Deploying EU biomethane potential for transports: Centralized/decentralized biogasrefinery schemes to SAF and maritime fuels

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Deploying EU biomethane potential for transports: Centralized/decentralized biogasrefinery schemes to SAF and maritime fuels

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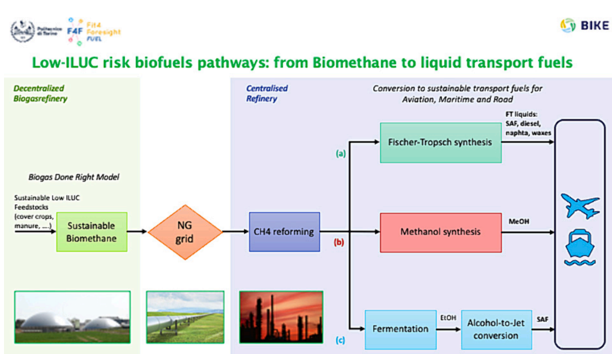
HIGHLIGHTS

- Decentralized biomethane-centralized Gas-to-Liquid can decarbonize EU aviation and maritime sectors.
- By 2030, GTL routes may satisfy 4–11% jet fuel and 25–56% of maritime fuel EU demands.
- By 2050, 9–25% of jet and 48–105% of maritime fuel EU needs could be covered by these paths.
- 2030 Italian jet fuel (7–18%) and maritime (69–152%) demands could be met by these routes.
- At 2050, 8–22% of jet fuel and 91–198% of maritime needs could be satisfied for Italy.

GRAPHICAL ABSTRACT



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ABSTRACT

As Europe faces the dual challenge of decarbonizing its energy sector while ensuring energy security, REPowerEU reinforces the ambitious targets outlined in the Green Deal, complementing the "Fit for 55" package. This work analyses sustainable biomethane production in Europe, with a specific focus on Italy, and its conversion into sustainable fuels. Under the light of existing policy targets and regulatory instruments, the study explores innovative and sustainable agro-energy chains, with biomethane as energy vector for producing sustainable aviation fuels (SAF) and methanol for maritime. Decentralized biomass digestion and centralized biomethane conversion in refinery are combined, considering three key Gas-to-Liquid (GTL) pathways: Fischer-Tropsch and methanol synthesis, and gas fermentation/alcohol-to-jet. A simulation model was used to estimate the performances of these routes, providing insights on process yields and energy balances. Additionally, preliminary investment cost estimates are considered by reviewing existing references and extrapolating unit-specific cost data.

As by 2030 biomethane in Europe could supply 38 bcm, the routes analysed could cover 4 to 11% of jet fuel demand, and from 25 to 56% of maritime fuel needs. By 2050, with a potential EU biomethane supply of 91 bcm, these pathways might meet 9–25% of jet fuel demand, and 48–105% of maritime fuel demand.

In Italy, by 2030, 5.6 bcm of biomethane could enable these pathways to meet 7–18% of jet fuel demand, and a remarkable 69–152% of maritime fuel demand. By 2050, with 8.2 bcm of biomethane, these routes might cover 8–22% of jet fuel demand, and potentially satisfy 91–198% of maritime fuel demand.

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Moreover, these pathways would also yield other added-value by-products (e.g. naphtha, diesel, waxes, hydrogen, gasoline), which should be considered in comparing them.
The average investment costs for each route were estimated at 791,970 USD/t/day for the Fischer-Tropsch based GTL plant, 130,275 USD/t/day for the methanol-based GTL plant, and 669,740 USD/t/day for the GTL plant involving gas fermentation/alcohol-to-jet conversion.

1. Introduction

In response to the urgent need to fight climate change, the European Union (EU) is taking decisive actions, focusing on accelerating the transition to a low-carbon economy and increasing the use of renewable energy sources, particularly in transportation, as outlined in the Renewable Energy Directive II (RED II) [1]. This directive sets an EU target of 32% for energy consumption from renewables by 2030, with a specific aim of reaching a 14% share in transport by the same year, including a minimum of 3.5% from advanced biofuels. Additionally, as regards GHG savings, RED II mandates a minimum 65% reduction in greenhouse gas (GHG) emissions for biofuels, emphasizing the sustainability criteria [2].

The "Fit for 55" climate package [3], adopted by the European Commission in 2021, further sets ambitious targets for emission reductions by 2030 and carbon neutrality by 2050. This includes revising the EU Emission Trading System (ETS) [4] to accelerate the decarbonization efforts in the energy-intensive industries and other high-emitting sectors, responsible for approximately 40% of EU greenhouse gas emissions. The revised EU ETS aims at reducing by 62% the emissions by 2030 compared to 2005 levels, with expanded coverage to include sectors like maritime transport. Furthermore, separate quota trading systems for buildings and road transport will be established from 2025.

Also due to the geopolitical events occurred in 2022, and the related evolution of the energy markets during the same year, the REPowerEU [5] plan set a series of measures to rapidly reduce EU dependence on fossil fuels and accelerate the green transition, while increasing the resilience of the EU energy system and reducing import dependency. Besides, on March 2023, the EU Institutions provisionally agreed on stronger legislation to accelerate the deployment of renewable energy, raising the EU's binding renewable energy target for 2030 to 42.5%, increasing from the prior 32% target, with an ambition to reach 45% [6]. The so-called RED III [5] was then published on the 31st of October 2023.

In the context of aviation, Sustainable Aviation Fuels (SAF) are gaining prominence as a necessary and immediate solution to reduce the carbon impact of air travel. Indeed, the European Union (EU) emphasized the adoption of SAF as a pivotal decarbonization strategy for the sector, suggesting a gradual increase in the amount of SAF available at EU airports [6]. The ReFuelEU aviation initiative thus introduced a mandate for SAF [7] for all flights departing from the EU territory. The agreement between the EU Parliament and the EU Council on April 26, 2023, surpassed the initial Commission's proposal [8], outlining a progressive and accelerated SAF adoption: 2% by 2025, 6% by 2030, rising to 20% by 2035, with a potential peak of 70% by 2050 at EU airports. This equates to a substantial demand for SAF, as the global aviation industry seeks to align with emission reduction targets and regulations.

Similarly, in the maritime sector, the demand for sustainable fuels is expected to significantly grow. As regulations progressively tighten on both GHG and non-GHG maritime emissions, and shipping come under greater scrutiny, maritime transport faces mounting pressure to transition toward cleaner energy sources. The International Maritime Organization (IMO) has set targets to reduce greenhouse gas emissions from international shipping by at least 50% by 2050 compared to 2008 levels [9]. This shift implies a substantial increase in the demand for sustainable maritime fuels, in particular deploying advanced biofuels. At EU level, the FuelEU Maritime regulation introduce progressive targets for carbon intensity reduction compared to average in 2020 for vessels larger than 5000 gross t: 2% (at 2025), 6% (2030), 14.5% (2035), 31% (2040), 62% (2045), 80% (2050). These vessels represent 55% of all ships, and 90% of emissions from the maritime sector.

Given these scenarios, it is thus necessary to quickly ramp-up the production of sustainable alternatives to conventional fossil fuels, while actively exploring innovative integration of high TRL pathways for their deployment.

However, designing, authorizing, building, commissioning, and starting to commercially operate new industrial biofuel facilities based on innovative sustainable technologies is complex, needs very large investments and requires a significant amount of time to complete. Moreover, in order to provide a quantitatively relevant contribution to the current and short−/medium-term volumes of EU liquid fuel demand, only process at or close to the FOAK (First Of A Kind) level, i.e. TRL 9, should be considered for the 2030–2040 targets. In addition, building sustainable supply chains for these sectors is a significant challenge, given the conditions set by the EU legislation in terms of eligible feedstocks, particularly in the lipid-based biofuel route, including hydroprocessed esters and fatty acids (HEFA) and hydrogenated vegetable oil (HVO). The combination of all these factors represents a major challenge to achieve the planned targets.

Biomethane, produced from organic waste and agricultural residues, is a very mature bio-based process that holds significant potential, not only as final product but also as intermediate energy carrier for further processing.

In fact, while the direct uses of biomethane already gathered attention over the past decades, there is a need to explore additional routes to maximize its deployment in achieving the decarbonization objectives in the transport liquid fuel sector. The production of biomethane, often called as *biogasrefinery* (given the multiple products and benefits that this value chain delivers), is a well proven but still innovative solution deployable at full commercial scale (TRL 9), thus able to deliver immediate contributions to achieving EU climate targets.

