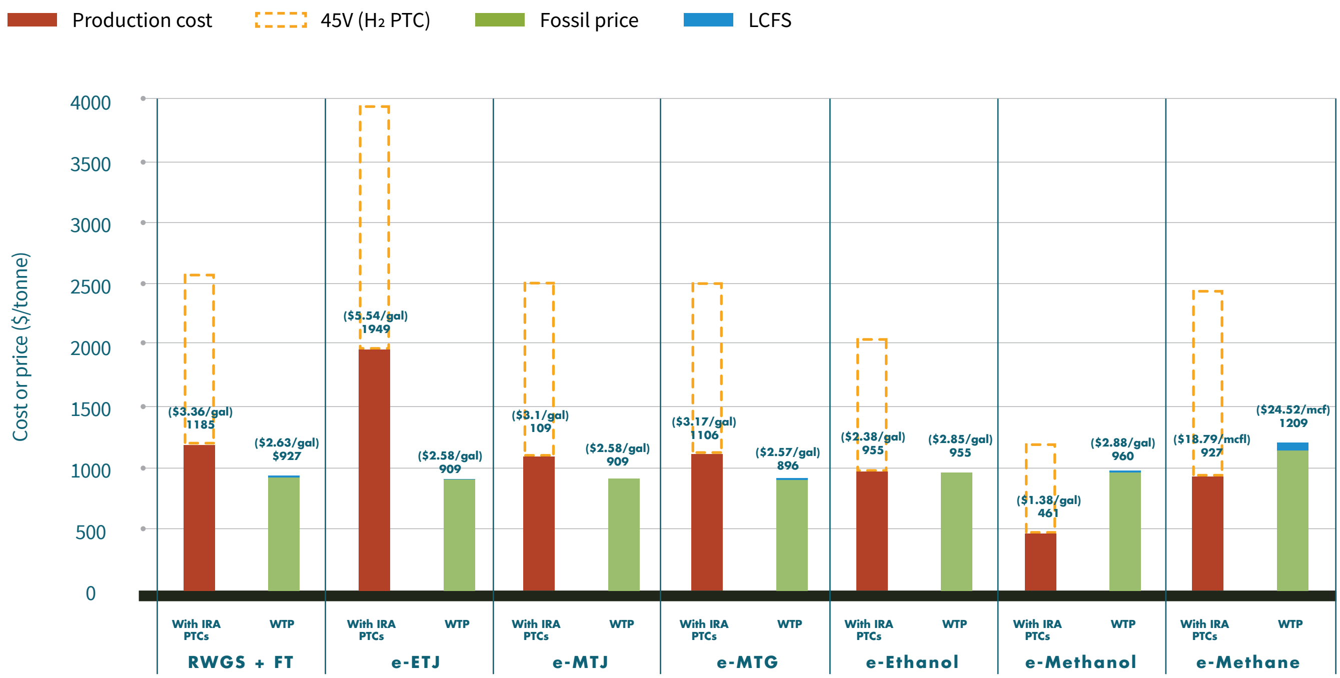


FIGURE 6-8. PRODUCTION COSTS INCLUDING SUPPORT FROM 45V PTC, COMPARED TO WTP FOR EACH PRODUCTION PATHWAY.



6.3 WILL GLOBAL FUEL POLICIES AFFECT E-FUEL SUPPLY IN THE U.S.?

As seen in Section 6.1, the U.S. does not currently set targets which would guarantee a market for e-fuels in the U.S. The U.S. instead relies on supply-side support to encourage producers to develop e-fuel plants in the U.S.

Outside the U.S., the EU and the UK have the most developed sustainable fuels policy portfolios, through policies like the EU Renewable Energy Directive and the UK SAF mandate, which set specific e-fuel demand targets and penalties for non-compliance.

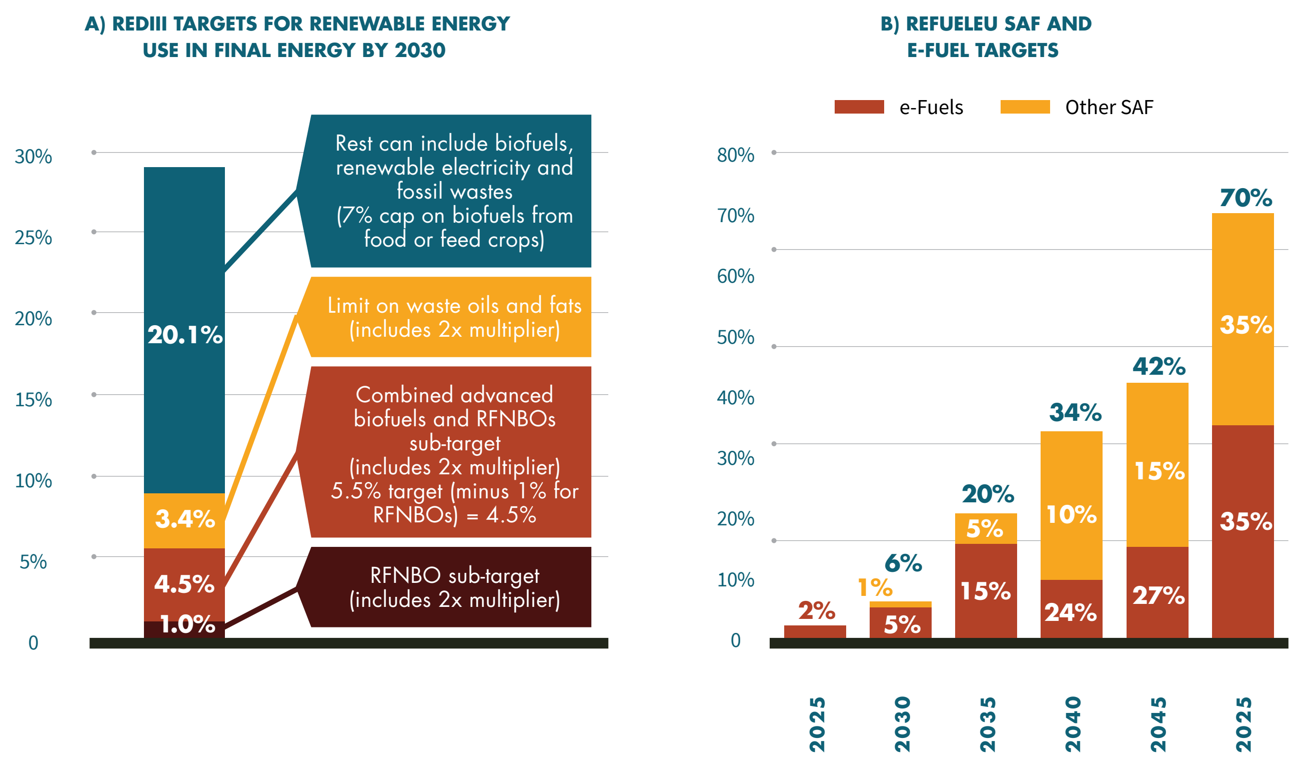
This section outlines the fuel policies in the EU and U.S., focusing on support for e-fuels, and discuss how they may affect U.S. production and supply of e-fuels.

6.3.1 EU FUEL POLICIES

Road

RED is the EU's legal framework that mandates renewable energy uptake across all sectors of the EU economy. The latest version of RED (RED III), was adopted by the European Council in October 2023, introducing a target for transport by 2030 of 29% renewables in final energy use or a 14.5% GHG reduction compared to 2005 levels. The target applies to all transport modes, including road transport, aviation, maritime and non-road mobile machinery, and incentivizes the uptake of sustainable fuels and other low carbon transport technologies. The target also sets a 5.5% combined sub-target for RFNBOs (i.e. Renewable Fuels of Non-Biological Origin, which includes hydrogen and e-fuels) and advanced biofuels, within which, at least 1% must be met by RFNBOs, by 2030 (as seen in Figure 6-9).

FIGURE 6-9. (A) REDIII TARGETS FOR RENEWABLE ENERGY USE IN FINAL ENERGY BY 2030 (B) REFUELEU SAF AND E-FUEL TARGETS



RFNBOs receive additional support in the form of this sub target and multiple counting towards several targets because of their high resource potential and GHG savings. Individual EU countries are responsible for setting penalties for breaching the regulation and designating competent authorities to enforce it. This means that the resulting policy mechanism and penalty could look very different across different EU countries.

Aviation

The EU has also introduced the **ReFuelEU Aviation** initiative which aims to decrease GHG emissions from the aviation sector and increase demand for SAF. The volume-based mandate obligates jet fuel suppliers to blend SAF into jet fuel, starting in 2025. Like RED III, ReFuelEU Aviation also has a sub-target for e-SAF (as seen in Figure 6-9) which will enable e-fuel uptake without direct competition with other SAF options. Jet fuel suppliers failing to meet these targets will face a penalty equal to at least twice the price difference between e-SAF and jet fuel. Currently, it is unclear how individual Member States will transpose RED III targets and how these will interact with ReFuelEU Aviation.

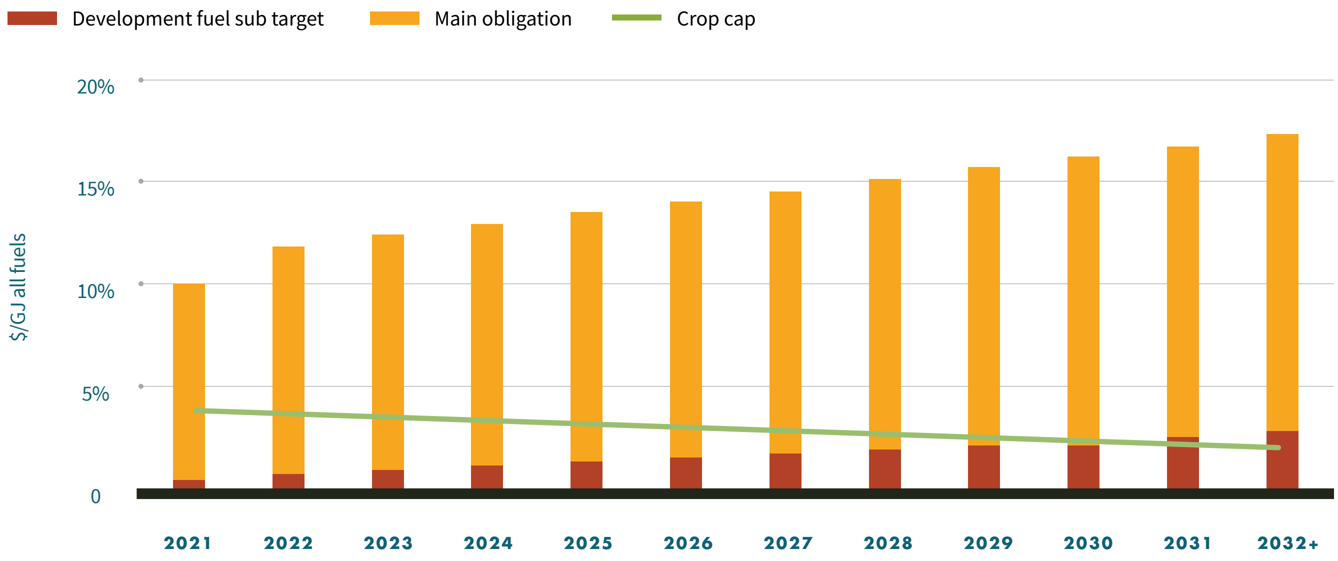
Demand for e-fuels

It is expected that approximately 0.5 Mt/year (167 million gallons)[82] of e-fuel will be required to fulfil the 2030 ReFuelEU Aviation target, increasing to 4.1 Mt/year (1.4 billion gallons) by 2040. The ramp-up model in Section 4 showed that the U.S. is expected to produce 0.9 Mt/year (300 million gallons) of e-fuel by 2030, increasing to 6-14 Mt/year (2-4.7 billion gallons) by 2040; global e-fuel production capacity is expected to be 4.3 Mt/year (1.4 billion gallons) in 2030 and 34-82 Mt/year (11.4-27.5 billion gallons) by 2040. This means that in 2030, the ReFuelEU target could be equivalent to 50% of the U.S. e-fuel production capacity, increasing to 30-70% by 2040. Depending on the competitiveness of U.S. e-fuels against EU local e-fuels, including supply side support from the IRA, a significant portion of U.S.-produced e-fuels could be redirected to the EU aviation sector to pursue a market with higher WTP.

