COMMITTEE   REPORT ON "POLICY   ON SYNTHETIC   FUELS"

Synthetic fuels: Future Transport Fuel

March 2024

Committee for Policy on Synthetic Fuels

Disclaimer

"This Committee Report titled "Policy on Synthetic Fuels - Synthetic Fuels: Future Transport Fuels" is a comprehensive exploration and analysis undertaken to evaluate the prospects and policy frameworks for Synthetic fuels in the Transport/Mobility Sector. The report compiles insights from various members and experts from corresponding fields, discussing the potential role of synthetic fuels in achieving sustainable transport goals.

The findings, discussions, and policy recommendations presented herein are the product of extensive literature survey, research, expert discussions, and the collective expertise of committee members, with the aim to contribute to the informed formulation and implementation of policies related to synthetic fuels in India. It is important to note that the report's content reflects the data and insights available up to the date of publication in March 2024.

The recommendations and viewpoints expressed in this report are intended for policy guidance and strategic direction. They do not constitute a binding commitment or an official policy position by any Regulatory Body or Government institution. As the field of synthetic fuels is rapidly evolving, some of the technologies and processes discussed may undergo significant changes post-publication. It is, therefore, advised that this report be used as a reference document and not as a definitive source of the latest technological or regulatory information.

The Committee and its Members assume No Responsibility for any errors or omissions in the report and shall not be liable for any actions taken based on the report's information. Stakeholders are encouraged to consult additional sources and experts when making decisions influenced by this report's content."

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Executive Summary

MoP&NG vide Office Memorandum F.No.R-11011(11)/1/2022-OR-II/E-43954 dated 18th Aug. 2022 has constituted a Committee to formulate a policy on Synthetic Fuels (e-Fuel). The members of the committee include representatives from Oil & Gas PSUs, automotive bodies, CHT, DGCA & academic institutes. The members of the committee had several discussions on different aspects of synthetic fuels including the need, production, transport, utilization, pros & cons, policy and way ahead. Further, the members were also continuously updated with the latest literature/reports in respect of techno-economic analysis, life cycle assessment, engine evaluation, CO_2 to synthetic fuels, ammonia-based fuels, synthetic fuel production technologies, etc. More than 150 publications/reports/articles have been scanned through by the committee members. Additionally, expert talks on these areas were also arranged by CHT through Webinars.

The committee mainly focused on synthetic fuels and e-fuels policy briefing, which attempts to improve awareness of e-fuel production technologies and consequences in terms of effectiveness, greenhouse gas (GHG) reduction, environmental impact, investment, costs, and prospective demand. A synthetic fuel programme should be developed, primarily for heavy-duty vehicles (HDVs), aviation, and the marine sector, to reach net-zero targets.

As there are few options for electrification in transportation sectors with high carbon emissions, such as heavy-duty transportation, aviation, and deep-sea shipping, e-fuels have received more attention. Electricity generated from renewable sources, carbon dioxide recovered from industrial emissions, and green hydrogen created by the electrolysis of water are all combined to create hydrocarbon-based e-fuels. By mixing airborne nitrogen that has been separated with green hydrogen using the Haber-Bosch process, e-ammonia is produced without the need for CO_2. Methanation for e-methane, methanol synthesis for e-methanol, reverse water-gas shift (RWGS) reaction to create syngas, followed by Fischer-Tropsch synthesis to make e-FT fuels are often

documented synthesis procedures for the generation of hydrocarbon-based e-fuels. The current state of e-fuel production is fraught with difficulties, necessitating further work before it can be used commercially.

The usage of synthetic fuels is anticipated to provide a platform for the decarbonization of the transportation industry. The use of renewable/synthetic fuel additives is crucial for achieving a Net Zero cycle powered by e/synthetic fuel. The function of additives will be crucial in fuel storage, stability, and engine performance as the search for cleaner, more fuel-efficient engines continues. In light of this, it is proposed to increase the use of possible additives to facilitate the decarbonization process.

With a market share of over 39% in 2021, the Asia Pacific area is projected to have significant expansion over the coming years. The market is predicted to expand during the forecast period due to a rise in car demand in the Asia Pacific region, particularly in India, China, and Japan. Fuels are in demand all around the world as a result of rising automotive demand. Throughout the projected period, the markets in North America and Europe are also anticipated to expand strongly. The demand for synthetic fuels is very concentrated, with the largest producers—Sasol, Petrochina, Shell, Exxon, etc.—accounting for 45–50% of the market.

Aviation biofuels are approved for limited usage at a specific blend level on commercial aircraft. Some of the options for producing sustainable aviation fuels at a commercial scale include alcohol-to-jet fuel (ATJ), synthesised paraffinic kerosene plus aromatics (SPK/A), Fischer-Tropsch of biomass feed-to-fuel (FT-SPK), renewable synthesised iso-paraffinic (SIP) fuel, and hydroprocessed non-edible vegetable oils or animal fats (HEFA-SPK). All of these alternatives are covered by current, authorised ASTM standards, which are then reflected in other global standards such as DEF STAN 91-091. To meet the impending CORSIA standards, it is imperative to aggressively build strong aviation biofuel supply networks.

Power-to-Liquid (synthetic methanol, gasoline, kerosene, and diesel) or Power-to-Gas (synthetic methane and ammonia) processes are utilised, depending on the form or kind of e-fuel required. Both of these production methods have two or three stages, beginning with the production of hydrogen (H_2) by water electrolysis using renewable electricity, which is then combined with another molecule, either CO_2 for the production of synthetic methane or methanol or N_2 for the production of synthetic ammonia. To create synthetic kerosene or diesel, synthetic crude oil from the FT process must be refined (much like fossil fuel). The cost of producing e-fuels is currently estimated to be relatively higher when compared to the production of fossil-based fuels, although there is no Indian-specific techno-economic studies concerning e-fuels that are available. It is essential; as a result, some form of government aid and a policy framework is needed to facilitate e-fuels. Policymakers must establish clear incentives for investment in their large-scale production and establish a level playing field for all pertinent emission reduction technologies to realize their full potential. Using the variety of energy infrastructures already in place enables these transformation paths to take more adaptable approaches to find answers, such as capitalizing on technological advancements by 2050 that cannot yet be predicted. Economic advantages and the benefits of learning are predicted to lead to a gradual decrease in investment costs for each technology over time.

Currently, there is no standard available in respect of the specification for synthetic fuels and the same shall be devised as and when technology for commercialization is implemented. The "Guidance on the Application of Sustainability Criteria for CORSIA Lower Carbon Aviation Fuel (LCAF) and Guidance on the Application of Sustainability Criteria for CORSIA Sustainable Aviation Fuels (SAF)" is outlined in the document "Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)" published by the International Civil Aviation Organization (ICAO) in November 2021 which is used as best practice across the world.

The focus areas that have been identified for accelerating the e-fuel development include:

a) Thermo-Catalytic CO_2 conversion route to SNG and methanol needs to be established by setting up demonstration units and thermos catalytic CO_2 conversion to ethanol.

b) Carbon Capture & Utilization (CCU) technology is to be promoted at various TRL levels wherein R&D technology development is required.

c) Indigenous development of catalyst for E-Fuels and synergy between various fuel policies of Govt.

d) Synergising various policies of the Government viz. CCU, Biofuel, Green Hydrogen, Auto Fuel, etc. and formulate a consolidated net-zero fuel policy for the countries covering synthetic fuels.

e) Municipal Solid Waste based synthetic fuel generation programs are to be initiated for localized production and utilization in automotive transportation.

f) Introduction of specific production/utilisation targets for e-fuels in aviation and marine sectors.

g) Life cycle and economic analysis from Indian context in collaboration with CoEGE-IITB and formulation of ISO standards for CO_2 measurement, monitoring and storage.

h) Developing classification and certification systems for renewables and low carbon fuels to promote clean fuels including green hydrogen and e-fuels.

i) Considering surplus ethanol scenario, alcohol to jet route is to be fostered for SAF. This route also offers e-ethylene.

j) As part of mid-term solution, reverse water gas shift technology development needs to be put on a fast track.

At few places in the report information on biofuels are also included. Though Bio fuel are not classified as e-fuels, for the sake of comparison, this is included.

The committee further proposes the following policies for implementing synthetic fuels programme in the country :-

i. Blended Fuel/Promoting Carbon Circular Economy : Phased rollout of blended e-fuel to reduce carbon footprint

ii.   Compatible Engines : Policy push for faster development, production and adoption of tuned engines/marine/aviation for synthetic and blended fuels

iii.   Inclusion of Aviation/Marine Sector : Sectors which are not covered under electrification like aviation, marine and heavy-duty vehicles to be notified under Synthetic Fuel Policy

iv.   Incentive to boost Production : Incentive to synthetic fuel manufacturers and end-users to nurture ecosystem

v.   Special Research Grants : Special grants for research projects to reduce cost of production, improve conversion efficiency, new generation electrolyser and improve competitiveness

vi.   Carbon Credit/Promoting Circular Economy : Fostering decarburization by creating a carbon credit market

vii.   Dedicated budget : Dedicated budget to improve infrastructure enabling all associated industries to develop and scale up.

viii.   Implementation of funding and incentives schemes for pilot projects, assigning them to research and development setups within the oil and gas industries under the Ministry of Petroleum and Natural Gas (MOP&NG).

ix.   Establishment of a Center for Excellence through international collaboration, involving academia, research institutes, industry bodies, and enterprises within the oil and gas sector to promote synthetic fuel production.

x.   Synthetic Fuel Exchange can be setup for sale and purchase of Synthetic Fuels.

xi.   R&D support for indigenous equipment development and establishing a definitive support system for e-fuel adoption, such as tax incentives and subsidies, and discouraging biomass export to encourage domestic investments.

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1. Introduction

1.1. Background

In recent years, India has taken extraordinary strides in renewable capacity development. Despite these efforts, many long-term forecasts indicate that fossil fuels would continue to play a key role in India's energy system in foreseeable future. Over the coming years, millions of Indian households are set to buy new appliances, air conditioning units and vehicles. India is in a unique position to pioneer a new model for low-carbon, inclusive growth as its energy future depends on buildings and factories yet to be built, and vehicles and appliances yet to be bought. India has envisioned cutting its emissions to net zero by 2070. Reduction of carbon footprint shall be achieved through putting electricity at the centre of India's modernisation, efficiency improvement, the increased role of gas and decarbonisation of energy mix with the increasing role of renewable energy – biomass, the solar, wind, nuclear and green hydrogen. To support and achieve the net zero target by 2070, India has announced the national hydrogen mission and National Policy on Biofuels, 2018.

Petroleum liquid fuels offer an unequalled combination of qualities i.e. high energy density, easy and safe handling, already existing infrastructure for production, distribution & storage, and low cost compared to the alternatives. About 98% of the fuel requirement in the road transportation sector is currently met by fossil fuels. However, India imports 85% of its oil requirement. Traditional IC engine is quickly becoming outdated around the world because they are polluting and are being quickly replaced by fully electric vehicles (BEVs). The running cost of an electric vehicle is much lower than an equivalent petrol or diesel vehicle. Electric vehicles have very low maintenance costs because they don't have as many moving parts as an internal combustion vehicle and have zero tailpipe emissions.

Hydrogen is touted as the fuel of the future since hydrogen is only as clean as its source of generation, green hydrogen will be necessary to achieve a truly low-carbon economy. Could it be a "zero-emissions" fuel for maritime shipping and aviation? Current green hydrogen production costs range anywhere between ₹320 and ₹330 per kilogram in India. Green hydrogen costs in India could potentially fall by half to as low as ₹160-170 per kg by 2030, bringing parity with grey hydrogen and other fossil fuels (KPMG study;25-Mar-2022). Beyond cost, there are challenges in hydrogen storage and the development of the supply chain, which are expensive to develop and will take time to develop. Therefore, it is very difficult to choose a single option that will deliver low-emission mobility across all transport sectors. Instead, many technologies will be needed, and it will be essential to develop effective industrial cooperation in India, supported by the right R&D frameworks. This will be the most effective way to deliver sustainable, low-emission fuels for use in future efficient engines.

The *Figure 1-1* below shows the battery weight that would be required if electrical power trains were adopted for different transport modes. It can be seen that battery technology will need to achieve at least a 10-fold reduction in weight to become a viable substitute for liquid fuels beyond passenger cars and light commercial transport. For low-duty vehicles, EV is a good option but for marine, aviation and heavy-duty road transport, the energy density of liquid fuels represents a fundamental advantage that will be difficult to overcome even with future battery technology due to charging time and battery weight. This is where synthetic fuels starts to make more sense. No modifications or updates are required to the vehicles to run them on synthetic fuels. And, there is no change required to be made in the existing fuel supply chain.
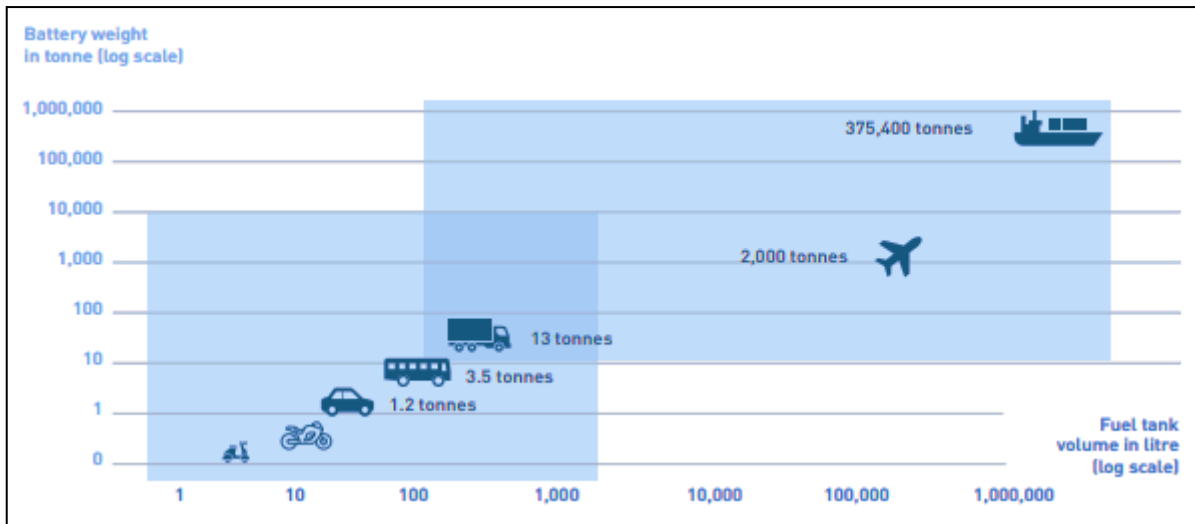
Figure 1-1 :Limited electrification beyond the bus and light truck segment

1.2. Synthetic fuel:

Synthetic fuel refers to fuels produced from non-petroleum sources through chemical processes, typically aiming to replicate the properties of conventional fossil fuels like gasoline, diesel, or jet fuel. These fuels can be derived from a variety of feedstocks, including biomass, coal, natural gas, or even captured carbon dioxide. Synthetic fuels offer several potential advantages, including reduced greenhouse gas emissions compared to traditional fossil fuels, enhanced energy security by diversifying fuel sources, and the potential to utilize existing infrastructure. However, the production of synthetic fuels may also require significant energy input and infrastructure investment. Ongoing research and development in synthetic fuel technologies aim to improve efficiency, reduce costs, and advance their contribution to sustainable energy systems. Among all synthetic fuel, e-fuels would be discussed in-detail in this report.

1.2.1 e-Fuels

e-fuels are synthetic fuels, resulting from the combination of 'green or e-hydrogen' produced by electrolysis of water with renewable electricity and CO_2 captured either from a concentrated source (e.g. flue gases from an industrial site) or from the air (via direct air capture, DAC). E-fuel is nearly carbon neutral in theory. They can be

manufactured as 'drop-in' replacements for fossil jet fuel, diesel and fuel oil. E-fuels are also referred to as electro-fuels, power-to-X (PtX), power-to-liquids (PtL), power-to-gas (PtG) and synthetic fuels. The most common conversion pathways for liquid fuel synthesis are the Fischer-Tropsch (FT) pathway and the methanol (MeOH) pathway. These technologies are well-known and used at scale. However, these existing processes use fossil carbon sources and new technologies and further innovation will be required to enable non-fossil carbon dioxide sources to be used.

1.2.2 Challenges with e-Fuels

e-fuel has its fair share of drawbacks and challenges.

First, the Production costs for e-fuels are currently more expensive than fossil fuels. The production processes are more energy consuming compared to fossil fuels due to the synthesis steps involved, converting at best half of the energy in the electricity into liquid or gaseous fuels. The energy losses from manufacturing are high due to the many processes involved. However, this might be justified where electrical propulsion is not practical and renewable electricity is cheap and plentiful. Innovation in each process stage has the potential to reduce these costs in the future to enable production and scale-up.
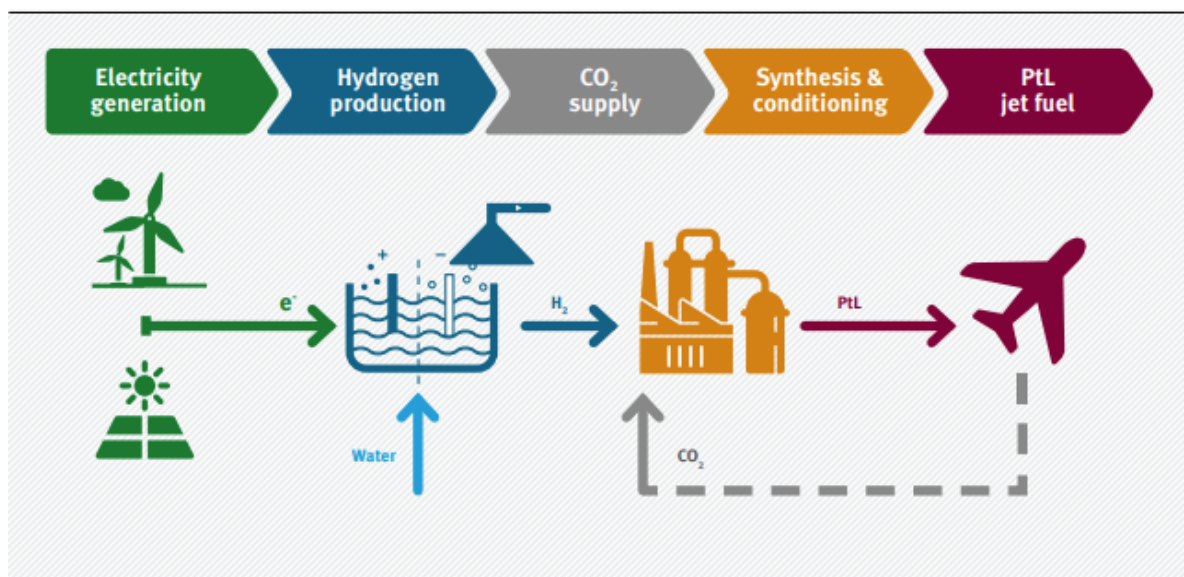
Figure 1-2: Power-to-liquids production (generic scheme)

e-fuel costs are currently relatively high (up to 7 \$/ litre) but are expected to decrease over time due to economies of scale, learning effects and an anticipated reduction in the renewable electricity price; this is expected to lead to a cost of 1–3 \$/ litre (without taxes) in 2050. The cost of e-fuels could therefore be 1–3 times higher than the cost of fossil fuels at that time.

IC Engine's efficiency

As shown in the *figure 1-3* below, 48% of the energy from renewable electricity is lost in the conversion to liquid fuels, using the average value for drop-in diesel technologies. Then 70% of the energy in those fuels will be lost when they are combusted in internal combustion engines, for a total efficiency of 16% for the e-fuels pathway. In contrast, the majority of energy used by electric vehicles goes to powering the wheels, losing only 10% in charging and 20% by the motor and for a total efficiency of 72%.
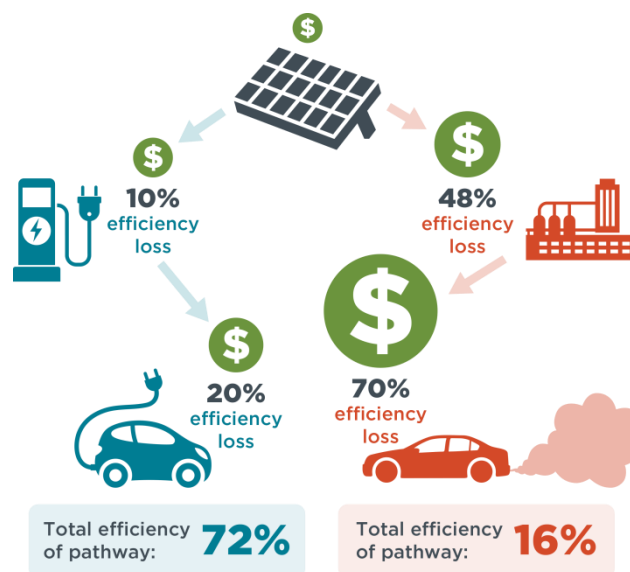
Figure 1-3: E-fuels pathways

The overall energy efficiency of electricity use in battery electric vehicles (BEVs) is 4–6 times higher than for e-fuels in combustion engines (see *Figure 1-4*) [1]. The battery electric vehicle has a total overall efficiency (from the power generation point to the final user) of around 69%, while a fuel cell vehicle has an efficiency of around 26–35%, and a liquid e-fuel car has an efficiency of around 13–15% [2].
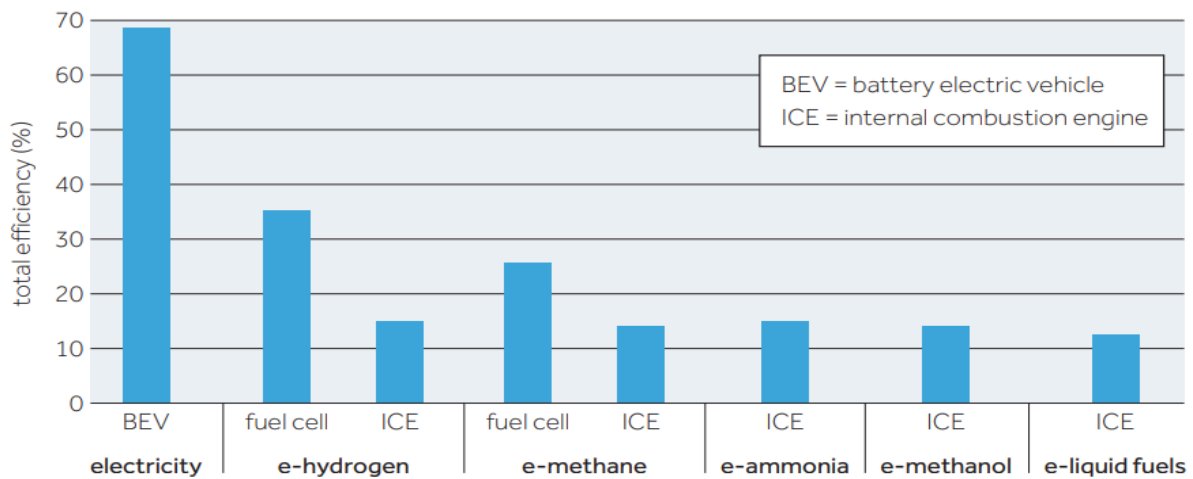
Figure 1-4: E-fuels final efficiency in engines (WTW approach) [3]

Further, some of the challenges associated with hydrogen remain here also, as E-fuels require green hydrogen for their production. There also may be synergies between the e-fuels and hydrogen pathway in a way that parts of the process change can later be used for the direct use of hydrogen as well.

Finally, e-fuels also emit carbon dioxide when burnt, therefore to fully understand the GHG emission savings a full life cycle assessment of E-Fuels has yet to be evaluated in depth.

1.3. Synthetic Aviation Fuels (SAF)

The global aviation industry contributes ~2.1% of human induces CO_2 emission and 12% of total transport-related CO_2 emission. Air transport is expected to grow at about 4 % p.a. until 2050. However, air transport is more difficult to decarbonize. One option to reduce climate-relevant emissions in the sector is increasing use of SAF. The International Civil Aviation Organization (ICAO) established the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) in 2016, intending to cap net carbon emissions of international flights at the 2020 level by 2027 and by 50% by 2050 relative to 2005 levels. Once CORSIA is in operation, airlines operating on covered routes will be able to meet their emission reduction obligations in two ways. One is to invest in emission reductions in other sectors (offsetting). The second is to

reduce emissions directly within the sector, for instance through energy efficiency in design and operation or by burning approved Sustainable Aviation Fuels (SAF) that emit less carbon on a lifecycle basis than conventional jet fuels. If using SAF, airlines could still have to purchase offsets but the amount would be smaller, depending on the lifecycle reduction in emissions achieved by the particular SAF used.

There are currently five internationally-approved processes through which SAFs can be produced. Each of these pathways has its benefits, such as the availability of feedstock, cost of the feedstock, carbon reduction or cost of processing. Some may be more suitable than others in certain areas of the world. But all of them have the potential to help the aviation sector reduce its carbon footprint significantly, assuming all sustainability criteria are met.

- **Fischer-Tropsch Synthetic Paraffinic Kerosene with aromatics (FT-SPK/A) –** made from renewable biomass such as municipal solid waste, agricultural wastes and forestry residues, wood and energy crops. The blending limit is up to 50%.

- **Hydroprocessed Esters and Fatty Acids (HEFA-SPK) –** made from oil-bearing biomass, such as algae, jatropha and camelina. The blending limit is also up to 50%.

- **Hydroprocessed Fermented Sugars to Synthetic Isoparaffins (HFS-SIP) –** made through the microbial conversion of sugars to hydrocarbon. The blending limit is up to 10%.

- **FT-SPK with aromatics (FT-SPK/A) –** made from renewable biomass such as municipal solid waste, agricultural wastes and forestry residues, wood and energy crops. The blend limit is 50%.

- **Alcohol-to-Jet Synthetic Paraffinic Kerosene (ATJ-SPK) [isobutanol, respectively ethanol] –** made from agricultural waste products, such as stover, grasses, forestry slash and crop straws. The blending limit is 30% for isobutanol and 50% for ethanol.

- **Catalytic hydrothermolysis synthetic jet fuel (CHJ) –** made from triglyceride-based feedstocks such as plant oils, waste oils, algal oils, soybean oil, jatropha oil, camelina oil, carinata oil and tung oil. The blending limit is 50%.

This report is intended to focus on synthetic fuels/E-fuels policy briefing which aims to build a better understanding of the e-fuel production technologies and implications in terms of efficiency, greenhouse gas (GHG) reduction, environmental impact, investment, costs and potential demand. There is a case for the development of a Synthetic Fuel Program mainly for Heavy duty vehicles (HDVs), Aviation and Marine sectors for achieving net Zero Targets.

This report also includes information on bio-fuels at appropriate places for the sake of comparison. Bio fuel is not classified as e-fuel though origin of Carbon-dioxide and Hydrogen for e-fuel may be from bio sources.

2. Raw materials, Production, Challenges

Synthetic fuel, a key focus in the chapter on raw materials, production, and challenges, represents a promising avenue in energy innovation. Derived from non-petroleum sources such as biomass, coal, or captured carbon dioxide, it mirrors conventional fuels through chemical processes. While offering reduced emissions and enhancing energy security, its production demands significant energy input and infrastructural development. Addressing these challenges through ongoing research endeavors is crucial to unlocking the full potential of synthetic fuels in our transition towards sustainable energy systems.

Production of synthetic fuel from coal gasification involves converting coal into syngas, a mixture of carbon monoxide and hydrogen, through a thermochemical process. This syngas can then be further processed to produce liquid hydrocarbon fuels such as diesel or jet fuel through Fischer-Tropsch synthesis. Coal gasification offers advantages such as flexibility in feedstock sourcing and the potential for carbon capture and storage to mitigate greenhouse gas emissions. However, challenges include high capital costs, environmental concerns, and the need for efficient utilization of by-products. Overall, coal gasification remains a significant pathway in the production of synthetic fuels, albeit with ongoing technological and environmental considerations.

The other synthetic fuels are electrofuels (E-fuels) produced by combining green hydrogen produced by the electrolysis of water with renewable electricity and carbon dioxide (CO_2) captured from industrial emissions or Direct Air Capture (DAC). E-ammonia does not require CO_2 and is generated by combining nitrogen separated from the air with green hydrogen through the Haber-Bosch process. E-fuels are also described in the literature as Power-to-X (PtX), Power-to-Liquids (PtL), Power-to-Gas (PtG) and synthetic fuels. Green hydrogen produced from water through electrolysis using renewable electricity is also described as e-fuel in the literature.

The concept of E-fuels has gained increased attention in recent years to decarbonize the transportation sector. E-fuels could be used in the existing vehicles and do not require significant investments in new distribution and fuelling infrastructure. They are of special interest in hard-to-abate transport sectors such as heavy-duty transportation, aviation and deep-sea shipping, where electrification opportunities are limited because liquid fuels with high energy density are difficult to substitute by batteries. E-fuels could also contribute to balancing intermittent renewable electricity production by providing use excess or low-cost electricity.

2.1 Raw materials for synthetic fuel

The raw materials for synthetic fuel production vary depending on the specific production process but commonly include biomass, coal, natural gas, or even captured carbon dioxide. Biomass, such as agricultural residues, forestry waste, or dedicated energy crops, provides renewable organic matter that can be converted into liquid or gaseous fuels through processes like pyrolysis, fermentation, or thermochemical conversion. Coal serves as a traditional feedstock, undergoing gasification or liquefaction to produce synthetic fuels like diesel or gasoline. Natural gas can be transformed into synthetic fuels through processes like steam methane reforming or Fischer-Tropsch synthesis. Additionally, captured carbon dioxide from industrial processes or direct air capture can be utilized as a raw material, contributing to the production of synthetic fuels while mitigating greenhouse gas emissions. The selection of raw materials depends on factors like availability, cost, environmental impact, and technological feasibility, with ongoing research focusing on optimizing processes and diversifying feedstock sources to enhance the sustainability of synthetic fuel production. The raw materials needed for e-fuel are discussed in details.