The production of biomethane is particularly attractive in those EU Countries where a significant gas infrastructure already exists, as it is the case of Germany or Italy (see Fig. 1).

Italy significantly supported the production of biogas for energy generation over the last decades through a series of specific norms and regulations, providing economic incentives for electricity generation plants. As a result, there are currently >2000 biogas power plants in Italy, with a total nominal power of 1.34 GW (as of April 2023 [11]).

A limited number of biogas plants have already been upgraded to biomethane production, mostly thanks to a previous incentive scheme (Ministerial Decree of 2 March 2018 [12]). Based on latest data given in the National Energy and Climate Plan, PNIEC, by the end of 2021 the production of biomethane achieved 159 Mill.m^3 (+60% compared to 2020) from 54 AD plants [13], but the potential is by far greater. Other estimations for 2023 report 85 biomethane plants for a total expected production capacity of 572 million standard cubic meters, but these are not yet confirmed in official statistics.

In Germany there are approximately 9600 biogas facilities. Among these, approximately 200 plants are equipped with an upgrading system to convert biogas into biomethane, which is subsequently integrated into the natural gas distribution grid [14].

In these Countries, as Italy, technical standards and regulatory systems are already in place, implementing a Guarantee of Origin system (in Italy primarily governed by the Ministerial Decree of July 6, 2012, no. 120 [15], which implements the European Directive 2009/28/EC

[16]). This allows to consider integrated decentralized-centralized schemes, i.e. the production of biomethane by a large number of biomethane plants (and injection in the National Grid, or transported by other means), and the collection of the same amount of biomethane in a centralized refinery, where the conversion to other transport fuel products can be carried out at the appropriate scale in existing installations.

Thus, the possibility of combining

- Decentralized *biogasrefinery*, delivering biomethane to the grid and Guarantees of Origin to the market operators (beyond biobased fertilisers)
- Injection of this biomethane in the national gas grid (or transport to refineries via other means)
- Conversion of the natural gas in a centralized refinery, with a volume matching that of the biomethane injected into the grid through associated Guarantees of Origin, thus effectively utilizing biomethane

appears as a very attractive option.

The concept of the proposed approach is shown in Fig. 2, where CH_4 is reformed to syngas and then converted to sustainable biofuels.

In fact

- The scheme offers the advantages of connecting decentralized biomass conversion (AD plants are relatively small scale in nature, reducing the needs for transporting large volumes of solid biomasses - associated to environmental impacts, as well as higher costs), with the centralized conversion in existing large-scale industrial refineries to sustainable liquid transport fuel products;
- The whole system is based on high-TRL fully commercial solutions. Biomethane is a technologically very mature bioprocess (even if open to further innovation), as well as the conversion of Natural Gas into fuels through technologies such as Fischer-Tropsch, partial oxidation, steam reforming, and gas fermentation.

The scope of this research work is to investigate and model the novel integration of these processes, combining sustainable biomethane technology with some Gas-to-Liquid (GTL) technologies, and to provide a preliminary insight into the current industrial investment costs. This research work covers energy modelling and the estimation of the potential contribution to aviation and maritime targets at EU and IT level: in a subsequent article, the economic and sustainability analysis will be discussed.

The goal of this paper is thus to assess the technical possibility to generate substantial volumes of sustainable aviation fuels (SAF) and maritime fuels, employing an integrated approach that encompasses various dimensions, elaborating mass and energy balances and thus the potential contribution to satisfy the expected demand.

The aforementioned proposed value chains leverage on advanced technologies and processes characterized by high Technology Readiness Levels (TRL), such as Biomethane and GTL technologies as Fischer-

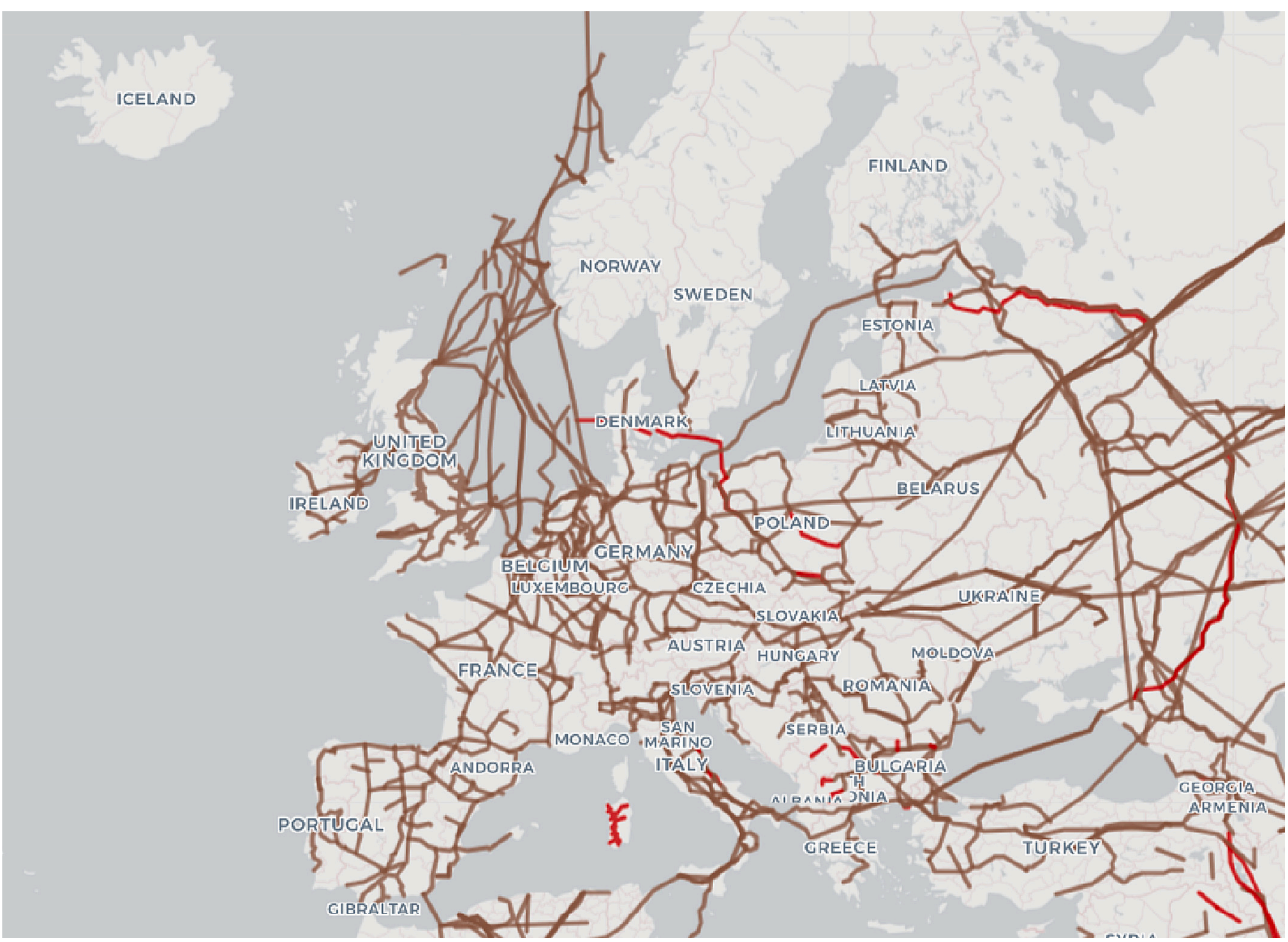

Fig. 1. *2023 EU natural gas grid in operation (brown) and under construction (red).* [10]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

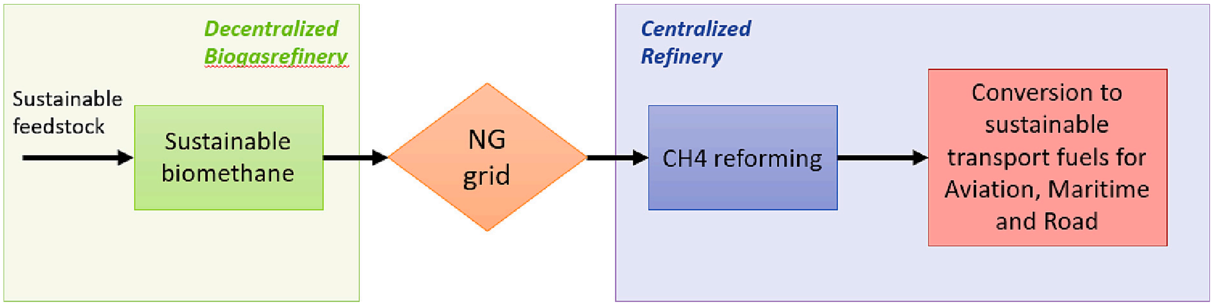

Fig. 2. Centralized/Decentralized scheme for liquid biofuels production (NG = natural gas).