There is much less certainty around the WTP for e-fuels in the EU road sector, as this will depend on the deployment of hydrogen and other advanced fuels in transport, and how targets are set by Member States. E-fuels may therefore face limited competition with the U.S. road market for e-fuels.

82 Approximated using a conversion value of 335 gallon/tonne, based on an average density of liquid fuels.

FIGURE 6-10. RENEWABLE TRANSPORT FUEL OBLIGATION TARGETS 2022



6.3.2 UK FUEL POLICIES

Road

RTFO is the UK's main policy driving uptake of low carbon fuels, which supports both biofuels and e-fuels alike. It places an obligation on any fuel suppliers selling over 450,000 liters/year of fuel to supply a certain volume of low carbon fuels determined by annual targets shown in Figure 6-10.

Suppliers can meet their obligation by redeeming Renewable Transport Fuel Certificates, of which there are 3 categories:

- General: fuels that do not fall under relevant crop nor development fuels.
- Relevant crop: A crop cap sets a maximum on the amount of crop-derived biofuels which may be counted towards the renewable transport target. The crop cap is set at 3.5%, decreasing to 2.0% by 2030.
- Development (dRTFCs): aims to incentivize novel fuel pathways. RFNBOs (i.e. e-fuels and hydrogen) can claim dRTFCs[83] if made from renewable energy or nuclear power and waste CO_2. The development fuel must be used in aviation or road transport.

The RTFO includes a sub-target for development fuels which increases annually towards 2032 (Figure 6 10). Suppliers can use eligible RFNBOs to contribute twice (i.e. be "double-counted") toward this sub-target, meaning the e-fuel and hydrogen would receive the highest support under the RTFO. However, like EU RED III, the demand for e-fuels will be uncertain as it will be highly influenced by the penetration of FCEVs.

Aviation

Currently SAF is rewarded, but not mandated, under the RTFO as a double-counted development fuel. However, the UK will introduce a SAF-specific mandate starting in 2025, which will replace RTFO support for SAF and likely provide significantly stronger support for SAF. This GHG-based mandate is currently being finalized, with several key aspects yet to be confirmed. The mandate aims to achieve 10% SAF usage by 2030 with multiple target scenarios

83 UK Government (2024), Renewable Transport Fuel Obligation (RTFO): compliance, reporting and verification. Available from: [link]

being proposed. The preferred scenario aims to achieve 75% by 2050. Additionally, it has been confirmed that the SAF mandate will include a sub-target for "Power-to-Liquid fuel" (i.e. e-fuels) but specific targets are yet to be determined. The proposed target scenarios from the consultation[84] are summarized in Table 24.

There will likely be two tiers of buy-out prices for fuel suppliers who fail to meet the mandated targets: the "standard certificate" for the main mandate and a "PtL (power to liquid) certificate" for e-fuels, as seen in Table 25. Therefore, e-fuels will likely trade at higher premium, thus having higher levels of WTP than other SAFs.

Demand for e-fuels

Demand for e-fuels under the Medium UK SAF Mandate may reach 0.01 Mt/yr (3 million gallons) by 2030 and 0.5 Mt/yr (167 million gallons) by 2040. Similar to the EU, there will be a much higher WTP for e-fuels in the UK aviation sector compared to the U.S. market, however, given the smaller targets in the UK, this may have less impact on the U.S. e-fuel market compared to the EU. It is unlikely that demand for e-fuels in the UK aviation sector will pose large competition with e-fuel demand in the U.S. for the U.S.' domestic supply.

There is much less certainty around the WTP for e-fuels in road transport in the UK and therefore likely limited competition with the U.S. road market for e-fuels.

TABLE 24. UK SAF MANDATE TARGET (LEFT) AND PTL (POWER TO LIQUID OR E-FUEL) SUB-TARGET (RIGHT) OPTIONS

UK SAF MANDATE TARGET				
OPTIONS	2025	2030	2035	2040
0 – Business As Usual	0.5%	2%	3%	4%
1 – Low	0.5%	10%	13%	17%
2 – Medium	2%	10%	15%	22%
3 – High	4%	10%	18%	32%

PTL (POWER TO LIQUID OR E-FUEL) SUB-TARGET				
OPTIONS	2025	2030	2035	2040
1 – Low	0%	0.05%	0.25%	1.5%
2 – Medium	0%	0.1%	0.5%	3%
3 – High	0%	0.2%	1%	6%
4 – Very High	0.05%	1%	3%	8%

TABLE 25. UK SAF MANDATE BUY-OUT OPTIONS CONSIDERED

OPTIONS	MAIN BUY-OUT	PTL BUY-OUT
Low	£2,051 per ton	£2,567 per ton
Medium (preferred)	£2,567 per ton	£3,525 per ton
High	£3,846 per ton	£5,320 per ton

84 UK Government (2023), Pathway to net zero aviation: Developing the UK sustainable aviation fuel mandate. Accessible from: [link]

6.4 SUMMARY

How do U.S. policies support e-fuels today?

U.S. policy primarily supports the domestic production and supply of e-fuels, through the IRA TCs, specifically the 45Q, 45V Clean Hydrogen and 45Z Clean Fuel Production TCs. Market-pull policies which creates demand for low carbon fuels through volume target setting are only available for e-fuels on a state level via GHG based transport policies such as the California LCFS. E-fuels are not expected to be eligible under the main federal level policy RFS2, which only supports biomass-derived fuels today.

TABLE 26. SUMMARY OF U.S. POLICIES RELEVANT TO E-FUELS

U.S. POLICY	POLICY SCOPE	TRANSPORT MODES	E-FUEL ELIGIBILITY	IMPLICATION FOR E-FUELS
RFS2	Federal mandate	Road, aviation can opt-in	Not eligible	Unlikely to provide demand-side support for e-fuels in the future
IRA	Federal production TCs	Road, maritime, and aviation. Aviation receives premium support	Eligible, U.S. production only	Provides strong supply-side support for the domestic production of e-fuels
CA LCFS	State mandate	Road, aviation can opt-in now but may become mandatory in the future	Potentially eligible if pathways approved	Could encourage uptake of e-fuels once pathways are approved

Are these policies enough to support e-fuels sales in the U.S.?

See Section 6.2.2 and Section 6.2.3 for details on production costs and policy support for E-fuel Plants. (Figure 6-4, Figure 6-6)

In 2025, even with policies to support both supply and demand, and full stacking of IRA TCs, most e-fuels pathways are not economically viable. E-methanol and e-methane pathways could be exceptions to this where their production costs are sufficiently lower than WTP with policy support to allow for uncertainties in both policy value and plant costs.

In the future, the economic viability for most pathways could improve and become more certain as production costs decrease. However, this would rely on most of the IRA TCs offered today remaining active and stackable, particularly the 45V Clean Hydrogen PTC, as it offers the highest production cost support. Without the IRA TCs, production cost will remain significantly higher than what the market is willing to pay under current demand-side policies.

Importantly, prioritizing jet fuel could yield higher production cost support due to the higher premium offered under the 45Z Clean Fuel PTC. However, this analysis has not considered the potential increase in production cost for this configuration.

How will global fuel policies affect e-fuel supply in the U.S.?

The EU and the UK have the most developed market-pull policy portfolios which focus on driving demand for low carbon fuels, and specifically e-fuels, through setting specific e-fuel sub-targets. As such, it is expected that U.S. e-fuel producers could claim IRA TCs but sell the final fuel product to the EU/UK market, generating financial support from both U.S. and European policy mechanisms. This could pose competition for U.S. e-fuel supply.

Amongst both current and proposed legislation in the EU and the UK, the strongest demand signal for e-fuels comes the aviation sector, while demand and WTP for road e-fuels are much lower. The total estimated demand from the EU and the UK SAF policies for e-fuel is estimated to be 0.5 Mt/year (167 million gallons) in 2030, growing to 4.1 Mt/year (1.4 billion gallons) by 2040. This creates market certainty for e-fuel which could continue to influence producers to prioritize the production of e-SAF as seen from planned e-fuel projects captured in Section 4.1.2.

TABLE 27. SUMMARY OF EU AND UK LOW CARBON FUEL POLICIES

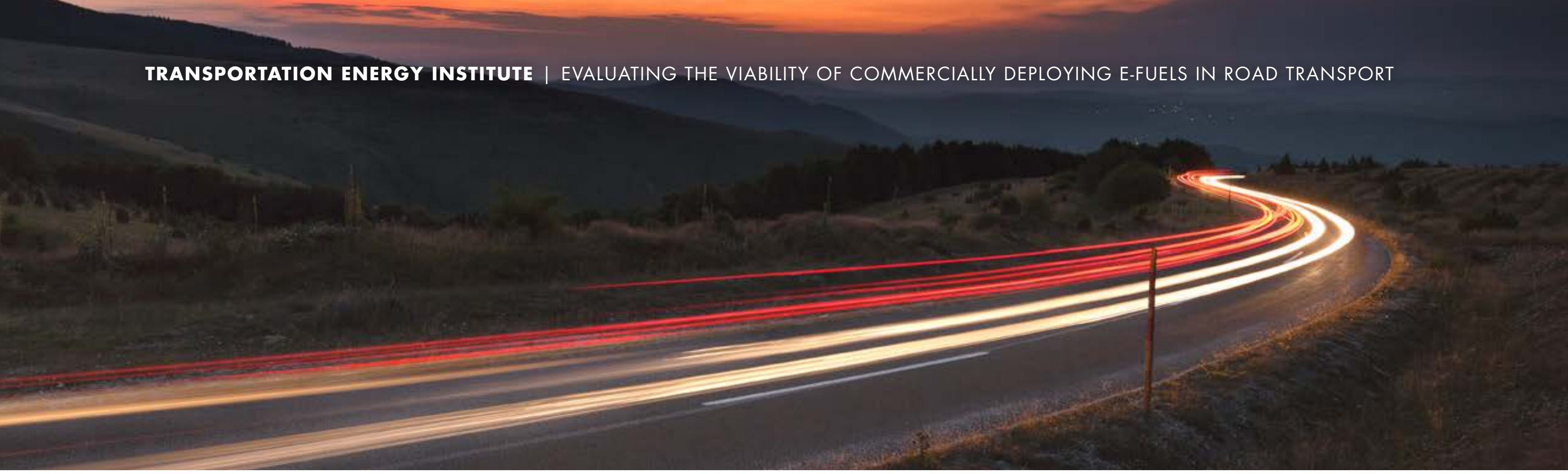
REGION	POLICY	POLICY DESCRIPTION	E-FUEL TREATMENT	E-FUEL DEMAND
EU	RED	Energy or GHG based mandate for low carbon fuels	Sub-target for e-fuels and hydrogen and double-counting	Uncertainty on demand for e-fuels in road transport as sub-target could be filled by hydrogen and other fuels.
EU	ReFuelEU Aviation	Volume based mandate for SAF	Sub-target for e-SAF with higher penalty set	0.5 Mt/year (167 million gallons) of e-fuel will be required to fulfil the 2030 sub-target, increasing to 4.1 Mt/year (1.4 billion gallons) by 2040. This could create competition for e-fuel supply.
UK	RTFO	Volume based mandate for low carbon fuels	Double-counting and sub-category for e-fuels used in some applications	Uncertainty on demand for e-fuels in road transport as sub-target could be filled by hydrogen.
UK	SAF Mandate	Volume based mandate for SAF	Sub-target for e-SAF with higher penalty set	0.01 Mt/yr (3 million gallons) by 2030 and 0.5 Mt/yr (167 million gallons) by 2040.