2.1.1   Raw materials for electrofuels

Hydrocarbon-based e-fuels are produced using renewable electricity, water and CO_2 as resources. E-fuel production involves first the production of green hydrogen through electrolysis of water using renewable electricity and then combining generated hydrogen with CO_2 and/or CO (CO generated from CO_2 through electrolysis) using a synthesis process to generate desired e-fuels. E-ammonia is produced by combining nitrogen separated from the air with green hydrogen through Haber-Bosch synthesis. *Figure 2-1* shows raw materials used for the production of hydrocarbon-based e-fuels and e-ammonia.
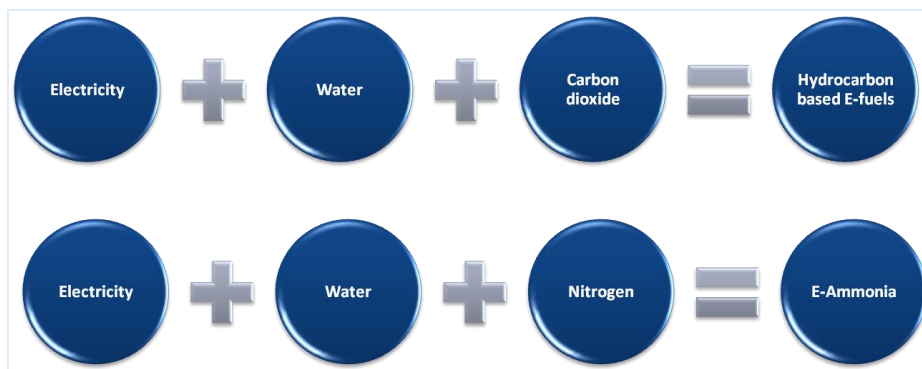
Figure 2-1: Raw materials used for the production of hydrocarbon-based E-fuels and E-ammonia

2.1.2   Green hydrogen

The Ministry of New and Renewable Energy (MNRE) defines Green Hydrogen as hydrogen produced using renewable energy sources or through processes that do not generate carbon emissions. Green hydrogen should have a carbon intensity below a certain threshold, such as 2 kilograms of CO2 per kilogram of hydrogen produced. However, these thresholds can vary, and there may be ongoing discussions and updates to establish more precise criteria as the technology and industry evolve. The hydrogen generated via water electrolysis using electricity from renewable sources like solar, wind, or hydropower comes under green hydrogen. Additionally, hydrogen produced from the conversion of biomass is also considered green according to MNRE's definition. The focus of MNRE's standard is on promoting hydrogen production methods that minimize environmental impact and contribute to

India's renewable energy goals, thereby supporting the transition to a sustainable and low-carbon economy.

Different electrolysis technologies can be used for producing hydrogen. These include low-temperature (50 to 80°C) technologies such as alkaline electrolysis cell (AEC), proton exchange membrane cell (PEMC), or high-temperature (700 to 1000°C) processes using a solid-oxide electrolysis cell (SOEC) [4].

Low-carbon hydrogen can be produced by the electrolysis of water using renewable electricity. This will become more commercially viable compared to steam methane reforming with CCS, as the price of sustainable electricity falls and electrolysers become more efficient. The source of sustainable electricity will also affect the cost, as intermittent sources (eg wind turbines) will increase the cost of electrolysers due to the more challenging intermittent duty cycle. Electricity generated from renewable energy sources such as solar and wind can be used for hydrogen generation. As electricity costs contribute to a significant portion of hydrogen production costs, periods of low electricity prices (e.g. during periods of excess production) can be utilized to minimize production costs. Hydrogen storage is required in the case of intermittent production [5].

Water is the feedstock for the production of green hydrogen, and it must be treated to ultrapure quality before feeding to the electrolyzer. Depending on the choice of electrolyzer technology, a suitable water treatment solution is required to be utilized as inadequate water quality can jeopardise the operation and damage the electrolyzer. Typically, AEC-based water electrolysis requires Type 2 water having an electrical conductivity of 1 µS/cm (as per ASTM D1193-91) whereas PEMC-based water electrolysis demands Type 1 water having an electrical conductivity of 0.056 µS/cm. Furthermore, 1 Kg of green hydrogen requires about 30 Kg of raw water. Considering such high-water requirements, seawater, which comprises more than 95% of the Earth's water, could become a key resource in the sustainable production of clean

hydrogen fuel. However, the use of seawater requires the development of suitable electrode material for sustainable operation under a corrosive environment.

2.1.3   Carbon dioxide

Carbon dioxide required for the production of hydrocarbon-based e-fuels can be sourced by CO_2 capture from industrial point sources such as ethanol production, bioenergy plants, cement production, power plants, steel and refining industries or CO_2 captured directly from the air. CO_2 concentrations in the different sources range from very small (400 ppm in air) up to almost 100% in some biofuel plants [6]. The concentration of CO_2 at the point sources affects the capture costs and efficiencies. Also, the choice of CO_2 capture technology has an impact on overall process economics. Widely reported CO_2 capture technologies to include absorption, membrane separation, cryogenic capture, or oxy-combustion. A relatively low capture cost can be achieved in e.g. bioethanol plants, where the exhaust stream has a high concentration of CO2, and no extra major purification step or additional energy is needed in the capture process [6].

2.1.4   Nitrogen

Nitrogen required for e-ammonia production is separated from the air by first cooling it until it liquefies, then selectively distilling the components at their various boiling temperatures. The low distillation temperature can be achieved by using an air separation unit (ASU), based on a refrigeration cycle, or more lately by using expansion turbines for cooling. Another method is pressure swing adsorption (PSA) which provides the separation of oxygen or nitrogen from the air without liquefaction. The principal disadvantage of the PSA cycle is the risk of high gas losses resulting from the pressure release [7].

2.2   Synthetic Fuel production technologies

Synthetic fuel production technologies encompass a range of processes designed to convert various feedstocks into liquid or gaseous fuels with properties similar to conventional fossil fuels. These technologies include coal gasification, biomass pyrolysis, Fischer-Tropsch synthesis, and hydroprocessing. Coal gasification involves converting coal into syngas, which can be further processed into fuels like diesel or jet fuel. Biomass pyrolysis utilizes high temperatures to break down biomass into bio-oil, which can be upgraded into transportation fuels. Fischer-Tropsch synthesis transforms syngas into liquid hydrocarbons, while hydroprocessing involves refining vegetable oils or animal fats into biodiesel or renewable diesel. Each technology has its advantages and challenges, with ongoing research focusing on improving efficiency, reducing costs, and minimizing environmental impacts to advance the viability of synthetic fuel production. The technologies related to e-fuel are discussed in details.

2.2.1   E-fuels production technologies

E-fuel production (except e-ammonia) consists of green hydrogen reacting with captured CO2 by following different conversion routes based on the final e-fuel. The most extensively reported e-fuel production routes are : i) Methanation for e-methane, ii) Methanol synthesis for e-methanol, iii) Reverse water-gas shift (RWGS) reaction to produce syngas, followed by Fischer-Tropsch (FT) synthesis to produce e-FT fuels. E-ammonia is produced by reacting green hydrogen with nitrogen by Haber-Bosch synthesis. A schematic representation of e-fuels production is shown in *Figure. 2-2*.
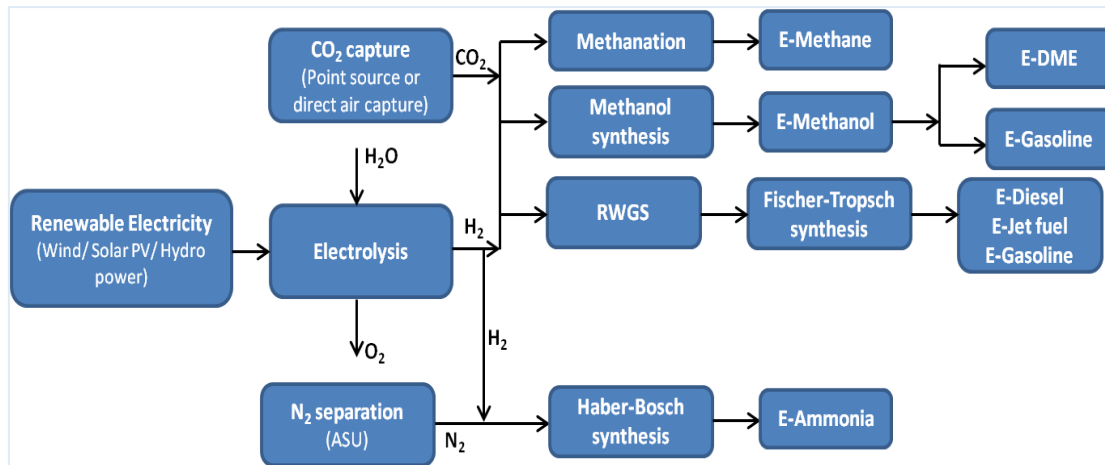
Figure 2-2: Schematic representation of the production of E-fuels

2.2.2 E-methane

Several processes to produce e-methane using green hydrogen and CO_2 are under investigation. These include thermochemical, photocatalytic, electrochemical and biogenic routes. Among these, thermochemical also known as catalytic methanation is the most extensively studied and currently used for e-methane production. Typically, methanation is carried out in a catalytic reactor in the temperature range of 250 - 350^{0}C and 25 bar pressure [8]. Catalytic methanation is highly exothermic and heat generated in catalytic methanation can be used as a heat source for high-temperature electrolysis, which can increase the overall efficiency of the process [6]. Some pilot plants on CO_2 to natural gas are reported in recent years. The pilot CO_2-SNG plant was designed and built at the Łaziska Power Station within the scope of the project implemented by the international consortium whose leader is TAURON Wytwarzanie. The pilot CO_2-SNG plant is aimed at testing, in real conditions, the methanation reactor and the end-to-end installation for generating methane off CO2 and hydrogen. We are testing its conversion capacity, operational flexibility and adjustment to the storage of excess energy in the form of synthetic methane. Therefore, the project combines two trends, which are the reduction of CO2 emissions at the power station and the provision of the large-scale accumulation of energy through the production of gas fuels when energy is cheap. The presented plant is an effect of earlier activities and achievements of the TAURON Group in the R&D field of CO2 capture

(https://www.innoenergy.com/discover-innovative-solutions/news-events/a-pilot-plant-will-convert-co2-into-natural-gas/). A list of pilot and commercial plants upto 2016 represented in Table 2-1.

Table 2-1 : Pilot plant and commercial scale projects for CO2 methanation around the world

Project name	Location	Collaborating partners	Capacity	Status
PtG project of University of Chicago	Chicago, IL, USA	University of Chicago, Electrochaea	kW	pilot plant 2013
PtG test plant Rapperswill	Rapperswil, Switzerland	Erdgas Obersee AG, Etogas, HSR	25 kW	pilot plant 2014
PtG ALPHA plant Bad Hersfeld	Bad Hersfeld, Germany	ZSW, IWES	25 kW	pilot plant 2012
PtG ALPHA plant Morbach	Morbach, Germany	Juwi AG, ZSW, Etogas, Etogas	25 kW	pilot plant 2011
PtG ALPHA plant Stuttgart	Stuttgart, Germany	ZSW, Etogas	25 kW	pilot plant 2009
PtG test plant Stuttgart	Stuttgart, Germany	ZSW, IWES, Etogas	250 kW	pilot plant 2012
The Copenhagen project of PtG	Avedore Copenhagen, Denmark	Electrochaea, BCH	1 MW	commercial operation 2016
E-Gas/PtG BETA plant	Werlte, Germany	ZSW, Audi, Etogas, EWE, IWES	6.3 MW	commercial operation 2013

2.2.3   E-methanol

E-methanol synthesis is similar to catalytic methanation, where CO_2 is catalytically combined with green hydrogen to generate methanol. The reaction is exothermic and gas phase single-step hydrogenation of CO_2 to methanol reaction operates in the temperature range 230-280^{0}C and at high pressures (60-80 bar). Generated raw methanol generally includes approximately 10% water which is removed by distillation.

Few commercial plants are producing e-methanol and several commercial plants are in pipeline. For example, Carbon Recycling International's (CRI) George Olah plant, in Iceland reported 5000 tons /year of e-methanol production, where the necessary

H2 is produced by water electrolysis using cheap hydro and geothermal electricity. Mitsui chemicals Osaka methanol plant also reported in 2008 to construct of an e-methanol plant where carbon dioxide capturing was planned from factories and hydrogen production was planned from water photolysis (https://jp.mitsuichemicals.com/en/release/2008/080825e.htm). There is no update related to the plant operation. Currently, the largest e-methanol production plant by CRI is under commissioning in China.

The major cost of e-methanol production is currently restricted by the cost of green hydrogen. Alternatively, novel methods to improve economic feasibility are under investigation. One possibility is to alter the reaction route to methanol using catalytic alcoholic solvents, which makes the process possible in the liquid phase at lower reaction temperatures [9]. The generated methanol can be further converted to dimethyl ether (DME) and gasoline using downstream methanol conversion processes.

2.2.4   E- Fischer Tropsch (FT) fuels

The FT process developed in the 1920s involves a series of chemical reactions for the conversion of syngas to liquid hydrocarbons over a catalyst surface. The gas to liquid technology has gained prominence as it produces high-quality fuels with no aromatics and sulfur. An alternative way to utilize CO_2 is to convert CO_2 to CO since CO_2 has very low reactivity. CO_2 can be converted to CO by reverse water shift reaction (RWGS) or by high temperature electrolysis of CO_2. RWGS reaction is highly endothermic and requires high temperature to drive the reaction forward. The syngas with desired H_2/CO ratio leaving the RWGS reactor is converted to liquid hydrocarbons using FT synthesis. FT synthesis comprises of series of reactions in which CO and H_2 react to form hydrocarbons. FT synthesis is classified into high-temperature (310–340°C) and low-temperature (210–260°C) reactions. The low-temperature and high-temperature methods give different compositional outcomes. Low-temperature provides a higher cetane number and paraffinic compounds more suitable as diesel fuels. High-temperature FT is more suitable as a gasoline substitute

[10]. Generated FT liquids are usually a mix of paraffin, olefins, and alcohols and require further downstream processing to generate desired transportation fuels [7].

Table 2-2: Sasol Gas to Liquid (GTL) technology with reaction conditions for the production of gasoline and diesel specifications.

Sasol Arge process	Sasol Synthol Process
Catalyst: Co	Catalyst Fe
Low-temperature process (220 – 270 °C)	High-temperature process (325 – 350 °C)
Gasoline to diesel ratio 1:2	Gasoline to diesel ratio 2:1
Cetane upto 80, octane upto 20	Cetane upto 60, octane upto 60
50-70% wax	Low wax 4%

Apart from above mentioned Sasol process, Shell and Ras Laffan (Qatar) operate plants with considerable commercial production capacity.

- Shell facility in Malaysia is one of the largest implementations of FT technology. The facility converts natural gas into low-sulfur diesel and food-grade wax. The scale is 12,000 barrels per day (1,900 m3/d).
- Ras Laffan (Qatar): The low temperature (LTFT) facility Pearl GTL in Qatar, is the second largest FT plant in the world after Sasol's Secunda plant in South Africa.
- It uses cobalt catalysts at 230 °C, converting natural gas to petroleum liquids at a rate of 140,000 barrels per day (22,000 m3/d).

Another plant in Ras Laffan, called Oryx GTL, has been commissioned in 2007 with a capacity of 34,000 barrels per day (5,400 m3/d). The plant utilizes the Sasol slurry phase distillate process, which uses a cobalt catalyst. Oryx GTL is a joint venture between QatarEnergy and Sasol.

2.2.5 E-ammonia

E-ammonia is synthesized by catalytically reacting green hydrogen with nitrogen by he Haber - Bosch process. An ammonia synthesis reaction is exothermic and requires

temperatures and pressures in the range of 400 - 500⁰C and 200 - 250 bar, respectively, to get the desired conversion. Ammonia is an effective hydrogen carrier with 1.5 mol of hydrogen per mole of ammonia which is equivalent to 107 kg of hydrogen per cubic metre of liquid ammonia [10]. Ammonia synthesis is normally designed to operate under continuous production. However, if future ammonia synthesis can operate dynamically, a flexible operation may make economic sense as a means to utilize hydrogen from intermittent renewable electricity avoiding costly hydrogen storage [7].

2.2.6   e-LPG

As LPG is a well-established fuel with distribution infrastructures in place, on-purpose production of LPG from renewable sources is also emerging. e-LPG can be synthesized from the following pathways :

- Direct synthesis from syngas
- Indirect synthesis from syngas via methanol or DME
- Indirect synthesis from CO_2 via methanol or DME
-

The required syngas can be generated via co-electrolysis of using CO_2 and H_2O using SOEC technology.

Recently, direct synthesis of e-fuel from CO_2 hydrogenation over the tandem catalyst is reported [11.a]. In the case of direct hydrogenation, the e-fuel can get by one pass CO_2 conversion in a single reactor. In the indirect route, the CO_2 first will be converted into methanol/CO in the first reactor, and further, the methanol/CO will be converted into e-fuel in the second reactor via MTG/MTO and FT process.

Common processes for fuel synthesis include Fischer Tropsch and methanol synthesis. Very large-scale plants using these processes are in operation, for example, methane and methanol from carbon monoxide and hydrogen. With research, these processes can be modified to use carbon dioxide as the carbon source, requiring modifications

to maintain desired conversion efficiencies and yields. Current demonstration e-fuel plant facilities details are given below :

Table 2-3 : Current demonstration of e-fuel plant facilities worldwide

Facility/Operator name	Country	CO$_2$ feedstock	E-fuel output	Output quantity
Carbon Recycling International (Vulcanol)	Iceland	Geothermal plant flue gas	Methanol	4000 tonnes/year
FReSME project (2020)[a]	Sweden	Blast furnace gas	Methanol	50 kg/hr
MefCO2 113 (final phase construction)	Germany	Power plant flue gas	Methanol	1 tonne/day (planned)
Soletair[b]	Finland	Direct Air Capture	Petrol, Kerosene and Diesel	100 kg/hr
Sunfire[c]	Germany	Direct Air Capture	E-Crude (E-diesel)	Demonstration: 3 tonnes in 1500 hrs
Sunfire (2022)[d]	Norway	Direct Air Capture	E-Crude (E-diesel)	8000 tonnes/year (planned 1st stage)
a. FReSMe. From Residual Steel Gases to Methanol. See http://www.fresme.eu/index.php#PROJECT (accessed 18 April 2019). b. MefCO2. Methanol fuel from CO2. See http://www.mefco2.eu/ (accessed 18 April 2019). c. Vázquez FV et al. 2018 Power-to-X technology using renewable electricity and carbon dioxide from ambient air: SOLETAIR proof d. Sunfire. 2017 Sunfire produces sustainable crude oil alternatives. See https://www.sunfire.de/en/company/news/detail/ sunfire-produces-sustainable-crude-oil-alternative (accessed 18 April 2019).				

2.3   Challenges associated with Synthetic Fuel

The production of synthetic fuels faces several challenges that impact its widespread adoption and scalability. These challenges include high capital costs associated with building and operating production facilities, particularly for technologies like coal gasification or biomass conversion. Additionally, the energy-intensive nature of synthetic fuel production can limit its economic viability, requiring significant energy

inputs for processes like coal liquefaction or hydrogen production from electrolysis. Environmental concerns also pose challenges, as some production methods may generate air and water pollutants or contribute to deforestation and land-use change, particularly in the case of biomass feedstocks. Furthermore, ensuring the sustainability of feedstock sourcing is crucial to prevent competition with food crops or exacerbating land degradation.

2.3.1   Challenges associated with E-fuels

Though the E-fuels have great potential for decarbonization of hard-to-abate transport sectors such as heavy-duty transport, aviation and shipping, they are currently associated with the following challenges:

- The main research challenges for e-fuels are:

  o Improving the fundamental understanding of catalysis

  o Developing more efficient and lower-cost electrolysis technologies for the conversion of water to low carbon hydrogen

  o Engineering and catalytic developments to make small-scale conversion of syngas or other electro-derived intermediate chemicals into chemicals and fuels more commercially attractive and scale better to renewable generators eg wind farms

  o Adapting to the intermittency of renewable electricity

  o Developing processes that can be scaled up to the gigawatt output size

  o Matching fuels to engine requirements, for example, tailor made e-fuels from methanol to optimize engine performance

- Technology Readiness Levels (TRLs) : There is a wide range of e-fuel technologies and some of them are already commercial, for example, those

developed by Carbon Recycling International to produce methanol from carbon dioxide, hydrogen, and renewable electricity (*Figure 2-3, 2-4*).

- Technologies at small to medium scale include e-methane, e-FT fuels etc. Technologies at the lower levels of development include electrolytic carbon dioxide conversion (perhaps TRL 4 – 6), and at very early-stage research are activities such as electro photocatalytic conversion (*Table 2-4*).
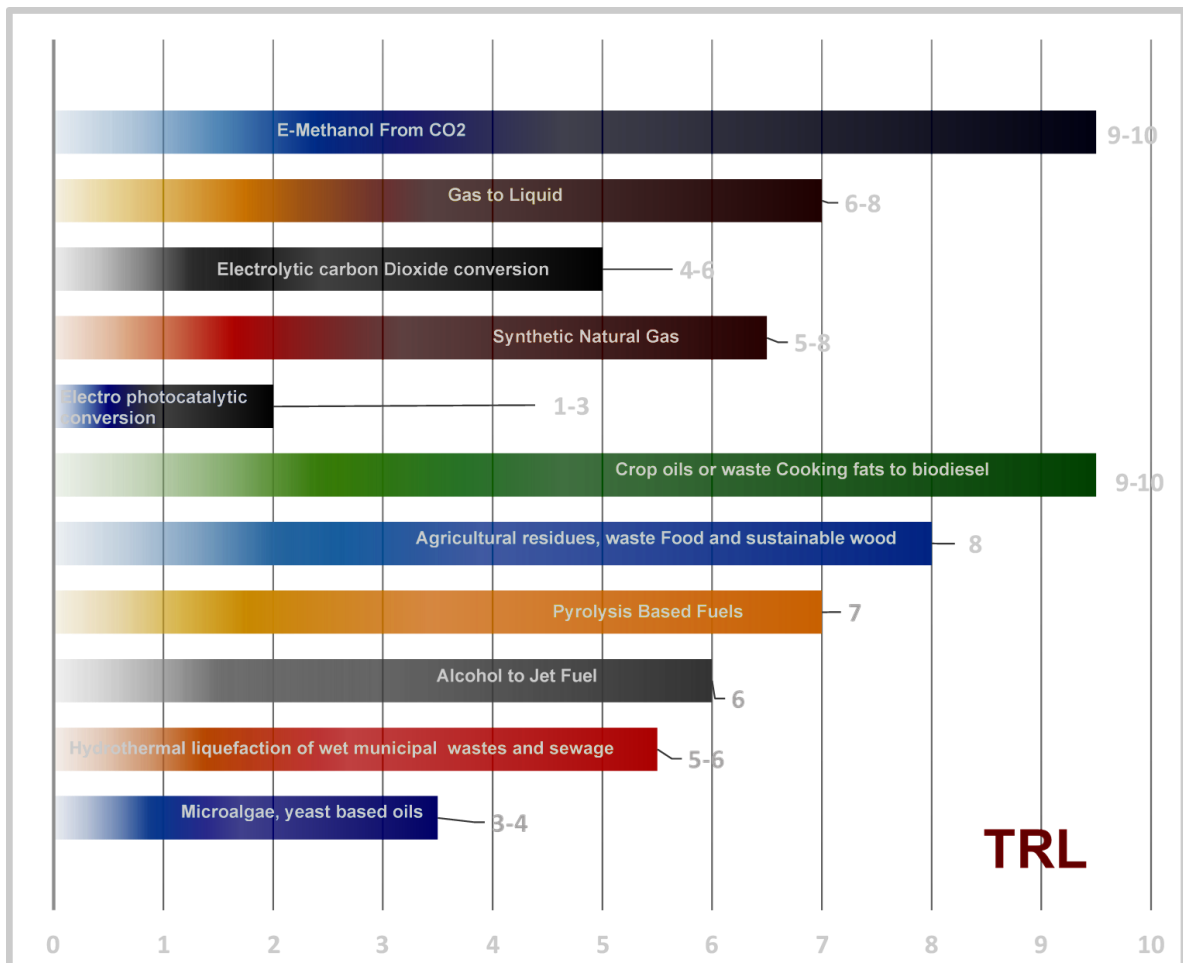
Figure 2-3 : Current Technology Readiness Levels (TRL) for e-fuels production.

- Technologies for the production of the e-fuels are not yet proven on a commercial scale. It requires further efforts to tackle the challenges associated with the development of large-scale commercial plants.

- Due to inherent thermodynamic conversion losses, e-fuel's overall energy efficiency in engines (WTW approach) is lower compared to the overall energy efficiency of electricity use in battery electric vehicles and hydrogen-powered fuel cell vehicles.

- The cost of e-fuels depends mainly on the cost of renewable electricity and the cost of CO_2 capture. At the current cost of renewable electricity and CO_2 capture, e-fuels are not cost-competitive with conventional fossil-based transportation fuels. In addition, the efficiency of CO_2 capture is also a challenge for e-fuel production.
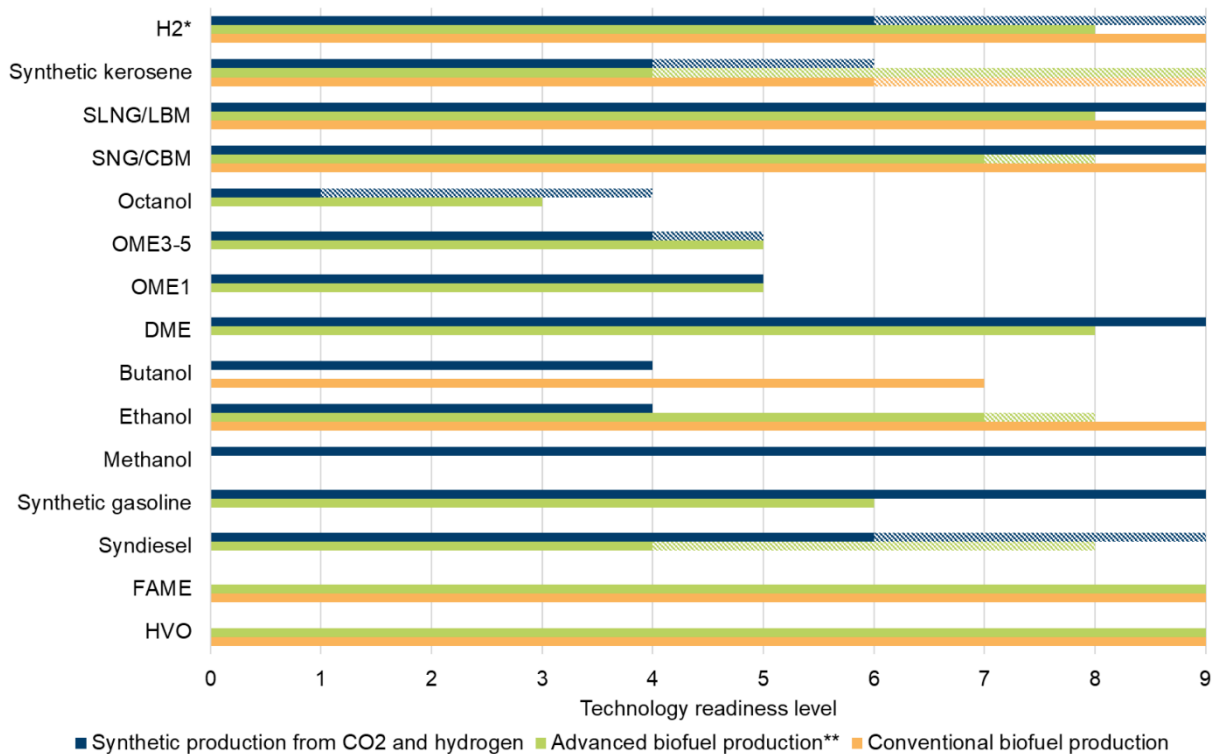
Figure 2-4: TRL of alternative fuels from synthetic production from hydrogen and renewable electricity, conventional biofuel production, and advanced biofuel production.

*Production from renewable electricity. ** If manure, sludge or waste is used for conventional biofuel production processes, the product will be classified as advanced biofuel.. SLNG: Synthetic liquefied natural gas, LBM: Liquefied biomethane, SNG: Synthetic natural gas, CBM: Compressed biomethane, OME: Oxymethylene ether, DME: Dimethyl ether, FAME: Fatty acid methyl ester, HVO: Hydrotreated vegetable oils. [11.b]*

- Renewable electricity systems are usually intermittent in nature, hence affecting the cost of e-fuel production; and increasing the capital cost of the systems to avoid or minimize intermittency.

- Deployment of e-fuels production technologies requires substantial capital investment and depreciation of existing assets generating conventional transportation fuels.

Table 2-4 : Current Technology Readiness Levels (TRL)

Current Technology Readiness Levels (TRL) of production pathways to renewable jet fuel

Jet fuel production pathway	Technology Readiness Level (today)	Critical technical element (e.g. determining bandwidth bottom)
PtL	**5 – 8**	**CO_2 extraction from air, co-SOEC**
Fischer-Tropsch (low-temp)	7	Large-scale reverse water gas shift (RWGS)
Fischer-Tropsch (high-temp)	5 – 6	High-temperature electrolysis (co-SOEC)
Methanol (low-temp)	8	ASTM approval, final conversion
Methanol (high-temp)	7 – 8	SOEC, ASTM approval, final conversion
BtL		
Lignocellulosic biomass	7	Feedstock quality
HEFA	**4 – 9**	**Algae feedstock**
Rape seed, soy, used cooking oil	9	
Algae	4 – 5	Algae cultivation, extraction
AtJ	**7 – 9**	**Conversion**
Sugar & starch	8 – 9	AtJ process
Lignocellulosic biomass	7 – 8	Conversion

HEFA – Hydroproccessed Esters and Fatty Acids, AtJ – Alcohol-to-Jet fuel   Source: LBST

- Renewable electricity is a prerequisite for low-carbon e-fuels to contribute to reducing GHG emissions. At present, excess renewable electricity is not available for the deployment of e-fuels technologies.