Tropsch (FT) synthesis, methanol (MeOH) synthesis, gas fermentation and Alcohol-to-Jet (ATJ).

This study assumes that the Biogasdoneright model is adopted, which implements innovative and sustainable agricultural practices [17]. This model is known to deliver high GHG performances as well as environmental benefits to the food farming system. This further strengthens and remarks on the sustainable character of the proposed approach.

Beyond deploying the latest technological innovation, the proposed value chain also offers the unique opportunity to exploit the existing EU gas infrastructure to ramp-up the uptake of the advanced biofuels.

Furthermore, the conversion of existing fossil-based technologies and refineries by immediate integration of renewable feedstocks, such as biomethane, represents a key element of the strategy. This retrofitting not only maximizes the utilization of existing resources but also aligns with the broader sustainability goals.

Under the socio-economic point of view, these pathways would also allow to maintain in operation – while greening - existing fossil refinery sites, with clear benefit to the local communities, with creation of permanent jobs, both direct and indirect, as well as investment in the entire chains.

The proposed approach also benefits from the regulatory mechanisms already in place in some EU Member States, which allows to accelerate the achievement of EU targets and thus the implementation of EU policies.

2. Materials and methods

2.1. Biomethane-to-Liquid routes for aviation and maritime biofuels: value chain description

The considered value chain entails the production of advanced liquid biofuels production comprising: (i) biogas production in decentralized plants and upgrading to biomethane; (ii) biomethane injection into the natural gas grid and release of Guarantees of Origin for the amount of produced biomethane; and (iii) equivalent volume of biomethane processing in a centralized refinery, where methane is first reformed to syngas and then synthetized to liquids (kerosene, diesel, methanol, ethanol, etc.).

The decentralized Biogasdoneright (BDR) model encompasses the production of low or zero indirect land use change (ILUC) feedstock at farm scale. The primary goal of this model is to contrast the adverse effects on land from bioenergy demand and GHG emitting food production, with a focus on improving soil health and promoting sustainable farming in the food/feed/energy sector. This objective is supported by the following principles: (i) reducing the reliance on primary crops as digester feed; (ii) mitigating greenhouse gas emissions in agriculture by utilizing digestate as a renewable fertilizer/amendment that increase soil organic carbon, implementing sustainable agricultural practices and recovering nutrients; (iii) integrating agricultural production with these appropriately sized bioenergy units to enhance competitiveness in the food, feed, and energy sectors. Thus, according to the BDR scheme, the feedstock to be provided to the digester should be based on double cropping, with a primary crop for food and a secondary crop for energy, and/or the valorisation of waste biomass, as animal manure, to generate biomethane and fertilisers [17].

As for the centralized conversion of biomethane into advanced sustainable liquid biofuels, the proposed value chain involves the Gas-To-Liquid (GTL) technology. GTL traditionally allows for the conversion of natural gas into liquid hydrocarbons and oxygenates through chemical reactions, with natural gas converted to syngas, first. These hydrocarbons are fully equivalent (e.g. in terms of main chemical composition and physical properties) to fuels and chemicals produced in a conventional oil refinery in the range of gasoline and middle distillate range: naphtha, diesel, kerosene, lubricants, and waxes. GTL products may include other chemicals such as ammonia, methanol, or methyl tert-butyl ether (MTBE), a motor gasoline additive. The chemical conversion of methane to liquids allows for an alternative high TRL source of liquids to the traditional refinery products deriving from crude oil. In addition, GTL facilitates the transportation of methane from remote production sources to consumption destinations [18].

The GTL technology is based on three main steps: (i) reforming of methane to synthesis gas (syngas), primarily constituting a mixture of carbon monoxide and hydrogen; (ii) catalytic conversion of syngas to liquid hydrocarbons; (iii) products separation and upgrading [18]. Various reforming technologies are currently utilized for syngas production, including Steam Methane Reforming (SMR), Partial Oxidation (POX), and Auto Thermal Reforming (ATR).

The POX process generates syngas with a hydrogen-to-carbon monoxide (H_2/CO) molar ratio of approximately 2:1, making it suitable for various industrial applications, including Fischer-Tropsch synthesis. The POX reaction is the following:

$$CH_4 + \frac{1}{2}O_2 \rightarrow CO + 2H_2 \tag{1}$$

SMR, a mature technology, yields high hydrogen content (H_2/CO ratio is ~3), which could be separated and considered as an additional valuable product of the refinery. However, it also generates carbon dioxide (CO_2) emissions as a by-product, in contrast to POX. SMR reactions are shown below as Eq. (2) and (3).

$$CH_4 + H_2O \rightarrow CO + 3H_2 \tag{2}$$

$$CO + H_2O \rightarrow CO_2 + H_2 \tag{3}$$

Toward Net Zero, Carbon Capture and Sequestration (CCS) should be used in combination with SMR and fossil feeds. Indeed, the CO_2 emissions generated during SMR could also be further valorised through Carbon Capture and Utilization (CCU), which however necessitates the availability of supplementary hydrogen.

ATR, on the other hand, combines elements of both SMR and POX.

These technologies are employed by several industries. For instance, Shell and Sasol utilize POX [19–21], Rentech uses SMR [22], and Exxon Mobil utilizes ATR [23].

This study explores three different routes, notably:

a) GTL-FT: syngas is converted to Fischer-Tropsch (FT) liquids. The GTL plant capacity being considered in this case is 10,000 barrels per day (bpd) of FT products;
b) GTL-MeOH: syngas is converted to methanol (MeOH). The capacity of the GTL plant under consideration in this case is 2000 t/d of MeOH;
c) GTL-F_ATJ: syngas undergoes a fermentation process to be converted to ethanol (EtOH) and then further processed to jet fuel through the alcohol-to-jet (ATJ) technology. In this case, the capacity being considered for the GTL plant is 1000 t/d of products.

These sizes have been selected based on the typical dimensions of industrial plants available on the market or, alternatively, on possible minimum industrial sizes (details in [25,26]).

Fig. 3 shows the conceptual scheme of the proposed value chain, encompassing both the sequence of steps and the diverse routes that may be undertaken.

2.1.1. *The value chain within the Italian regulatory system*

Notably, these value chain aligns well with the Italian incentive scheme specified in the National Recovery and Resilience Plan (NRRP) "*Development of biomethane, according to criteria for the promotion of the circular economy*". This measure aims to support new biomethane production plants and the conversion of existing biogas facilities. The Ministerial Decree 15 September 2022 [24] enables access to the financial provisions of the NRRP and promotes the production of biomethane to be supplied to the existing natural gas network, allowing for both a CAPEX incentive (equal to a maximum of 40% of the costs incurred) and a feed-in incentive (incentive tariff applied to the net production of biomethane).

The Decree refers to the Guarantee of Origin (GO) – as also introduced in the REDII, a certificate that allows biomethane producers to demonstrate the renewable origin of their product, thereby determining the feed-in premium (TP) based on the average monthly price of natural gas (NGP) and the monthly average price of Guarantee of Origin (GOP). The GOs remain the property of the producer and can be sold to refineries. Consequently, the refinery purchasing the biomethane also gains ownership of the GO, enabling them to demonstrate the renewable origin of their products to final customers even if not physically connected to the anaerobic digestion unit.

The conceptual scheme of the overall system is shown in Fig. 4.