This demand is approximately 50% of the U.S.'s e-fuel production capacity in 2030, increasing to 30-70% in 2040, as seen in Table 28. Depending on the competitiveness of U.S. e-fuels against EU produced e-fuels, a significant portion of U.S.-produced e-fuels could be redirected to the EU aviation sector to pursue a market with higher WTP.

TABLE 28. EU AND UK E-FUEL DEMANDS COMPARED TO PRODUCTION CAPACITIES

REGION	POLICY	POLICY DESCRIPTION	E-FUEL TREATMENT	E-FUEL DEMAND
	(Mt/year)	(Billion gal/year)[85]	(Mt/year)	(Billion gal/year)
EU and UK e-fuel demand	0.5	0.2	4.6	1.5
U.S. e-fuel production capacity	0.9	0.3	6-14	2.0-4.7
Global e-fuel production capacity	4.3	1.4	34-82	11.4-27.5

85 Approximated using a conversion value of 335 gallon/tonne, based on an average density of liquid fuels.



SECTION 7.

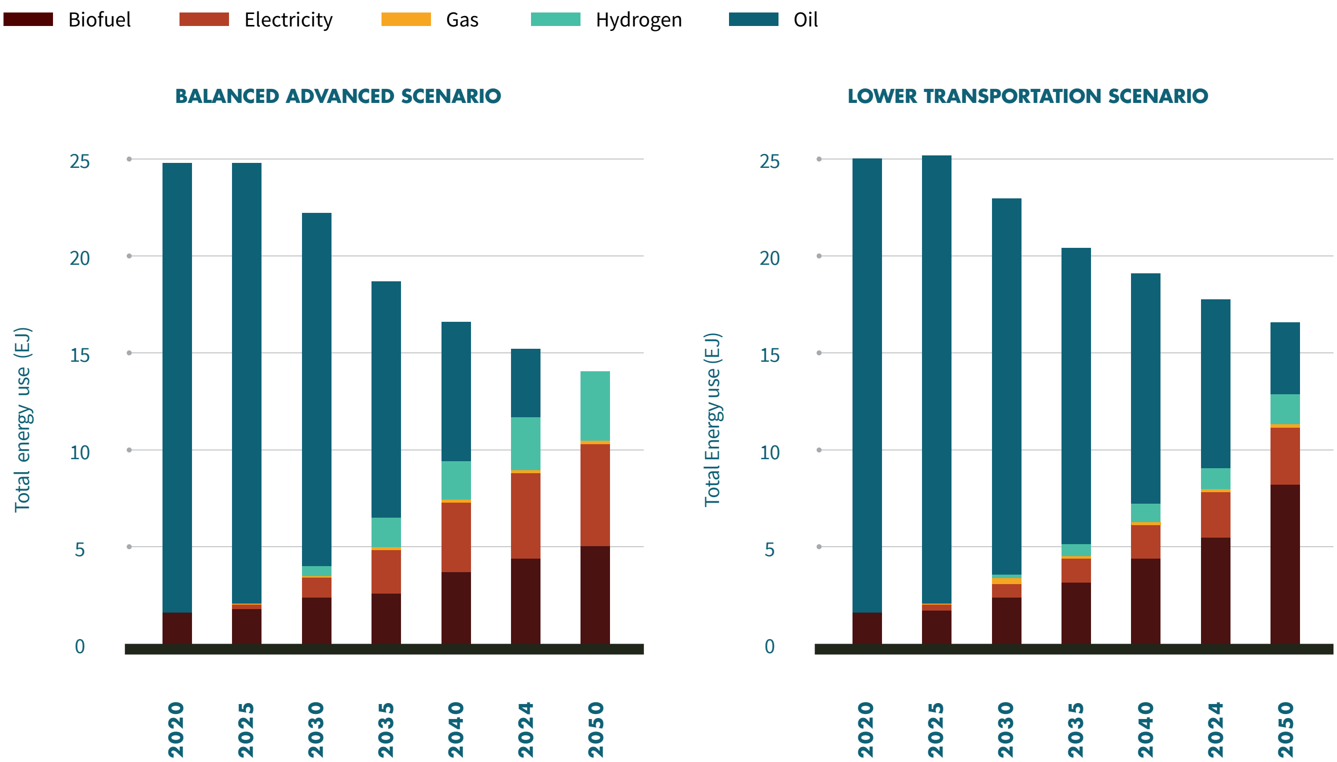
What role will e-fuels have in decarbonizing U.S. road transport?

E-fuels are technically viable and have high GHG savings, but face challenges with high production cost which means they will require policy support to be economically viable. Drawing from key findings from this report, this section examines how e-fuels could be deployed to support the decarbonization of the road transport sector in the U.S., whether there will be enough supply to meet this need, and how this may change over time with ramp up in supply and competing demands from non-road sectors. Based on these considerations, this section concludes by making recommendations on key actions that policymakers could take to enable wider e-fuels uptake in the U.S.

7.1 WILL E-FUELS BE NEEDED TO DECARBONIZE U.S. ROAD TRANSPORT?

The decarbonization pathway for road transport in the U.S. is highly uncertain. Multiple vehicle stock projections are available in the public domain which are based on drastically different levels of emission reduction ambitions as seen in Table 29, but all of which expect that ICEVs will continue to be used on the road in 2040. Although BEVs offer higher energy efficiency and lower costs than low carbon liquid fuels, technical and infrastructure requirements could limit how quickly they are adopted, and which vehicles can be electrified. This makes low carbon fuels that can be used in ICEVs – including e-fuels - potentially important decarbonization options, especially in existing ICEVs that could still be on the road by 2040. As shown in the Lower Transportation Scenario below, the market for low carbon fuel could be much larger if the BEV uptake rate is slow. This energy mix covers all transport sectors where road accounts for 75% of this demand.

FIGURE 7-1. TRANSPORT ENERGY MIX MODELLED UNDER U.S. LONG-TERM STRATEGY[86]



In the U.S. Long-Term Strategy's (LTS) Lower Transportation scenario,[30] no e-fuels contribution is modelled. However, it is projected that there will be demand for approximately 101 million tonnes (36 billion gallons) of biofuel. Importantly, this scenario is not forecasted to achieve net zero in 2050 – if this were to be achieved the demand for low carbon fuels would be even larger. This demand could be met through both biofuels and e-fuels, with e-fuels being more important if non-food biofuels are slow to ramp up.

86 Balance advanced scenario represents a scenario with few technological and political barriers to GHG mitigation. The lower transportation scenario represents a scenario in which decarbonization challenges emerge in the transport sector. See Table 29 for EV sale assumptions.

TABLE 29. LOW CARBON FUEL DEMAND IN TRANSPORT EMISSION REDUCTION MODELLING

	LOW CARBON FUEL DEMAND (MT)			CO_2 REDUCTION COMPARED TO 2005 BASELINE			EV SALE ASSUMPTIONS FOR LDV
YEAR	2030	2040	2050	2030	2040	2050	
LTS - Balanced advanced scenario[30,31]	54	83	115	43%	82%	100%	**2030:** >50% **2050:** 100%
LTS - Lower transportation scenario[30,31]	54	101	188	26%	58%	82%	**2030:** >30% **2050:** 70%
Annual Energy Outlook (AEO) 2023[32]	37	42	44	16%	20%	17%	**2030:** 7% **2050:** 18%

7.2 HOW MUCH OF THIS DEMAND COULD BE MET BY E-FUELS, AND HOW WOULD THIS INTERACT WITH E-FUEL USE IN OTHER SECTORS?

E-fuels production capacity could grow significantly from a very low level today to 0.9 million metric tons per year (Mt/year or 0.3 billion gallon/year) in 2030, based on planned project announcements. By 2040, if there was significant demand under strong policy support and supply was profitable, e-fuels could scale up even further to reach around 6-14 Mt/year (or 2-4.7 billion gallon/year) in the U.S. These volumes are relatively insignificant compared to the projected demand for biofuels overall under the U.S. Long-Term Strategy, which can be used as a proxy for low carbon fuels demand – about 2% in 2030 compared to the Lower Transportation Scenario and 6-14% in 2040. Whether this limited supply will reach the road transport sector in the U.S. will be largely influenced by policy.

Currently, e-fuels are much more costly to produce than fossil fuels and biofuels, and while costs could come down in future, e-fuels are unlikely to reach cost parity. Because of this, policy support plays a key role in bridging the cost gap, but also in determining in which transport sectors e-fuels could be deployed.

Today, the demand signal for e-fuels in the U.S. is largely non-existent. The federal level blending mandate RFS2 does not currently apply to e-fuels, and state level emissions reduction targets could potentially be met with cheaper technologies. This means that there is currently **no guaranteed market demand for e-fuels in the U.S.** In comparison, fuel policies in the EU and UK include sub-targets for e-fuels and penalties for non-compliance, which create clearer and stronger demand signals, particularly in the aviation sector.