- Water is one of the consumables in the e-fuel life cycle. It is required in elecrtolyzers as well as in some carbon capture and fuel synthesis processes. Fresh water is a scarce resource and is not available in the required quantity in some regions.

- E-fuels appear to generally offer emission reductions if produced from low-carbon renewable electricity, but if the electricity is produced using fossil energy sources, GHG emissions can become higher compared to fossil fuels.

- Production of e-fuels is associated with increased system complexity and lower overall efficiency.

- **Timelines:** In the medium term (5 – 10 years), e-fuel processes will most likely be incorporated into existing fuel manufacturing processes to improve carbon efficiency and initially, make use of any excess renewable energy. This gradual introduction into the marketplace will be driven by the availability of renewable energy. In the longer term (10+ years), processes with highly innovative fuels are likely to appear in the marketplace; such as the new DME and OMEx fuels as drop-ins for internal combustion engines.

- **Integration within refinery assets :**

  The design of an e-fuel plant is different from a traditional refinery/petrochemical facility. The intermittent character of renewable power introduces challenges when it is integrated with electrolysers and CO_2 capture plants. Due to the fluctuating nature of renewables, the dimensioning and operating strategy of the plant are not straightforward.

The challenge associated with intermittency comes from two aspects: both the limited technical flexibility and the lower capacity factor of the e-fuel production units. A typical synthesis plant does not allow fast ramp-up and ramp-down rates (minutes to hours), but requires a steady and continuous operation.

Moreover, turning down the throughput to less than 50% might be challenging and may require a more specific and hence expensive design. The CO_2 capture unit will very likely resemble traditional separation units, which also operate on a a continuous basis. Low-temperature electrolysers, in particular, PEM electrolysers can be switched on and off in matter of seconds. However, the capacity factor deteriorates with fluctuating feedstock, which will result in higher investment costs because the capacity is not fully utilized.

Technical solutions to cope with intermittency within the refinery include:

a) The combination of different renewable energies such as solar PV, wind energy, and (pumped) hydro to reduce intermittency,

b) To build storage facilities for electricity, hydrogen and/or carbon dioxide,

c) To introduce novel flexible downstream designs that allow both a low turndown level and agile operation. All these solutions come with additional complexity and cost, and the optimal solution can be a blend of these solutions. For example, including a hybrid fossil-renewable feed strategy for the elements of the plant must be run at high utilisation and which cannot be rapidly switched.

For an actual design targeting minimal production cost, the optimal sizing of the individual units (solar PV or wind, CO2 capture unit, electrolyser, storage facilities and downstream synthesis) will depend on the location (abundance of renewable sources and its temporal distribution over the year), the relative cost of the units (e.g.

cost of battery versus gas storage), and the availability of flexible designs (e.g. a high turndown ratio of the synthesis process).

Assuming the e-fuels synthesis and CO2 capture units can only run continuously at high load, with mild throughput variations, energy storage will be required to cover day-night fluctuations or to manage a series of cloudy days with limited fresh feed production. The exact sizing of the storage facilities will also depend on the total installed electrolyser capacity. When a large electrolyser capacity is installed to operate intermittently to follow the output profile of solar PV, the electricity storage requirement will be minimal, but hydrogen storage is still necessary to provide constant feedstock to the downstream units.

2.4 Conclusions

E-fuels have gained increased attention in recent years to decarbonize hard-to-abate transport sectors such as heavy-duty transportation, aviation and deep-sea shipping, where electrification opportunities are limited. Hydrocarbons based e-fuels are produced by combining green hydrogen produced by the electrolysis of water with renewable electricity and carbon dioxide (CO_2) captured from industrial emissions. E-ammonia does not require CO_2 and is generated by combining nitrogen separated from the air with green hydrogen through the Haber-Bosch process. Widely reported synthesis processes for the production of hydrocarbon-based e-fuels are methanation for e-methane, methanol synthesis for e-methanol, reverse water-gas shift (RWGS) reaction to produce syngas, followed by Fischer-Tropsch (FT) synthesis to produce e-FT fuels. Production of e-fuels is currently associated with various challenges and requires additional efforts for commercial deployment of e-fuels.

3. Chemicals/Additives for Synthetic Fuels

Synthetic fuels are produced using biomass, coal, natural gas, or even captured carbon dioxide as a feedstock.

They are classified as

i. Biofuels are made through fermentation, chemical or thermal treatment of biomass.

ii. Synthetic fuel produced from coal, natural gas, or even captured carbon dioxide. One specific classification of synthetic fuel is Electro fuels (e-fuels) made using captured carbon dioxide and reacting with hydrogen, generated by water electrolysis from sustainable electricity sources e.g. wind, solar and nuclear power.

Biofuels are mainly divided into two categories:

a) Oxygenates-based biofuels (Bio-alcohols and bio-esters)

b) Deoxygenated biofuels (namely Bio-ATF, Green LPG, gasoline and diesel)

The molecular level distribution of these fuels is substantially different vis-à-vis fossil fuels. Hence, the use of additives to improve their combustion characteristics differ from conventional additives. The present chapter provides a brief overview of potential additives and their function in improving the performance of synthetic fuels.

3.1 Additives for Bio-Fuels

3.1.1   Bio-gasoline:

Oxygenates are one of the most important fuel additives to improve fuel efficiency. A few oxygenates such as ethanol, methanol, methyl tertiary butyl alcohol, and tertiary butyl ether have been used as fuel additives. The process of using oxygenates makes more oxygen available in the combustion process and has a great potential to reduce spark ignition engine exhaust emission.

Oxygenate-based biofuels (bioethanol and biobutanol) are formed *via* fermentation of biomass and are mainly used as blend stocks along with conventional gasoline and offer a platform for 100% replacement of conventional gasoline. The use of a 20% blend does not warrant a change in the internal combustion engine. With an increase in the blending ratio, the calorific value of the fuel drops which deteriorates the engine performance and warrants change in the engine components. Currently, there are no specific additives reported to enhance the calorific value of blended gasoline, however, literature reports the use of mechanical devices based on the cavitation principle for attaining calorific values as per the fuel specifications [12].

Unlike fossil fuels, such fuel is prone to corrosion due to the hygroscopic nature of the alcohol. To mitigate this issue, corrosion inhibitors are added.

3.1.1.1   Green additives for corrosion protection

Bio-based green corrosion inhibitors are a better alternative to many organic / synthetic additives due to their non-toxicity and biodegradability in the environment. Green corrosion inhibitors are mainly derived from natural polymers, amino acids, oleo-chemicals and plant extracts. The usage of synthetic long-chain fatty acid-based additives containing amino/ aldehyde/ ketone groups and aromatic rings are mainly preferred for hydrocarbon systems due to their high production yields and economics. Oleic, Linoleic and palmitic acid-based chemistry are also useful for acidic corrosion mitigation. Likewise, bio-based vapor phase corrosion inhibitors find good applications in fuel storage tanks in form of various internal coatings. Typical corrosion inhibitors are depicted below.
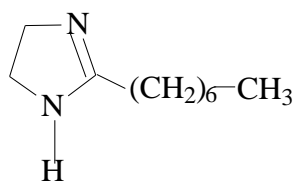
Imidazoline-based corrosion inhibitor

$$CH_3-(CH_2)_{10}-\overset{\overset{\displaystyle O}{\|}}{C}-NH-NH-\overset{\overset{\displaystyle S}{\|}}{C}-NH-\text{(phenyl)}$$
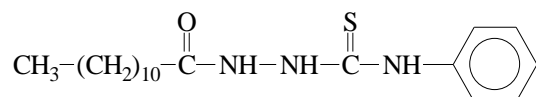
Thiosemicarbazide-based corrosion inhibitor

These corrosion inhibitors exhibit their inhibiting action via physisorption or chemisorption onto the metal-solution interface by removing molecules of water on the surface for compact barrier film formation.

3.1.1.2   Dehazer/Demulsifier

Ingress of water by ethanol/ butanol can lead to haziness, translucency and eventual phase separation in gasohol blends. The problem amplifies with the increasing blend ratio of alcohol. Dehazers/ demulsifiers are frequently added to such fuel blends to prevent a hazy appearance and prevent water accumulation.

Popular choices for dehazing/demulsifying gasohol blends include non-ionic detergents such as polyethers and sugar-fatty acid esters in optimized HLB ratios.

3.1.1.3   Biocides

Water-contaminated fuels also often suffer from fungi and bacterial growth in storage tanks and would require biocides for prevention. Most common examples of fuel-compatible biocides include thiazoles, thiocyanates, isothiazolins, cyanobutane, dithiocarbamate etc.

3.1.2 Biodiesel

On the other hand, bio-ester (FAME, fatty acid methyl ester) is derived by the transesterification of vegetable oils with methanol. FAME is also used as blend stock along with fossil diesel fuel. However, the low-temperature flow properties and oxidation stability are a matter of concern. Therefore, suitable additives are required to meet diesel standards. Furthermore, vegetable oil-based additives have been developed as green additives for cetane, lubricity and oxidation stability enhancements for meeting diesel specifications.

A gist of green additives used to improve fuel properties wis given below.

3.1.2.1 *Oxygenate-based cetane improver*

Bio-mass derived oxygenated compounds such as methanol or dimethyl ether (DME) are promising alternative cetane improver additives for meeting SOx, NOx, methane, and BC (black carbon) emissions [13-14].

3.1.2.1.1 Cetane improvers for biodiesel fuel: DEE (diethyl ether):

Diethyl ether (DEE), an oxygenated additive can be added to diesel/biodiesel fuels to suppress NOx emission. DEE is an excellent ignition enhancer and has a low auto-ignition temperature [15]. It is an aid for cold starting and an ignition improver for diesel water emulsion [16].

$$H_3C \diagup O \diagup CH_3$$

(DEE)
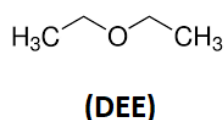
3.1.2.1.2 Nitrogen-based cetane improver.

Nitrate derivative of methyl oleate (MODN) has been reported as a cetane improver. It also acts as a lubricity enhancer at the same concentrations used to provide the

cetane enhancement. It exhibits increased stability and lower volatility as compared to conventional 2-EHN [17].

3.1.2.2   *Lubricity Improver:*

Synthetic esters based on vegetable oil fatty acids and alcohols are reported as excellent lubricity enhancers for diesel fuel. They can lubricate at high temperatures as they have much lower volatility at a given viscosity.

One such ester-based lubricant viz. methyl oleate is produced using methanol and oleic acid.

Likewise, a by-product of the biodiesel process, glycerol is reported to be utilised for the production of Solketal, which is an excellent oxidation stability enhancer for gasoline, diesel and biodiesel. Furthermore, it also acts as an octane booster for conventional gasoline.

Solketal

Production scheme for Solketal

3.1.2.3 *Pour point depressant*

The use of ozonized vegetable oils as a pour point depressant for neat biodiesel has been reported in the literature. Ozonized vegetable oils (1–1.5% by weight) were found to be effective in reducing the pour point of biodiesel prepared from sunflower oil, soybean oil and rapeseed oil to -24, -12 and -30 °C, respectively [18].
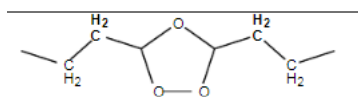
General Structure of ozonized vegetable oil.

3.1.3 Bio-olefin based oxygenates as octane boosters.

Ether-based additive for octane boosting

Bio-isobutylene based production of ethers such as ethyl *tert*-butyl ether (ETBE) or *tert*-amyl ethyl ether (TAEE), methyl *tert*-butyl ether (MTBE) or *tert*-amyl methyl ether (TAME) is used as octane booster additives for fossil gasoline.
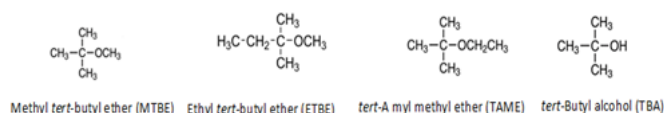
Bio-isobutylene based oxygenates as octane boosters

3.2 Additives for e-fuels

e-Diesel and e-gasoline are rich in paraffinic hydrocarbon content with low aromatic content and a negligible amount of sulphur, nitrogen, and olefinic compounds. The lack of sulphur leads to a drop in lubricity for e-diesel and e-gasoline and hence lubricity enhancers are required to maintain the engine life. Typically, long chain fatty acids and their corresponding esters with methanol are extensively used as lubricity

enhancers. Depending on the composition of the e-diesel fuel cetane improvers as mentioned in section 1.2.1 can be used.

Additionally, as e-fuels are typically abundant in straight-chain hydrocarbons, they usually suffer from poor cold flow properties. Different methacrylate polymers and copolymers have been successfully used as CFPP improvers and Pour Point Depressants.

Further to mitigate emissions synthetic additives e.g. Oxymethylene dimethyl ethers (OMEn) are developed for e-fuels.   They are produced using methanol from waste biomass [19-23]. They are non-toxic and miscible with diesel fuel and thus can be part of a carbon–neutral combustion process, both as additives or substitutes in diesel engines.

(OME)
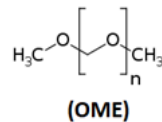
3.3   Sustainable Aviation Fuel (SAF)

SAF can be derived from the following ASTM-approved reaction pathways using biomass as feedstock:

- Alcohol to Jet (ATJ)
- Hydroprocessed esters and fatty acids
- Hydrothermal Liquefaction
- Pyrolysis
- Gas to jet fuels (GTJ)
- Direct sugars to hydrocarbons (DSHC)
- Aqueous phase reforming (APR)

Compared to conventional jet fuels, SAF has the potential to lower emissions by up to 80% over its lifecycle [24].

Additives are required to improve the performance, ease of fuel handling and storage of SAF. Some of the common additives added to the SAF are given below:

3.3.1   Antioxidants (gum inhibitors)

These kinds of additives are used in SAF to prevent the formation of gum and other antioxidation products. Typically, bulky phenols like 2,6 di-tertiary-butyl phenol, 2,6 di-tertiary-butyl-4-methyl phenol and others are excellent antioxidants [25].

3.3.2   Fuel system icing inhibitors

These additives reduce the freezing point of any water that may be in the fuel system and prevent ice crystal formation that could restrict fuel flow. Diethylene Glycol Monomethyl Ether is the anti-icing additive added to SAF to prevent the formation of ice crystals [26].

3.3.3   Antistatic additive

Electrostatic charges can quickly accumulate when high-refined, low-sulfur fuels are used at rapid fuel flow rates. A discharge from an electrically charged fuel to the side of the tank could ignite the fuel vapour and result in an explosion, making slow dissipation a potential risk. As fuels have become "cleaner", the risks of electrostatic ignition have further increased. It is therefore essential to use additives that increase the electrical conductivity of fuels, reducing the risk of electrostatic hazards. Stadis 450 is used as an antistatic additive. It is a registered trademark marketed by Innospec Inc.

3.4   Supply chain framework for green additives:

The development and utilization of vegetable oils-based additives for diesel and hydro-processed vegetable oils for synthetic fuel highlight the importance of addressing the supply chain framework for producing these green additives. A robust supply chain framework would involve sourcing sustainable and ethically produced vegetable oils, ensuring traceability and transparency throughout the

supply chain. This includes establishing partnerships with farmers and suppliers committed to environmentally friendly practices, such as sustainable agriculture and fair labor standards. Additionally, infrastructure investments are needed to support the production, refining, and distribution of these green additives and SAF, including blending facilities, transportation networks, and storage facilities. Regulatory frameworks and certification schemes may also play a role in verifying the sustainability credentials of green additives and SAF throughout the supply chain, providing assurance to consumers and stakeholders. Collaboration among stakeholders across the supply chain, including government agencies, industry players, NGOs, and research institutions, is essential to address common challenges and accelerate the adoption of sustainable practices in the production of green additives and SAF.

3.5 Summary

The development of vegetable oils-based additives for diesel and hydro-processed vegetable oils for synthetic fuel is set to offer a platform for the decarbonisation process in the transportation sector. To achieve an e/synthetic-fuel based Net Zero cycle, it is essential to use renewable/synthetic fuel additives With the continuing quest for a cleaner and more fuel-efficient engines, the role of additives is going to play a vital role in fuel storage, stability and engine performance. Moreover, the framework for supply chain must prioritize sustainable sourcing practices, including traceability and transparency, while also requiring infrastructure investments to support production, refining, and distribution. Regulatory frameworks and certification schemes play a vital role in ensuring sustainability standards are met throughout the supply chain. Considering this fact, the use of potential additives as mentioned in the present chapter is envisaged to enhance to aid the decarbonisation process.

4. Demand /Future Demand of Synthetic Fuels

The global synthetic fuel market size was valued at US$ 3.45 billion in 2021 as shown in Figure 4-1 and it is projected to surpass around US$ 21.7 billion by 2030 and growing at a compound annual growth rate (CAGR) of 22.67% during the forecast period 2022 to 2030 [27]. Another study estimated the Global Synthetic Fuel Market size to grow at a CAGR of 28.7% over the forecast period (2021 to 2027) [28].
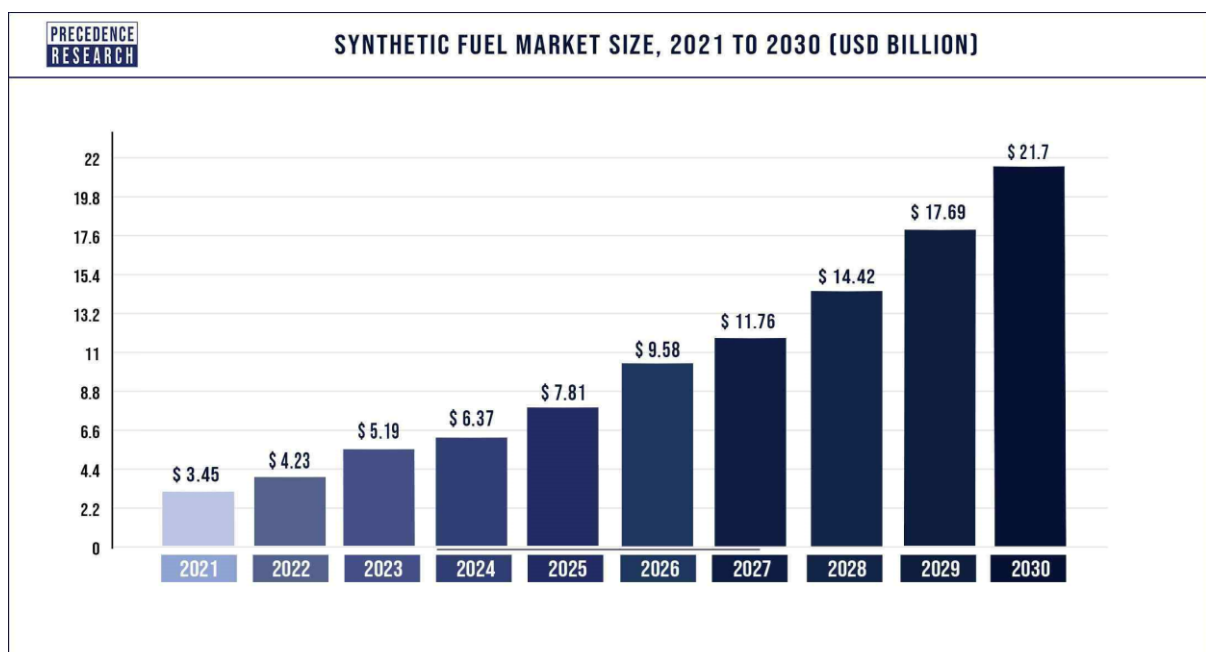
Figure 4-1 : Synthetic Fuel Market Size

Synthetic fuels are an alternative to the existing fuel market. Synthetic fuels are obtained from a mixture of hydrogen and carbon monoxide which are synthetic gases. This mixture of two gases is a renewable source of energy. Due to the use of synthetic fuels the economies will become independent as they will not rely on crude oil. The crude oil market keeps fluctuating now and then. The cost of fuel derived from crude oil also keeps on changing. With the use of synthetic fuels, the economies will make use of green energy which has no harmful emissions. The process of

manufacturing liquid fuel involves the production of hydrogen from water. The produced hydrogen is then mixed with carbon to produce the liquid fuel. The combination of carbon dioxide and hydrogen results in the formation of synthetic fuels. With the help of industrial processes carbon can be recycled and it can even be captured with the use of filters.

4.1   Growth Factors

The market for synthetic fuels is expected to grow well during the forecast. In the past, the market has seen good growth owing to several reasons. As the crude oil market fluctuates and the prices of oil rise on and off there is a growing demand for the use of synthetic fuels. The governments of various developing as well as developing economies are focusing on the use of synthetic fuels to meet the zero emissions target by the year 2050. The most important factor which is boosting the synthetic fuels market is the fear of depletion of natural resources. The political unrest among the oil-producing countries and other dependent countries across the globe is creating a major demand for synthetic fuels across the globe. The other most important factor leading to the growth of this market is that synthetic fuels are environmentally friendly. The use of synthetic fuels does not cause a great amount of pollution as compared to the other fuels existing in the market. The growing attention of various governments on the production of synthetic fuels and the increasing oil prices are also expected to boost market growth during the forecast period.

The feedstock which is used to produce synthetic fuels or renewable and hence synthetic fuel is also known as a green fuel. As the fuel is available in the liquid format the storage and distribution of this fuel are similar to that of petroleum-based fuels. Synthetic fuels can be used with the already existing infrastructure in the market and this happens to be the nature driver for the growth of this market. Synthetic fuels are user-friendly as they reduce carbon emissions from the environment. The use of this fuel in the existing cars does not require any modification in the engines and therefore there is no need for a lot of expenditure or investment for new infrastructure. As compared to petroleum fuels synthetic fuels are clean as the pollutants like metal and

sulfur from petroleum fuels can be captured in synthetic plants. Multiple feedstocks can be used in the production of synthetic fuels and this is another reason why the market is expected to grow during the forecast period.

Synthetic fumes can be generated from gas, biomass or coal. The energy density of synthetic fuels is very close to that of gasoline which means that the space taken by synthetic fuels is less but it will provide the same amount of output. Unlike the battery-operated vehicles, there is no new infrastructure required as the synthetic fuels can be used in the already existing vehicles as they are compatible. Synthetic fuels also operate in cold climates which makes them a suitable option for many countries across the globe.

4.2   Report Scope of the Synthetic Fuel Market

Table 4-1 : Synthetic Fuel Market Scope

Report Coverage	Details
Market Size by 2030	USD 21.7 Billion
Growth Rate from 2022 to 2030	CAGR of 22.67%
Asia Pacific Market Share in 2021	39%
Fastest Growing Region	North America
Base Year	2021
Forecast Period	2022 to 2030
Segments Covered	Raw Material, Type, Application, Geography
Companies Mentioned	Sasol, Petrochina International Jinzhou Petrochemical Co., Ltd., Reliance Industries Ltd., Robert Bosch GmbH, Indian Oil Corporation Ltd, Royal Dutch Shell Plc.,

	Phillips 66, Exxon Mobil Corporation, Red Rock Biofuels, SG Preston Company

4.3   Raw Material Insights

By raw material, the coal segment is expected to dominate the market during the forecast period. With the use of a chemical conversion process which involves cool synthetic fuels are produced on a large scale. Due to the easy availability of coal across most countries, the segment is expected to grow well during the forecast period. The political uncertainty across the globe it's creating a greater demand for synthetic fuels in the market.

Synthetic fuels manufactured from coal are a great alternative to fuels derived from crude oil. The use of natural oil and gas can be substituted by the use of synthetic fuels. The amount of pollution caused due to the manufacturing of synthetic fuels could be one of the restraining factors for the growth of the market. Even though the cost of raw materials used for manufacturing synthetic fuels may not be extremely costly but the installation of the manufacturing plant is it expensive and it requires a large amount of investment. When the cost of manufacturing synthetic fuels which involves the installation of plants required for manufacturing compared with the petroleum-based fuels the cost of synthetic fuels is more. This shall inhibit the growth of the synthetic fuels market in the global scenario. Synthetic fuel it's compatible for use in diesel engine as well as gasoline engines.

4.4   Type Insights

As depicted inf Figure 4-2, by type, the extra heavy oil segment is expected to dominate the market during the forecast period [27-28]. The extra heavy oil segment has done well in the past. Extra heavy oil is similar to crude oil and it is present inside the earth. Extra heavy oil commonly used in marine vessels and industrial settings, poses significant environmental challenges due to its high sulfur content and carbon

intensity. However, this segment is expected to grow as it does not require any additional investment for the already existing vehicles running on the roads to use synthetic fuel. The demand for this segment is expected to grow due to an increase in the sales of automobiles across the globe. Initiatives taken by the government to generate pollution-free fuels for use in the future the market for synthetic fuels, is expected to go up. Due to the high content of octane in synthetic fuels the market is expected to grow well as the benefits of this octane are improved efficiency of the engine. Fuel can be stopped and distributed similarly to petroleum-based fuels. The increasing cost of oil due to political unrest among many countries across the globe is creating more demand for synthetic fuels [27]. The process of turning natural gas into liquid fuels is known as gas-to-liquids. Shale oil is a type of synthetic petroleum made from marlstone, a naturally occurring rock that is frequently referred to as oil shale. Tar sand is another name for oil sand. It is made out of a mixture of water, clay, sand, and bitumen [28].

Depending on the type of fuel used synthetic fuel can be used without any modifications to the diesel engines. Synthetic fuel it's compatible with the already existing vehicles running on the roads. Even though the use of synthetic fuels in vehicles does not cause a lot of emissions but the production of synthetic fuels in a manufacturing plant leads to a lot of pollution which can be compared with the pollution caused by gasoline [27].
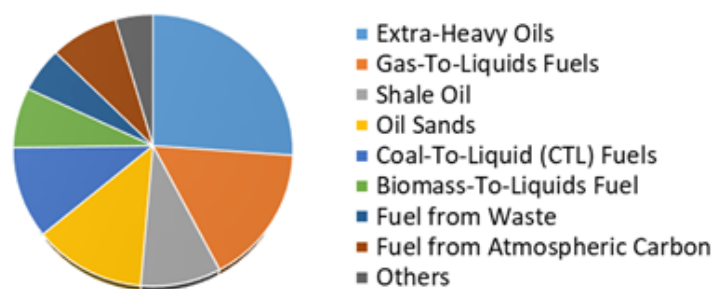
Figure 4-2 : Synthetic Fuel Market by Type (%) in 2021

4.5　Regional Insights

In 2021, the Asia Pacific region had the largest market share of about 39% and is expected to have significant growth during the forecast period. Due to a growing demand for automobiles in the Asia Pacific region specifically in India, China and Japan the market is expected to grow during the forecast period. The growing demand for automobiles is creating a demand for fuels across the globe. In the Asia Pacific region, China is expected to be a major consumer of synthetic fuels. It is estimated that there shall be a good amount of production of synthetic fuels in China. Apart from China India is also expected to witness good growth during the forecast period. With increasing demand for automobiles and alternative crude oil-based fuels the market for synthetic fuels is expected to grow well in the Indian market. The availability of low-cost labour and cheap raw material in countries like India and China is expected to give a boost to the synthetic fuels market. The quantity of synthetic fuel produced in the Asia Pacific region compared to other regions like North America or Europe will be more due to the availability of low-cost labour and easily available raw material [29].

The North American market is also expected to grow well during the forecast period. In recent years, the North American market has dominated the synthetic fuels market. Due to a high amount of investments in technological advancements in the North American region, the market will grow well. Investments from the public and private sectors in promoting the manufacturing of synthetic fuels in the North American region will lead to increased production of synthetic fuels in this region.

The European market is also expected to have steady growth during the forecast period. Due to the growing automotive industry in the European region, the market for synthetic fuel is expected to grow up. The awareness regarding the availability of synthetic fuels and the benefits of using these synthetic fuels will drive market growth in these regions. To reduce the emissions of greenhouse gases many countries in Europe are promoting the use of synthetic fuels for transportation. Synthetic fuels are used as a substitute for gas and oil across many nations in the North American

region. To reduce the carbon emission and reach the target of net zero carbon emissions the North American region is expected to utilize synthetic fuel for the transportation segment.

4.6   Key players Operating in the Market

Demand within the synthetic fuels market is highly concentrated with top producers accounting for approximately 45-50% of the market [30]. A few of the key players operating in the synthetic fuels market include

- Sasol

- Petrochina International Jinzhou Petrochemical Co., Ltd.

- Reliance Industries Ltd.

- Robert Bosch GmbH

- Indian Oil Corporation Ltd

- Royal Dutch Shell Plc.

- Phillips 66

- Exxon Mobil Corporation

- Red Rock Biofuels

- SG Preston Company

4.7   Key Market/Industry Developments

- Sasol announced an investment of dollar 396 billion in South Africa to open up a coal mine in the year 2019. To support the production of synthetic fuel in the

Sasol Secunda synthetic fuel operation this coal mine will provide the raw materials and 4000 jobs will be created to extract coal from this region [27-29].

- The US had proposed or planned of converting coal to liquid fuel in the year 2019. The investment required for the proposed project will be $1.2 billion and the location will be Virginia. This proposed project is expected to increase the production of synthetic fuel [27-29].

- In Jun 2019, Quadrise Fuels International PLC has inked an agency agreement with industrial infrastructure firm Redliner to fast-track projects for its MSAR synthetic fuel technology in Mexico. This agreement helps to improve new technology for the oil & gas industry [28-29].