2.2. *Value chain assessment*

The assessment of the three distinct biofuel production routes along the proposed value chain was based on an extensive literature review encompassing legislative frameworks, potential incentives, the identification of industrial reference plants for all technologies, investment costs, and notably, employs a simulation model specifically developed for this analysis to allow for the calculation of process yields and mass/energy balances. The model was developed using the software Aspen Plus to simulate both GTL-FT and GTL-MeOH pathways. The main input to the model is the quantity of biomethane in the supply chain, which is set based on the size of the GTL plants, while the primary outputs consist of the quantity of liquid biofuels produced by the specific route, the by-products, and the energy consumption. As for the GTL-F_ATJ route, the level of analysis for this route is not as detailed as for the others in this study, since this pathway only recently achieved full industrial scale. The ATJ pathway has been certified under ASTM specifications ASTM D7566 Annex 5 for the production of drop-in aviation fuel in April 2016 for isobutanol as feedstock, and June 2018 for ethanol [60]. Therefore, it has been opted to rely on references from the literature for yield and

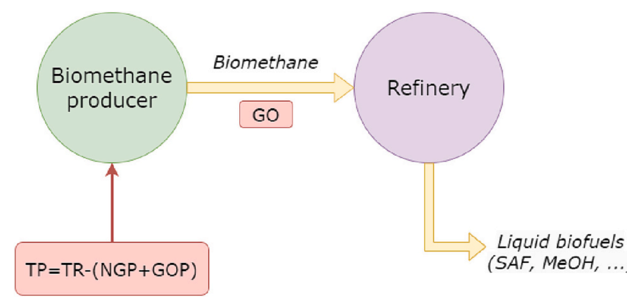

Fig. 4. Conceptual scheme of the Italian Biomethane Decree and the proposed integrated approach with refineries (TP = feed-in premium, TR = reference fare, NGP = average monthly price of natural gas, GOP = monthly average price of guarantees of origin, GO = guarantees of origin, SAF=Sustainable Aviation Fuels, MeOH = methanol)

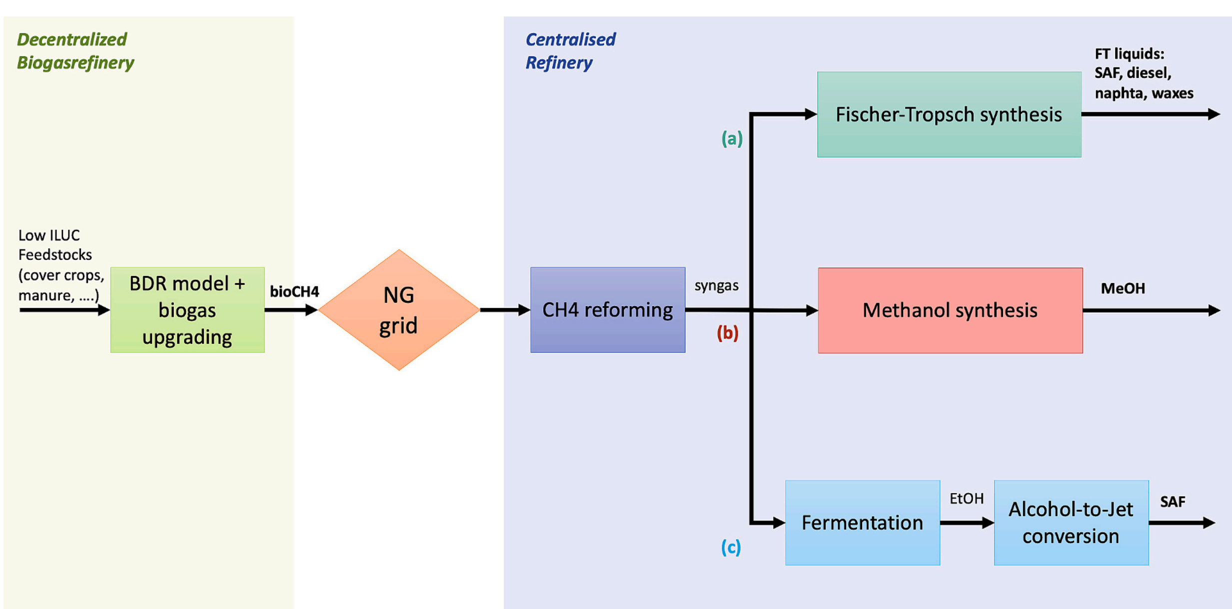

Fig. 3. Liquid biofuels production chain scheme (BDR = Biogasdoneright model; NG = natural gas; FT = Fischer–Tropsch; MeOH = methanol; EtOH = ethanol; SAF = Sustainable Aviation Fuels)

energy consumption data.

2.2.1. Modelling

The simulation model developed for the GTL-FT and GTL-MeOH routes builds upon the results of our previous review work [27] aimed at investigating a broad spectrum of suitable biomass-to-liquid conversion pathways and their modelling. The initial segments of both models are identical, encompassing a reforming section, with the primary distinction between the models residing in the final block—where one replicates FT synthesis and the other replicates MeOH synthesis. As for the reforming section, both the SMR and POX methods have been modelled. The modelling approach and process conditions draw from reference simulation models: Ayad et al. [22] for POX, and Er-Rbib et al. [28] for SMR.

Within the Fischer-Tropsch synthesis unit, the output consists of water, off gas (C1-C4) and syncrude, categorized by carbon content: naphtha (C5-C9), kerosene (C10-C16), diesel (C17-C21), and waxes (C21+). Kerosene is regarded as the main product of interest for retaining kerosene-based jet fuel, and therefore, Sustainable Aviation Fuel (SAF). Our primary reference simulation model for the FT synthesis segment was based on Dahl et al. [29].

As for the GTL-MeOH plant, the reference simulation model considered for the methanol synthesis unit is Gamero et al. [30].

As previously mentioned, the syngas produced by the SMR has a $H_2/CO > 2$, which is the required ratio for FT and MeOH synthesis. Consequently, excess hydrogen is generated in this process. This excess hydrogen is an additional refinery product that can be marketed alongside the primary products (FT liquids and methanol). In modelling, a separator has been included after the SMR reforming stage: this separator allows to obtain one stream with the H_2/CO ratio of 2, which is then directed to the FT and MeOH synthesis reactors. Simultaneously, another stream containing the excess hydrogen is released as a separate final product.

Concerning the GTL-F_ATJ pathway, the methane reforming stage was simulated in a similar way to the other routes examined, employing Steam Methane Reforming (SMR) technology with a target syngas H_2/CO ratio of 2. The syngas fermentation process, just appearing on the market, was modelled based on recent literature reviews and published data, particularly leveraging information from [31] that details the technology, as well as [32,33]. Notably, the gas fermentation process is versatile, operating with a wide range (up to 5 [34]) of H_2/CO gas compositions [35]. The data for the alcohol-to-jet (ATJ) process was then sourced from [36]. It is important to underline that SMR was selected as the reforming technology for this pathway due to the ATJ process's hydrogen demand during the CO_2 hydrogenation phase. Integrating hydrogen production within the refinery, in tandem with syngas generation, offers potential advantages. Moreover, any surplus hydrogen produced can be commercially exploited alongside the primary output, jet fuel.

3. Results

3.1. Reference plants and investment costs

In this section, a brief overview of reference industrial plants and their associated investment costs is presented, as an outcome of the literature review conducted within this study.

3.1.1. GTL-FT route

The leading technology in the market is the FT technology by Shell and Sasol [37], with large-scale GTL plants. Traditional GTL facilities normally utilize coal or natural gas to attain economies of scale, producing over 10,000 bpd of liquid products [25]. The Oryx GTL plant and the Pearl GTL plant in Qatar and Bintulu, Malaysia are two examples. Table 1 reports the main commercial-scale GTL-FT plants in operation around the world.

Table 1
Main GTL FT-based plants worldwide [25].

Plant/Company	Capacity [bpd]	CAPEX [USD Billion]	Location	Year
Mossel Bay GTL, PetroSA	22,500	4	South Africa	1992
Bintulu GTL, Shell	12,000	0.85	Malaysia	1993
Oryx GTL, Qatar Petroleum and Sasol	34,000	6	Qatar	2007
Pearl GTL, Shell and Qatar Petroleum	140,000	19	Qatar	2011
Escravos GTL, Chevron, Sasol, and Nigerian National Petroleum Corp	33,000	10	Nigeria	2014
Turkmenistan, Turkmenistan's state-owned	15,500	2.5	Turkmenistan	2018
Uzbekistn, Sasol, Petronas, and Uzbekneftegaz	38,000	3.7	Uzbekistan	2020

As regards investment costs, information derived from Table 1 is plotted in Fig. 5 to show the capacity in barrels per day (bpd) and the pertaining Capital Expenditures (CAPEX).

Fig. 5 shows how the capacity GTL FT-based plants and related CAPEX do not have a linear relationship.