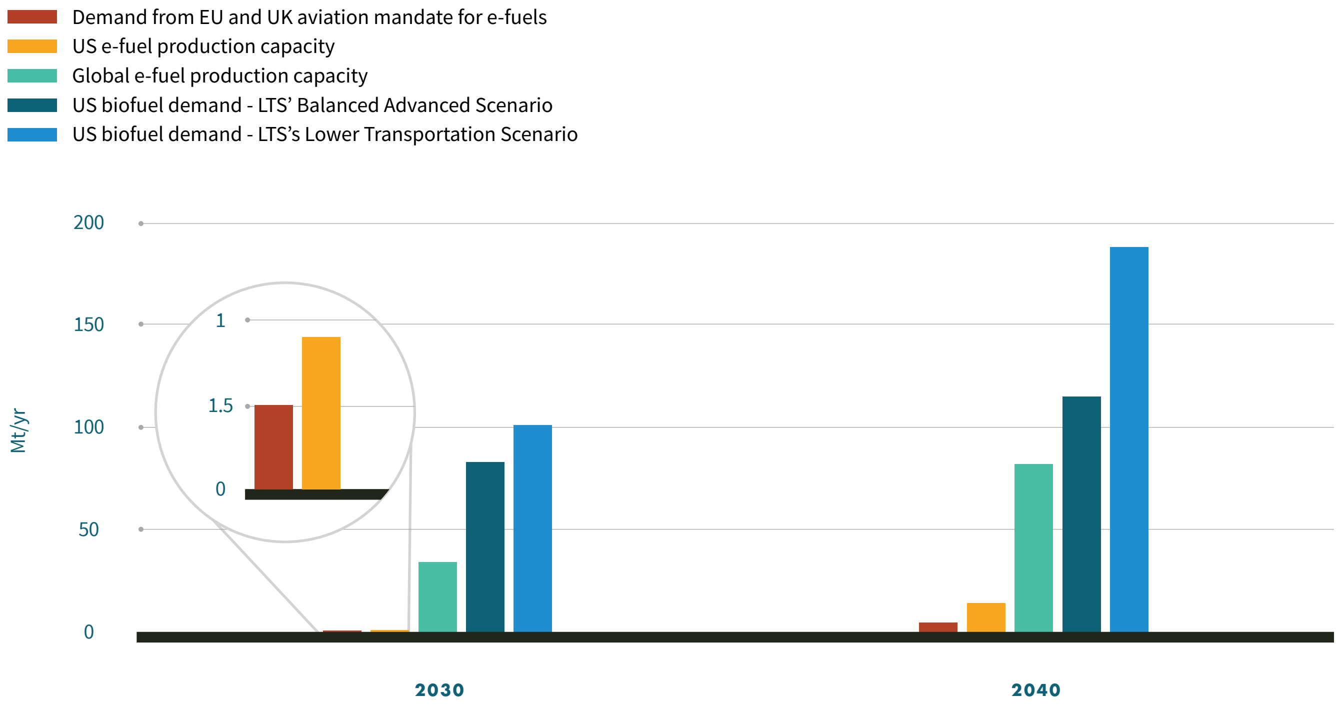
The policy environment in the U.S. instead focuses on incentivizing supply, where several TCs have been introduced through the IRA that could bring down production costs for e-fuels producers. However, the 45Z Clean Fuel Production TC will provide **higher support for sustainable aviation fuels** over fuels for road. Both of these factors could result in e-fuels producers favoring markets other than the U.S. road market:

- E-fuel projects are likely to be developed in the U.S. where producers can benefit from the 45Q, 45V and 45Z PTC, but sell the final fuel product to the EU/UK market, capitalizing on financial support from both supply and demand policies in the U.S. and Europe (including the UK). The European market could also prioritize supply from the U.S. as they are likely to outcompete e-fuels without significant supply side support.
- E-fuel producers could tune production capacity to maximize e-SAF volumes over road fuels due to the higher policy premium available.

Despite the competition for e-fuel supply, e-fuel demand driven by the EU and the UK aviation mandates is small compared to potential supply (Figure 7-2). This means that there could be domestic e-fuel supply available even if e-fuel producers prioritize the EU and UK aviation markets. Additionally, because most e-SAF pathways produce diesel and naphtha as co-products, their ramp-up will also provide fuels for road. High WTP from the aviation industry could also potentially help support road e-fuel prices.

Scaling capacity to these levels relies on the availability of renewable electricity and CO_2. There are likely no physical limits on the availability of feedstock when considering the wind and solar resources available in the U.S. and the source of CO_2 in the atmosphere. However, in practice, interlinking market (e.g. costs) and supply chain factors (e.g. raw material availability, inflation) could affect the development rate of additional renewable electricity generation assets, and the development risks of DAC technologies, which may constrain the availability of renewable electricity and CO_2. The extent to which development of these feedstock sources could be constrained is highly uncertain. However, it is important to keep in mind that under sufficiently strong policy support, demand for e-fuels could be a driver for the development of additional renewables, which could also benefit other sectors. In a scenario where additional renewable electricity and CO_2 will be readily available, and strong demand signals exist, e-fuels supply could ramp up quickly and could reach higher capacities than projected in this study.

FIGURE 7-2 E-FUEL PRODUCTION CAPACITIES COMPARED TO DEMAND



7.3 KEY ACTIONS NEEDED TO SUPPORT E-FUEL UPTAKE

The U.S. e-fuel landscape currently lacks the support required to drive significant uptake of e-fuels in the road market and become competitive with alternatives. The policy support analysis in Section 6 showed that it could be challenging for most early e-fuel plants to be economically viable in the near-future, despite policy support driving down costs. While the production cost could decrease sufficiently for e-fuel plants to become profitable, policy uncertainties (e.g. whether TCs can be stacked, the timeline in which TCs will be available, and whether e-fuels will be included in the RFS or LCFS) will cause market risks which could deter investments from e-fuel projects. Without a guaranteed market, e-fuel uptake will also be highly unpredictable in the road transport sector given that cheaper alternatives are already commercially available.

Given this highly uncertain outlook, enabling the uptake of e-fuels requires a multifaceted approach across technology, sustainability, policy, and market development. If U.S. policymakers are keen to further incentivize e-fuel uptake in the transport sector, some recommendations they could consider include the following:

Clearer Transport Decarbonization Pathways, Targets and E-fuels Road Map

- Develop a knowledge base on U.S. transport decarbonization, including all decarbonization options: There is currently very little detailed analysis and scenarios that show the role of all transport decarbonization options in all modes in the U.S.
- Set clear emission reduction targets for the transport sector, including by mode: Allow market to anticipate what types of low emission transport solutions (including e-fuels) will be needed in road transport decarbonization.
- Develop a U.S. road map for e-fuels production and use: Include the demands of road, aviation, maritime and rail sectors, so that the production plants, infrastructure and policy for these can be developed together, rather than being seen as competing markets.

Sustainability Criteria

- **Standardize lifecycle assessment methodologies:** The U.S. currently does not have an agreed and published methodology for calculating the GHG emissions of e-fuels, including the treatment of renewable electricity used. Because some policies set GHG thresholds to determine eligibility or provide higher support for options that provide further GHG emission reduction, developing standardized methodologies that account for the benefits of e-fuels will allow stakeholders to evaluate the environmental performance quantitatively to make informed decisions about prioritization.

Policy and Market Development

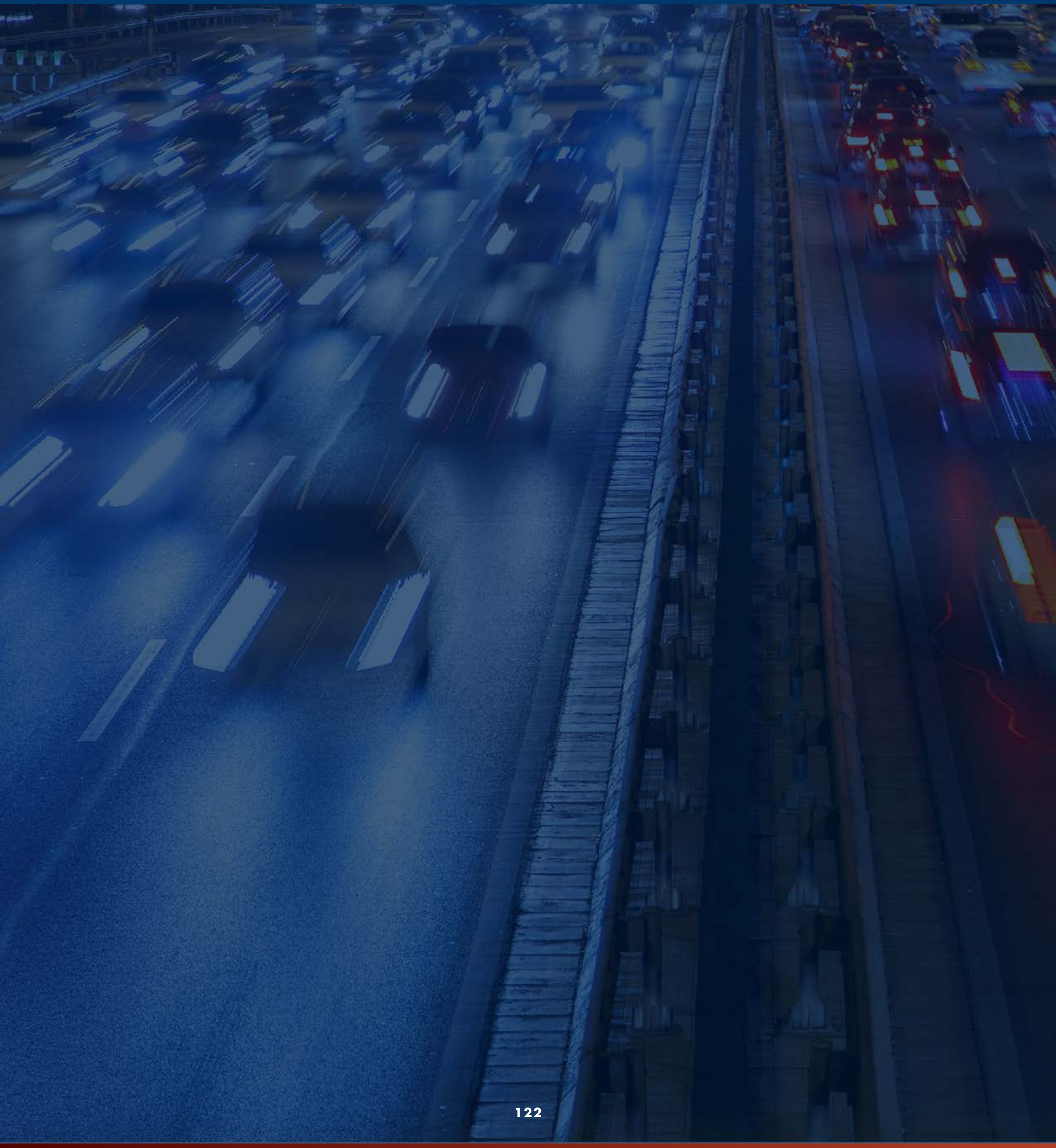
- **Guarantee markets for e-fuel producers:** The U.S. e-fuel policy landscape currently lacks demand-side policy support to promote the uptake of e-fuel. Policy makers could consider mandating a minimum share of e-fuel use in the road transport sector. Unlike the technology-neutral approach taken by the LCFS, an e-fuel sub-target is the most direct way to facilitate market access and provide market certainty to e-fuel developers and investors. The cellulosic sub-target within the RFS2 is an example of this. This could be designed to ensure that e-fuels plants in the U.S., which will receive production-side support, prioritize domestic demand instead of being drawn away to UK/EU with mandated markets. Some have argued that a technology neutral CI based target is more appropriate for meeting GHG reduction goals, however guaranteed markets for emerging technologies can help to give confidence in markets and so secure investment.