5. ASTM/CEC/BIS approved Synthetic Fuel Technologies

Aviation biofuels are certified for specified blend-level limited use in commercial flights. Hydroprocessed non-edible vegetable oils/animal fats (HEFA-SPK), Fischer-Tropsch of biomass feed to fuel (FT-SPK), renewable synthesized iso-paraffinic (SIP) fuel (renewable fire-safe hydrocarbon), alcohol-to-jet fuel (ATJ), and synthesized paraffinic kerosene plus aromatics (SPK/A) are some of the options available to produce sustainable aviation fuels at commercial scale. All these options are included in existing approved ASTM standards, which are subsequently reflected in other international standards such as DEF STAN 91-091. There is a vital need to pro-actively develop robust aviation biofuel supply chains to meet the imminent requirements of CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation). CORSIA aims to regulate and mitigate the total CO_2 emissions above 2020 levels to ensure international aviation's long-term carbon-neutral growth.

In June 2011, the ASTM committee gave technical approval for a 50% biofuel/kerosene mix for use as Jet A1 fuel. Detailed specifications and test methods for these specifications were listed as a new ASTM standard, ASTM D7566, for aviation turbine fuel containing synthesized hydrocarbons [31-32]. Since 2011, 6 additions (7 annexures) have been made to the ASTM documents. A comparison of various specifications approved by ASTM under D7566 to date is listed in Table 5-1.

The significant pathways certified by ASTM or in consideration for Bio–ATF production is (a) Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK, Annex A1), (b) Hydroprocessed Ester of Fatty Acids - Synthetic Paraffinic Kerosene (HEFA- SPK, Annex A2), (c) Synthesized Iso-Paraffins (SIP) from Hydroprocessed Fermented Sugars (Annex A3), (d) Alcohols-to-Jet Synthetic Paraffinic Kerosene (ATJ-SPK,

Annex A4), (e) Fischer-Tropsch Synthetic Kerosene with Aromatics (FT-SKA, Annex A5), (f) Catalytic Hydrothermolysis (CHJ, Annex A6), (g) Synthesized paraffinic kerosene from Hydroprocessed hydrocarbons, esters, and fatty acids (HC-HEFA SPK, Annex A7) (h) Hydro-Deoxygenated Synthesized Aromatic Kerosene (HDO-SAK), (I) Hydrotreated Depolymerized Cellulosic Jet (HDCJ), (j) Hydrothermal Liquefaction (ARA-CLG), (k) Hydro-Deoxygenated Synthesized Kerosene (HDO-SK).

Table 5-1 details the differences in the limits for different specifications of the approved pathways. SIP-SPK (A3) has a different limit for volatility, i.e., 10% boiling, and FBP, compared to other approved processes. The limit for the density for different approved processes is in the range of 730-770 kg/m3, except SIP-SPK (765-780 kg/m3), SPK/A (755-800 kg/m3), CHJ (775-840 kg/m3) and HC-HEFA-SPK (730-800 kg/m3). The sulfur limit for all other approved processes is 15 PPM except SIP-SPK and SPK/A, for which the limit is 2 PPM. The maximum allowable existent gum for A4 is 4, while it is 7 mg/100ml. There is no limit to Micro-separometer (MSEP), except SPK/A, where the maximum allowable MSEP is 90. For all the approved processes, the limits for neat fuel for aromatics are set at 0.5% by weight); the limit for A4 is 20 and A 6 (minimum limit 8.4%, maximum 21.2%).

A list of various bio-jet fuel production processes and their status of approval is provided in Table 5-2. Since these fuels cannot be used directly in aviation engines, ASTM also provides a maximum allowable blend percentage with a 50% conventional ATF cut for HEFA-SPK, FT-SPK, ATJ-SPK, FT-SKA, and CHJ. For SIP and HC-HEFA SPK, it is as low as 10% of the overall mix. This is because bio-jet typically contains low aromatic content, often below 0.5%. In comparison, many aircraft designs require aviation fuels of aromatic content in the range of 8-22% to attain critical physical properties for ASTM specifications [31]. The ability to add 50% of HEFA-SPK, SPK/A, or FT-SPK blending components (SPK) to Jet A or Jet A-1 is limited by the fuel's physical properties with which it is blended. The practice has shown that the density, aromatic content, or both, of the refined fuel, often limits the amount of SPK that can be added to the final blend to less than 50 % [31]. The ability

to add 10% of SIP blending components to Jet A or Jet A-1 may be limited by the physical properties of the fuel with which it is blended. In extreme cases, the refined fuel's viscosity may limit the amount of SIP that can be added to the final blend to less than 10% [31].

In the commercial distribution system, aromatics blending adds to another entry in the supply and distribution system, making supply chain management even more complex. From Table 5-2, hydro-deoxygenated synthesized aromatic kerosene (HDO-SAK), hydro-treated depolymerized cellulosic jet (HDCJ), Single Step-HEFA-SPK, and Fischer-Tropsch Synthetic aromatic kerosene (FT-SKA) are some of the processes producing aromatics in the fuel. Since aromatics in the renewable jet limit, the blending percentage with Jet-A/Jet A1, a process that produces aromatics along with other components may completely replace fossil aviation fuel.

5.1 Fuel Standards for synthetic aviation fuel

5.1.1 Aviation Turbine Fuel Containing Synthesized Hydrocarbons (ASTM D7566)

ASTM D 1655 specifications specify the conventional fossil-based aviation turbine fuel. The ASTM D7566 [31] covers the manufacturing of aviation turbine fuel that consists of traditional fossil-based fuels and synthetic blending components. Table 5-2 details the R&D technologies, technology provider, status, feedstock, aromatics in their product, and their status in ASTM approval. All the processes currently developed fall under three major categories. They are oleochemical, thermochemical, and biochemical processes. Oleochemical processes include the hydroprocessing of lipid feedstocks obtained from lipids sources such as palm oil, tallow oil, and jatropha oil. The thermochemical process converts biomass to fluid intermediates, which are then catalytically upgraded to hydrocarbon fuels. In biochemical processes, biological sources such as starch, sugar, and lignocellulosic feedstocks are converted by biological processes to hydrocarbons and longer-chain alcohols.

ASTM D4054 provides the steps to be followed in the certification process. The qualification process by ASTM is rigorous and time-consuming, and hence it takes a

much longer time for new processes developed to reach the industry. Currently, there are only seven pathways for bio-aviation fuel production which ASTM and separate specialized standards approved are provided for each pathway in the annexure of ASTM D566. But a significant advantage of the ASTM D7566 standards is that they can be directly interlinked with ASTM D1655, which provides specifications for Jet – A and Jet – A1 grades from petroleum feedstocks. Thus BIO–ATF meeting ASTM D7566 specifications also fulfil the ASTM D1655 specifications and can be directly used as a replacement for conventional ATF.

The test properties for the characterization of fuel containing synthesized hydrocarbons are broadly classified into nine classifications: composition, volatility, fluidity, combustion, corrosion, thermal stability, hydrocarbon composition, non-hydrocarbon composition, and additives. Among these hydrocarbon compositions, non-hydrocarbon composition and additives were added explicitly for synthesized hydrocarbons and were previously not included in ASTM D 1655 turbine fuel classification. The hydrocarbon composition class details the amounts of cycloparaffins, aromatics, paraffin, and combined carbon and hydrogen mass percentages (Table 5-1,5-2). The non-hydrocarbon composition class details the specific quantities of heterogeneous atoms such as nitrogen, oxygen, sulfur, metals, and halogens present in these synthesized hydrocarbons (Table 5-1). As the origin of these hydrocarbons is an oxygen-containing renewable compound and the slightest amounts of oxygen in the final processed products may lead to oxidation reactions and gumming. Hence anti-oxidants are a must in these synthesized hydrocarbons.

Additives in another class included explicitly limiting the number of anti-oxidants present in these synthesized hydrocarbons (Table 5-1). There is a relaxation in terms of fluidity for batches of both FT-SPK and HEFA-SPK with freezing point specifications of -40 $^\circ$C compared to -47 $^\circ$C in Jet-A1. The temperature for thermal stability evaluation has also been increased to 325 $^\circ$C (Annex A1-A7) from 260 $^\circ$C (Jet A1) to provide a recurring, batch-by-batch verification of process stability and compositional consistency for this synthesized paraffinic kerosene (Table 5-2). Also, in addition, a limit to fatty acid methyl esters (FAME) the content in the HEFA-SPK

has been set to <5 ppm (Table 5-2). In totality, the final blended turbine fuel needs to meet the specifications of Jet A1 (Table 5-2) as mentioned in ASTM D 7566 and ASTM D 1655.

5.1.2 ASTM approval process ASTM D4054

For every new candidate fuel to be added as a new annexure in ASTM D 7566, the ASTM has defined a specific procedure. The detailed procedure is provided in the ASTM D4054 user guide. The document provides guidance to alternative jet fuel producers for testing and evaluation. It is an iterative process where the fuel developer tests the subject fuel samples for their properties, composition, and performance. The tests are classified as Tier 1 and Tier 2 tests, which include basic specification properties, expanded properties known as fit-for-purpose (FFP) properties, engine rig tests, and component tests. Full-scale engine testing is also carried out if necessary. This is a rigorous mandatory process required for the approval of alternative fuels.

ASTM D4054 was created as a reference by engine and airplane OEMs with ASTM International members' help. It informs the manufacturer of an alternative fuel about what is needed in terms of required testing and OEM participation. *Figure 5-1* depicts an outline of the ASTM D4054 assessment and acceptance process. The fuel manufacturer can work with the leading organizations in the international aviation jet fuel group that generally promote the assessment and acceptance of new fuels. ASTM International, the Coordinating Research Council (CRC), and Commercial Aviation Alternative Fuels Initiative (CAAFI) are leading organizations promoting alternative aviation fuel.
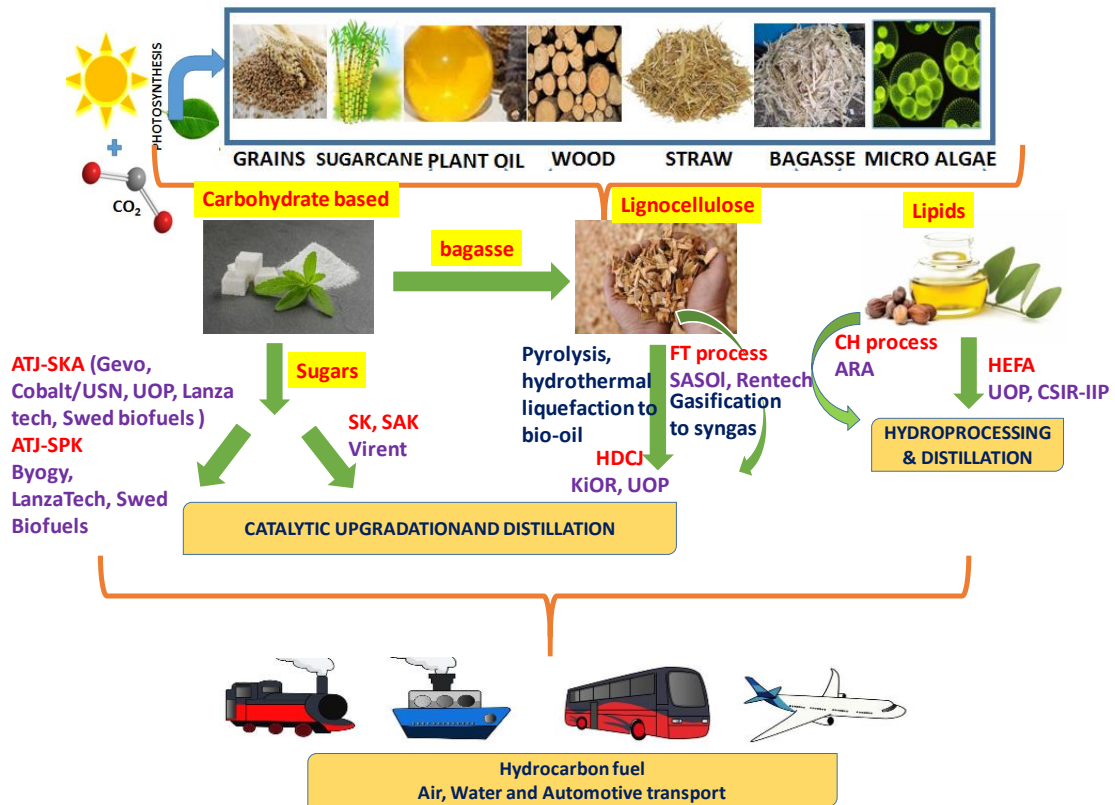
Figure 5-1 : Pathways for renewable bio-jet production

A task force is organized within ASTM's Emerging Fuel Subcommittee to solicit stakeholder comments on testing and preparing an ASTM study paper. OEMs will be included in the task force. The manufacturer submits an ASTM study report to the ASTM committee to secure final approval for the new fuel. Engine and airplane OEMs, airworthiness associations, and international fuel specification requirements organizations will review the study report.

The D4054 requires that the specification properties of the subject fuel being tested are not be affected by the process variability during large-scale production. The D4054 data are then used to develop a proposed annex for inclusion in D7566 as drop-in synthetic jet fuel. This D4054 user's guide details the list of facilities to conduct the D4054 aviation fuel property testing. It also provides a list of rigs and test facilities of aircraft and engine OEMs. OEMs are actively interested in researching new alternative jet fuels, with many test facilities at their laboratories. For updates on their research facilities' availability, one can contact the aircraft and engine suppliers directly.

5.2   Fischer–Tropsch (FT) synthesis to renewable jet fuel (FT-SPK)

Fischer–Tropsch (FT) synthesis is an effective process for producing clean hydrocarbon fuels from syngas from different routes. The carbonaceous material is converted into CO and H_2 by gasification through the thermochemical process. At an industrial scale, primarily auto-thermal gasification route is preferred. Biomass is reacted with a sub-stoichiometric quantity of oxygen at temperatures in the range of 800–1200 °C. Many varieties of gasification technologies are available around the globe [33].

Long-chain paraffin is produced by Fischer-Tropsch (FT) using syngas with an H2/CO ratio of ~ 2. The reaction occurs as follows: CO + 2H2 -> -[CH2]- +H2O (ΔHrxn=159MJ/kmol). In FT synthesis, cobalt and iron-based catalysts are known to be effective [34-35]. Many consider Cobalt FT synthesis catalysts to have advantages over iron-based catalysts, such as high per-pass conversion, long lifespan, and greater hydrocarbon selectivity. With only one product slate, FT synthesis is not a single technology. Many different combinations of catalysts, operating parameters, and reactor designs have been produced since the invention of FT synthesis to achieve demonstration-scale or commercial implementation. Despite the variety of technologies, only two specific forms of industrially generated FT synthesis products are viewed when FT synthesis is viewed from a product perspective. The first is a high-temperature Fischer-Tropsch (HTFT) synthesis product using Fe-based catalysts operating at a temperature of 320 °C and above. The second is the low-temperature Fischer-Tropsch (LTFT) synthesis product primarily using Fe- and Co-based catalysts. Operating temperatures for LTFT depend on the catalyst and reactor configuration and vary from about 170 °C to 270 °C in practice. It must be known that F-T synthesis can be manipulated to promote the refining of aviation turbine fuel supply. It is important to control the composition of the oil product from F-T synthesis [34-35], unlike crude oil, where the natural resource determines the composition. To achieve commercial fuel specifications, the liquid mixture of hydrocarbons must be properly separated, and conversion steps are needed to transform molecules of high molecular weight into molecules of lower molecular

weight of hydrocarbons or add other compounds. Fischer-Tropsch Synthesis does not produce isomers and aromatic compounds.

5.3   Hydroprocessing of Lipids (HEFA-SPK)

Hydroprocessed Esters and Fatty Acids (HEFA), also referred to as Hydrogenated Vegetable Oil (HVO) or Hydroprocessed Renewable Jet (HRJ), covers aviation hydrocarbon fuel provided by the hydroprocessing of animal or vegetable oils (triglycerides). Lipids (triglycerides, diglycerides, monoglycerides), free fatty acids, and their derivatives Hydroprocessed produce liquid hydrocarbons.

The ASTM D7566 specification is designed in its appendices to support different groups of alternative fuels, and HEFA has been licensed for use in blends with traditional kerosene in ASTM D7566 at up to 50% volume. In a 2-step process, the product formed in the first step (hydrodeoxygenation step) is subsequently processed by cracked and isomerized to meet the required cold flow standards of aviation fuel. Although the triglyceride form is common to almost all oils and fats, the chain lengths and degree of unsaturation vary significantly. Also, it is required to remove all alkali metals and impurities before the process since the metals may cause catalyst deactivation and coke formation due to preferential adsorption on the catalyst surface [36].

Hydroprocessing reactions remove oxygen over non-acidic support such as γ-Al2O3, activated carbon [37-40] or acidic support such as zeolites, silica-aluminium, silica-aluminophosphates, titanosilicates, etc. [41-47]. Acidic/Non-acidic supports are provided with strong hydrogenation functionality provided by mono-metallic Pd, Pt, Ni, etc., or by bi-metallic catalysts such as Pt-Re, NiW, NiMo, CoMo catalysts. The hydrogenation feature is used to conduct hydrocracking, hydrogenation, and hydroisomerization reactions [35,48]. Catalyst material properties, such as the functionality of hydrogenation, acidity, porosity, surface area, hydrothermal stability, etc., can be tuned and surface morphology regulated to benefit a specific set of reactions and increase the performance of catalyst life. The reactions occurring

during the process are (1) Deoxygenation, (2) Isomerization, (3) Cracking and (4) Isomerization/Aromatization in a single step/multiple steps. The catalysts must handle the conditions inside the reactor caused by the formation of CO and H_2S, which inhibits the deoxygenation reaction. The product obtained in the process must contain normal/ isomerized paraffin, cyclic, and aromatics. The problem of high normal-paraffin content in the products leading to low cold flow properties also has to be addressed.

These hydroprocessing reactions require hydrogen as an input along with a lipid source; in fact, nearly 300-420 m3 of H2/m3 of vegetable oil is needed to obtain desirable hydrocarbons [40-47]. Commercially Neste Oil's Next [49] and UOP/Eni's EcofiningTM™ processes [50] are processing non-edible oils to produce biofuels in a two-step reaction comprising of hydro-deoxygenation and hydro-isomerization/selective cracking. CSIR-Indian Institute of Petroleum, a research laboratory in India, is producing bio-aviation fuels at the pilot-plant scale from non-edible oils such as jatropha, palm stearin, palm fatty acid distillates, used cooking oil, and Karanja, meeting the ASTM specifications by single-step catalytic process [41-47]. Table 6 shows various catalyst hydroprocessing technologies available in the Indian and Global scenarios.

High hydrogen consumption and deactivation of catalysts due to coking are the main factors delaying lipids' commercial success in hydroprocessing into bio-aviation fuels. Researchers have also investigated single-step processes for biofuel production with reduced hydrogen consumption [44,46]. The primary reactions involved during the lipids' hydro conversion are deprotonation (-C3H8). The lipid molecule glycerol linkage is hydrogenated, and propane is formed along with the corresponding acid/aldehyde molecule [44-47]. The oxygen removal in hydrocracking takes place by three methods – hydrodeoxygenation (HDO), Hydrodecarbonylation (HDCN), and hydro-decarboxylation (HDCX). Hydrogen consumption, product yield, catalyst inhibition, and heat balance are affected by the extent of these three mechanisms. While the HDO process consumes 16 moles of H_2, HDCX consumes only 7 moles of H_2. But the subsequent conversion of CO_2 to CO and to methanol may lead to the

consumption of 35 moles of H2 [51]. In HDCX, the HC yield is 94% of HDO. Hence conditions must be maintained such that HDO is favoured. HDCN and HDCX mechanisms increase with increasing reaction temperature and decreasing pressure. After removing the oxygen molecule, the corresponding hydrocarbon is further cracked and isomerized into aviation-range hydrocarbons. Researchers focus on maximizing the decarboxylation pathway to minimize hydrogen consumption and reduce water formation [44-46]. Favouring the HDO pathway has some advantages, such as decreasing coking as it occurs in HDCX and HDCN mechanisms to a greater extent. Coking is a significant problem since it is the primary reason for reducing the catalyst life and activity in hydroprocessing units. Coking also causes plugging of the hydrocracking units' channels, causing wall effect and undesirable pressure drops in the system. Thus, bimetallic catalysts are more predominantly used as HDO is predominant in such catalysts.

5.4   Alcohol to Aviation Fuel (ATJ-SPK)

Alcohol-based Jet (ATJ) fuel is produced from alcohol with the aid of a thermochemical route. Many companies (Table 8) use various alcohols and oxygenated intermediates to convert ethanol to jet fuel [52-53]. The pathways can be classified according to the chemistry involved: (1) production of aviation fuel by ethylene as an intermediate, (2) production by intermediate propylene, (3) production by intermediate higher alcohol, or (4) production by intermediate carbonyl. ATJ is developed to form jet-fuel range hydrocarbons through alcohol dehydration/oligomerization, which involves linking short-chain alcohol molecules (e.g., methanol, ethanol, and others). The alcohol molecules lose water and oxygen, and hydrogen is added to the starting volume of alcohol is decreased to create a slightly more valuable hydrocarbon jet fuel (at current market prices). Methanol, ethanol, butanol, isopropanol, other alcohols, or a combination of them can be the alcohol intermediates. With the minimization of the operation steps of this process, a significant cost advantage can be achieved. In all cases, following the oligomerization process, the products are converted to primarily jet-range paraffin components through a hydrotreating process [53].

5.5   Pyrolysis of Biomass to Aviation Fuel

There are numerous technologies currently being investigated to convert renewable biomass feedstocks into liquid mixtures suitable for aviation; however, jet fuel's stringent international standards lead to a relatively narrow range of molecules. A significant research area that concentrates on producing liquid fuels from biomass is thermochemical conversion [54-55]. Bio-oil obtained by lignocellulosic biomass pyrolysis can be used as fuel, such as gasoline, diesel, or jet fuel. Still, it needs to be upgraded by oxygen removal before widespread use can be found [57]. A catalytic process is found to be the most powerful of the many oxygen removal techniques. Different kinds of catalysts, both mesoporous and microporous, have already been studied. It seems that a promising catalyst is a ZSM-5 catalyst. Bio-oil upgrades have also been studied using hydrodeoxygenation and catalytic cracking processes. The research challenge for deoxygenation is to develop novel catalysts with improved activity and selectivity and, in particular, better stability for deactivation. As co-processing with petroleum can be further upgraded, partially deoxygenated bio-oil is possibly the best option. The challenge is to design catalysts with less coke formation or use bio-oil with fewer phenolic components for the catalytic cracking process. Catalytic deoxygenation (HDO) processes include atmospheric catalytic rapid pyrolysis and high-pressure hydrodeoxygenation. The use of microporous zeolites (HZSM 5, HY, HBeta, etc.) and mesoporous materials (Al-SBA-15, Al-MCM-48, Al-MCM-41, etc.) requires catalytic fast pyrolysis [58].

5.6   Algae to Jet Fuel

Biofuels of algae may provide a viable alternative to fossil fuels, but this technology must overcome several obstacles before competing in the fuel market and being widely deployed [59-60]. Further research and development are required before micro-algae technologies can be used for large-scale, cost-effective, energy-efficient fuels and chemicals [59]. All algae can generate oils that are rich in energy, and several species of microalgae have been found to accumulate high oil levels in total dry biomass naturally. Optimizing algae's growth in open ponds is a key component of

achieving economic sustainability and remains a major industry challenge. In several laboratories, finding species that grow well under these conditions is a focal point of the study. In a wide range of temperatures, algae can expand, with growth being restricted mainly by the availability of nutrients and light. Light provides the energy for carbon fixation and is transformed by photosynthesis into chemical energy. Providing the building blocks for biofuel production—pathways for producing bio aviation fuel share many standard features regardless of the biomass feedstock being used. Oil-producing crops, such as soybean, jatropha, and camelina, are harvested, and the oil is separated for subsequent processing. It is the same pathway to produce biofuel using microalgae. Sulfide hydrocracking (such as Ni-W/SiO2-Al2O3) and hydrotreatment (such as Ni-Mo/Al2O3, Co-Mo/Al2O3) catalysts are widely used for the deoxygenation of triglyceride and fatty acid molecules into pure hydrocarbons [41-47]. Fuels with the necessary viscosity, low oxygen content, better cold flow properties, and lubricity would result in such a process. There are many benefits to the production of algal lipids by hydrotreating. Algae are rich in oil content than other crops and easier to crack, hence giving higher aviation range hydrocarbons during its conversion [61].

As the emphasis moves from the development of alcohols and esters and towards the production of 'drop-in' hydrocarbon fuels, thermochemical pathways for the conversion of biomass to fuels have garnered interest. A benefit of thermochemical technologies is that they are primarily agnostic feedstock and can tolerate any kind of biomass, including aquatic microalgal and macroalgal species biomass. The production of algal biomass for biofuel production is highly promising because algae produce higher energy yields and need far less space to grow than conventional feedstocks. The production of algal biomass does not require fertile or arable land. Green Fuel Technologies Company named algae the fastest growing plant in the world so that algae will not compete with food and could be developed with limited inputs using a variety of nutrient and carbon sources [61]. Fast growth rates, substantial growth densities, and high oil content were all cited as why significant capital was invested in transforming algae into biofuels. However, there is a range of

hurdles to overcome for algae to mature as an economically viable platform to offset petroleum and, ultimately, mitigate CO_2 release, ranging from how and where to cultivate these algae to improve oil extraction fuel processing [63]. Strain isolation, nutrient sourcing and utilization, production management, harvesting, co-product growth, fuel extraction, refining, and residual biomass utilization are significant challenges. Of course, liquid algae fuels are technically feasible but costly compared to petroleum fuels. The pre-treatment (dewatering) cost for algae is energy-intensive and hence less economical. The vulnerability of petroleum prices to significant and volatile fluctuations is a significant impediment to investment in fuel-from-algae technologies [61-62].

5.7 Biomass conversion pathway to renewable jet through biotechnology platform

A sustainable approach creates alternative energy sources that emit fewer greenhouse gases and partner oil and gas to meet global energy demand. Biomass accounts for about 10% of the world's energy consumption and is primarily used for heating and cooking at the moment. For biomass conversion processes, resourcing feedstock is a significant challenge. Sustainability pathways will be produced through lignocellulose, a non-edible component of the plant, and non-edible plant-like jatropha. Biofuels include charcoal, corn-derived ethanol (maize), methane-rich biogas and non-edible plants such as jatropha, wood, and straw. Biomass conversion through the biochemical route induces microorganisms (yeast and bacteria) to convert biomass into fuel and chemicals [50,53]. While many other countries have vast biomass resources, they do not make the most of their resources. For example, millions of tons of straw are still burned in fields every year after harvesting in Australia and India; this 'waste' could generate electricity. Biomass conversion pathways have an industrial and technological challenge that must balance technical efficiency, environmental performance, social acceptability, and economic viability [32,38,42]. The aviation industry has identified biofuels development as one of the significant ways to reduce its greenhouse gas emissions and has set a goal of halving

its greenhouse gas emissions by 2050 [42]. Many commercial aviation industries such as Total and Amyris have developed breakthrough aviation fuel blend with up to 10% fire-safe, leading to a meaningful reduction of greenhouse gas emissions. Farnesane is produced by yeast by fermenting sugars. Goal genes are selected to alter the yeast's metabolism, transforming the yeast into a hydrocarbon-producing organism from an ethanol-producing organism. The Amyris technology allows selected molecules to be generated at high purity levels. Through biochemical pathways using algal biomass as feedstock, depending on the processing conditions, jet fuel yield is 3 times more than that from sugar fermentation, approximately 1.5 times more than FT synthesis and alcohol to the jet route. Thus, the biochemical pathway though still in its infancy but is the most promising future route to produce aviation biofuel. The pyrolysis route provides the least amount of jet yield among the different discussed routes. But based on the availability of feed, FT synthesis is the most promising pathway for the production of aviation jet fuel. The production yield of jet fuel via FT synthesis is approximately 2 times more than that of the sugar fermentation pathway and almost the same as the alcohol-to-jet route. But paraffinic composition is less through the FT route (<70%) compared to the alcohol-to-jet route (97%). Based on biomass, technology, food security, and production yield, FT Synthesis and hydroprocessing routes are attractive routes in producing renewable Jet fuel.

5.8   Power to Liquid (PtL)

5.8.1 CO_2 conversion technologies

CO_2 is a thermodynamically stable and chemically inert molecule. The conversion of CO_2 to hydrocarbon via hydrogenation usually favours short-chain formation rather than desirable long-chain hydrocarbons. Hence the research in this area is focused on light hydrocarbon production rather than long-chain hydrocarbons. Most of the available literature deals with the selective hydrogenation of CO_2 into methane, methanol, formic acid, light olefins, or other lighter oxygenates [44]. Long-chain hydrocarbon from CO_2 conversion is very limited. There are two pathways, to convert CO_2 to hydrocarbon molecules (a) an indirect route in which CO_2 is converted

to CO or methanol and subsequently into liquid hydrocarbons, (b) a direct CO_2 hydrogenation route, in which CO_2 is converted to CO via the reverse water gas shift (RWGS) reaction and then hydrogenation of CO to long-chain paraffin via Fischer-Tropsch synthesis (FTS) [69-70]. The direct route involves fewer steps and is expected to be more economically viable.