Moreover, other data available in literature show some volatility as concerns the Capital Expenditure of GTL plants. For instance, Wang and Economides [18] stated that the capital expenditure for a GTL plant in the 1950s was about 120,000 USD/bpd and decreased in the first decade of the 2000s to <50,000 USD/bpd, with a target to reach below 20,000 USD/bpd. Moreover, Velocys is developing a 1000 bpd plant with estimated CAPEX of 100,000 USD /bpd, while INFRA Technology and Greyrock offer similar capacities at 60,000 to 100,000 USD/bpd [37]. On the other hand, Calvert Energy Group and Primus offer GTL technology at USD 45,000/bpd and USD 74,000/bpd respectively [37]. Arno De Klerk [38] indicates a CAPEX of 62,000 UDS/bpd (price in 2010), with a cost breakdown shown in Fig. 6.

Considering both the average costs per barrel per day for GTL plants reviewed and the observed high variability in the data, in line with Wang and Economides' theory of decreasing prices over time, we've specifically chosen 80,000 USD as the estimated cost per barrel per day of products for the GTL-FT plant. This corresponds approximately to $791,970 USD per ton per day.

Also, in the presented case study, it was assumed the existence of an operational refinery. In this scenario, certain costs would be inherently absorbed by the presence of pre-existing infrastructure.

3.1.2. GTL-MeOH route

As for the GTL-MeOH plant, similarly to the GTL route from natural gas, methanol production from syngas is a commercially demonstrated

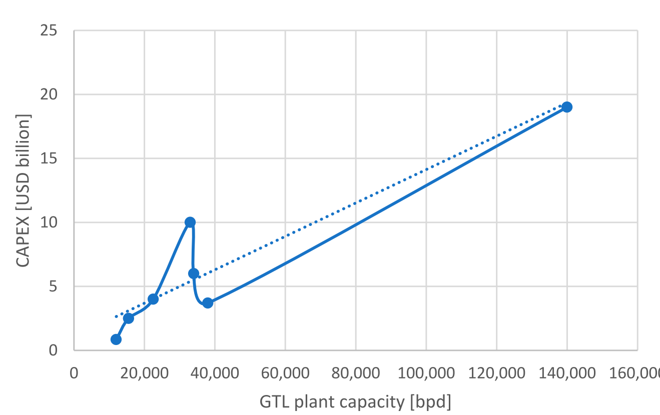

Fig. 5. Existing GTL FT-based plants capacity and related CAPEX.

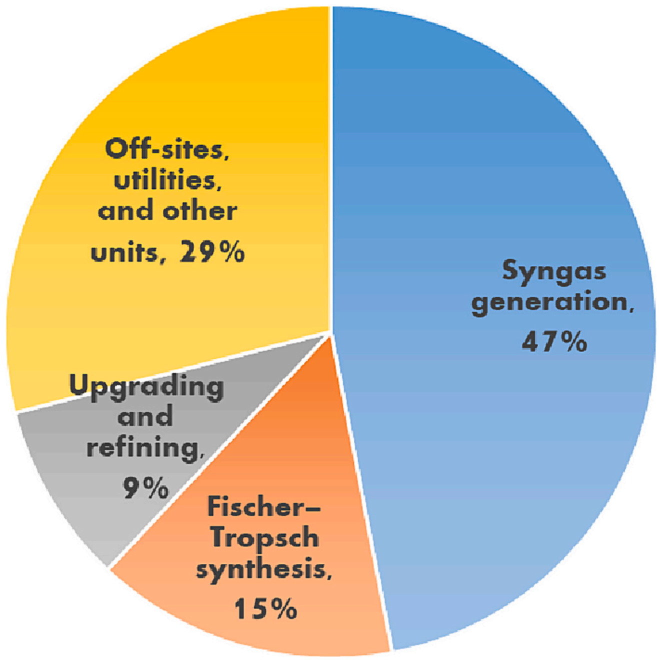

Fig. 6. Breakdown of CAPEX for a GTL plant [38].

technology, and the average size of the current top-tier methanol facilities worldwide is in the range of 2000 to 2500 t/d. Larger-scale applications (5000 t/d) are also possible [39]. Nowadays, the largest producer and supplier of methanol is Methanex Corporation. As examples of MeOH plants, we can report the Titan plant (850,000 t/y) and the Atlas plant (1.7 Mt./y, world's largest methanol plant), both in Trinidad.

Among the most recent news, the construction of Methanex Geismar 3 is approaching completion, with a budget of 1.23–1.3 billion USD, aimed at an annual methanol production capacity of 1.8 Mt. [40]. Geismar 3 leverages a significant portion of the existing infrastructure originally developed for Geismar 1 & 2.

In addition, in the United States, the Koch Methanol St. James [41] plant was previously commissioned, initially estimated at USD 1.85 billion for constructing a greenfield plant with a capacity of 1.7 Mt.

Table 2 presents the primary operational commercial-scale GTL-MeOH plants in the United States and Canada [26].

Concerning investment costs, data in Table 2 are graphically represented in Fig. 7, showing the capacity in tons per day (t/d) alongside the corresponding CAPEX. As highlighted in the figure, the capacity of the reviewed GTL-MeOH plants and their associated CAPEX do not have a linear relationship. However, referencing the information in Table 2, we can derive an average figure and estimate a specific CAPEX cost of 130,276 USD/(t/d).

Methanol, in addition to its role as a biofuel, is a bulk chemical, serving as a key building block to various chemicals and materials. It finds demand across diverse sectors, including formaldehyde, acetic acid, olefins, polymers, fuel blending, and solvents. Examples of

Table 2
Recent US MeOH plants (2011–2015) [26]

Plant/Company	Capacity [t/d]	CAPEX [USD Billion]	Location	Year
Methanex	1392	0.06	Alberta, Canada	2011
OCI	2227	0.06	Texas, US	2012
LyondellBasell	2172	0.15	Texas, US	2013
Celanese/ Mitsui	3619	0.9	Texas, US	2015
Geismar #3	4932	1.3	Louisiana, US	2023

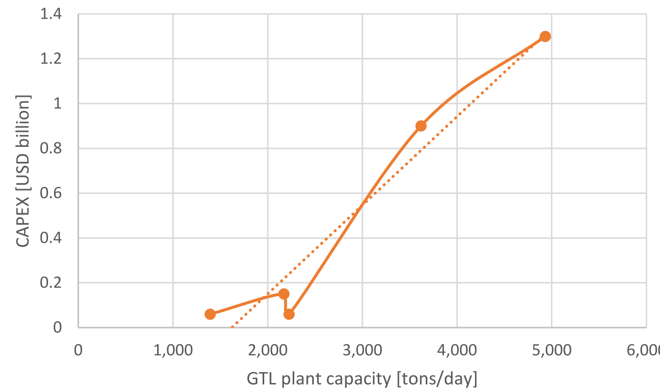

Fig. 7. Existing GTL MeOH-based plants capacity and related CAPEX.

methanol projects for chemical applications are provided in Table 3.

In 2022, according to Methanol Institute data, the global supply of renewable methanol is estimated at approximately 300,000 t, while global demand stands at around 88.7 Mt. Most of this renewable methanol supply is derived from bio-methanol. In the United States, companies like OCI, Methanex, Proman, Mitsui/Celanese have obtained sustainability certification for their bio-methanol using the mass balance method. Within existing natural gas-based methanol production facilities, these companies can procure biogas or biomethane injected into the pipeline system. Maersk is fuelling its inaugural voyage of the first carbon-neutral container ship with bio-methanol supplied by OCI Fuels [42] [43]. Methanex embarked on its inaugural carbon-neutral ocean voyage, utilizing a blend of bio-methanol and traditional fossil natural gas-derived methanol [44].

3.1.3. GTL-F_ATJ route

A number of companies have been developing and started to commercialize the Alcohol-To-Jet (ATJ) process. Leading industries in these efforts are LanzaTech and Gevo, specialized in ethanol and isobutanol production, respectively. LanzaTech demonstrated successful production of sustainable aviation jet fuel (SAF) from gas fermented ethanol in partnership with Virgin Atlantic and Pacific Northwest National Laboratory [36]. In 2016, Gevo's ATJ pathway received approval for a 30% blend mix with jet fuel, whereas Lanzatech's ATJ pathway obtained approval for a 50% blend mix with jet fuel in 2018 [45].

As for the CAPEX of this specific route, according to the reviewed literature, the syngas fermentation section would cost about 235,881 USD/(t/d_{EtOH}) [46], while the ATJ section would be around 229,906 USD/(t/d) [36]. Thus, by combining the two parts of the process chain and normalizing the cost of syngas fermentation from ethanol tonnage to SAF tonnage, the capital cost per unit of product is estimated at 669,740 USD/(t/d).