Technology and infrastructure development

- **Increase public funding for e-fuel projects:** E-fuel production is capital intensive with CAPEX contributing 17-24% of the levelized production costs. It is challenging to secure private investment for early development technologies due to large risks associated with low maturity plants. Having access to public funding to secure capital costs for early plants could help promote e-fuel plant roll-out in the U.S., like the AFF[87] in the UK. While funding programs for biofuel and hydrogen projects are available in the U.S., none to our knowledge exist which targets e-fuels. Securing public funds can also provide confidence to investors and unlock additional private investment to projects as well.

87 For more information on the AFF, see [link]

APPENDICES, ACRONYMS & ABBREVIATIONS



LIST OF ACRONYMS AND ABBREVIATIONS

AEO Annual Energy Outlook

AFF Advanced Fuels Fund

ALK alkaline

BEV battery electric vehicle

CAPEX capital expense

CCS carbon capture and storage

CCU carbon capture and utilization

CI carbon intensity

CNG compressed natural gas

DAC direct air capture

DOE Department of Energy

E10 gasoline with 10% ethanol blend

EIA Energy Information Administration

EPA Environmental Protection Agency

EPC engineering, procurement and construction

ETJ ethanol-to-jet

FCEV hydrogen fuel cell electric vehicle

FFV flexible fuel vehicle

FOAK first-of-a-kind

FT Fischer Tropsch

GHG greenhouse gas

GREET Greenhouse Gases Regulated Emissions and Energy Use in Technologies

HDV heavy-duty vehicle

HEV hybrid electric vehicle

HFO heavy fuel oil

HIF highly innovative fuel

HRS hydrogen refueling station

ICCT International Council on Clean Transportation

ICE internal combustion engine

ICEV internal combustion engine vehicle

IRA Inflation Reduction Act

LCFS Low Carbon Fuel Standard

LCOE levelized cost of renewable energy

LDV light-duty vehicle

LNG liquified natural gas

LTS long-term strategy

MDV medium-duty vehicle

MTG methanol-to-gasoline

MTO methanol-to-olefins

NG natural gas

NGV natural gas vehicle

NOAK nth-of-a-kind

OECD Organization for Economic Co-operation and Development

OEM original equipment manufacturer

OPEX operational expense

PEM polymer exchange membrane

PHEV plug-in hybrid electric vehicle

PM particulate matter

pRWGS partial reverse water gas shift

PTC Production Tax Credit

PtL power to liquid

PV photo-voltaic

RED Renewable Energy Directive

RFS Renewable Fuel Standard

RIN renewable identification numbers

RTFO Renewable Transport Fuel Obligation

RWGS reverse water-gas shift

SAF sustainable aviation fuel

TC tax credit

TRL technology readiness level

WTP willingness to pay

APPENDIX A

E-fuel Product Slate References

[1] Mass and Energy balance lower range: internal modelling, close to theoretical limit upper range: literature [Konig et al. 2015] and [de Klerk 2011]

[2] Albrecht et.al., (2017) A standardized methodology for the techno-economic evaluation of alternative fuels – A case study. Available at [link]

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APPENDIX B

Technical Characteristics of Alternative Powertrains—Supporting Information

Table 30 provides supporting information for Table 8 in Section 2.2.2.

TABLE 30. TECHNICAL CHARACTERISTICS OF DIFFERENT POWERTRAINS IN ROAD TRANSPORT

POWERTRAIN	POWERTRAIN EFFICIENCY	MAXIMUM RANGE OF CURRENT MODELS (LDV)	MAXIMUM RANGE OF CURRENT MODELS (MDV/HDV)
Conventional ICEV and FFV	12-30% for gasoline[88] Up to 40% for diesel (HDV)[89] **FFV:** up to 5% pts. higher than gasoline ICEV for E85 blends[90]	**ICEV:** Up to 500 mi, depending on fuel tank size **FFV:** Up to 300 mi for light pickups and vans	Over 1000 mi for long-haul HDVs **FFV:** Up to 500 mi for heavy pickups
HEV	21-40%	Up to 500 mi, depending on fuel tank size	NA
PHEV	21-40% when using gasoline 75-85% when using electricity (including energy lost during charging)	Up to 50 mi all-electric range, up to 500 mi with gasoline	NA
BEV	75-85% (including energy lost during charging)[88]	Up to 350 mi	Up to 500 mi estimated,[91] other models up to 300 mi
FCEV	50-60%[92]	Up to 400 mi	Up to 500 mi[93]
NGV	30-35%[94]	NA	Up to 700 mi

88 DOE (n.d), Availablle from: [Link] (specific links for gasoline, HEV, BEV and FFV). PHEV efficiencies taken from HEV and BEV figures for gasoline and electricity efficiency respectively.

89 Cengel and Boles (2007), Thermodynamics: An Engineering Approach

90 Delavarrafiee and Frey (2018), Real-world fuel use and gaseous emission rates for flex fuel vehicles operated on E85 versus gasoline. Available from: [link]

91 Tesla Semi, first delivery 1st Jan 2024. Available from: [link]

92 Argonne National Laboratory (2020), Automotive fuel cell stack and system efficiency and fuel consumption based on vehicle testing on a chassis dynamometer at minus 18°C to positive 35°C temperatures. Available from: [link]

93 Nikola TRE FCEV (2024). Available from: [link]

94 Stettler et. al., (2019), Natural gas as a fuel for heavy goods vehicles

APPENDIX C

Avoided Emissions of Using Renewable Electricity–Assumptions

To estimate the carbon reduction per unit of renewable electricity used as shown in Section 3.1, the following values, sources and assumptions below were used. These values do not include other lifecycle emissions or energy use in each pathway (including compression of hydrogen, post processing of e-fuels, transportation of electricity/hydrogen/e-fuels, production emissions of different vehicles). Accounting for these additional factors will change the below values, but are unlikely to significantly change the order of emissions avoided per kWh RE. For example, reducing the emissions avoided for a BEV by 20 gCO_2e/mile to account for the worst-case increased production emissions of a BEV would reduce the gCO_2e avoided per kWh RE to 624 gCO_2e/kWh: still higher than displacing natural gas, hydrogen in FCEVs and e-gasoline in ICE cars.

TABLE 31. LIST OF ASSUMPTIONS FOR RENEWABLE ELECTRICITY APPLICATIONS

REDUCTION TYPE	EMISSIONS AVOIDED (unit)	RENEWABLE ELECTRICITY REQUIRED	GCO_2E AVOIDED PER KWH RE	SOURCE/ASSUMPTION
Displace coal in electricity generation	868 tCO_2e/yr	831,512 kWh/yr	1,044 gCO_2e/kWh	EIA [link] carbon emissions and energy from coal generation, 2022
Displace gasoline in cars with a BEV	275 gCO_2e/mile	0.408 kWh/mile	673 gCO_2e/kWh	Emissions per mile as calculated in Section 4, electricity consumption per mile as described in Appendix E. Electricity consumption includes energy losses when charging BEVs, with 4.5% transmission losses added (EPA eGrid) [link]
Displace natural gas in electricity generation	742 tCO_2e/yr	1,687,067 kWh/yr	440 gCO_2e/kWh	EIA [link] carbon emissions and energy from gas generation, 2022
Displace gasoline in cars with hydrogen in a FCEV	275 gCO_2e/mile	21 gH_2/mile =	261 gCO_2e/kWh	Using 50 kWh/kg hydrogen produced (value quoted for some industrial systems [link] [link]. Emissions per mile as calculated in Section 3.4, hydrogen consumption per mile as described previously in this Appendix.
Displace gasoline in cars with e-gasoline	8,887 gCO_2/ gallon gasoline	1.053 kWh/mile	127 gCO_2e/kWh	Assuming RE is only used to produce hydrogen (not for carbon capture or other processing steps), with 0.5 kg H_2 required for 1 kg of e-gasoline.

APPENDIX D

Production Cost Assumptions

For Section 5, the following values, sources and assumptions have been used to estimate the production cost of e-fuels per GJ of all fuels.

PRODUCTION PATHWAYS CONSIDERED

The following processes are considered in the production costs for the base scenario, breaking down the various e-fuel production technologies:

<table>
<tr><th colspan="2">FEEDSTOCK</th><th>H2 PRODUCTION</th><th>1ST PROCESSING STEP</th><th>2ND PROCESSING STEP</th><th>FINAL PRODUCT</th></tr>
<tr><td rowspan="7">Renewable Electricity</td><td rowspan="7">Point-source CO_2</td><td rowspan="7">PEM electrolysis</td><td>FT via RWGS</td><td>Hydrocracking</td><td>Jet and/or diesel, naphtha</td></tr>
<tr><td rowspan="2">pRWGS followed by fermentation</td><td colspan="2">Ethanol</td></tr>
<tr><td>ETJ</td><td>Jet and/or diesel, naphtha</td></tr>
<tr><td rowspan="3">Methanol synthesis via MTO</td><td colspan="2">Methanol</td></tr>
<tr><td>MTJ</td><td>Jet and/or diesel, naphtha</td></tr>
<tr><td>MTG</td><td>Gasoline</td></tr>
<tr><td>Methanation</td><td colspan="2">Methane</td></tr>
</table>

PRODUCTION PATHWAYS FOAK TIMELINE ASSUMED

The FOAK year can be estimated by looking at the first commercial plant to be operational in the planned plants list in Appendix C. The following FOAK timelines were assumed:

TABLE 31. LIST OF ASSUMPTIONS FOR RENEWABLE ELECTRICITY APPLICATIONS

PATHWAY	LIKELY FOAK YEAR
e-FT	2026
pRWGS followed by fermentation	2027
e-ETJ	2027
Methanol synthesis	2025
e-MTJ/G	2027
Methanation	2028

PRODUCTION COST ASSUMPTIONS

The production costs in this study have been estimated using the following assumptions:

KEY INPUT	ASSUMPTION	2030	2040	REFERENCE
CO_2	Point-source CO2 from cement production	$125/ton CO2	$131/ton CO2	Modelled
H2	Integrated PEM electrolysis	$3.1-4.3/kg H2	$2.9-4.1/kg H2	Modelled
Renewable Electricity	Texas grid PPA prices	$42.5-55/MWh	$42.5-55/MWh	Internal sources
Grid Electricity	Assumed the same and renewable electricity	$42.5-55/MWh	$42.5-55/MWh	Internal sources
Natural Gas	Industrial rates in the U.S.	$4.06/Mcf	$4.96/Mcf	EIA AEO[95]

Other economic assumptions include:

- **8% discount rate over an economic lifetime of 20 years.**
- **Utilization ramp-up from commissioning to 85% at start up (i.e. 7,446 hours per year) unless otherwise specified.**

FOAK PLANT ASSUMPTIONS

The following FOAK size and timeline have been assumed for each pathway, indicative of planned commercial plants mentioned in Appendix A.

PATHWAY	TYPICAL SIZE FOAK (kt/yr all fuels)	TYPICAL FOAK YEAR
FT via RWGS	50	2026
pRWGS followed by fermentation	50	2029
e-ETJ	80	2025
Methanol synthesis	50	2025
e-MTJ	80	2026
e-MTG	80	2026
Methanation	50	2025

95 EIA (2023), AEO (2023). Available from: [link]

APPENDIX E

Cost and Emissions Per Mile Assumptions and Sources

For Section 3.3 and 5.5, the following values, sources and assumptions have been used to estimate the cost per mile for different powertrains.