The reverse water gas shift reaction:

$$CO_2 + H_2 \longrightarrow CO + H_2O \quad (\Delta H°298 = +41 \text{ Jk/mol})$$
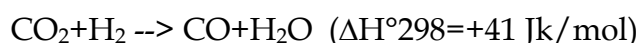
The Fischer-Tropsch synthesis reaction:

$$CO + 2 H_2 \longrightarrow -(CH_2) - + H_2O \quad (\Delta H°298 = -166 \text{ Jk/mol})$$
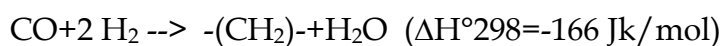
Recently a group of researchers from Oxford University has converted carbon dioxide (CO_2) to aviation fuel via the catalytic process. Targeting CO_2 as feedstock will for sure have a significant impact on global greenhouse gas reduction. This process could be a game-changer if implemented on a commercial scale. Benzehen et al. [71] have used Fe-Mn-K (iron-manganese-potassium) catalyst by the organic combustion method (OCM). The reported conversion for CO_2 was 38.2%, with a yield of 17.2% for jet fuel and a selectivity of 47.8%. Selectivity towards carbon monoxide (5.6%) and methane selectivity (10.4%) was reported. Light olefins ethylene, propylene, and butenes, totalling a yield of 8.7%, are formed as a by-product, which is the critical feedstock to the petrochemical industry. The two significant challenges in making the process economical are a) the process of atmospheric carbon capture and b) the synthesis of hydrocarbons by CO_2 hydrogenation typically favours the formation of short-chain rather than the desirable long-chain needed for aviation fuel synthesis. This new method is a significant social advance that highlights the recycling of CO_2 and the conservation of resources as a vital, pivotal component of greenhouse gas management and sustainable growth. This catalytic process is supposed to be the path to the aviation industry's near-future net-zero carbon emissions, that is, before we as a society are entirely prepared to operate on eco-friendly electric aircraft. In this process, carbon dioxide extracted from the air is used for conversion and, when

combusted in flight, is later re-emitted from jet fuels. Consequently, a carbon-neutral fuel is the ultimate result of this process.

5.9   Power to Liquid (PtL)

The main constituents of PtL are electricity, water, and carbon dioxide (CO_2) [42]. PtL consists of hydrogen production by electrolysis using solar power, followed by CO_2 and H_2 combination to hydrocarbon fuel. There are two different pathways for the production of PtL: the Fischer-Tropsch (FT) pathway and the methanol pathway, as shown in Figure 5-2. Currently, only a few small-scale PtL plants in operation produce liquid hydrocarbon products such as kerosene. Water electrolysis, hydrogen storage tanks, FT or methanol synthesis, and refining processes are the relevant process stages in PtL supply chains. Only the reverse water gas shift reaction (RWGS) reactor has yet to be demonstrated at the relevant scale. The cost of renewable energy is the primary driver of overall PtL production costs. The heat produced by the exothermic reactions in FT synthesis/methanol conversion can be used to supply heat to the temperature swing adsorption plant for the CO_2 capture cell and the heat demand of the solid oxide electrolysis plant in case of high-temperature electrolysis. Large-scale implementation's primary requirement is a continuous cost reduction of renewable hydrogen production from water electrolysis powered by solar and wind energy [72].
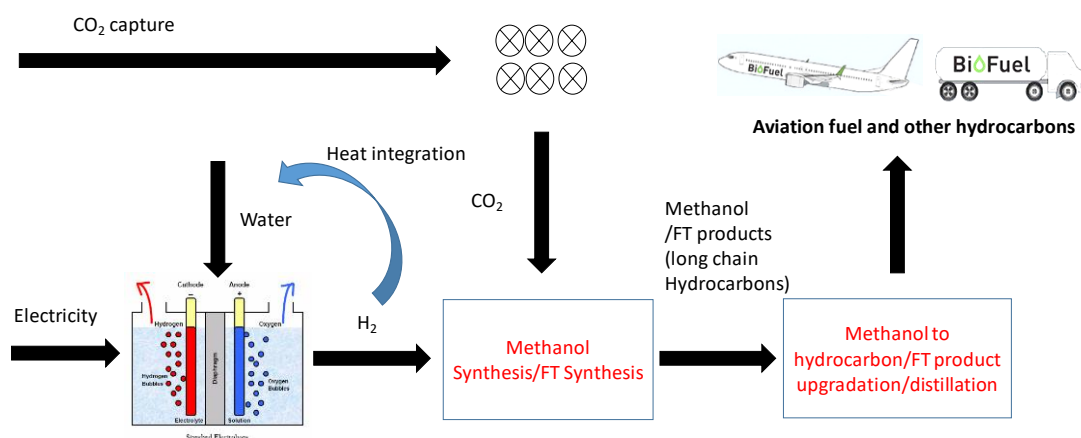
Figure 5-2 : Power to liquid (PtL) pathways

5.10 Techno-commercial analysis of various technologies available for bio-jet fuel production

The primary difficulties associated with the commercialization of any bio-jet technology are feedstock cost and availability, apart from the feed cost and availability, refinery infrastructure, logistics, supply chain development, higher operational costs, difficulties in the certification of technologies, lack of sufficient subsidies, and investments to meet global targets, and lack of an international level playing field for investment by the aviation sector.

Hydroprocessing is a mandatory step in HEFA-based pathways (HEFA-SPK, FT-SPK). HEFA pathways require hydrogen to upgrade oxygen-rich lignin, lipids, and carbohydrates to hydrogen-rich compounds. There are also non-hydrogen processes available such as catalytic or thermal cracking. They remove carbon as coke and tar. But these processes consume feedstock and decrease the overall yield of the process. However, they can be favourable alternatives if the loss due to cracking processes is much lesser than the cost requirement for H_2 production.

Logistics and supply chain development is complex as current products use only bio-jet as blends with conventional ATF. Since they become indistinguishable, current infrastructure owners must agree with the new players in sharing the infrastructure. Otherwise, separating the components until the delivery points, i.e., the airports, will complicate the process and compromise product quality.

HEFA – diesel produced during bio-jet production has more market demand and does not require any additional blending or rigorous specifications. Hence most hydroprocessing plants currently in operation concentrate more on producing HEFA-diesel. This challenge for bio-jet to compete with HEFA-diesel reduces the net output of bio-jet from the existing plants.

At present, the aviation sector is expected to boom in the developing regions of Asia, Africa, South America, and the Middle East. These countries need to focus on the

abundant cheap oleochemical feedstocks available in their regions, such as using waste coconut oil in the Philippines via the HEFA pathway to meet the demands in the short term.

Cost estimates for bio-jet fuels are difficult to achieve due to less availability of data. Hence many assumptions are being made in the cost calculations. Although HEFA is an industrially mature technology, its economic feasibility is still a question since; historically, vegetable oil rates were consistently higher than fossil fuels as well as jet fuels themselves. For example, in 2016, the conventional jet fuel cost was about 400 USD per ton. At the same time, crude palm oil was at 727 USD per ton. Similar conditions apply to most vegetable oils where non–edible vegetable oils such as jatropha oil will significantly cut down the cost as they do not demand other industries such as food and cosmetics. But at present, the commercial production of such oils is deficient, and hence their costs are high.

De Jong et al. [73] in 2015, the minimum fuel selling price (MFSP) was calculated for bio-jet via different conversion routes. But his estimates are based on modelling studies since no actual data was available. Lignocellulosic feedstocks were chosen for the modelling purpose except for HEFA waste cooking oil are used. The feedstock rates were fixed at USD 106 per ton for forest residues and USD 190 per ton for wheat straw. Since the MFSP was calculated based on European costs for feedstocks, the estimated values may vary depending on the type of feedstock and the region's local geography and economy.

The MFSP estimated is very high when compared to that of conventional bio-jet fuels. Hence more focus is needed on reducing the feedstock costs and capital investments as well as government subsidies to bring down the rates to economically feasible levels. In this regard, IEA bioenergy put forward a set of recommendations for steps to be taken to meet future targets.

Targets put forward for R&D by IEA bioenergy to increase the commercial viability of drop-in bio-jet:

- The advancement of commercially viable processes for the production of renewable hydrogen of industrial grade;

- Establish more cost-effective and area-efficient systems for the development of oleochemical feedstocks based on land or water;

- Improve the cost, performance, lifetime, and recyclability of oxygenated biomass feedstock hydroprocessing catalysts.

- Creating commercially feasible processes of small-scale gasification and syngas cleanup;

- Produce intermediates for biofuels that are miscible and can be better co-processed with petroleum feed;

- Establish the possible synergies of bio-oil and fossil liquids co-processing in thermochemical processes and established oil refineries;

For a better economy of the process, the use of the side-products plays crucial importance. Since most of the available pathways, the final stage of the production chain involves distillation. The other component produced is mostly lighter hydrocarbons, i.e., LPG and gasoline, and heavier fractions, i.e., diesel. All the processes, except hydro-deoxygenated synthesized aromatic kerosene (HDO-SAK), hydro-treated depolymerized cellulosic jet (HDCJ), Single Step-HEFA-SPK, and Fischer-Tropsch Synthetic aromatic kerosene (FT-SKA), have low aromatics. Hence, they will produce the paraffinic component in gasoline/diesel components along with aviation range hydrocarbons. HEFA-SPK and FT-SPK are expected to produce a significant yield of diesel and FT waxes. The high demand for high cetane (low sulfur) diesel and low sulfur waxes makes these two processes more viable than other processes. Similarly, higher alcohols and platform chemicals produced from the ATJ process and green aromatics from HTL make these two processes attractive and potentially economical.

Among all the research pathways, FT–SPK and HEFA–SPK are the only ones undergoing commercial production processes. Both processes utilize fossil fuel-derived natural gas in their processes. In HEFA, natural gas is the potential and cheaper source of hydrogen production. Most FT plants utilize natural gas as their source for syngas. Although FT–SPK was certified earlier than HEFA, it is not commercialized more than HEFA. This may be attributed to difficulties in syngas cleanup, catalyst contamination, and economies of scale. The number of steps involved in the FT pathway is more than all other available alternative aviation fuel production processes. This subsequently increases the capital and operating costs required for FT-SPK production. An FT plant with a capacity of 200,000 TPA will require the same investment as a HEFA plant with four times the same capacity [87]. By 2016 total HEFA production capacity in the world was 4.3 billion litre/year [87]. There are two leading HEFA technologies, Neste's NEXBTL and UOP, and ENI's EcofiningTM. CSIR-IIP has recently patented its single-step HEFA process for bio aviation fuel production. Companies producing renewable jet fuel on a commercial scale are provided in table 5-2.

Fuel readiness level (FRL) indicates the maturity level of technology for being introduced into commercial production. Mawhood et al. [74] categorized all the available pathways for renewable fuel production under these criteria. HEFA has the highest rating with FRL9, followed by FT with FRL between 7 and 8 and SIP with a range of FRL5 to FRL7. All other pathways fall in the range of FRL4 to FRL7. As much as these methods show the maturity or readiness of these pathways, they don't indicate the processes' commercial viability. Vegetable oil-based HEFA bio-jet was concluded as the only economically viable option in the future in a recent report by France's Académie de l 'air et de l'espace.

Table 5-1 : Key difference of specification for the different approved processes as per ASTM D 7566 processes [39]

Test Properties	Jet A1 D 1655	FT-SPK	HEFA-SPK	SIP-SPK	SPK/A	ATJ-SPK	CHJ	HC-HEFA SPK
Annex Name		A1	A2	A3	A4	A5	A6	A7
Blending ratio approved-Max.%		**50**	**50**	**10**	**50**	**50**	**50**	**10**
COMPOSITION								
Acidity, total mg KOH/g (max)	0.1	0.015	0.015	0.015	0.015	0.015	0.015	0.015
Aromatics, vol % (max)	25	-	-	-	**20**	-	-	-
Sulfur, mercaptan, C mass % (max)	0.003	-	-	-	-	-	-	-
Sulfur, total mass % (max)	0.03	-	-	-	-	-	-	-
VOLATILITY								
Distillation temperature, °C:								
10 % recovered, °C (max)	205	205	205	**250**	205	205	205	205
50 % recovered, °C	Report	Report	Report	Report	Report	Report	Report	Report
90 % recovered, °C	Report	Report	Report	Report	Report	Report	Report	Report
Final boiling point, °C (max)	300	300	300	**255**	300	300	300	300
T50-T10 °C (min)	-	-	-	-	-	-	15	-
T90-T10, °C (min)	40	22	22	5	22	21	40	22
Distillation residue, % (max)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Distillation loss, % (max)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Flash point, °C (min)	38	38	38	100	38	38	38	38
Density at 15°C, kg/m³	**775-840**	730-770	730-770	765-780	755-800	730-770	775-840	730-800

Property								
Smoke point, mm, min	25.0	-	-	-	-	-	-	25.0
FLUIDITY								
Freezing point, °C (max)	-47	-40	-40	-60	-40	-40	-40	-40
Viscosity −20°C, mm^2/s (max)	8							
COMBUSTION								
Net heat of combustion, M.J./kg (min)	42.8	-	-	**43.5**	-	-	-	-
Naphthalenes, vol, % (max)	3	-	-	-	-	-	-	-
Smoke point, mm (min)	18	-	-	-	-	-	-	-
CORROSION								
Copper strip, 2 hr at 100 °C (max)	No. 1	-	-	-	-	-	-	-
THERMAL STABILITY, (2.5 h at control temperature)								
Temperature, °C (min)	260	325	325	355	**355**	325	325	325
Filter pressur9 drop, mm Hg (max)	25	25	25	25	25	25	25	25
Tube deposits less than (max)	3	3	3	3	3	3	3	3
Existent gum, mg/100 mL (max)	7	-	7	7	**4**		7	7
MSEP, min					**90**			
FAME, ppm (max)	-	-	**<5**	**-**	**-**	**-**	**<5**	**<5**
ADDITIVES								
Antioxidants, mg/L (min - max)	-	17-24	17-24	17-24	17-24	17-24	17-24	17-24
HYDROCARBON COMPOSITION								
Cycloparaffins, mass % (max)	-	15	15	15	15	15	**report**	**50**
Aromatics, mass % (max)	-	0.5	0.5	0.5	**20**	0.5	**21.2**	0.5
Aromatics, mass % (min)		-	-	-	-	-	**8.4**	-

Property		FT-SPK	HEFA-SPK	SIP	ATJ	SPK/A	CHJ	HC-HEFA SPK
Paraffins, mass %	-	report	report	report	report	report	report	report
Carbon and hydrogen, mass% (min)	-	99.5	99.5	99.5	99.5	99.5	99.5	99.5

NON-HYDROCARBON COMPOSITION

Property		FT-SPK	HEFA-SPK	SIP	ATJ	SPK/A	CHJ	HC-HEFA SPK
Saturated Hydrocarbons, mass percent	-	-	-	**98**	**-**	-	-	-
Farnesene, mass percent, max	-	-	-	**97**	**-**	-	-	-
Hexahydrofarnesol, mass percent	-	-	-	**1.5**	**1.5**	-	-	-
Olefins, $mgBr_2$/100 g	-	-	-	**300**	**300**	-	-	-
Nitrogen, mg/kg (max)	-	2	2	2	2	2	2	2
Water, mg/kg (max)	-	75	75	75	75	75	75	75
Sulfur, mg/kg (max)	-	15	15	**2**	**2**	15	15	15
Metals (Al, Ca, Co, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, Pb, Pd, Pt, Sn, Sr, Ti, V, Zn), mg/kg (max)	-	0.1 per metal	0.1 per metal	0.1 per metal	0.1 per metal	0.1 per metal	0.1 per metal	0.1 per metal
Halogens, mg/kg (max)	-	1	1	1	1	1	1	1

FT-SPK – Fischer-Tropsch Hydroprocessed Synthesized Paraffinic Kerosene

HEFA-SPK – Hydroprocessed Esters and Fatty Acids Synthesized Paraffinic Kerosene

SIP- Synthesized iso-paraffins from Hydroprocessed fermented sugars

ATJ- Alcohol-to-jet synthetic paraffinic kerosene

SPK/A)-synthesized paraffinic kerosene plus aromatics

CHJ -synthesized catalytic Hydrothermolysis jet

HC-HEFA SPK -synthesized paraffinic kerosene from Hydroprocessed hydrocarbons, esters, and fatty acids

Table 5-2 : R&D technologies for Bio-aviation fuel and their status

Technology Pathway	Technology Provider	STATUS	Feedstock	Aromatics	ASTM Status
Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK)	Sasol, Shell, Syntroleum, TRI (FT-SPK)	Commercial/ Demo	Mature technology Economics at a very large scale	Low	Annex A1
Hydroprocessed Ester of Fatty Acids - Synthetic Paraffinic Kerosene (HEFA- SPK)	CSIR-IIP	Demonstration Scale-0.5 TPD processing Capacity	Used cooking Oil, Jatropha, Palm waste oil (Palm stearin and Palm fatty acid distillate), Pongamia, Animal fat, and Algae Oil	Moderate 6-10%	Annex A2 after aromatics removal Fuel in clearing house
	Honeywell UOP	Commercial	Vegetable Oil, Animal Fat, recycled oil	Low	Annex A2
	Axens	In Design		Low	
	Neste	Commercial		Low	
Synthesized Iso-Paraffins (SIP) from Hydroprocessed Fermented Sugars	Amyris, Total	Demo	Sugar feed, flight, proven	Low	Annex A3
Fischer-Tropsch Synthetic Kerosene with Aromatics FT-SKA	Sasol		Coal, natural gas, biomass	High	Annex A4
Alcohols-to-Jet Synthetic Paraffinic Kerosene (ATJ-SPK)	Byogy / Swedish Biofuels/ LanzaTech	Pilot	Lignocellulosic feed, ATJ Process, Flight proven	Low	Annex A5
Catalytic Hydrothermolysis CHJ	Chevron Lummus Global, Applied Research		Vegetable oil, animal fat, recycled oils	Low	Annex A6

	Associates, Blue Sun Energy				
Hydro-Deoxygenated Synthesized Kerosene HC-HEFA SPK	Virent		Starch, sugar, cellulosic biomass	Low	Annex A7
Hydrothermal Liquefaction (ARA-CLG)	Applied Research Associates (ARA) and Chevron Lummus Global (CLG)	Demo	Lignocellulosic feed, HTL process, flight-proven	Low	
Hydro-Deoxygenated Synthesized Aromatic Kerosene HDO-SAK	Virent		Starch, sugar, cellulosic biomass	High	
Hydrotreated Depolymerized Cellulosic Jet HDCJ	Honeywell UOP, Licella, KiOR		Cellulosic biomass	High	

6. Techno-Economics of Synthetic Fuel Technologies

6.1   Introduction

E-fuels are of interest for all transport modes; many hydrocarbon e-fuels could be used in existing vehicles and may not require significant investments in new distribution and fuelling infrastructure. They are of special interest in sectors such as long-distance aviation and deep-sea shipping, where electrification opportunities are limited because liquid fuels with high energy density are difficult to substitute. E-fuels could also contribute to balancing intermittent electricity production by providing a use for excess or very low-cost electricity. E-fuel production also generates marketable by-products such as high-purity oxygen and heat. However, according to the literature, the combined efficiency of energy conversion and utilization is a challenge compared to options that use electricity directly

Capturing carbon to produce electrofuels typically comes with a cost. There is, however, a special case in which externally provided hydrogen reacts with surplus CO or CO_2 produced within a biofuel production process (e.g., biomass gasification reactor or anaerobic digestion) giving products that we call bio-electrofuels. Depending on production technology, the resulting electrofuels and bio-electrofuels can be either liquid or gaseous, including electro-methane, electro-methanol, electro-gasoline, electro-diesel, and electro-ammonia.

Both energies flows and material flows are illustrated, i.e., electricity and biomass (energy inputs), CO_2, N_2 and biomass (material inputs) and hydrocarbons, methanol, and ammonia (energy carrier outputs)
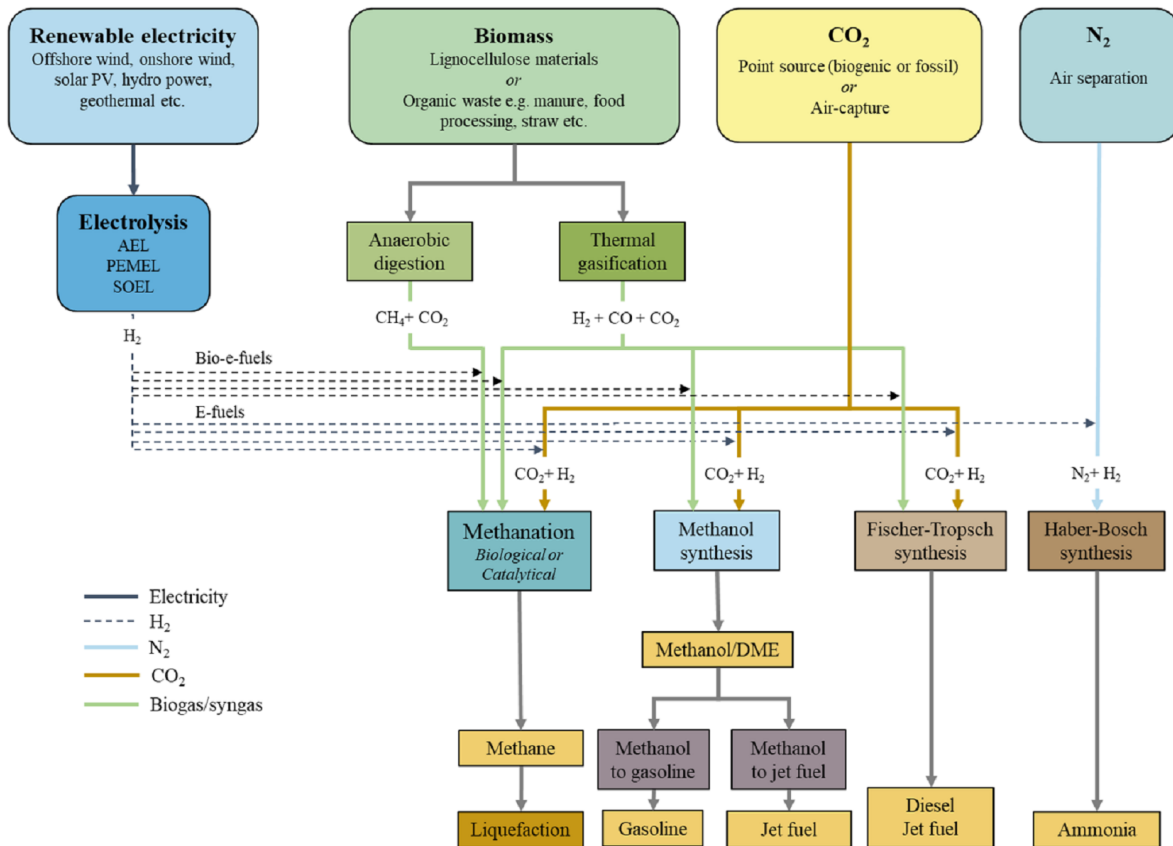
Figure 6-1 : Production pathways, including feedstocks and fuels produced.

(PV: photovoltaic solar panels; AEL: alkaline electrolysis; PEMEL: polymer electrolyte membrane electrolysis; SOEL: solid oxide electrolysis; DME: dimethyl ether)

6.2 Cost review of separate production steps for different electrofuel pathways

As shown in *Figure 6-1*, multiple pathways exist for each E-Fuel. For each pathway, different alternatives are available for sourcing raw materials and utilities e.g. For the production of E-hydrogen, the electricity required for electrolyser can be sourced from a renewable source or nuclear or from the grid itself. Renewable electricity comes with the options of PV, hybrid PV & wind (on-shore or off-shore). Similarly for the use of water, depending upon the availability, freshwater, desalinated water or recycled treated process water needs to be considered. Further, electrolysis can be carried out using alkaline electrolysis (AEL) or polymer electrolyte membrane electrolysis (PEMEL) or solid oxide electrolysis (SOEL). Similarly, for synthetic fuel

production, carbon dioxide can be sourced directly from the air or a concentrated point source or biomass origin (thermal gasification or anaerobic digestion). These multiple pathways coupled with multiple routes along with the costs incurred for pre-processing, post-treatment/purification, fuel storage, transport etc make the generalised cost estimation very undependable. Geographic location, local energy demand and supply scenario, availability of raw materials and availability of fuel distribution infrastructure may significantly affect the outcome of such a cost economic analysis. A detailed study is needed for a specific case of concern; however, a general idea based on available literature is provided below.

From the literature, it is found that most of the techno-economic analysis studies so far carried out are from the European region. As per the literature information, the most important parameters for e-fuel cost estimation and sensitivity analysis are annual average electricity price ($€ MWh^{-1}$), Electrolysis CAPEX and direct air capture (DAC) ($€$ per t CO_2 captured).

Table 6-1 : Most important parameters for e-fuels cost estimation and sensitivity analysis

	2020-2025	2030	2050
Annual average electricity price, ($€ MWh^{-1}$),	50±10	50±10	30±10
Electrolysis CAPEX, ($€ kW^{-1}$)	1100±389	625±258	334±189
DAC, ($€$ per t CO2 captured)	460±90	150+150/-50	50+50/-10

Dominant factors impacting production costs are electrolyzer and electricity costs, the latter connected to capacity factors and cost for hydrogen storage. Electrofuel production costs also depend on regional conditions for renewable electricity generation.

6.2.1 Renewable electricity

The costs of renewable electricity shown in Table 6-2 have been obtained from literature which is calculated based on CAPEX, OPEX, and the equivalent full load

period of photovoltaic (PV) and wind power plants in the different European regions, Australia, Saudi Arabia, Chile and Morocco.

Table 6-2 : Cost of renewable electricity in different regions (€ /kWh)

	2020			2030			2050		
RE-source	PV	Wind onshore	Wind offshore	PV	Wind onshore	Wind offshore	PV	Wind onshore	Wind offshore
Region			0.126			0.084			0.078
Europe	0.038-0.055	0.047-0.069		0.03-0.043	0.044-0.065		0.025-0.037	0.042-0.061	
Australia	0.037	0.050		0.030	0.047		0.025	0.045	
Saudi Arabia	0.032	0.047		0.026	0.045		0.022	0.042	
Chile	0.029	0.053		0.023	0.050		0.019	0.048	
Morocco	0.034	0.043		0.027	0.040		0.023	0.038	

6.2.2   Water

The production of e-fuels requires purified water, for which Brynolf et al suggest a cost of 1 € m−3, while others suggest 2.05 € m−3. In regions where water is scarce, seawater desalination is required for the supply of water for the electrolysis plants. However, the impact of water desalination on the overall electricity consumption and the costs of e-fuel supply is low. Aquatech, a manufacturer of seawater desalination plants based on seawater reverse osmosis (SWRO) indicates an electricity consumption of less than 3 kWh per m³ of desalinated water. The water requirement for hydrogen production via water electrolysis amounts to about 0.27 kg per kWh of hydrogen based on the LHV. As a result, the electricity requirement for seawater desalination will be 0.00081 kWh per kWh of hydrogen based on the LHV.

6.2.3   Hydrogen production

There are several ways to produce hydrogen from renewable and non-renewable energy sources. Renewable pathways include electrolysis, thermolysis, and

thermochemical cycles. The most mature process is electrolysis. Electrolysis uses electricity as the main source of energy. Water is separated into hydrogen and oxygen by a current between two electrodes that are separated and immersed in an electrolyte to raise ionic conductivity. A diaphragm or separator is used to avoid the recombination of oxygen and hydrogen. Electricity is used in an electrochemical process called electrolysis where water molecules are split into hydrogen and oxygen. To keep the resulting gases apart, the reacting compartments are separated by an electrolyte, which is also used to classify the main technologies: alkaline electrolysis (AEL), polymer electrolyte membrane electrolysis (PEMEL), and solid oxide electrolysis (SOEL). Table 6-3 provides an overview of the available costs and efficiency ranges from the literature [76], which vary significantly. The low and high values of the ranges for CAPEX represent the most optimistic data provided by the author, but should not necessarily be compared across as not all authors assess all technologies. *Brynolf et al* provide a detailed discussion of the causes of the wide range of cost assumptions. In general, the efficiency of electrolysis has a high impact on the total fuel production efficiency because of the large amounts of hydrogen required in the synthesis [77].

Table 6-3 : Near- (approx. 5–10 years) and long-term (approx. 20–30 years) electrolysis cost (₹ 2019 kWel−1)

(Values in parentheses are the range in the literature)

		Near-term (5–10 years)	Long-term (20–30 years)
AEL (alkaline electrolysis)	CAPEX (₹kW$_{el}^{-1}$)	71940 (35970–116903)	42265(34172–50358)
	OPEX (% of CAPEX)	2%–9%	2%–5%
	Efficiency (LHV basis)	67% (63%–71%)	68% (66%–70%)
PEMEL (polymer electrolyte membrane electrolysis)	CAPEX (₹kW$_{el}^{-1}$)	93523 (44962.79–215821.37)	49009 (35970.23–85429.29)
	OPEX (% of CAPEX)	2%–11%	2%–5%

	Efficiency (LHV basis)	64% (58%–69%)	68% (62%–71%)
SOEL (solid oxide electrolysis)	CAPEX ($₹kW_{el}^{-1}$)	115104.73 (40466.51–382183.68)	34171.72 (26977.67–40466.51)
	OPEX (% of CAPEX)	2%–3%	2%–3%
	Efficiency (LHV basis)	78% (76%–81%)	79% (75%–83%)

6.2.4 Carbon and nitrogen sources

As shown in Figure 6-1, e-fuels can be produced within a range of pathways using carbon (CO or CO_2) or nitrogen sources.

6.2.4.1 CO_2 capture

Various point sources and activities that give rise to surplus capturable CO_2 are e.g., biofuel production, flue gases from fossil and biomass combustion plants, industrial plants, such as iron and steel, pulp and paper, and cement, as well as geothermal activity, air, and seawater. The CO_2 concentrations in the different sources range from very small (400 ppm in the air) up to almost 100% in some biofuel/gasification plants. The highest concentrations can be found in plants producing ethanol through fermentation of sugar, in plants where anaerobic digestion of household waste produces biogas, and in plants where gasification of biomass produces syngas further converted into methane, as well as ammonia plants. The concentration of CO_2 at the point sources affects the capture costs and efficiencies. Also, the choice of capture technology has an impact. Capture technologies include absorption, membrane filtering, cryogenic capture, or oxy-combustion. Direct air capture (DAC) involves removing CO_2 from the air (air-sourced carbon). This method is challenging because of the low CO_2 concentrations in ambient air but has gained interest, especially in combination with carbon storage as a method for achieving negative emissions by offsetting past and future CO_2 emissions. A relatively low capture cost can be achieved in e.g. bioethanol plants, where the exhaust stream has a high concentration of CO_2, and no extra major purification step or additional energy is needed in the

capture process. The fermentation of household waste into biogas leads to raw biogas that contains methane, CO_2 (40%), and some trace components. An upgrading of the raw biogas to fuel quality, demands a cleaning step to remove the CO_2, and the capture cost from the upgrading facility has similar costs as for the bioethanol plant. An extra purification step increasing the capture cost is needed when capturing CO_2 from industries, such as petrochemical, refinery, cement, iron and steel, as well as fossil, or biomass combustion plants.