3.2. Modelling the process routes

This section reports the outcomes derived from the simulation model. The paragraph is structured into three primary segments: the initial segment discloses findings related to the GTL-FT route, followed by the subsequent segment which showcases results from the GTL-MeOH pathway. In both instances, the results are presented whether the refinery utilizes POX or SMR. Lastly, the third part encompasses assessments pertaining to the GTL-F_ATJ route.

3.2.1. GTL-FT route

3.2.1.1. POX scenario. In the assumed scenario of a 10,000 barrels per day (bpd) GTL FT-based plant using POX, results from the simulation model indicate a demand for approximately 2.8 million cubic meters per day (1.02 billion cubic meters per year) of biomethane. Assuming the

Table 3
MeOH projects around the world, 2022 (Chemical Market Analytics by OPIS, a Dow Jones Company).

Methanol Projects [kt]							
COMPANY	LOCATION	2021	2022	2023	2024	2025	2026
Methanex	Geismar, LA	–	–	–	1800	1800	1800
Big Lake Fuels	Lake Charles, LA	–	–	–	–	–	1400
US Methanol	Institute, WV	–	17	200	200	200	200
Koch Methanol St. James, LLC	St James Parish, LA	144	1700	1700	1700	1700	1700
Celanese Mitsui JV	Clear Lake, TX	1300	1500	1530	1620	1620	1620
Caribbean Gas Chemical	La Brea, Trinidad	1000	1000	1000	1000	1000	1000
Alpont LLC	Ohio, US	–	–	91	91	91	91
JSC Shchekinoazot	Shchekino, Russia	–	500	500	500	500	500
Dena Petrochemical	Iran	–	–	–	–	1650	1650
Sabalan	Iran	140	1650	1650	1650	1650	1650
Assam PC	Namrup, India	–	14	165	165	165	165
Jiutai Energy	Inner Mongolia, China	–	–	1000	1000	1000	1000
Guangxi Huayi Energy Chemical	Guangxi, China	1008	2000	2000	2000	2000	2000
Guoneng Yulin Chemical	Shaanxi, China	1504	1800	1800	1800	1800	1800
Zhongmei Mengda	Inner Mongolia, China	500	1000	1000	1000	1000	1000
Sarawak Petchem	Sarawak, Malaysia	–	–	–	568	1700	1700
Others		561	1750	2768	2858	2858	2858
Closures	Various	–	1000	2000	2400	2400	2400
	NET TOTAL INCREASE	**–**	**5774**	**1450**	**2171**	**2782**	**1400**

refinery is supplied by biogas facilities of 1 MWe equivalent capacity, this would theoretically result in approximately 516 plants needed to adequately support this specific refinery configuration. The 1 MWe size has been considered since it was the reference dimension in the previous Italian decrees, supporting biogas for renewable heat and power generation: thus, there is a large network of plants potentially available for retrofitting to biomethane. It is however worth to remark that typical biomethane plants have in average a larger size, of some 2–3 to 5 MWe capacity: therefore, the calculation of the number of plants needed is for reference only and could be considerably reduced if different biomethane sizes are considered, and the market grows as expected.

In terms of power requirements, the GTL plant calls for approximately 28.85 MW of electricity and 197.77 MW for cooling duties.

The distribution of products from the GTL plant is given in Table 4. Fig. 8 provides the mass and energy balance of the value chain, including: the oxygen generated by the Air Separation Unit (ASU) for supply to the Partial Oxidation (POX) segment, the resultant off gas from the overall process, and the water produced via the Fischer-Tropsch synthesis.

It is however also possible to implement smaller scale FT units - of the order of 1000 bpd - given the status of technology development in this field and thanks to decoupling biomass sourcing for biomethane from its conversion in existing refineries: this strongly reduce the need for biomass mobilization compared to a centralized approach. At the same time, the possibility to feed a full industrial scale fossil refinery with large volumes of biomethane through Guarantees of origin will deliver better performances.

3.2.1.2. SMR scenario. In the case that the 10,000 bpd GTL FT-based refinery employs SMR, the model indicates a demand for approximately 6.1 million cubic meters per day (equivalent to 2.23 billion cubic meters per year) of biomethane. Assuming again the refinery is theoretically supplied by AD facilities with a capacity of 1 MWe each, this dimension would require approximately 1128 plants to adequately support this specific refinery configuration. As an additional product, the plant produces about 1063 t/d of hydrogen.

In terms of power requirements, the GTL plant requires around 985.38 MW of electricity, 664.5 MW for heating duties, and 242.94 MW for cooling duties. Results are shown in Fig. 9.

Table 4
10,000 bpd GTL FT-based plant: products distribution. Source: simulation model developed by the authors.

Product	[bpd]	[t/d]
Naphtha (C5-C9)	2981	218.74
Kerosene (C10-C16)	2240.6	221.91
Diesel (C17-C21)	956.8	94.92
Waxes (C21+)	3821.6	474.56

3.2.2. GTL-MeOH route

3.2.2.1. POX scenario. For a GTL MeOH industrial plant processing 2000 t/d, the model calculated a demand of around 1.82 million cubic meters per year (1.82 Mm^3/d) of biomethane. Assuming the refinery is supplied by biomethane facilities with a 1 MWe equivalent capacity, approximately 336 such plants would be required to sufficiently support this specific refinery configuration.

Regarding power requirements, the GTL plant needs about 73.48 MW of electricity (primarily for compressor operation) and 176.83 MW for cooling purposes.

Fig. 10 provides a complete mass and energy balance of the modelled value chain.

3.2.2.2. SMR scenario. For a GTL MeOH industrial facility processing 2000 t/d with SMR, a biomethane demand of roughly 3.98 Mm^3/y (equivalent to 1.45 Mm^3/d) is estimated. Assuming the refinery is supplied by biomethane facilities with a 1 MWe equivalent capacity, 735 such plants would be necessary to adequately feed this specific refinery configuration. Additionally, the plant generates approximately 693.2 t/d of hydrogen. In terms of power requirements, the GTL plant necessitates around 690.2 MW of electricity, primarily for compressor operation, 433.2 MW for heating duties, and 256.8 MW for cooling purposes. Fig. 11 shows the mass and energy balance of this specific case.

3.2.3. GTL-F_ATJ route

The chosen scale for the GTL plant produces 1000 t/d of valuable products, such as about 100 t/d of gasoline, 700 t/d of jet fuel and 200 t/d of diesel.

This approximately requires 6.64 Mm^3/d (2.42 billion m^3/y) of biomethane, which would translate into 1226 biomethane plants - at the stated 1 MWe reference capacity.

Additionally, as the process requires 11.1 t/d of hydrogen, it will also generate the extra yield of 1144 t/d of hydrogen from SMR, alongside the production of jet fuel, gasoline, and diesel.

The total electric power required by the system for electricity is about 278.12 MW, the total thermal power for heating duties is about

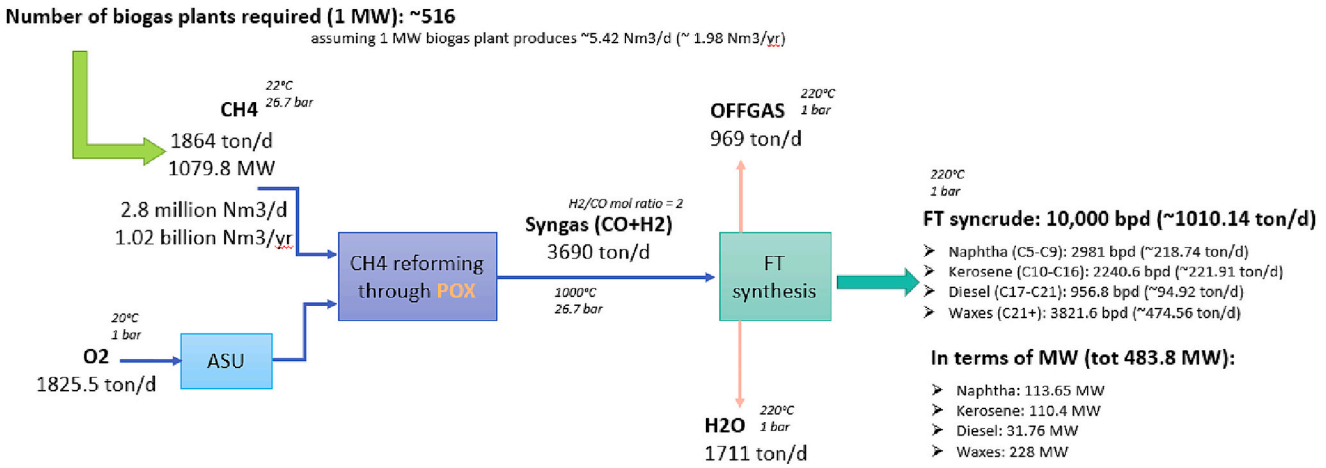

Fig. 8. 10,000 bpd GTL-FT based plant (POX scenario): simulation results.