ASSUMPTIONS MADE AND POTENTIAL IMPACT ON RESULTS

For the values shown in the main report, a set of assumptions were made to simplify the calculations. The main assumptions made are listed below, with a qualitative assessment on the risk of the assumption and commentary on the impact of the assumption on the comparison between powertrains.

ASSUMPTION	POTENTIAL IMPACT ON RESULTS	QUALITATIVE IMPACT OF ASSUMPTION ON RESULT
Exclusion of vehicle taxes in cost	Low	Over the course of a vehicle's useful lifetime, the tax burden is relatively low compared to purchase cost and running costs. Including this would benefit lower emission powertrains (e.g. BEV, FCEV) where tax rebates are applied for these technologies.
Vehicles are purchased outright with no financing	Medium	Including financing costs will increase the cost of alternative powertrains compared to old and new ICE, as alternative powertrains have a higher purchase price. This is most pertinent to HDVs in 2023, where there is a large difference in purchase. By 2040, vehicle prices are similar enough that this won't make a significant impact for new vehicle purchases.
Residual value is negligible at end of life	Low	As the cost of ownership is performed over the vehicle's lifetime, the residual value is likely to be negligible as the vehicle is likely to be sold for scrap. For alternative powertrains, the residual value could be higher if battery and fuel cell is developed, decreasing the cost of ownership of these technologies compared to ICE.
Cost of ownership is over vehicle lifetime	Low	Alternatively, the calculation could be done over the vehicle's first ownership, with the vehicle then sold to another owner. This adds additional uncertainty around vehicle residual value, so hasn't been performed in this study to reduce uncertainty.
Subsidies and tax rebates are not included	High	Subsidies are likely to play a significant role in encouraging lower emission options (either fuels or powertrains). These are excluded from the analysis in Section 5.5 to provide a level playing field to assess the need for policy support.
Vehicle purchase price of all cars is equal in 2040	Low	Apart from FCEV, the difference in purchase price between the powertrains in 2023 is <$5,000. This is likely to decrease further over time, but this decrease does not make a significant impact to the cost over the vehicle's lifetime (cost over lifetime is ~$70,000 for all new purchases except for FCEV).
All new vehicles have the same total lifetime, and this doesn't change over time	Medium	Vehicle lifetime will have a large impact on cost per mile, as longer lifetimes mean the purchase cost is spread over more distance, reducing the cost per mile. An Argonne National Laboratory report (2021, link) assumes that BEVs and FCEVs are capable of matching the lifetime of conventional ICE vehicles without a battery or fuel cell replacement, citing the rarity of battery replacements for BEV LDVs and OEM battery warranties for transit buses covering the full 12 year expected lifetime. If vehicle lifetimes were increased over time, this would benefit powertrains with lower running costs (BEV, NGV) compared to vehicles with lower purchase cost but higher running costs (liquid fuel ICE).

VEHICLE PERFORMANCE

Values of vehicle lifetime used in this study are shown below:

VEHICLE TYPE	ASSUMED LIFETIME MILEAGE (2023 AND 2040)	SOURCE
Car	200,000 miles	Argonne National Laboratory (2021): Comprehensive Total Cost of Ownership Quantification for Vehicles with Different Size Classes and Powertrains [link]
HDV	750,000 miles	

These assumptions are kept constant between different powertrains, as done in the ANL (Argonna National Laboratory) study.

For "Old ICE" vehicles, it is assumed that they are halfway through their lifetime, so have a remaining mileage of 100,000 miles or 375,000 miles for cars and HDVs respectively.

The values used for fuel economy in this study are shown below:

VEHICLE TYPE AND POWERTRAIN	FUEL ECONOMY IN 2023 (MPGE)	FUEL ECONOMY IN 2040 (MPGE)	SOURCE/ASSUMPTION
Old ICE - Car	31.3	31.3	U.S. EIA AEO (2023). Small utility vehicle. Old ICE has not improved over time.
New ICE – Car	31.3	38.3	
HEV – Car	43.9	52.2	
PHEV – Car	227 (gasoline) plus 98 (electricity)	278 (gasoline) plus 101 (electricity)	Worldwide Harmonized Light Vehicle Test Procedure methodology: assuming a 50-mile electric range. Equivalent to ICE for gasoline and BEV for electricity, with 86% of energy coming from electricity.
FCEV – Car	48.0	49.8	U.S. EIA AEO (2023). Half of values for BEV (pre-charging adjustment), as seen by other car segments
BEV – Car	86.4	89.8	U.S. EIA AEO (2023). Assuming a charger efficiency of 90%.
Old ICE – HDV	6.8	6.8	International Council on Clean Transportation (ICCT)ICCT: Total cost of ownership of alternative powertrain technologies for class 8 long-haul trucks in the U.S. (2023) [link]
New ICE – HDV	6.8	10.1	
FCEV – HDV	7.4	11.4	
BEV - HDV	11.9	16.0	ICCT (2023), including assumed 90% charger efficiency
NGV – HDV	6.8	10.1	Assumed equal to New ICE NREL (2022) [link]

VEHICLE AND FUEL PRICES

The vehicle prices used in the study are shown below. Old ICE vehicles are assumed to have already been purchased, so do not have a purchase cost. The price of cars of different powertrains is assumed to converge in 2040.

VEHICLE TYPE AND POWERTRAIN	PURCHASE PRICE IN 2023	PURCHASE PRICE IN 2040	SOURCE/ASSUMPTION
New ICE – Car	$35,600	$35,600	Kelley Blue book (KBB) industry transaction prices for compact SUVs (Jul 2023) [link]
HEV – Car	$37,100	$35,600	Currently $1.5k premium vs ICE (U.S. DOE 2023) [link].
PHEV – Car	$39,600	$35,600	Currently $4k premium vs ICE (U.S. DOE 2023) [link]
FCEV – Car	$60,000	$35,600	Price of Hyundai Nexo (KBB 2023) [link]
BEV – Car	$40,000	$35,600	Price of Kia Niro or VW ID.4 (KBB 2023) [Kia Niro] [VW ID.4]
New ICE – HDV	$200,000	$212,000	ICCT: Total cost of ownership of alternative powertrain technologies for class 8 long-haul trucks in the U.S. (2023) [link]
FCEV – HDV	$560,000	$250,000	
BEV - HDV	$460,000	$230,000	
NGV – HDV	$220,000	$215,000	~10% premium currently, decreasing over time to equal Diesel ICE in 2050: B. Noll et al., Applied Energy (2022), 306 part B, 118079 [link]

The cost per mile of maintenance used in the study is shown below. All maintenance costs are from Argonne National Laboratory: Comprehensive Total Cost of Ownership Quantification for Vehicles with Different Size (2021) [link]. Maintenance costs are assumed to remain stable over time.

CLASSES AND POWERTRAINS

VEHICLE TYPE AND POWERTRAIN	MAINTENANCE COST ($/MI)	ASSUMPTION
Old ICE - Car	0.118	Average cost per mile for a 6-10 year old car
New ICE – Car	0.101	Average cost per mile for a 1-10 year old car
HEV – Car	0.094	
PHEV – Car	0.090	
FCEV – Car	0.060	
BEV – Car	0.060	
Old ICE – HDV	0.345	Average cost per mile for a 6-10 year old semi
New ICE – HDV	0.265	Average cost per mile for a 1-10 year old semi
FCEV – HDV	0.159	
BEV - HDV	0.159	
NGV – HDV	0.265	Assumed to be the same as a new ICE

The fuel prices used in this study are shown below, in $/kWh:

FUEL TYPE	COST IN 2023 ($/kWh)	COST IN 2040 ($/kWh)	SOURCE/ASSUMPTION
Gasoline	0.106	0.091	EIA AEO (2023)
Diesel	0.119	0.100	EIA AEO (2023)
E-Gasoline	0.241	0.205	Average of FT WGS, MtJ and MtG pathways in section 5.
E-Diesel	0.241	0.205	Average of FT WGS, MtJ and MtG pathways in section 5.
Bio-gasoline	0.184	0.184	Based on production cost
Bio-diesel	0.155	0.130	30% uplift on diesel, consistent with recent prices (AFDC) [link]
Hydrogen	0.306	0.261	ICCT (2023) [link]
Domestic Electricity	0.141	0.139	EIA AEO (2023)
Commercial Electricity	0.122	0.109	EIA AEO (2023)
Public charging electricity	0.282	0.278	Assumed double of domestic electricity, based on current cost of public charging in CA [link].
Methane	0.081	0.061	**2023 value:** Alternative Fuels Data Center, Oct 2023 CNG price [link]. **2040 value**: 2023 value scaled by predicted change in methane price in EIA AEO (2023)

EMISSIONS

To calculate the emissions per mile of each powertrain and fuel type, the CI of each fuel was multiplied by the fuel consumption as previously detailed in this appendix. For E-fuels, the emissions factors use come from Section 3. The emissions factors and their source used for each fuel is shown below.

FUEL TYPE	EMISSIONS FACTOR IN 2023 (gCO_2e/kWh)	EMISSIONS FACTOR IN 2040 (gCO_2e/kWh)	SOURCE/ASSUMPTION
Gasoline and Diesel	0.106	0.091	RFS fossil comparator
Bio-gasoline	0.119	0.100	Renewable gasoline made from forestry residues or vegetable oil (pathways approved by the CA LCFS, 2023)
Bio-Diesel	0.241	0.205	Renewable diesel made from waste oil or vegetable oil (pathways approved by the CA LCFS, 2023)
Grid electricity	0.241	0.205	EPA eGrid data for 2023, EIA AEO 2023 for 2040 average, with high and low reduced proportionally from 2023 (reference case) [link]
Renewable electricity	0.184	0.184	Production emissions of solar panels/wind turbines not considered
Hydrogen	0.155	0.130	2023: Range of emissions intensity of hydrogen to be classed as "clean hydrogen". (DOE) [link]
Methane	0.306	0.261	As reported by the CA LCFS (2023)
Landfill Biogas	0.141	0.139	Emissions intensity of biogas from landfill (pathways approved by the CA LCFS, 2023)
Manure Biogas	0.122	0.109	Emissions intensity of biogas from manure (pathways approved by the CA LCFS, 2023)