Table 6-4 : Capture cost for different CO_2 sources found in the literature *[77]*

	CO_2 capture cost Short Term (€2015/T CO2)	CO_2 capture cost Long Term (€2015/T CO2)
NG power plant	20-60	10-60
Coal based power plant	30-170	10-100
Petroleum refining/petrochemical	60-140	30-90
Cement industry	70-150	30-50
Iron & steel industry	50-70	30-60
Ammonia production	<20	<20
Bio ethanol production, biogas upgrading	<20	<20
Ambient air		20-950

6.2.4.2   Nitrogen Capture

Pure gases, such as N_2, can be separated from the air by first cooling it until it liquefies, then selectively distilling the components at their various boiling temperatures. The low distillation temperature can be achieved by using an air separation unit (ASU), based on a refrigeration cycle, or more lately by using expansion turbines for cooling. Another option is pressure swing adsorption (PSA) which provides the separation of oxygen or nitrogen from the air without liquefaction. The principal disadvantage of the PSA cycle is the risk of high gas losses

resulting from the pressure release. Nitrogen is assumed to be captured using the ASU process, also generating potential by-products such as oxygen and sometimes argon.

Costs for carbon capture and nitrogen capture are presented in various ways in the literature, such as CAPEX, final production costs or avoided CO_2 costs. Table 6-4 shows the reported costs for capturing CO_2 and nitrogen. While carbon-based e-fuels are the most investigated in the literature, ammonia has also been considered as a hydrogen carrier or as a fuel itself. E-ammonia has the advantage of not generating any CO_2 when used and can therefore be attractive if CO_2 is restricted in exhaust emissions.

Table 6.5. Carbon and nitrogen production costs calculated from CAPEX identified in the literature at an interest rate of 5%, with lifetimes of 25, 20, and 30 years and OPEX of 4%, 5%, and 2% of CAPEX for point-source carbon capture (fossil and biogenic), air-source carbon capture and nitrogen capture, respectively. The cost of electricity is excluded when calculating these values.

Table 6-5 : Carbon and Nitrogen Production Cost

	Near-term (approx. 5–10 years) €2019 /TCO2 or N2	Long-term (approx. 20–30 years) €2019 /TCO2 or N2
Point-source carbon	50 (20–260)	25 (10–100)
Air-sourced carbon	300 (25–778)	90 (15–105)
Nitrogen capture	9 (8–10)	(5–14)

6.2.5 E-fuel synthesis

Producing syngas, a blend of CO and H_2 is the starting point for the large-scale production of valuable chemicals like fuels and methanol using air-captured CO_2 or tail gas-captured CO_2.

Hydrogen and carbon can be combined to give a variety of fuel products using three technologies: methanation, methanol synthesis, and Fischer–Tropsch (FT) synthesis. In addition, hydrogen can be combined with nitrogen to produce ammonia in the Haber–Bosch synthesis. Methanation can be achieved using catalysts (catalytic methanation) or using methanogenic microorganisms (biological methanation). Biological methanation can be implemented as an additional process in biogas plants and has a relatively low operational temperatures, while catalytic methanation operates at high temperatures and is highly exothermic. The excess heat can be used for other purposes, such as for district heating networks or as the heat source for high-temperature electrolysis, which can increase the overall efficiency of a plant.

E-fuels can tap into the low-cost and vast global potentials of low-carbon wind and solar photovoltaic (PV) power. The resulting gaseous and liquid fuels feature characteristics that make them perfect substitutes for their fossil counterparts: a high energy density, storability, transportability and combustibility.

6.2.5.1 E-Methanol

Methanol synthesis is similar to catalytic methanation, where CO_2 and CO in syngas are combined with H2 to generate methanol. The reaction is exothermic and operates at high temperatures and pressures. The resulting methanol can be further reacted to give dimethyl ether (DME), gasoline, diesel, or jet fuel. The raw methanol produced includes approximately 10% water which is removed by distillation. FT synthesis is a series of reactions in which CO and H_2 react to form hydrocarbons. The reactions occur at high temperatures and pressures. A reverse water-gas shift reaction usually precedes the FT synthesis to achieve the optimal H_2/CO stoichiometry. The resulting FT liquids are a mix of paraffin, olefins, and alcohols and the reaction are not particularly selective. Depending on the mix and the length of the upgrading process, the resulting products would usually be gasoline, diesel, jet fuel, and high-quality lubricants, alcohols etc.

6.2.5.2 E-Ammonia

Ammonia synthesis by the Haber–Bosch process uses a catalyst under high temperature and pressure. As with the other syntheses, it is exothermic and normally designed to operate under continuous production. However, if future ammonia synthesis can operate dynamically, the flexible operation may make economic sense as a means to utilize hydrogen from intermittent renewable electricity avoiding costly hydrogen storage.

6.2.5.3 E-Methane

E-Methane also called synthetic Natural Gas can be produced from H_2 and CO_2/CO by catalytic and biological methanation. The process is used to produce synthetic natural gas from synthesized gas derived from coal and biomass. There are three main reactions involved in catalytic methanation,

the Sabatier reaction, $CO_2(g) + 4H_2(g) \leftrightarrow CH_4(g) + 2H_2O(g)$ - 165 kJ (at 298 K),

the hydrogenation of CO, $CO(g) + 3H_2(g) \leftrightarrow CH_4(g) + H_2O(g)$ - 206 kJ (at 298 K),

and the RWGS reaction. $CO_2(g) + H_2(g) \leftrightarrow CO(g) + H_2O(g)$ +41kJ (at 298K)

It is possible to convert more than 99.5% of the syngas (mixture of carbon dioxide and hydrogen) to methane. The synthesis process is exothermic, so the highest efficiency is achieved at low temperatures. The investment costs for catalytic and biological methanation have been estimated at 2697.77–80933.01 €2015/kW fuel in the literature, for different plant sizes and technological maturity.

6.2.5.4 E-Gasoline and E-kerosene via methanol-to-gasoline (MTG, MTK)

The generation of e-gasoline or e-kerosene both starts with the production of hydrogen via electrolysis. The hydrogen is together with CO_2, used to synthesise Methanol. In that process heat results as a by-product and is reused in the CO_2 supply. The carbon dioxide can be supplied through various procedures, either a mix

of natural gas and biomass power plants (NG-PP), direct air capture (DAC), or flue gas from steam methane reforming (SMR) plants. After the Methanol is distilled, it can be converted into Gasoline or Kerosene via the methanol-to-gasoline (MTG) process. Transportation and distribution are executed via trucks. The Gasoline is delivered to refuelling stations where it is used to fuel road vehicles. The Kerosine is brought to storage at airports where it can be dispensed to airplanes.

6.2.5.5   *E-Kerosene and E-diesel via Fischer-Tropsch route (FTK & FTD)*

To generate e-kerosene and e-diesel initially there is hydrogen need. This is produced via water electrolysis and then synthesised with carbon dioxide to e-crude through the Fischer-Tropsch process. The carbon dioxide can be supplied through various procedures, either a mix of natural gas and biomass power plants (NG-PP), direct air capture (DAC), or flue gas from steam methane reforming (SMR) plants. The heat used for these processes is the by-product of the Fischer-Tropsch synthesis. The e-crude is converted into kerosene or diesel and then transported via truck to their respective destination. For kerosene, this is the airport where it is stored and dispensed. Diesel is distributed to refuelling stations where it is utilized to fuel road vehicles

Table 6-6. CAPEX and efficiencies for e-fuel syntheses. Values shown for near-term (approx. 5–10 years) and long-term (approx. 20–30 years) horizons are base values used in this article while values in parentheses are the range identified in the reviewed literature. The CAPEX per kW_{fuel} depends on the size of the facility; the near-term numbers reflect small-scale plants below 50 MW and the long-term numbers reflect larger plants.

Table 6-6 : Capital Expenditure and Efficiencies for e-fuel syntheses

		Near-term	Long-term
Hydrogen to methane	CAPEX ($€2019 \ kW_{fuel}^{-1}$)	450 (125–1350)	250 (75–700)
	Process efficiency	70%–83%	70%–83%

Hydrogen to methanol	CAPEX ($€2019\ kW_{fuel}^{-1}$)	700 (300–1200)	300 (200–650)
	Process efficiency	69%–89%	69%–89%
Hydrogen to DME	CAPEX ($€2019\ kW_{fuel}^{-1}$)	700 (300–1200)	300 (200–650)
	Process efficiency	69%–89%	69%–89%
Methanol to gasoline (MTG)	CAPEX ($€2019\ kW_{fuel}^{-1}$)	600	300 (250–370)
	Process efficiency	86%	86%
Methanol to jet fuel (MTJ)	CAPEX ($€2019\ kW_{fuel}^{-1}$)	1000	500 (370–900)
	Process efficiency	74%	74%
Hydrogen to Fischer–Tropsch	CAPEX ($€2019\ kW_{fuel}^{-1}$)	1600 (400–2100)	750 (300–1030)
	Process efficiency	59%–78%	59%–78%
Hydrogen to Ammonia#	CAPEX ($€2019\ kW_{fuel}^{-1}$)	1300 (1300–2200)	800 (580–1100)
	Process efficiency	61%–79%	61%–79%

 # CAPEX for ammonia in this table is without the air separation unit. MTJ process is still on a test and demonstration scale and therefore near-term (as well as long-term) costs, and efficiencies, are very uncertain.

6.2.5.6   Bio-E-fuel synthesis

Bioenergy sources such as animal manure, organic waste from food processing, straw, and other energy crops are suitable feedstocks for different anaerobic processes such as digestion or fermentation. Anaerobic digestion plants can convert biodegradable organic material into biogas which is composed primarily of methane (CH_4) and CO_2. Lignocellulosic feedstocks, such as wood chips, wood pellets, straw, tops and branches or even biogas plant residues, are considered suitable for thermal gasification or other deconstructive processes. In gasification, the solid biomass is endothermically converted into a synthetic gas (syngas) in the presence of an oxidizing agent such as oxygen or steam. Syngas is a mixture of H_2, CO, CO_2, CH_4,

water, and light hydrocarbons that can be synthesized into other fuels. In both gasification into syngas and anaerobic digestion, biofuels are produced through a reaction between hydrogen and carbon (CO or CO_2). The produced fuels do not utilize all the carbon content in the biomass, with the excess carbon generally being released as biogenic CO_2. To utilize this excess biogenic carbon, it is possible to insert additional hydrogen into the production process which will generate additional fuel without the need for carbon capture. This special case of a hybrid between biofuels and e-fuels as bio-e-fuels. Bio-e-fuel production costs include those for gasification/anaerobic digestion, biomass feedstock/biogas substrate, electrolyzer, electricity, fuel synthesis and eventual liquefaction. Costs are spread over the entire volume of fuel produced.

In the literature, gasifier CAPEX is in the range of 1100–1700 €2019 /kW_{syngas} for the near term and 350–1300 €2019 /kW_{syngas} for the long term while anaerobic digestion plant costs are 200–235 €/ kWh_{biogas} in the near-term and 160–205 € /kWh_{biogas} in the long-term depending on the type of biomass used, with lower costs for manure-based feedstocks and higher costs for straw or industrial waste feedstocks. In literature, assumed CAPEX for gasification (including gas cleaning) of 1250 and 1150 €/MWdry biomass as well as CAPEX for biogas plants of 1900 and 1650 €/MW_{biogas} for near-term and long-term, respectively. The costs for biomass feedstock are assumed to be 7 and 1.2 €/GJ for solid biomass and biogas substrate, respectively, for both the near and long-term. Conversion efficiencies are assumed 77% in near term and 83% in long term for the gasifier.

6.2.6   Hydrogen storage & transport

A challenge for renewable e-fuel production is the desire for continuous operation of the synthesis process while using the available low-cost renewable electricity which is typically from variable, intermittent sources. Depending on the operating profile of the e-fuel production plant, hydrogen storage may be needed. Hydrogen storage can be in underground caverns or steel tanks, with the latter potentially more suitable

for e-fuel production due to its versatility and widespread availability, but at a higher cost.

Table 6-7 : Hydrogen storage costs (€2019/ kWh) in the near- (approx. 5–10 years) and long-term (approx. 20–30 years).

	Near term	Long Term
Cavern storage	2-3	0.8-1.5
Steel tank, incl compressors, installation & man-hrs	45-57	21-27
Steel tank, without compressors, installation & man-hrs		7.6
Steel tank, other	16	20

6.2.7   Other costs and components

Depending on the type of e-fuel, additional fuel processing may be needed after fuel synthesis. For use in road transportation vehicles, gaseous fuels (methane and hydrogen) require compression or liquefaction for improved volumetric density and storage. Liquefied methane (LNG) is already used in the transport sector. LNG is also used in heavy-duty vehicles and is a possible fuel for aircraft. Liquefied hydrogen has been suggested for heavy road vehicles, shipping, and aviation. DME and ammonia are also liquefiable but require only a modest temperature and pressure change for liquefaction.

Table 6-8 : Cost of liquefaction prior to use in transport sector (€2019 kWh-1) for near-(approx. 5–10 years) and long-term (approx.20–30 years) horizons.

Liquefaction	Near term (€2019/ kWh)	Long term (€2019/ kWh)	Electricity consumption (kWHel/kWhfuel)
Methane	0.37 (0.30-0.45)	0.31 (0.28-0.35)	0.06-0.11
Hydrogen	0.30 (0.21-0.44)	0.17	0.28
The OPEX are estimated as 8-12 €/ kW for methane liquefaction and 25 €/ kW for hydrogen liquefaction			

6.2.8   Potential by-product revenues

Production of e-fuels generates by-products that could bring revenue streams, potentially leading to improved business models for fuel producers. The primary by-products are excess heat from electrolysis and fuel synthesis and O_2 from electrolysis, but also fuel gases and naphtha could be by-products from the synthesis processes. The production of N_2 from air separation generates by-products such as O_2, argon, and other noble gases that can help the economics of e-ammonia production. Different electrolysis types generate different amounts of excess heat at various temperatures that can be adjusted to fit potential district heating temperature levels. However, the waste heat can also be used within the process to maximize the synergies and efficiency of e-fuel production if SOEL is used. It may also be possible to gain revenues from the ancillary services by the participation of electrolysis units in the frequency regulation and load balancing required for the reliable operation of the electric grid.

Table 6-9 : Potential revenues from e-fuel by-products based on current market prices found in the literature

By-products	Current market price	Remark
Low temperature district heat	30-40 €/MWh$_{heat}$	
High temperature industrial process heat	25-34 €/MWh$_{heat}$	LP & HP steam
Oxygen	23.7- 87 €/t	
Fuel gas	36 €/MWh	A by-product of methanol to gasoline process
LPG equivalent	43 €/MWh	A by-product of methanol to gasoline process
Naphtha	30.6 €/MWh	A by-product of FT synthesis

6.3   Cost of production

Calculating production costs of hydrogen and e-fuels faces several parameter uncertainties, especially for 2030 and 2050 estimates. There is a wide diversity of

assumptions and approaches among different studies, resulting in a broad range of e-fuel production cost estimates. The data and literature typically show substantial cost reductions due to energy integration, technological progress and large-scale production etc. For example, in a recent techno-economic study by Junaid Haider et al (2022), E- methane unit production cost is estimated to be 0.223 $/kWh, using ASPEN integrated energy modelling using H2 produced via SOEC-based water electrolysis, which is approximately 6.5 times higher as compared to conventional natural gas [80]. Likewise, in a techno-economic study by Ralf Peters et al (2019) for E-methane production in Germany under different pathways involving renewable hydrogen via electrolysis from wind combined with different CO_2 sources, i.e., from biogas production, tail gas from power plants, provided by a supplier and estimated in the range of €3.51-€3.88 per kg and for direct air capture and methane costs estimated to be around € 5.5/kg which is approximately 7–15 factors higher than the normal NG [81].

In this context, production costs of different e-fuel options for near-term and long-term costs of key components, along with other cost assumptions (Grahn et. al.), are presented in Table 6-9. Revenues from by-products will benefit from the cost aspects. In the data shown below, potential revenues from by-products are not included when calculating the production cost. Potential by-product revenues and their inclusion in the calculation of production cost in the future markets for by-products, e.g. oxygen and heat, is very uncertain, particularly with large-scale e-fuel production. The costs for fuel infrastructure are also omitted in this cost analysis.

In Figure 6-2, production costs for a range of bio-e-fuels, e-fuels and electrolytic hydrogen are presented and compared with a range of 0.2–0.7 € liter^{-1} for the production cost of fossil gasoline/diesel, corresponding to an oil price range of $30–$100/barrel. Near-term production costs are in the range of approximately 110–230 € MWh^{-1}, with the lowest cost for liquefied bio-e-methane from biogas (similar to bio-e-methanol, bio-e-DME, and liquefied bio-e-methane from syngas), and highest for e-kerosene through the methanol-to-jet process. All fuel options have the potential to have a production cost between 90 and 160 € MWh^{-1} in the long term. From Figure 6-

2, it can also be seen that bio-e-fuels have lower production costs than their e-fuel versions. Although hydrogen is used to produce all types of e-fuels and bio-e-fuels it can be noted that it is not obvious that the costs for hydrogen are lower than the e-fuels and bio-e-fuels when including costs for liquefaction or compression. The reason that bio-e-methane, co-produced with anaerobically digested biogas, is marginally cheaper than compressed hydrogen is that production costs are spread over the entire volume of fuel produced, i.e. for the bio-e-methane case, the inclusion of the energy in biogas. All e-fuels and bio-e-fuels have higher production costs than fossil gasoline/diesel/kerosene, assuming an oil price of $30–$100/barrel.

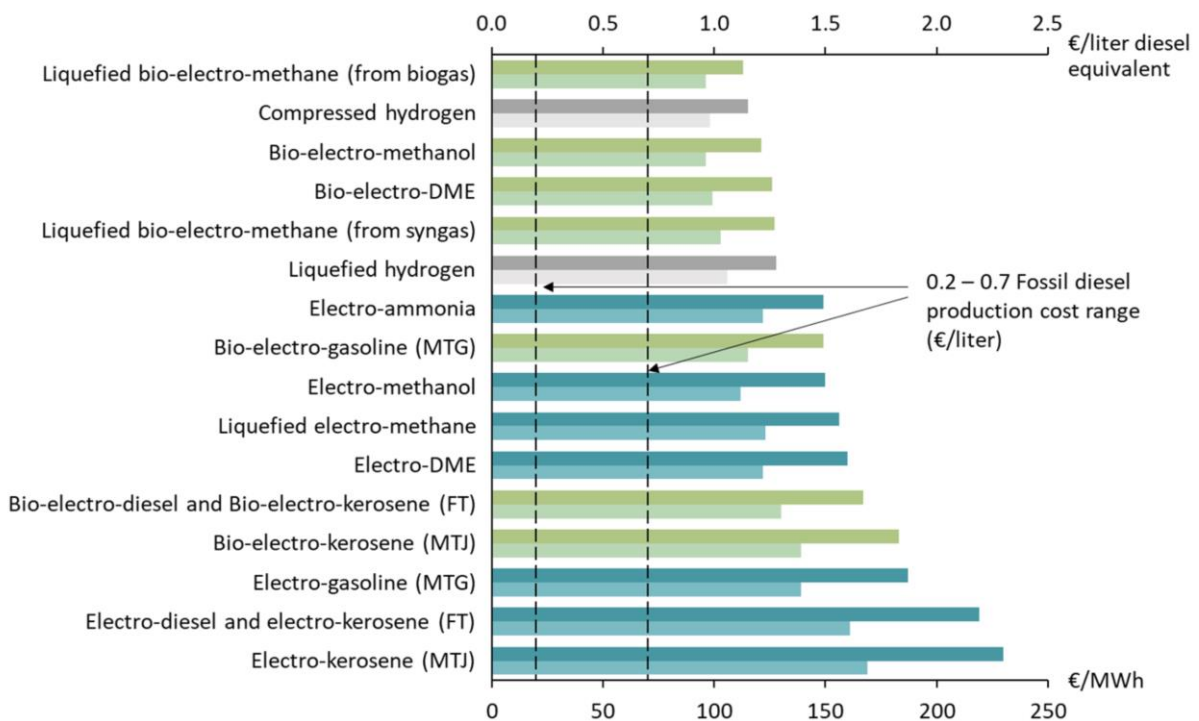*Figure 6-2 : Production costs for electrolytic hydrogen, bio-e-fuels, and e-fuels using base values from the literature review*

The near-term costs, approx. 5–10 years in future, are the dark-coloured bars and long-term costs, approx. 20–30 years in future, are the light-coloured bars. The black dotted lines show the production costs of fossil gasoline/diesel/kerosene for an oil price of $30–$100/barrel.

Acronyms used: DME, dimethyl ether; MTG, methanol-to-gasoline; MTJ, methanol-to-jet; FT, Fischer–Tropsch.

Table 6-10 : Production costs for e-methanol and liquid hydrogen built up by the different component costs using our base values (long-term).

Electrolysis	Unit	Near-term	Long-term
CAPEX electrolyser (near-term: an average of AEL and PEMEL, long-term: an average of AEL, PEMEL and SOEL)	€kW$_{el}^{-1}$	900	500
OPEX (including replacement of the stack)	Share of CAPEX	0.04	0.04
Conversion efficiency	H$_{2,LHV}$/electricity input	65%	74%
Demand for water (assuming 2X stoichiometric demand)	Ton MWh$_{H2}^{-1}$	0.54	0.54
Cost of deionized water	€/ton$_{water}$	1	1
Bio-e-fuel processes	**Unit**	**Near-term**	**Long-term**
CAPEX gasification (including gas cleaning)	€MW$_{drybiomass}^{-1}$	1250	1150
Conversion efficiency	GJ$_{syngas}$/GJ$_{Input\ biomass}$	77%	83%
Biomass feedstock	€GJ$_{biomass}^{-1}$	7	7
CAPEX biogas plant (anaerobic digestion)	€MW$_{biogas}^{-1}$	1900	1650
Biogas substrate feedstock	€GJ$_{biogas\ substrate}^{-1}$	1.2	1.2
Fuel synthesis	**Unit**	**Near-term**	**Long-term**
CAPEX synthesis reactor and conversion efficiency in parentheses			
Hydrogen to methane	€MW$_{CH4}^{-1}$	450 (83%)	250 (83%)
Hydrogen to methanol	€MW$_{MeOH}^{-1}$	700 (84%)	300 (84%)
Hydrogen to DME	€MW$_{DME}^{-1}$	700 (81%)	300 (81%)
Methanol to gasoline	€MW$_{Gasoline}^{-1}$	600 (88%)	300 (88%)
Methanol to jet fuel	€MW$_{Jet-fuel}^{-1}$	100 (74%)	500 (74%)
Hydrogen to Fischer-Tropsch liquids	€MW$_{fuel\ liquids}^{-1}$	1600 (66%)	750 (66%)
Ammonia synthesis (including ASU)	€MW$_{NH3}^{-1}$	1400 (79%)	850 (79%)
OPEX	Share of CAPEX	0.04	0.04
Other	**Unit**	**Near-term**	**Long-term**
Cost of CO2 capture (point source)	€ton$_{CO2}^{-1}$	50	25
Electricity price	€MWh$_{el}^{-1}$	50	50
Hydrogen liquefaction	€kW$_{fuel}^{-1}$	0.30	0.17
Other investments (e.g. cost for installation and unexpected costs)	Factor multiplied to CAPEX	1.5	1.5
Capacity factor for electrolysers (in base case assumed to operate without H2 storage)	Share of max capacity	0.70	0.70
Interest rate		0.05	0.05
System Life time	Years	25	25

The main reason for including liquid hydrogen is that electrolytic hydrogen is utilized for all e-fuel options but costs are, added for liquefaction when used as a fuel itself. Costs represent €2019

a. Bio-e-fuels production costs are built up by costs for gasification/anaerobic digestion, biomass feedstock/biogas substrate, electrolyzer, electricity, fuel synthesis and eventual liquefaction.

b. Although one can expect the two processes MTG and MTJ to be similar, there is currently very little information in the literature. The MTJ process is still on a test and demonstration scale and therefore near-term (as well as long-term) costs, and efficiencies, are very uncertain.

c. Assumed production efficiency from H_2 to FT liquids of 73%, and 90% of this output can be a commercialized fuel after upgrading (of any type). For simplicity reasons it is assumed that all commercial FT liquids are diesel and jet fuels (and thereby disregarding that a certain share of the commercial FT products is gasoline, feedstock for chemicals and other products).

d. The cost for carbon transport or storage is not included, essentially assuming that carbon is captured close to the e-fuel production site and the rate of capture exactly matches the demand. This is a simplifying assumption that deserves further scrutiny in future assessments

e. The cost for CO_2 capture is very uncertain, but the contribution from this cost factor to the production cost is relatively small and therefore the uncertainties are less critical

f. Future electricity prices are uncertain and depend on different factors such as the future demand for electricity, the share of variable renewable power sources, and the potential phase-out of nuclear power, the integration with other energy sectors. An average electricity price of approximately 50 € MWh-1 by both 2030 and 2050, is assumed.

Another reference, Soler *et. al.*, wherein extensive economic analysis has been performed for each e-fuel pathway is shown in Figure 6-3, 6-4 & 6-5 [78]. This analysis is done for the Europe region, covering North, Central and South Europe. A full cost assessment from renewable power production to the final e-fuel dispensing has been carried out by them. The following approach and economic modelling assumptions were made by them :-

- e-fuels production and distribution (Well-to-tank approach) is considered. Vehicles/fuel use combination (tank-to-wheel) is not considered. Hence, no business case analysis, no net present value (NPV), or return on investment (ROI) have been calculated. Therefore, neither taxes/levies nor exemptions thereof and no inflation have been taken into account (cost figures are given in today's purchasing power). Learning curves have been considered for technologies with the potential for cost reductions from series production.
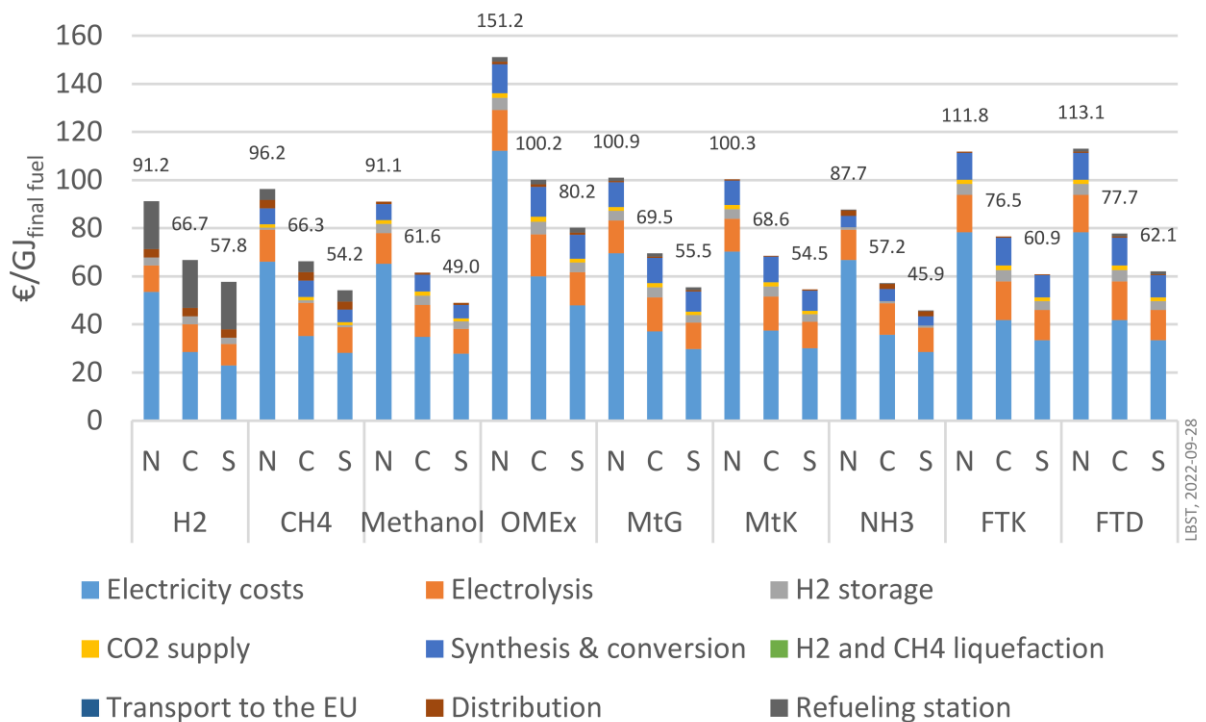

Figure 6-3 : Costs of e-fuels produced inside Europe by zone in 2020

- CAPEX is converted to an Equivalent Annual Cost via the Excel 'PMT' function using the discount rate (baseline: 8%) and the depreciation time

(process-specific lifetime). Annual costs for maintenance and repair are added. The resulting annual costs divided by the average annual production volume result in the specific product costs (€/kWh electricity supply, €/t CO_2 supply, €/kWh intermediary product supply, etc.).