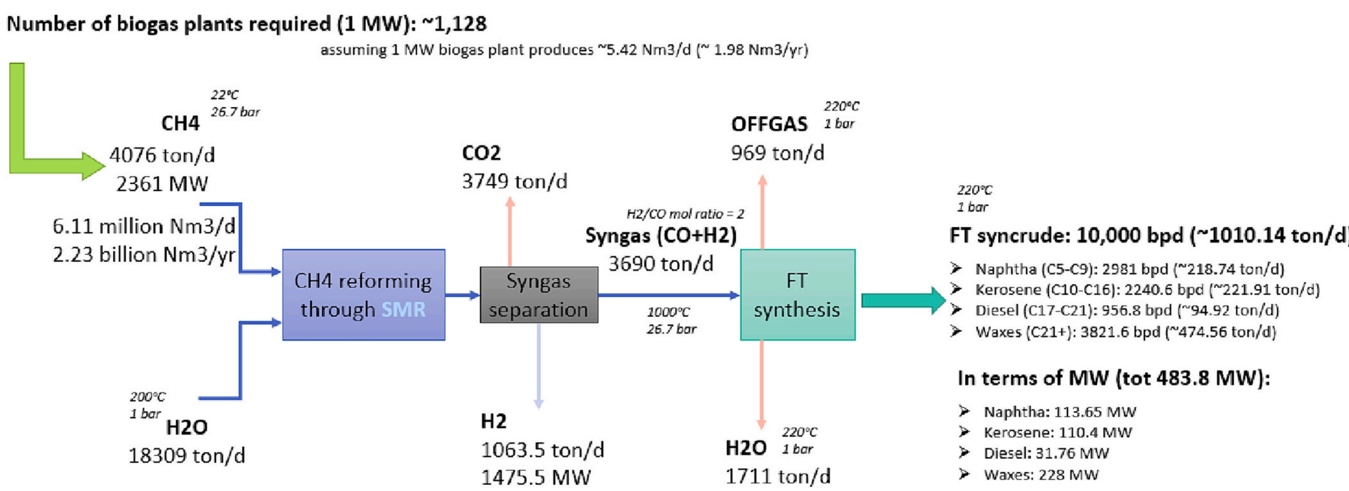

Fig. 9. 10,000 bpd GTL-FT based plant (SMR scenario): simulation results.

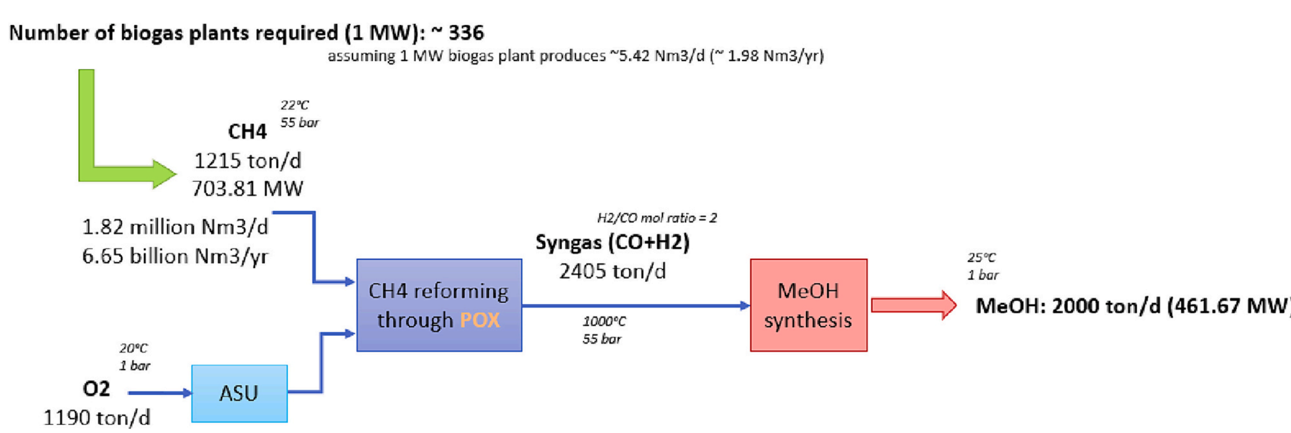

Fig. 10. 2000 t/d GTL-MeOH based plant (POX route): simulation results.

722 MW, while for cooling duties it is about 902.23 MW. Also, note that the power requirement calculation did not account for the syngas fermentation section due to the absence of comprehensive and non-aggregated information on the consumption of this innovative process in the literature. Fig. 12 reports the mass balance of the process.

4. Discussion

In this study, three distinct pathways to produce advanced liquid biofuels are examined, all sharing a common decentralized feedstock and sustainable biomethane production model, known as the Biogasdoneright model, with biogas upgrading to biomethane and injection into the natural gas grid. Additionally, for the GTL-FT and GTL-MeOH

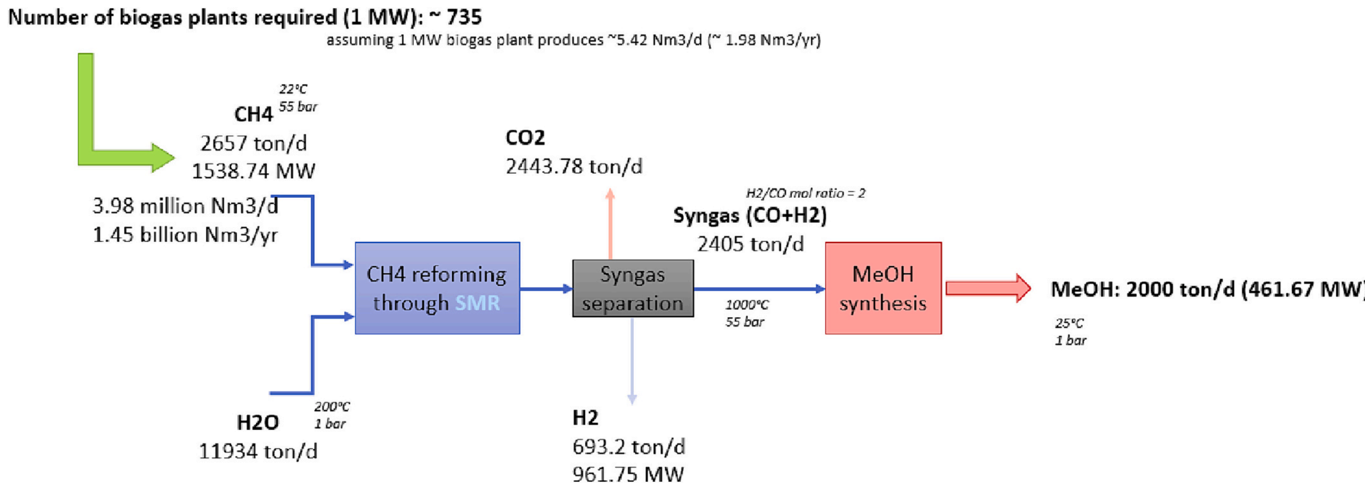

Fig. 11. 2000 t/d GTL-MeOH based plant (SMR route): simulation results.