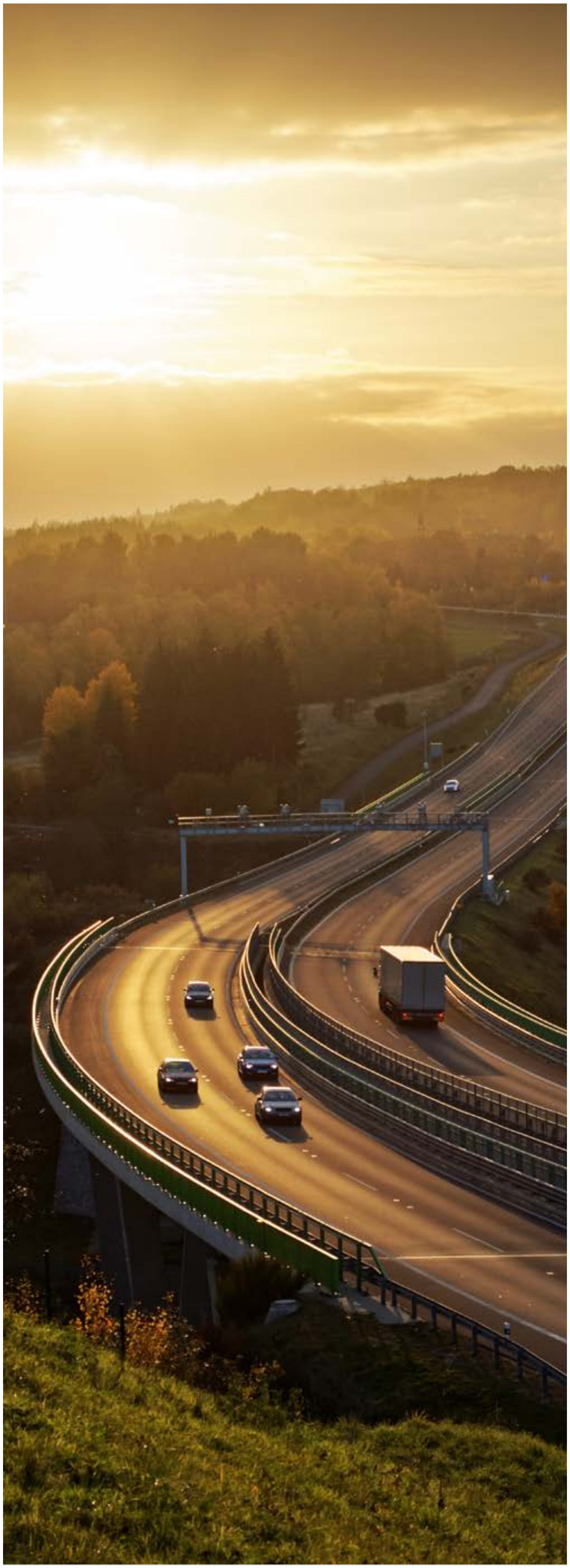
For all vehicles, there are emissions associated with the production of these. Foremost of this are BEVs, as battery production can produce relatively higher emissions. However, considering a worst-case scenario (batteries produced in China, no optimization of supply chains to reduce emissions), this could result in 6 tCO_2e of extra emissions per large car produced today.[96] This would be equivalent to 30gCO_2e/mile driven, assuming a 200,000 mile lifetime, which is significantly lower than the use-phase emission associated with most technologies investigated.

In addition, it is likely that the carbon emissions associated with battery production will decrease over time, the same report estimates that producing a large BEV in 2030 could only produce an extra 1.2 tCO_2e compared to a gasoline car (equivalent to 6 gCO_2e/mile over the vehicle's lifetime), if the battery is produced in the EU and the battery supply chains optimized to reduce emissions.

96 How Clean are Electric Cars? Transport & Environment (2022). Available from: [link]

APPENDIX F

Policy Support



POLICY SUPPORT ASSUMPTIONS

- **RFS eligibility –** it is assumed that e-fuels will not receive RFS support as focus remains on biofuels.
- **TC stacking** - the total cost support claimed by a U.S.-based e-fuel producer will depend on whether the three IRA production credits can be stacked and claimed for the same product. This section assumes that the production facility can be structured so that the 45V, 45Q and 45Z production credits can all be claimed for the same product.
- **Labor requirements –** for each PTC, it is assumed the production facility meets the labor requirements which allow the base credit value to be multiplied by 5.
- **CI of hydrogen –** it is also assumed that hydrogen will be produced with renewable electricity meeting rules set under the 45V, thus having CI of less than 0.45 CO_2e/kg H_2, which can receive the maximum base credit value ($0.60/kg H_2).
- **California LCFS fossil reference –** for a FOAK plant, we use the reference CI values for 2025 (85.77 and 86.64 gCO_2/MJ for gasoline and diesel/SAF respectively). For the future scenario, we use the reference CI values for 2040 as suggested under the proposed LCFS amendment (24.86 and 25.01 for gasoline and diesel/SAF respectively).
- **California LCFS carbon price –** $75.50/tonne CO_2e (calculated from average LCFS ticket prices in 2023).
- **Extension of federal programs –** we assume the proposed IRA credits (currently set to expire between 2027-2033) will be extended and therefore available to future plants in 2040.

CALCULATIONS FOR POLICY SUPPORT

The 45V Hydrogen PTC is calculated as:

$$\underset{[\$/t]}{45V\ Premium} = \underset{[\$/kg\ H_2]}{Base\ credit} \times \underset{[kg\ H_2/\ kg\ product]}{H_2\ Consumption} \times 5 \times 1000$$

The base credit is assumed to be \$0.60/kg H_2.

The 45Q Carbon capture credit is calculated as:

$$\underset{[\$/t]}{45Q\ Premium} = \underset{[\$/tCO_2]}{Base\ credit} \times \underset{[tCO_2/\ t\ product]}{CO_2\ consumption} \times 5$$

The 45Q base credit is \$12/tCO_2 for CO_2 utilization, unless DAC is used as the CO_2 source in which case the base credit is \$26/tCO_2.

The 45Z Clean Fuel Production Credit is calculated as:

$$\underset{[\$/t]}{45Z\ Premium} = \underset{[\$/gal]}{Base\ credit} \times \frac{\left(\underset{[gCO_2/MJ]}{Reference\ CI} - \underset{[gCO_2/MJ]}{Fuel\ CI}\right)}{\underset{[gCO_2/MJ]}{Reference\ CI}} \times 5 \times Gal/tonne$$

The 45Z base credit for SAF is \$0.35/gal; for all other eligible fuels, the credit is \$0.20/gal. The reference CI is 47.4 gCO_2/MJ.

The California LCFS premium is calculated as:

$$\underset{[\$/t]}{LCFS\ Premium} = \underset{[\$/tCO_2]}{Certificate\ Price} \times \left(\underset{[gCO_2/MJ]}{Reference\ CI} - \underset{[gCO_2/MJ]}{Fuel\ CI}\right) \times \underset{[MJ/kg]}{LHV} /\ 1000$$

The WTP for e-fuels in California is calculated as:

$$\underset{[\$/t]}{WTP} = \underset{[\$/t]}{Fossil\ Market\ Price} + \underset{[\$/t]}{LCFS\ Premium}$$

TOTAL POLICY SUPPORT FOR E-FUELS PLANTS

The following graphs display total cost and price support for the e-fuel production pathways considered in this report. Note the graph for e-FT + RWGS production are already shown in Section 6.2.

FIGURE F-1. PRODUCTION COST AND POLICY SUPPORT FOR AN E-ETJ PLANT, ASSUMING A PRODUCT SLATE OF 75% SAF, 15% DIESEL AND 10% NAPHTHA.

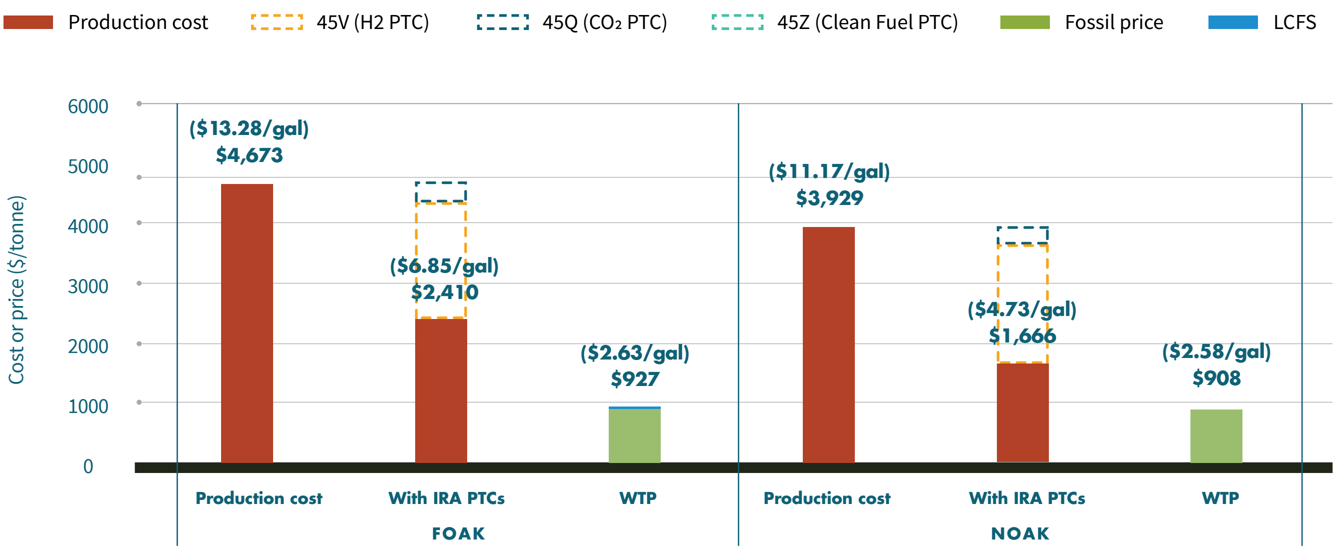


FIGURE F-2. PRODUCTION COST AND POLICY SUPPORT FOR AN E-MTJ PLANT, ASSUMING A PRODUCT SLATE OF 75% SAF, 15% DIESEL AND 10% NAPHTHA.

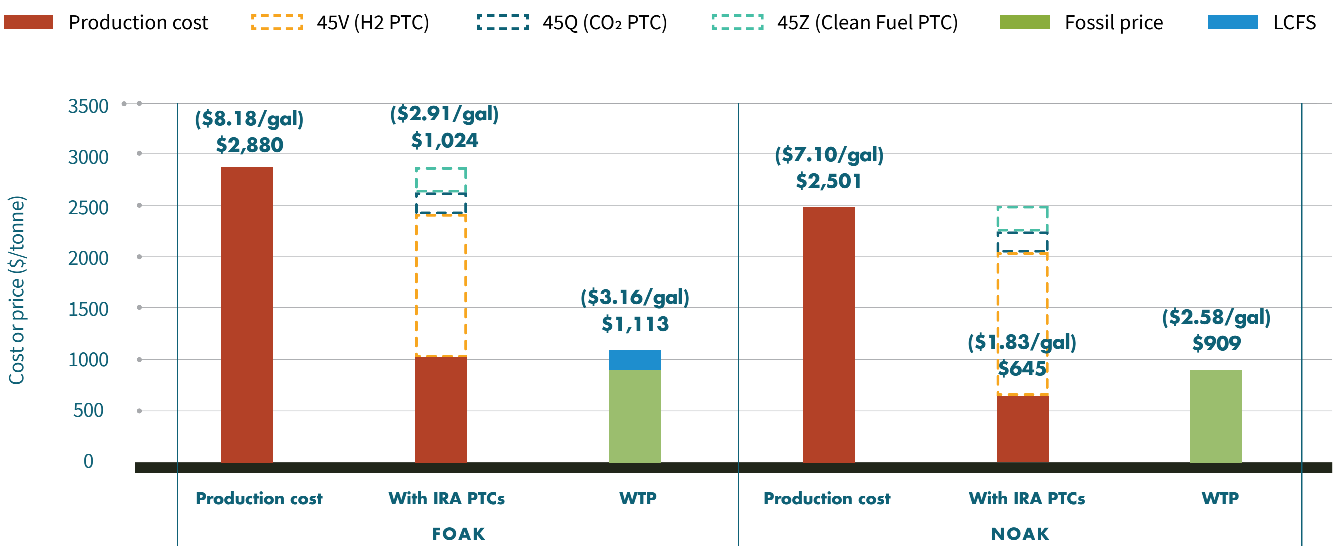


FIGURE F-3. PRODUCTION COST AND POLICY SUPPORT FOR AN E-MTG PLANT, ASSUMING A PRODUCT SLATE OF 90% GASOLINE AND 10% LPG.