- The specific costs are aggregated according to pathway definition and expressed in € per unit of final energy. All facilities, such as plants for power generation, synthesis and conversion/upgrading, are newly built (from scratch) and depreciated over their lifetime (in many cases some 25 years). The same applies to vehicles used for the transport of the final fuel. Conversion and upgrading are included in the economic assessment, aligned with the LCA assessment.
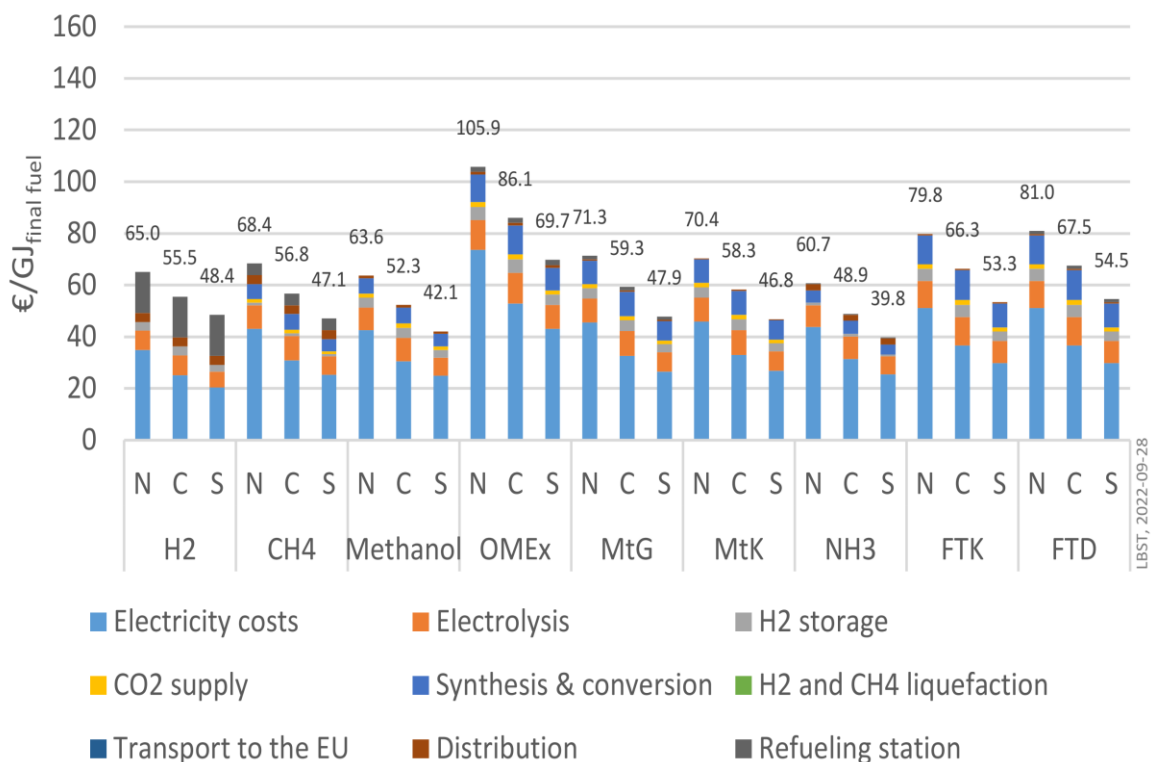

Figure 6-4: Costs of e-fuels produced inside Europe by zone in 2030

- In the case of cost data from earlier publications, these are converted to today's costs via Chemical Engineering Plant Cost Index (CEPCI). Inflation is not taken into account for future costs. Costs for spare parts are part of annual O&M

costs, i.e. no investment/discount rate is assumed for overhauls/spare parts. New plants are assumed for each time horizon (Today, 2030, 2050), thus capturing the picture of cost reduction potentials over a series of projects over time.

- For the base case, a nameplate capacity of 1 million t of e-diesel equivalent per year or about 114 t/h has been assumed (1,370 MW of final e-fuel, based on the LHV).
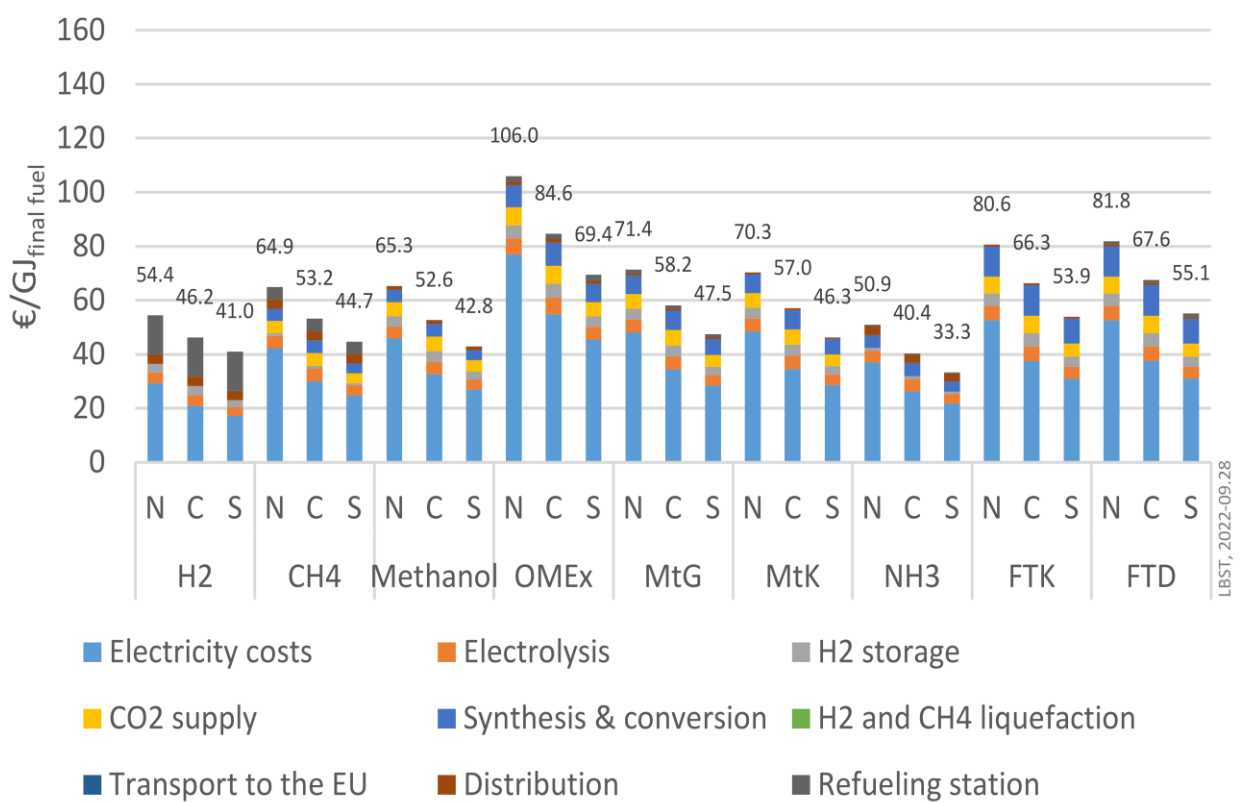

Figure 6-5 : Costs of e-fuels produced inside Europe by zone in 2050

- Discount rate: 8%

- Depreciation period: Lifetime

- For 2020 and 2030 a concentrated source with a CO_2 concentration of 45% (flue gas from SMR plants as proxy) has been assumed for CO_2 supply. For 2050, Direct Capture of CO_2 from the air has been assumed as the base case for e-

fuels produced in Europe, assuming that Direct Air Capture will be technically developed and anything else may not be recognized by the EU regulations. Figure 6-6 & 6-7 shows the base case results for e-fuels produced within Europe by zone (North, Central, South) for time horizon 2020, 2030 and 2050 respectively.

The above economic assessment of e-fuels towards 2050 shows that fuel supply costs range between 1.6 and 4.1 € per litre of diesel equivalent in the short and between 1.2 and 2.9 € per litre of diesel equivalent in the long term.

Cost-breakdown for liquid and gaseous e-fuels and comparison of E-fuel cost by various EU organizations with fossil gasoline is depicted below. E-fuels are relatively costlier as mentioned above [79].
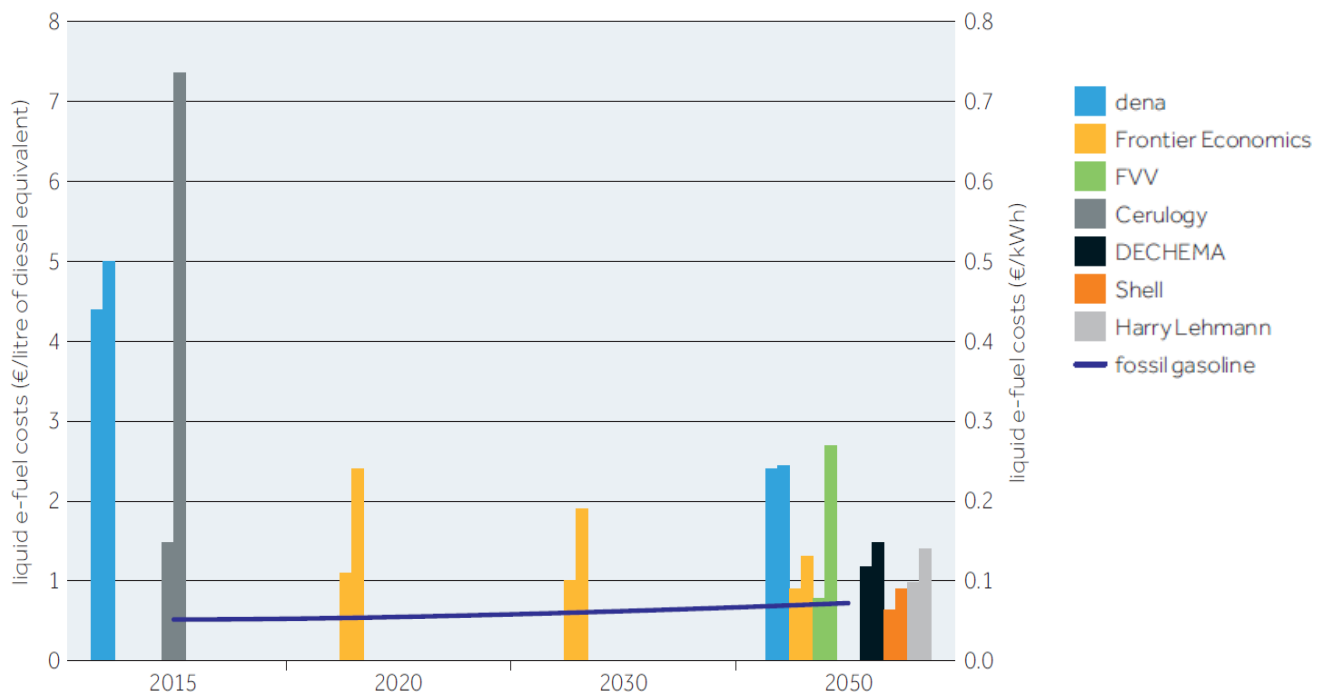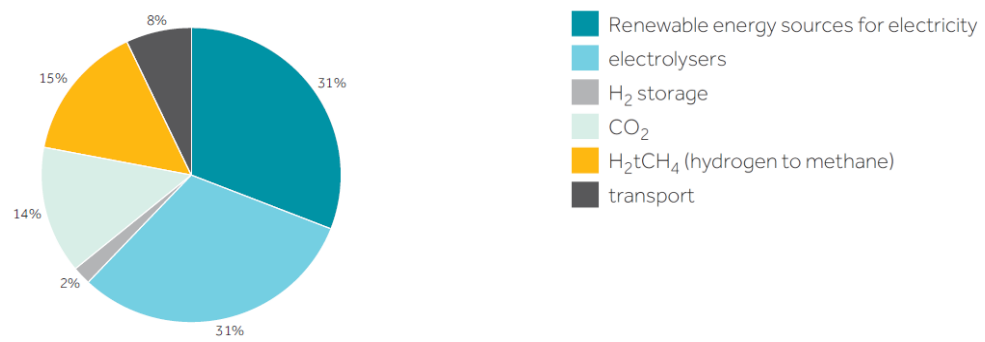

Figure 6-6 : Liquid hydrocarbon e-fuel costs (min/max) (€/l and €/kWh)

Cost breakdown for e-fuels Source: Frontier Economics (2018)

For e-Methane

For e-Liquids
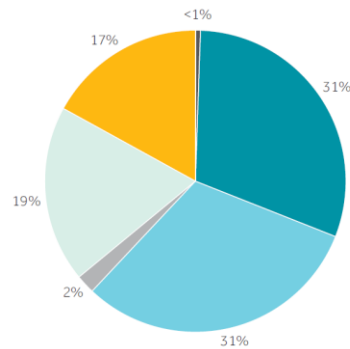
Figure 6-7 : Cost breakup of E-Fuels

All cost shares (%) and absolute figures (ct/kWh) are rounded. North Africa, reference scenario 2030, PV-wind-combination, CO2 from DAC, 6% weighted avg. cost of capital (WACC)

6.4 Sensitivity analyses

The two largest cost factors that impact e-fuel production costs are the electricity price and the electrolyzer CAPEX. Both these cost factors are uncertain, and it is, therefore, of interest to explore how varying these would impact the total cost. Electricity prices vary with time and between regions, depending on the supply and demand of electricity and transmission capacity. Furthermore, the electricity prices in the future may vary more than today, both in the near-term, but especially in the long-term perspective, as more fluctuating renewable electricity sources, such as wind and solar power, provide a larger share of electricity generation. We will most likely have more hours with lower, and more hours with higher, electricity prices than today. Therefore, using current yearly average electricity prices to estimate future

production costs is not an appropriate assumption. In addition, to the electricity price, producers of e-fuels will likely need to pay a grid fee. The grid fee varies depending on the location of the production unit and the price scheme from the grid utility company. Detailed sensitivity analysis needs to be done for each of the e-fuel in the Indian context and domestic energy scenario.

The versatility of e-fuels gives rise to the vision of a wide-scale replacement of fossil fuels without the transformational burden on the demand side. However, this versatility comes at huge costs. Depending on the e-fuel application, electricity-to-useful-energy efficiencies range from roughly 10% to 35%, which translates into renewable electricity generation requirements that are 2–14 times higher than for direct electrification alternatives. As a result, the e-fuel climate effectiveness critically hinges on very high renewable electricity shares as well as the renewability of the carbon source. Multifold supply-side investments translate into high e-fuel mitigation costs: ~€800 per tCO_2 for e-gasoline and ~€1,200/tCO_2 for e-methane in 2020–2025. Technological progress could reduce the abatement cost vis-à-vis fossil alternatives substantially to ~€20/tCO_2 for e-gasoline and ~€270/tCO_2 for e-methane in the long term (~2050).

The cost of electrolyzer and electricity are dominant factors in both the case of e-methanol and electrolytic hydrogen whereas the costs for methanol synthesis and carbon capture are minor and the cost for water negligible. Approximately 1.2 energy units of hydrogen are required to produce 1 unit of e-methanol which increases the demand for electricity in the e-methanol case. For the hydrogen case, the liquefaction process needs electricity, around 0.28 $kWh_{electricity}$/$kWh_{hydrogen}$. The two different reasons for increased electricity demand are in the same size order leading to a total cost of electricity of 83.1 and 83.7 for e-methanol and liquefied hydrogen, respectively. The cost for electricity constitutes 70% of the total production cost for e-methanol and 80% of the total production cost for liquefied hydrogen. For both the e-methanol case and the hydrogen case, the potential revenue from selling excess oxygen is 5% of the total production cost.

Different fuels involve different degrees of complexity to distribute, for example, the cost for a hydrogen fuelling infrastructure is greater than for liquid fuels (not requiring cooling or compressing). The infrastructure cost for all fuel options, further, depends on different factors such as distribution distance and type of end-user.

6.5   Conclusions

Depending on the form or the e-fuel required, either a Power-to-Gas (synthetic methane and ammonia) or Power-to-Liquid (synthetic methanol, gasoline, kerosene and diesel) process is used. Both of these production processes involve two or three phases, with first of all hydrogen (H_2) production by water electrolysis from renewable electricity, associated with another molecule - CO_2 for synthetic methane or methanol, or nitrogen (N_2) for synthetic ammonia. Synthetic crude oil from the FT process must be refined (like fossil oil) to produce synthetic kerosene or diesel.

As per the European context, E-fuel costs are currently relatively high (up to 7 euros/litre) but are expected to decrease over time due to economies of scale, learning effects and an anticipated reduction in the renewable electricity price; this is expected to lead to a cost of 1–3 euros/litre (without taxes) in 2050. The cost of e-fuels could therefore be 1–3 times higher than the cost of fossil fuels by 2050.

Although Indian-specific techno-economic studies concerning e-fuel are not available, based on the above EU studies it is assessed that, at present, the e-fuels costs are relatively higher, when compared to fossil-based fuel production routes. It is imperative, therefore, some kind of government assistance & policy framework to facilitate e-fuels is required. To unlock their full potential, policymakers need to set clear incentives for investment in their large-scale production and create a level playing field for all relevant emission reduction technologies. The use of existing energy infrastructures in their diversity allows these transformation paths more flexible approaches to solutions paths, such as capitalising on technological developments by 2050 that cannot yet be foreseen. A progressive reduction in

investment cost per technology over time, due to economies of scale and learning effects is expected.

Key enablers : The main key enablers for the deployment of e-fuels on a commercial scale are listed below:

a) Technical development and scale-up: the need to scale up the current demonstration-scale technology to a commercial plant level highlights the magnitude of the assets and investment needed in a new value chain (electrolysers, carbon capture, syngas and e-fuels conversion facilities).

b) Operational full-load hours: to function in a manageable and economically efficient manner, e-fuel facilities need to have a capacity for sustained operation over a high number of full-load hours despite the likely intermittency of a renewable power supply.

c) Accessibility of affordable renewable energy: due to conversion losses, the price of electricity is the major determinant of the variable costs of e-fuels production. Access to a sustainable and affordable source of renewable power is therefore essential for the economically viable operation of an e-fuels production facility. Importing e-fuels could become an important element, allowing the use of highly favourable locations for generating renewable electricity, which can have a positive impact on the cost of e-fuel production.

The most important drivers for the future cost of e-fuels are the costs of renewable power generation and the capacity utilization of conversion facilities.

7. BIS Standards

INDIAN STANDARDS ON PETROLEUM AND RELATED PRODUCTS

Indian standards for petroleum and related products are prepared by the Technical Committees with the approval of the Petroleum, Coal and Related Products Division Council. Technical Committee PCD3 "Petroleum and their Related Products of Synthesis or Biological Origin" is responsible to formulate Indian Standards for terminology; petroleum, petroleum products, biofuels (liquid and gas), fuels produced through synthesis route, specification for natural gas and codes of practice for storage, handling, transport and application. Indian Standards published under the PCD3 are given in Annex I

Technical Committee PCD1 "Methods of Test for Petroleum, Petroleum Products (including gaseous fuels) And Lubricants" is responsible to formulate Indian Standards for Methods for Sampling and testing for Petroleum and related products of synthetic or biological origin including lubricants, greases, speciality products, additives and gaseous fuels (excluding bitumen) and to organize correlation schemes for evaluating the accuracy and the performance of fuel and lubricant testing engines.

Being a National Standard Body of India, the Bureau of Indian Standards is actively participating in the formulation of International Standards related to all areas. India has P-Membership in the Technical Committees of Natural gas (ISO/TC 193), Biogas (ISO/TC/255) and Petroleum and related products, fuels and lubricants from natural or synthetic sources (ISO TC/ 28) and their Sub Committees, Working Groups. The Scope of the Committees along with details of Subcommittees and Working Groups are given in Annex III

CARBON OFFSETTING AND REDUCTION SCHEME FOR INTERNATIONAL AVIATION (CORSIA)

The document "Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)" published by International Civil Aviation Organization (ICAO) in November 2021specifies the "Guidance on the application of sustainability criteria for CORSIA Lower Carbon Aviation Fuel (LCAF) and Guidance on the application of sustainability criteria for CORSIA Sustainable Aviation Fuels (SAF) [82].

INTERNATIONAL STANDARDS

Direct air capture plays an important and growing role in net zero pathways. Capturing CO_2 directly from the air and permanently storing it removes the CO_2 from the atmosphere, providing a way to balance emissions that are difficult to avoid, including from long-distance transport and heavy industry, as well as offering a solution for legacy emissions. Air-captured CO_2 can also be used as a climate-neutral feedstock for a range of products that require a source of carbon.

Measurement, monitoring and verification (MMV) of CO2 stored:

The permanence of CO_2 storage is a vital factor for carbon removal via direct air capture (DAC) facilities. International standards (ISO 27914:2017) have been developed for the geological storage of CO_2, including MMV technical requirements and best practices that can be adopted by policymakers and regulators. Carbon accounting frameworks for CDR will need to consider the potential for reversal or re-release of the CO_2.

ISO 27914:2017 Carbon dioxide capture, transportation and geological storage - Geological storage

a) ISO 27914:2017 establishes requirements and recommendations for the geological storage of CO_2 streams, the purpose of which is to promote commercial, safe, long-

term containment of carbon dioxide in a way that minimizes risk to the environment, natural resources, and human health,

b) It is applicable for both onshore and offshore geological storage within permeable and porous geological strata including hydrocarbon reservoirs where a CO_2 stream is not being injected for hydrocarbon production or storage in association with CO_2-EOR,

c) It includes activities associated with site screening and selection, characterization, design and development, operation of storage sites, and preparation for site closure,

d) It recognizes that site selection and management are unique for each project and that intrinsic technical risk and uncertainty will be dealt with on a site-specific basis,

e) It acknowledges that permitting and approval by regulatory authorities will be required throughout the project life cycle, including the closure period, although the permitting process is not included in ISO 27914:2017,

f) It provides requirements and recommendations for the development of management systems, community and other stakeholder engagement, risk assessment, risk management and risk communication.

8. Engine/Vehicle Performance

8.1   IC engines

A diesel engine running on KDV synthetic diesel fuel (SDF) resulted in the maximum brake thermal efficiency decreased by 1.6% and 4.0%, and the minimum bsfc values increased by 2.6% and 4.5% compared to normal diesel running at respective 1400 and 2200 rpm speeds [83]. The emissions (NOx, CO and HC) were observed higher with KDV synthetic diesel fuel whereas smoke opacity was lower compared to conventional diesel fuel. Compared with 100% petroleum diesel, a 20% synthetic diesel blend reduced diesel fleet emissions by 24% for CO, 30% for total HC, 5.5% for NOx, and 19% for fine particulate matter (PM2.5) while using 100% synthetic diesel decreased emissions by 36% for CO, 48% for total HC, 10% for NOx, and 34% for PM2.5 [84]. Life-cycle assessments show that synthetic fuels produced from crop residues emit fewer greenhouse gases than fossil fuels, and usually reduce greenhouse gas emissions more than first-generation biofuels produced from edible crops [84]. National Renewable Energy Laboratory (NREL) conducted Fischer-Tropsch Synthetic Fuel Demonstration in a Southern California Vehicle Fleet [85]. The six trucks used in the study were of identical configuration Three of the vehicles were designated as "baseline" vehicles. No modifications were made to these vehicles, which were fueled with standard California Air Resources Board (CARB) specification diesel fuel. The remaining three "test" vehicles were fitted and fueled with Shell's GTL Fuel (Fischer-Tropsch Synthetic Fuel) during the study period. In general, the trucks fueled with GTL fuel performed similarly to the trucks fueled with CARB specification diesel fuel. Operators reported no noticeable difference in acceleration or power. Results indicate that the average fuel economy during the diesel-fueled group study period exceeded that of the GTL-fueled group by approximately 8%. The maintenance cost comparison between the two groups is much closer and comparable.

Carbon black is one of the products obtained from the pyrolysis of waste automobile tyres. 10% CB and 90% diesel (Carbodiesel10), with advanced injection timing of 26°CA bTDC, the brake thermal efficiency was found to be higher by about 6.4% while the fuel consumption was found to be lower by about 11.9%. Also, NO emission was noticed to be higher by about 23% and the smoke was lower [86]. Common Rail injection system, fed on blends of advanced diesel fuel and Diethylene-Glycol-Dimethyl-Ether (Diglyme - $C_6H_{14}O_3$). The experiments represent the potential of diesel reformulation technology with synthetic fuels coupled with the new diesel technology generation [87]. Dimethyl ether and diethyl ether in diesel engines as alternative fuels resulted in lower cylinder temperature and pressure, and thus lower engine performance. Brake power declines by about 32.1% and 24.7% and BSFC consumption increases by about 47.1% and 24.7% for dimethyl ether and diethyl ether, respectively [88]. In another study with synthetic biogas, composed of 60% methane and 40% carbon dioxide, with increasing equivalence ratio (fuel-air) (ϕ), the ignition delay tends to become longer and the peak of heat release rate was increased. NOx, HC and CO emissions decrease by 60%, 77% and 58% respectively [89]. Oxymethylene Ether (OME) as a diesel substitute, can significantly reduce CO_2 and pollutant emissions. With OME, a significantly shorter ignition delays as well as a shortened combustion duration could be observed, despite a longer injection duration. In addition, the maximum injection pressure increases. Particulate matter was reduced by more than 99% and particle number (>10 nm) was reduced by multiple orders of magnitude. The median of the particle size distribution shifts from 60 to 85 nm (diesel) into a diameter range of sub 23 nm (OME) [90]. Methanol-to-diesel synthetic diesel fuel shows no significant difference in the power value, however, while fuel consumption increases around 14%, and much lower emissions of exhaust [91].

The potential of synthetic fuel (SF) derived from waste plastics tested as blends in a direct injection diesel engine. BTE reduced, however, smoke and carbon monoxide emissions also reduced. SF20 showed superior performance - emission aspects and

the engine can operate smoothly up to 60% of SF blending at all loading conditions [92]. Another study claimed for 100% waste plastic oil as fuel in diesel engines [93].

Fischer-Tropsch (FT) synthetic fuels have been shown to produce lower soot and oxides of nitrogen emissions than petroleum-based diesel, which is attributed to the very low aromatic and zero sulfur content. Oxides of nitrogen emissions are always equal to or lower running FT compared to diesel, this result is attributed to the higher cetane number of FT leading to lower peak in-cylinder pressures. At intermediate-advanced injection timings and high CR, the FT fuel showed no PM advantage with possibly worse levels at some operating conditions. The PM was seen to always decrease with increasing pre-mix burn fraction [94]. In another study, a military jet fuel (JP-5 specification), a Fischer-Tropsch (FT) synthetic diesel, and normal hexadecane (C_{16}), a pure component fuel with a defined cetane number of 100, are compared with the operation of conventional military diesel fuel (F-76 specification). Despite having a significantly higher cetane number, the FT fuel showed a longer ignition delay, probably due to the lower density of this synthetic fuel, which leads to slower penetration into the chamber. Peak pressure was lower with JP-5, FT, and C16, relative to diesel due to both differences in ignition delay and combustion duration. BMEP with the JP-5, FT, and C16 changed little relative to diesel, but was reduced with FT operation (10-20%) in the high-speed, low-load region of the operating map. BSFC was improved for JP-5 and C16 (approximately 5%), but slightly worse for FT fuel (approximately 5%) particularly in the high-speed, low-load region [95]. Synthetic fuel derived from polymeric waste tested as a 7% diesel fuel blend. A minor increase in NO2 emissions was observed, which may be explained by the increased combustion temperature. Simultaneously, the reduction of the smoke was obtained [96].

Two series of tests were performed on a gasoline spark ignition engine fuelled with synthetic gases obtained from the catalytic decomposition of biogas. The selection of the right equivalence ratio and spark timing allowed the achievement of efficiencies above the gasoline. It was also detected that the variation in the ignition timing has

an important effect on parameters of combustion like maximum pressures, mass fraction burned, heat release ratio and cyclic irregularity. Such effects were extended to some pollutants like HC and NOx, which are strongly influenced by combustion temperatures [97]. In another work, research is able to generate and determine the effect of fuel mixture gasoline-synthetic fuel on levels of exhaust emissions, to determine the effect of fuel mixture gasoline-synthetic fuel for engine performance. Based on the analysis of performance and exhaust emissions test on a gasoline engine, for most engines performance is good and efficient set at first to mix synthetic fuel [98].

8.2   Jet Engines

Natural gas–derived FT synthetic fuel and Jet A-1 with 50/50 blend show reduced NOX emissions and may reduce CO emissions. Replacing petroleum jet fuel with zero aromatic alternatives decreases the emissions of aromatic hydrocarbons [99]. In another study, "zero sulfur" and "zero aromatic" synthetic fuel were produced from a natural gas feedstock using the FT process. FT fuel combustion greatly reduced SO_2 (>90%), gaseous hydrocarbons (40%), and NO (6−11%) content compared to JP-8 combustion. FT combustion dramatically reduces soot particle number, mass, and size relative to JP-8, but increases effective soot particle density. As expected, FT combustion plumes support the negligible formation of nucleation/growth mode particles (the number of nucleation growth mode particles is <20% of the number of soot particles compared to >500% for sulphur-containing JP-8). However, particle nucleation/growth for blended fuel combustion is enhanced relative to JP-8, despite the lower sulphur content of the FT/JP-8 fuel blend [100].

Evaluation and certification of Hydroprocessed Renewable Jet (HRJ), a fuel produced from animal fat and/or plant oils (triglycerides) by hydroprocessing, as the next potential synthetic aviation fuel. This study discusses the laboratory testing performed to characterize HRJs and results from the basic engine operability and emissions studies of the alternative fuel blends [101]. Carbon-free fuels namely

hydrogen and ammonia, and carbon-rich fuels, i.e. methane and methanol, are synthesized using CO_2 as a precursor termed carbon capture and utilization (CCU). Power-CCU fuel-power systems exhibit an energy loss from 65 to 86%, whereas the energy loss of power-CCU fuel-propulsion systems increase to 83 - 94% [102]. Bio-Synthetic Paraffinic Kerosene (Bio-SPKs). Assessment of Life Cycle Emissions of Biofuels revealed that Camelina SPK, Microalgae SPK and Jatropha SPK delivered 70%, 58% and 64% life cycle emissions (LCE) savings relative to the reference fuel, Jet-A1 [103]. The conventional fuel Jet A-1, the synthetic blending component from hydrotreated esters and fatty acids (HEFA) and its blend interacted with the sample nitrile rubbers. The conventional fuel Jet A-1, the synthetic blending component from hydrotreated esters and fatty acids (HEFA) and its blend interacted with the sample nitrile rubbers [104].