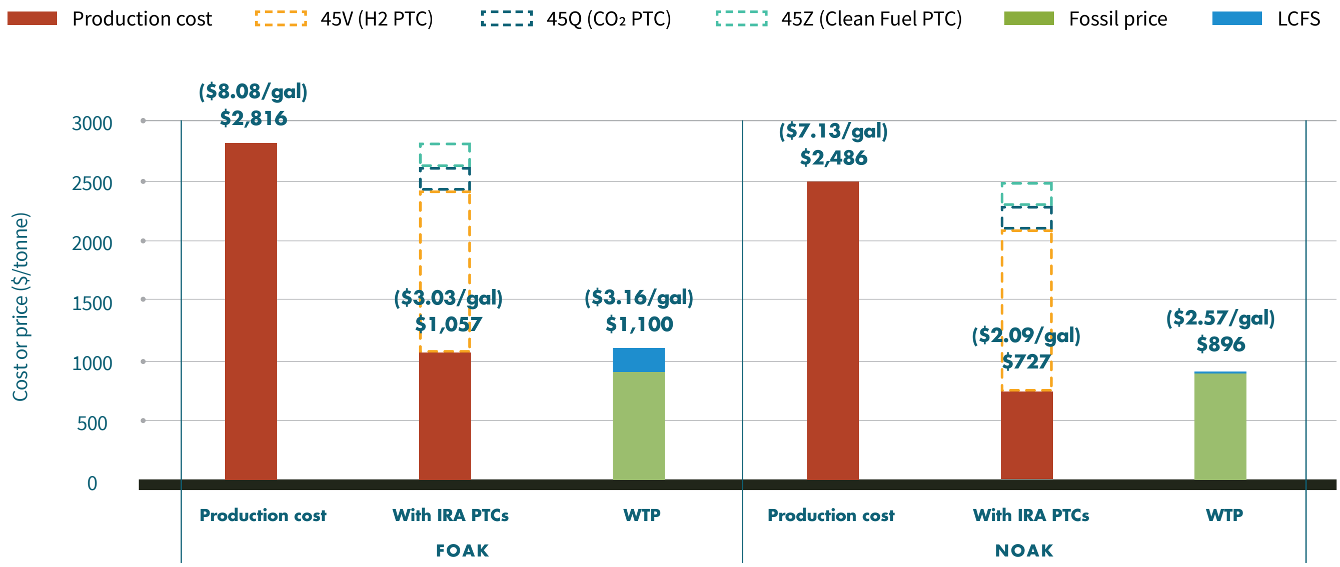


FIGURE F-4. PRODUCTION COST AND POLICY SUPPORT FOR AN E-ETHANOL PLANT.

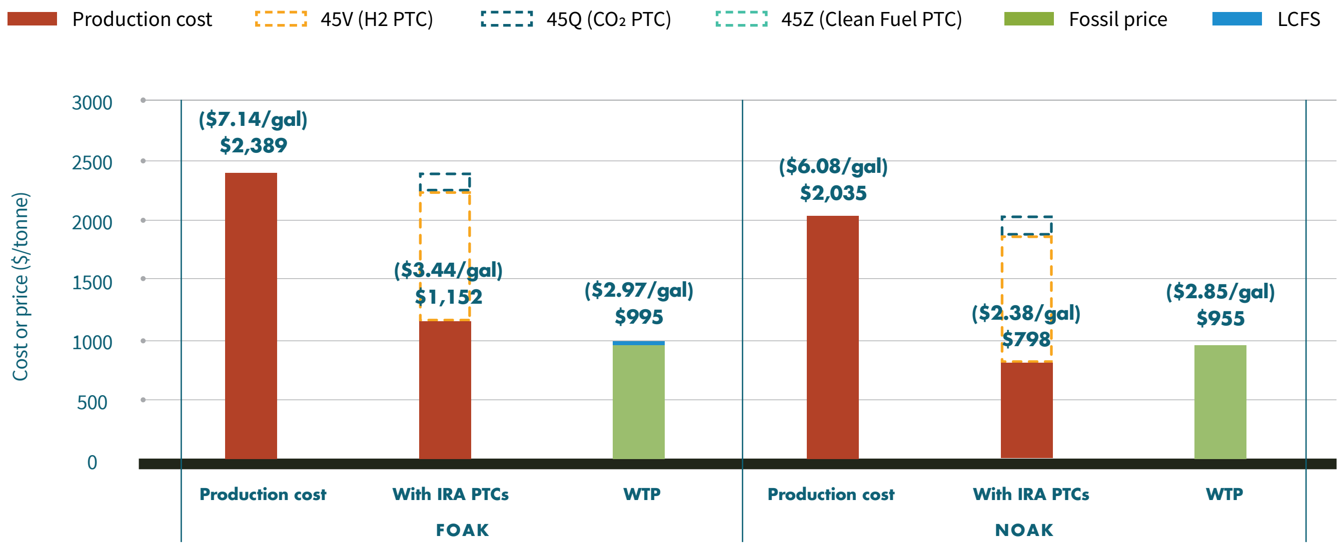


FIGURE F-5. PRODUCTION COST AND POLICY SUPPORT FOR AN E-METHANOL PLANT.

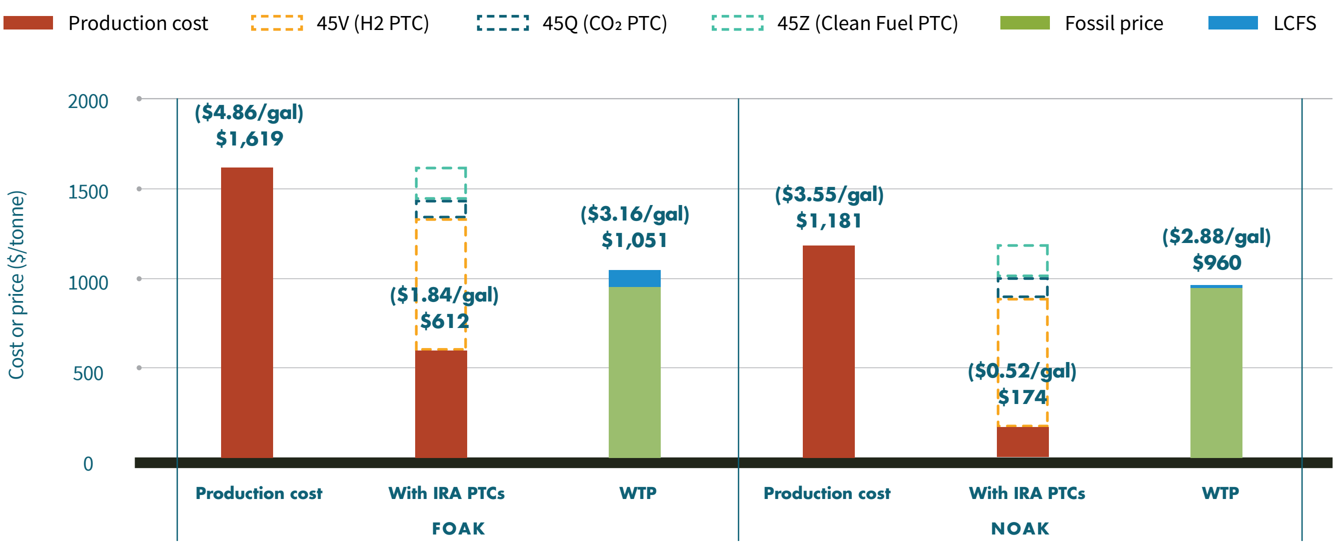
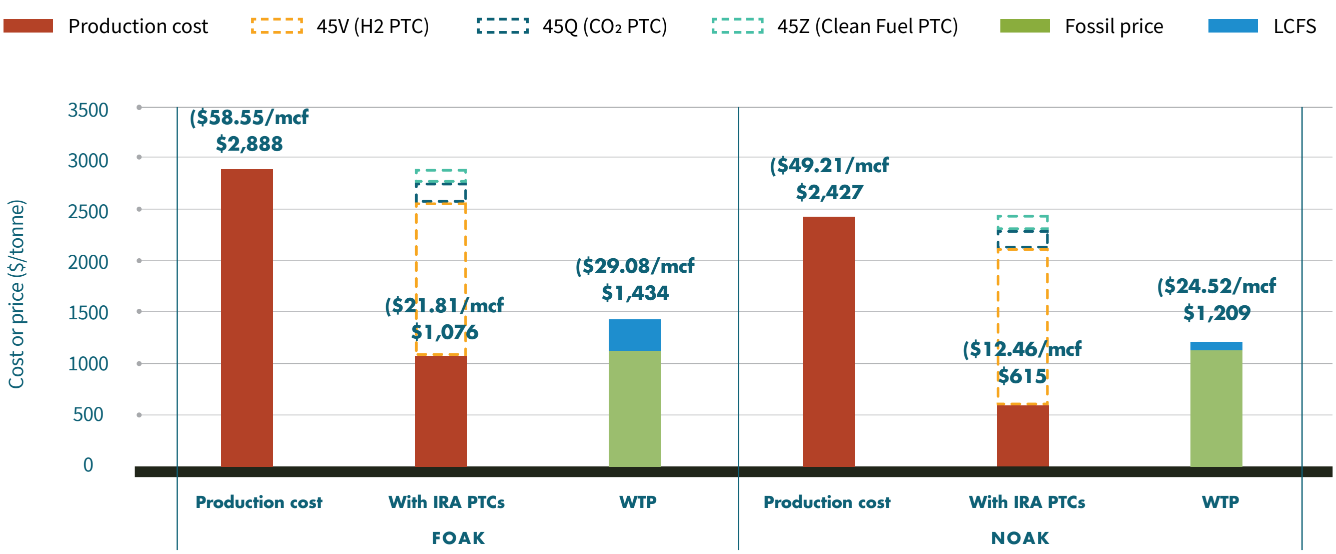


FIGURE F6. PRODUCTION COST AND POLICY SUPPORT FOR AN E-METHANE PLANT.



About the Transportation Energy Institute

The Transportation Energy Institute, founded by NACS in 2013, is a 501(c)(4) nonprofit research-oriented think tank dedicated to evaluating the market issues related to vehicles and the fuels that power them. By bringing together diverse stakeholders of the transportation and fuels markets, the Institute helps to identify opportunities and challenges associated with new technologies and to facilitate industry coordination to help ensure that consumers derive the greatest benefit.

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