8.3   Turbine fuel

The development of coal IGCC (Integrated Gasification Combined Cycle) technology has made it possible to exploit electricity generated from coal at a low cost. When a new fuel is adapted to a gas turbine (such as syngas for IGCC), it is necessary to study the gas turbine combustion characteristics of the fuel, because gas turbines are very sensitive to its physical and chemical properties. This experimental study was conducted by investigating the combustion performance of synthetic gas, which is composed chiefly of hydrogen and carbon monoxide. The results of the combustion test of both gases were examined in terms of the turbine's inlet temperature, combustion dynamics, emission characteristics, and flame structure. From the results of this experimental study, we were able to understand the combustion characteristics of synthetic gas and anticipate the problems when synthetic gas rather than natural gas is fuelled by a gas turbine [107].

9. Future trends in synthetic fuel production

9.1   Compact Fischer Tropsch plants for synthetic fuel production

The FT process is an established technology that has already been applied on a large scale but its adoption is limited by high capital costs and high operation and maintenance costs. With coal being the primary energy source, this technology could be used if conventional oil were to become more expensive. A combination of biomass gasification and Fisher-Tropsch synthesis is also a promising route to produce renewable transportation fuels.

Commercial Fischer Tropsch plants are normally built on a large scale. Smaller-scale Fischer Tropsch plants would be needed to take advantage of isolated renewable electricity or carbon sources. These are being developed, for example, Compact GTL have a fully commercialised modular plant in Kazakhstan that produces 2500 barrels/day of synthetic crude [106].

9.2   Electrolysis

Producing low-carbon hydrogen through the electrolysis of water will become more commercially viable as the price of renewable electricity falls and the electrolysers become more efficient. Research is underway to improve the costs of electrolysis and is already starting to yield benefits. For example, Thyssenkrupp claims their advanced electrolyser technology can make large-scale hydrogen production from renewable electricity economically attractive by achieving high efficiencies of around 69% LHV [107]. There is interest in the direct conversion of carbon dioxide to fuels using electricity with special electro-catalyst electrodes, for example, reducing carbon dioxide to carbon monoxide and then converting it to fuel or reducing it directly to methanol or methyl formate [108-110].

9.3   Bacterial conversion

Bacterial conversion of carbon dioxide to e-fuels without directly using biomass is also an area of current research. Electrochaea GmbH has developed a biocatalyst to combine low-carbon hydrogen and atmospheric carbon dioxide in a bioreactor to produce synthetic methane [111].

9.4   Solar to fuels

Solar or photocatalytic conversion of carbon dioxide has been actively studied for several years [112-114]. It involves the activation of catalysts using light to convert carbon dioxide directly into fuels such as methanol. Catalysts based on titanium dioxide are most commonly used because of their high efficacy. Despite progress, there have been many challenges limiting its widespread uptake and in particular, more work needs to be done on conversion rates, overall yields and selectivity. Recent work focussing on modified graphene has reported useful rates of production for methane and ethane from carbon dioxide with sunlight [115]. While these levels are still ultimately very low, this work suggests that with further development higher rates could be achievable. Research is also continuing into the direct solar conversion of water vapour into hydrogen with efficiencies of up to 15% being reported [116].

Another pathway for producing solar syngas based on two-step redox cycles is in the research phase. Syngas is first produced from water and CO_2 using a two-step thermochemical cycle based on metal oxide redox reactions through concentrated solar radiation followed by the synthesis of Fischer-Tropsch fuels. This has been demonstrated on a laboratory scale within the EU project SOLAR-JET [117].

9.5   PtX & BtL Fuels Technology

Electricity-based synthetic fuels otherwise called Power-to-X fuels (PtX) are emerging as an apt solution for decarbonizing sectors such as shipping and airways. PtX fuels encompass various synthetic fuels ranging from a gas such as hydrogen, and synthetic methane and liquids such as gasoline, diesel and jet fuel derived from the

renewable power sources. Hydrogen generated by electrolysis (PtG) from renewable energy (green hydrogen) would be a promising solution in future energy transition for its use in different applications such as heating, chemical production (as feedstock) and mobility (as fuel) [118].

Power-to-Liquid (PtL) fuels constitute another promising type of synfuel. PtL fuels derive from the reaction between green hydrogen with carbon oxide during Fischer-Tropsch-Synthesis.

Due to the multiple conversion steps, PtX fuels have the disadvantage of relatively low overall efficiency for the entire process. They also suffer from high production costs, which impedes further market penetration. PtL fuels are expected to pick up momentum in the long term with decreasing cost of renewable electricity.

Biomass-to-Liquid (BtL) fuels will also become one of the promising routes for sustainable synthetic fuel production through the thermochemical conversion of biomass.

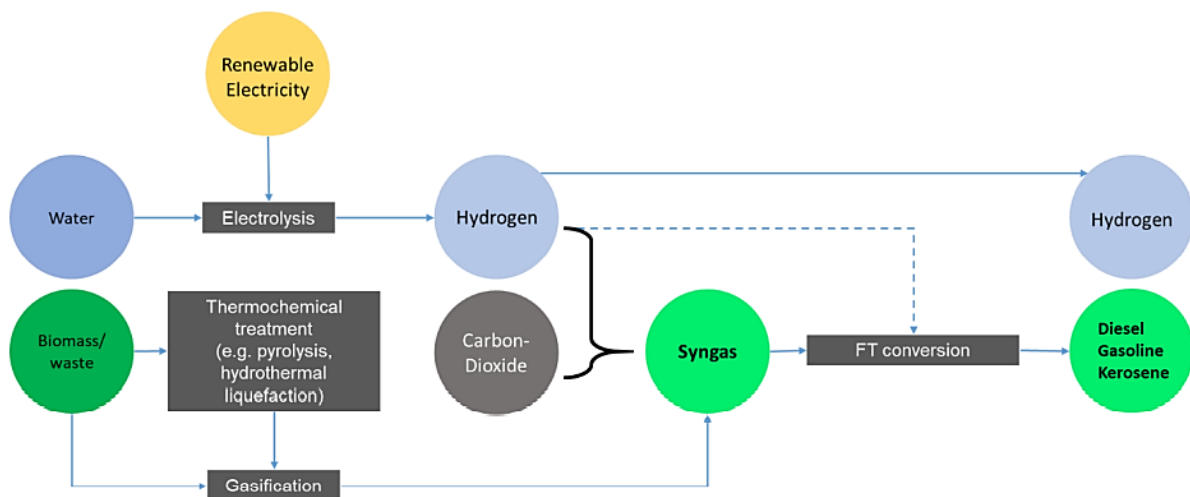A Schematic representation of the above technologies is given in Figure 9-1 below.

Figure 9-1 : Schematic representation of different technologies

9.6   New e-fuels

The development of new e-fuels raises the potential to improve existing internal combustion engines about efficiency, greenhouse gas contribution and emissions. Newly oxygenated e-fuels are being developed for use in existing diesel engines, and molecules such as dimethyl ether (DME) and oxymethylene ethers (OMEx) have been developed and deployed in heavy-duty vehicles by companies such as Ford and Volvo Trucks. Reduced carbon dioxide emissions from DME/OMEx are claimed [119-120], but the extent is yet to be proven as much of the data is from idealised test scenarios.

$x = 0 = OME_0 = DME$
$x = 1 = OME_1$
$x = 2 = OME_2$ etc
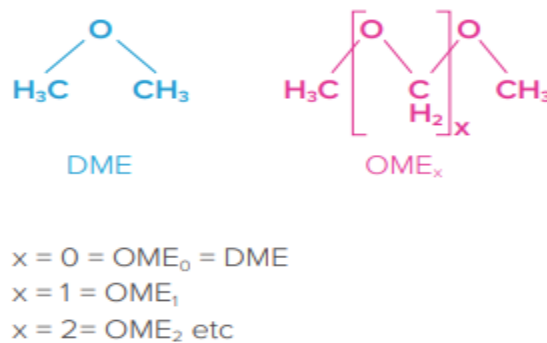
DME and the lower OMEs are gaseous under ambient conditions and need to be stored under pressure in tanks for distribution and use in the vehicle. Work is ongoing to create longer-chain OMEs which are liquids under ambient conditions and easier to store and use.

A Life cycle assessment (LCA) study has shown that a 22% OME/fossil fuel diesel blend by volume could reduce the global warming impact of diesel by 11%. The OME would be produced using hydrogen from electrolysis via intermittent wind energy and carbon dioxide derived from biogas. Further benefits may also be derived from simultaneous fuel/combustion system optimisation and new e-fuel formulations that reduce engine pollutant emissions.

Ethanol is well established as a fuel or fuel blend in some countries and other alcohols are becoming popular. These include methanol produced from carbon dioxide which has found increasing use in marine engines (eg Stena Line [121]), where fuel tolerance is less of an issue than in road vehicle engines. Butanol is also an interesting petrol alternative as it has a low vapour pressure, is non-corrosive [122] and has an energy density between ethanol and petrol.

9.7   Demand for synthetic fuels
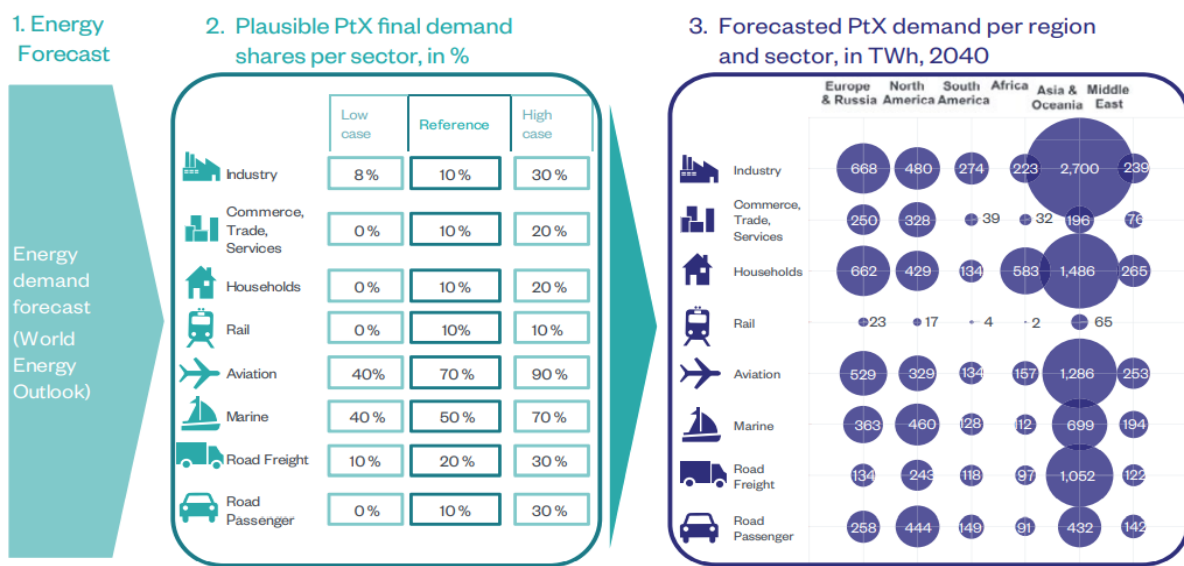
Figure 9-2 : Sectorial and regional consumption of hydrogen-based fuels by 2040.

Frontier economics expects a global demand of 20,000 TWh in the base case and 41,000 TWh in the high case [123].

10.   Best international practices

ICAO

INTERNATIONAL CIVIL AVIATION ORGANIZATION

ICAO document

CORSIA Sustainability Criteria for CORSIA Eligible Fuels

November 2021

CORSIA

Carbon Offsetting and Reduction Scheme for International Aviation

[124]

This ICAO document is referenced in Annex 16 — *Environmental Protection*, Volume IV — *Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)*. This ICAO document is material approved by the ICAO Council for publication by ICAO to support Annex 16, Volume IV and is essential for the implementation of the CORSIA. This ICAO document is available on the ICAO CORSIA website and may only be amended by the Council.

Table A shows the origin of amendments to this ICAO document over time, together with a list of the principal subjects involved and the dates on which the amendments were approved by the Council.

Table A.   Amendments to the ICAO document "CORSIA Sustainability Criteria For CORSIA Eligible Fuels"

Amendment	Source(s)	Subject(s)	Approved
1st Edition	Eleventh Meeting of the Committee on Aviation Environmental Protection	First edition of the document, which applies until December 31st, 2023 (end of the CORSIA pilot phase).	7 Jun 2019
2nd Edition	2019 Steering Group meeting of the Committee on Aviation Environmental Protection	Inclusion of Sustainability Criteria applicable for batches of CORSIA Sustainable Aviation Fuel (SAF) produced by a certified fuel producer on or after 1 January 2024	10 November 2021

CORSIA SUSTAINABILITY CRITERIA FOR CORSIA ELIGIBLE FUELS

Chapter 1: CORSIA SUSTAINABILITY CRITERIA APPLICABLE FOR BATCHES OF CORSIA ELIGIBLE FUEL PRODUCED BY A CERTIFIED FUEL PRODUCER BEFORE 1 JANUARY 2024

Theme	Principle	Criteria
1. Greenhouse Gases (GHG)	Principle: CORSIA eligible fuel should generate lower carbon emissions on a life cycle basis.	Criterion 1.1: CORSIA eligible fuel will achieve net greenhouse gas emissions reductions of at least 10% compared to the baseline life cycle emissions values for aviation fuel on a life cycle basis.
2. Carbon stock	Principle: CORSIA eligible fuel should not be made from biomass obtained from land with high carbon stock.	Criterion 2.1: CORSIA eligible fuel will not be made from biomass obtained from land converted after 1 January 2008 that was primary forest, wetlands, or peat lands and/or contributes to degradation of the carbon stock in primary forests, wetlands, or peat lands as these lands all have high carbon stocks.
		Criterion 2.2: In the event of land use conversion after 1 January 2008, as defined based on the Intergovernmental Panel on Climate Change (IPCC) land categories, direct land use change (DLUC) emissions will be calculated. If DLUC greenhouse gas emissions exceed the default induced land use change (ILUC) value, the DLUC value will replace the default ILUC value.

Guidance on the application of sustainability criteria

a) Compliance with Themes 1 and 2 is granted on the basis of independent attestation by Sustainability Certification Schemes included in the ICAO document "CORSIA Approved Sustainability Certification Schemes" which is available on the ICAO CORSIA website.

b) A fuel producer can produce batches of CORSIA eligible fuels for 365 calendar days after it has been certified by an SCS for compliance with the CORSIA Sustainability Criteria, after which the fuel producer shall be re-certified for compliance with the sustainability criteria applicable at the time of re-certification.

c) CORSIA Sustainability Criteria for CORSIA Eligible Fuels does not set a precedent for, or prejudge the outcome of negotiations in other fora.

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Chapter 2: **CORSIA SUSTAINABILITY CRITERIA APPLICABLE FOR BATCHES OF CORSIA SUSTAINABLE AVIATION FUEL PRODUCED BY A CERTIFIED FUEL PRODUCER ON OR AFTER 1 JANUARY 2024**

Theme	Principle	Criteria
1. Greenhouse Gases (GHG)	Principle: CORSIA SAF should generate lower carbon emissions on a life cycle basis.	Criterion 1.1: CORSIA SAF will achieve net greenhouse gas emissions reductions of at least 10% compared to the baseline life cycle emissions values for aviation fuel on a life cycle basis.
2. Carbon stock	Principle: CORSIA SAF should not be made from biomass obtained from land with high carbon stock.	Criterion 2.1: CORSIA SAF will not be made from biomass obtained from land converted after 1 January 2008 that was primary forests, wetlands, or peat lands and/or contributes to degradation of the carbon stock in primary forests, wetlands, or peat lands as these lands all have high carbon stocks.
		Criterion 2.2: In the event of land use conversion after 1 January 2008, as defined based on the Intergovernmental Panel on Climate Change (IPCC) land categories, direct land use change (DLUC) emissions will be calculated. If DLUC greenhouse gas emissions exceed the default induced land use change (ILUC) value, the DLUC value will replace the default ILUC value.
3. Water	Principle: Production of CORSIA SAF should maintain or enhance water quality and availability.	Criterion 3.1: Operational practices will be implemented to maintain or enhance water quality.
		Criterion 3.2: Operational practices will be implemented to use water efficiently and to avoid the depletion of surface or groundwater resources beyond replenishment capacities.
4. Soil	Principle: Production of CORSIA SAFs should maintain or enhance soil health.	Criterion 4.1: Agricultural and forestry best management practices for feedstock production or residue collection will be implemented to maintain or enhance soil health, such as physical, chemical and biological conditions.
5. Air	Principle: Production of CORSIA SAF should minimize negative effects on air quality.	Criterion 5.1: Air pollution emissions will be limited.

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6. Conservation	Principle: Production of CORSIA SAF should maintain biodiversity, conservation value and ecosystem services.	Criterion 6.1: CORSIA SAF will not be made from biomass obtained from areas that, due to their biodiversity, conservation value, or ecosystem services, are protected by the State having jurisdiction over that area, unless evidence is provided that shows the activity does not interfere with the protection purposes.
		Criterion 6.2: Low invasive-risk feedstock will be selected for cultivation and appropriate controls will be adopted with the intention of preventing the uncontrolled spread of cultivated alien species and modified microorganisms.
		Criterion 6.3: Operational practices will be implemented to avoid adverse effects on areas that, due to their biodiversity, conservation value, or ecosystem services, are protected by the State having jurisdiction over that area.
7. Waste and Chemicals	Principle: Production of CORSIA SAF should promote responsible management of waste and use of chemicals.	Criterion 7.1: Operational practices will be implemented to ensure that waste arising from production processes as well as chemicals used are stored, handled and disposed of responsibly.
		Criterion 7.2: Responsible and science-based operational practices will be implemented to limit or reduce pesticide use.
8. Human and labour rights	Principle: Production of CORSIA SAF should respect human and labour rights.	Criterion 8.1: CORSIA SAF production will respect human and labour rights.
9. Land use rights and land use	Principle: Production of CORSIA SAF should respect land rights and land use rights including indigenous and/or customary rights.	Criterion 9.1: CORSIA SAF production will respect existing land rights and land use rights including indigenous peoples' rights, both formal and informal.
10. Water use rights	Principle: Production of CORSIA SAF should respect prior formal or customary water use rights.	Criterion 10.1: CORSIA SAF production will respect the existing water use rights of local and indigenous communities.
11. Local and social development	Principle: Production of CORSIA SAF should contribute to social and economic development in regions of poverty.	Criterion 11.1: CORSIA SAF production will strive to, in regions of poverty, improve the socioeconomic conditions of the communities affected by the operation.
12. Food security	Principle: Production of CORSIA SAF should promote food security in food insecure regions.	Criterion 12.1: CORSIA SAF production will, in food insecure regions, strive to enhance the local food security of directly affected stakeholders.

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Guidance on the application of sustainability criteria

a) compliance with the sustainability criteria will be certified by an approved Sustainability Certification Scheme (SCS) included in the ICAO document "CORSIA Approved Sustainability Certification Schemes" which is available on the ICAO CORSIA website. An aeroplane operator seeking to claim emissions reductions from the use of CORSIA Sustainable Aviation Fuel (SAF) will provide evidence of the SCS' certification in its emissions reporting in accordance with Annex 16, Volume IV;

b) in assessing compliance with the sustainability criteria, an SCS will apply only ICAO-approved sustainability criteria for the certification of CORSIA SAF, on the following basis:

   i. compliance with Themes 1 and 2 will be assessed by the SCS;

   ii. compliance with Themes 3 to 7 will be assessed by SCS taking into account the guidance approved by the Council[1] and in accordance with the following procedure:

   a) prior to an SCS conducting an assessment in a State in which it never operated before, the SCS will consult with the competent authority of the State concerned, if required, in order to discuss the detailed process of assessment and for the SCS to be fully aware of the national and local requirements applying to the production of SAF. In the case of States that establish such requirement, the assessment by SCS will only take place after such consultations and common understanding between the competent authority and SCS on the detailed process of assessment by the SCS. With a view to implementing this consultation process, Member States which require consultation will notify ICAO which competent authority should be contacted by the SCS; and

   b) in the case of diverging approaches between the competent authority and the SCS, the Member State concerned may refer the matter to the ICAO Council to review the disagreement relating to the interpretation and application of the guidance for Themes 3 to 7. The review may include the support of relevant UN domain experts, as appropriate, on the request of the Member State. The Member State concerned will participate in this review process;

   iii. compliance with Themes 8, 9 and 10 can be demonstrated to the SCS by a national attestation from the State in whose territory the SAF is produced, without further assessment by the SCS;

   iv. compliance with Themes 11 and 12 will be demonstrated to the SCS by the economic operator reporting to the SCS the actions being taken to meet the related criteria, without further judgement of those actions by the SCS.

c) CORSIA sustainability criteria for CORSIA SAF does not set a precedent for, or prejudge the outcome of negotiations in other fora.

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[1] Guidance on the application of Sustainability Criteria, Themes 3 to 7, is available on the "CORSIA eligible fuels" website.

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Chapter 3: CORSIA SUSTAINABILITY CRITERIA APPLICABLE FOR BATCHES OF CORSIA LOWER CARBON AVIATION FUEL PRODUCED BY A CERTIFIED FUEL PRODUCER ON OR AFTER 1 JANUARY 2024

Note.— The development of sustainability criteria for these batches of CORSIA Lower Carbon Aviation Fuel is ongoing under the Committee on Aviation Environmental Protection (CAEP) and will be subject to approval by the Council.

-END-

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11. Conclusion and Policy Recommendations

Production of e-fuels is currently not cost-competitive in comparison to conventional fossil fuel-derived transportation fuels. For the promotion of e-fuels in India, it requires to introduce of various policy interventions in the near and long term. Following are the recommendations proposed that shall cover what as a country India should do for the next 20-30 years wherein R&D shall be a priority followed by mandate/incentives for carbon credit, etc. and a separate policy for e-fuels in line with green hydrogen, biofuels, ethanol is also proposed. Further, these proposed strategies are intended to overcome challenges associated with the production and utilization of e-fuels in India.

1. **CCUs & Green Hydrogen for Production of E fuels road transportation, Aviation and Marine sectors**

   a. Promote indigenous development and demonstration of technologies / catalysts for efficient carbon capture and production of e-fuels

   b. Detailed analysis of different kind of feedstock supply needs to be made for its sustainability aspects and availability.

   c. Quality check of drop-in (synthetic natural gas) fuel to be readily used in existing natural gas pipelines.

   d. More focus on CO_2 conversion to e-fuels needs to be taken (CO_2 to methanol/ synthetic natural gas, dry reforming, etc.)

   e. Promote zero carbon marine fuel close to ports creating a significant opportunity for synthetic fuel manufacturers.

   f. CCU technology is to be promoted at various TRL levels wherein R&D technology development is required.

g. Promotion of Ammonia as a carrier of Hydrogen.

h. Thermo-catalytic CO_2 conversion route to SNG and Methanol needs to be established by setting up demonstration units.

i. As a part of mid-term solution, reverse water gas shift technology development needs to be put on a fast track for syn-gas production.

2) Other Synthetic fuels SAF/Bio Ethanol/Bio Diesel etc.,

a. For reducing the cost of e-fuels production, reduce or exempt taxes and duties like the GST and custom duties on sustainable aviation fuels (SAF) and e-fuels for maritime

b. Newer kinds of feedstock through biotechnological interventions like algae; use of hydroprocessed vegetable oils (HVO) as a cetane booster as well as renewable diesel.

c. Promotion of Dimethyl ether (DME) as a diesel substitute for transportation (DME is already notified as an auto fuel) and for blending with LPG for domestic applications. Moreover, SNG needs to promote for auto fuel as well as domestic usages

d. Municipal Solid Waste based synthetic fuel generation programs.

e. Considering the surplus ethanol scenario, Alcohol to Jet (ATJ) route is to be fostered for SAF. This route also offers a platform for bio-ethylene which can be exploited as a part of the circular economy. Also, the ATJ route consumes much less hydrogen (~0.02 Kg of H2 per litre of SAF) compare to OTJ (~0.14 Kg of H2 per litre of SAF)

3) R&D, Budget and Demo plants for promotion of E-Fuels.

a. Support to undertake R&D in the field of CO_2 capture to reduce cost of CO_2 production (< USD 20 per MT).

b. Initial funding to the projects to promote R&D activity on e-fuel (hydrogen, biofuel, drop in fuel) should be arranged through cess.

c. R&D for technology development for 100% drop-in sustainable aviation fuel (SAF).

d. Carrying out research work to check the technology readiness of power-to-gas conversion for the production of natural gas.

e. Techno-economic study on e-fuel needs to be done in the Indian context

f. ISO standards to be verified to formulate BIS standards for example standards for measurement, monitoring, verification of CO_2 storage, etc.

g. Under the PCD committee, future e-fuel standards shall be made

h. Specific research grants to reduce the cost of production and improve feedstock conversion efficiency.

i. Dedicated budget to improve infrastructure enabling all associated industries to develop and scale up.

j. GOI funding for R&D promotion in the area of e-fuels and CO_2 utilization. In addition, funding to promote the development and adoption of Synthetic Natural Gas (SNG) technologies, aligning with efforts to reduce reliance on fossil fuels and mitigate greenhouse gas emissions

k. Fast-track approvals for synthetic fuel plants.

l. Public Awareness campaigns for explaining the benefits of using synthetic fuels.

m. R&D Funding for developing new prototypes of applications using synthetic fuel.

n. Detailed life cycle assessment while identifying or promoting fuel routes. The LCA numbers can be revised as more data becomes available. The LCA shouldn't be limited to only the processing stage but should have a true cradle-to-grave perspective.

o. R&D efforts to be target on thermos-catalytic CO_2 conversion to ethanol.

p. Power to liquid fuel scenario can be explored as an export option (owing to cost) by setting up facilities at the upcoming RE park at Kutch, Gujarat. For this purpose, the Indigenous FT process developed under the CTL project (sponsored by CHT) needs to be scaled up while fostering the development of indigenous SOEC technology.

q. Prioritization on global partnerships, technology tie-ups, and research and development collaboration to promote synthetic and facilitate their adoption.

4) **Policy and Fiscal Incentives, Carbon credit etc.,**

a. Prepare a comprehensive roadmap focusing on all aspects of e-fuels production and utilization with details on the government vision for use of e-fuels in different sectors with timelines and investment aspirations.

b. Establish an aspirational cost reduction target for e-fuels production in line with national green hydrogen production cost targets

c. Incentivization of demonstration/ commercial implementation of carbon capture and utilization (CCU) technologies

d. Introduce specific production/ utilization targets for e-fuels in the aviation and marine sectors

e. Implement a national policy for e-fuel blending obligations for aviation and marine sectors

f. Provide Central Financial Assistance (CFA) in the form of VGF (viability gap funding) or PLI (production-linked incentives) for the production of e-fuels

g. Develop classification and certification system for renewable and low-carbon fuels to promote clean fuels, including green hydrogen and e-fuels

h. Develop mechanisms by which the pricing of fossil fuels and natural gas will incorporate the extent of carbon emissions associated with the fuel

i. The policy shall cover the transport sectors which can't be electrified like aviation, heavy-duty vehicles and marine that require liquid/gaseous fuel through e-route

j. Focus should be on the use of bio-ATF and ammonia as a prominent e-fuel.

k. India should join CORSIA in near future for the mandated use of e-fuels.

l. Incentives in respect of technology intervention (support to demo plants similar to PM JIVAN), minimum support price and de-risk the investment (different financial measures CO_2 tax, carbon credit) and blending mandate from GOI.

m. Govt. intervention to implement e-fuels

n. Blended fuels (e-fuel/conventional fuel) to be released in phased out manner

o. Policy push for faster development, production and adoption of tuned engines/marine/aviation.

p. Fostering decarburization by creating a carbon credit market.

q. An incentive to synthetic fuel manufacturers and end-users to nurture the ecosystem.

r. The need for synergy between various fuel policies of the government (CCUS, biofuel and Green H_2).

s. Tax Concessions for encouraging green synthetic fuels.

The committee further proposes the following policies for implementing synthetic fuels programme in the country :-

  i. Blended Fuel/Promoting Carbon Circular Economy : Phased rollout of blended e-fuel to reduce carbon footprint

  ii. Compatible Engines : Policy push for faster development, production and adoption of tuned engines/marine/aviation for synthetic and blended fuels

  iii. Inclusion of Aviation/Marine Sector : Sectors which are not covered under electrification like aviation, marine and heavy-duty vehicles to be notified under Synthetic Fuel Policy

  iv. Incentive to boost Production : Incentive to synthetic fuel manufacturers and end-users to nurture ecosystem

  v. Special Research Grants : Special grants for research projects to reduce cost of production, improve conversion efficiency, new generation electrolyser and improve competitiveness

  vi. Carbon Credit/Promoting Circular Economy : Fostering decarburization by creating a carbon credit market

  vii. Dedicated budget : Dedicated budget to improve infrastructure enabling all associated industries to develop and scale up.

  viii. Implemenation of funding and incentives schemes for pilot projects, assigning them to research and development setups within the oil and gas industries under the Ministry of Petroleum and Natural Gas (MOP&NG).

  ix. Establishment of a Center for Excellence through international collaboration, involving academia, research institutes, industry bodies, and enterprises within the oil and gas sector to promote synthetic fuel production.

  x. Synthetic Fuel Exchange can be setup for sale and purchase of Synthetic Fuels.

xi. R&D support for indigenous equipment development and establishing a definitive support system for e-fuel adoption, such as tax incentives and subsidies, and discouraging biomass export to encourage domestic investments.

12. Acknowledgements

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