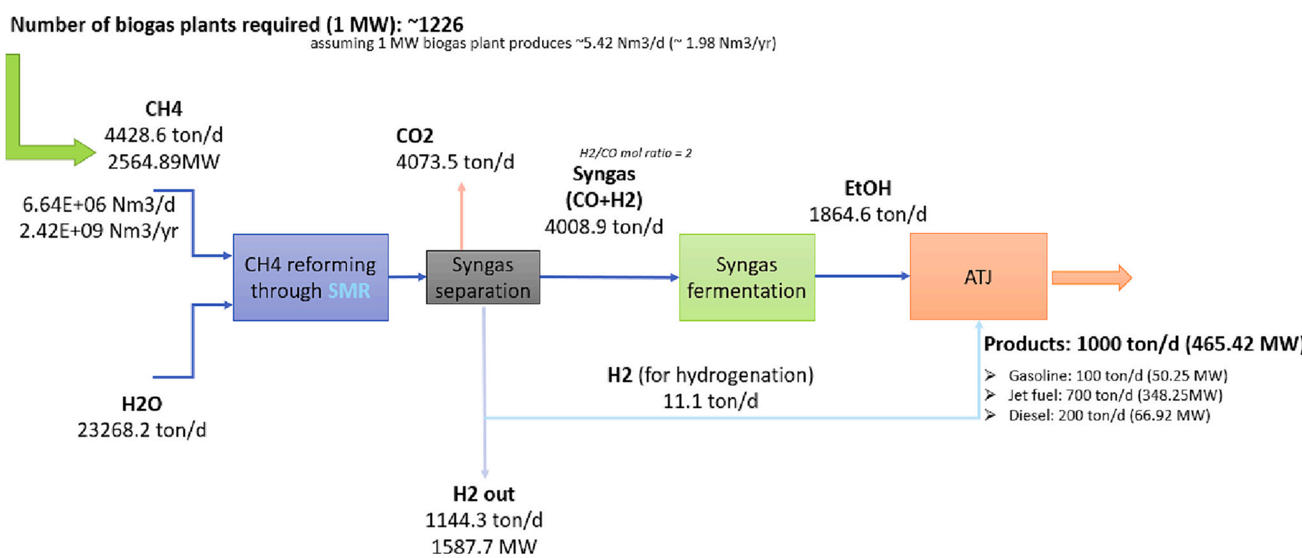

Fig. 12. 1000 t/d GTL-F_ATJ based plant: model results.

routes, we explored two different options, namely the use of Steam Methane Reforming (SMR) and Partial Oxidation of Methane (POX) as reforming technologies, considering energy consumption, efficiencies, and resulting by-products in each case. Table 5 reports the conversion efficiencies (MJ of product per MJ of CH_4 as feedstock) of the three GTL routes and their various configurations, calculated based on the higher heating values (HHV) of the fuels.

Table 5
MJ of products per MJ of CH_4 as feedstock for the three GTL routes.

Route	Product	POX	SMR
		[MJ/MJ$_{CH4}$]	[MJ/MJ$_{CH4}$]
GTL-FT	*Naphtha*	0.102	0.047
	Kerosene	0.099	0.045
	Diesel	0.042	0.019
	Waxes	0.211	0.096
	Hydrogen	–	0.666
	Total	**0.454**	**0.874**
GTL-MeOH	*Methanol*	0.682	0.312
	Hydrogen	–	0.666
	Total	**0.682**	**0.978**
GTL-F_ATJ	*Gasoline*	–	0.019
	Jet fuel	–	0.132
	Diesel	–	0.037
	Hydrogen	–	0.660
	Total	**–**	**0.847**

Table 6 presents results in terms of yields (t of products per t of CH4) and potentials for FT liquids, MeOH, and ATJ products production from biomethane in Italy (IT) and the European Union (EU), projected for the years 2030 and 2050. Additionally, the table highlights alternative methane reforming options to syngas and shows the potential hydrogen production for each route. Details on the potential production of biomethane in Italy and Europe are sourced from the Gas for Climate [47], and will be further discussed in the following, for comprehensive understanding of these figures.

Considering the POX option, both GTL-FT and MeOH exhibit higher yields in terms of methane conversion into the main products of interest, namely SAF and MeOH. Fig. 13 and Fig. 14 provide a comparative analysis of conversion efficiencies (MJ of product per MJ of CH_4 as feedstock) between the two options, POX and SMR, for both the GTL-FT and GTL-MeOH cases.

Nevertheless, in the case of SMR utilization, there is a noteworthy production of green hydrogen, a highly valuable commodity in any refinery operations.

When considering the implementation of SMR and POX within an

Table 6
FT liquids, MeOH, ATJ products, and H2 production potential from biomethane in IT and EU, in 2030 and 2050.

	Year	CH_4 potential [Mt/y]	Reforming process	Conversion route	Fuel yield [t_{fuel}/t_{CH4}]	H_2 yield [t_{fuel}/t_{CH4}]	Liquid fuel [Mt/y]	H_2 [Mt/y]
IT	**2030**	3.68	SMR	GTL-FT	0.2478	0.2609	0.91	0.96
		3.68	POX	GTL-FT	0.5418	–	1.99	–
		3.68	SMR	GTL-MeOH	0.7500	0.2609	2.76	0.96
		3.68	POX	GTL-MeOH	1.6500	–	6.07	–
		3.68	SMR	GTL-F_ATJ	0.2258	0.2600	0.83	0.95
	2050	5.39	SMR	GTL-FT	0.2478	0.2609	1.34	1.41
		5.39	POX	GTL-FT	0.5418	–	2.92	–
		5.39	SMR	GTL-MeOH	0.7500	0.2609	4.04	1.41
		5.39	POX	GTL-MeOH	1.6500	–	8.89	–
		5.39	SMR	GTL-F_ATJ	0.2258	0.2600	1.22	1.39
EU	**2030**	24.97	SMR	GTL-FT	0.2478	0.2609	6.19	6.51
		24.97	POX	GTL-FT	0.5418	–	13.53	–
		24.97	SMR	GTL-MeOH	0.7500	0.2609	18.72	6.51
		24.97	POX	GTL-MeOH	1.6500	–	41.19	–
		24.97	SMR	GTL-F_ATJ	0.2258	0.2600	5.64	6.45
	2050	59.79	SMR	GTL-FT	0.2478	0.2609	14.82	15.60
		59.79	POX	GTL-FT	0.5418	–	32.39	–
		59.79	SMR	GTL-MeOH	0.7500	0.2609	44.84	15.60
		59.79	POX	GTL-MeOH	1.6500	–	98.65	–
		59.79	SMR	GTL-F_ATJ	0.2258	0.2600	13.50	15.45

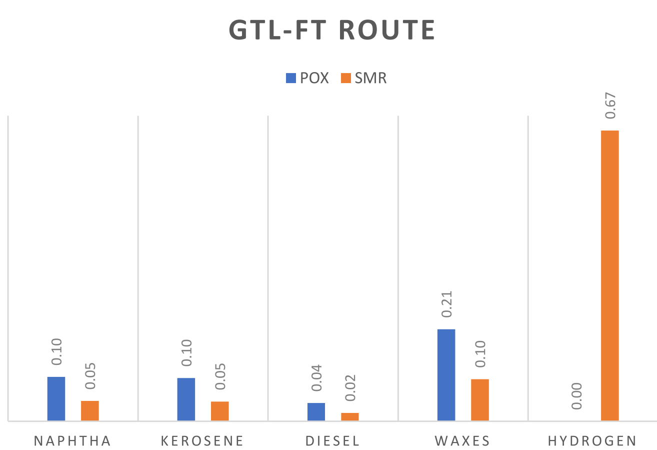

Fig. 13. Comparison between POX and SMR reforming configurations in terms of feedstock conversion (MJ of product per MJ of CH_4 as feedstock) for the GTL-FT route.

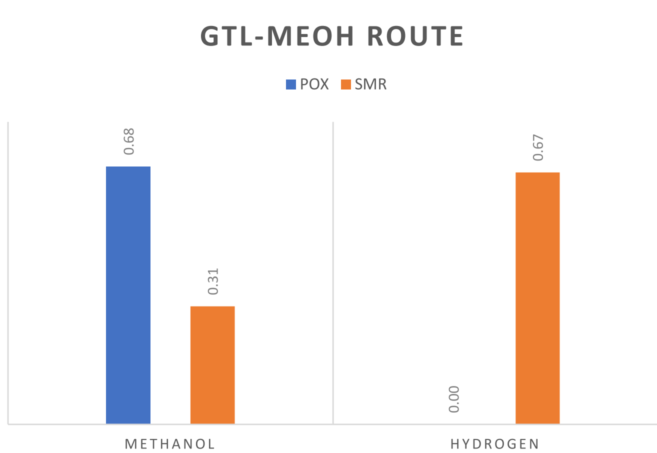

Fig. 14. Comparison between POX and SMR reforming configurations in terms of feedstock conversion (MJ of product per MJ of CH4 as feedstock) for the GTL-MeOH route.

industrial complex, several crucial factors must be carefully considered. These factors encompass existing infrastructure, operational requirements, feedstock availability, and environmental impact.

SMR stands out for its ability to provide a stable and reliable hydrogen supply, a critical necessity for processes demanding consistent access to hydrogen. SMR relies on a steady supply of natural gas and steam, typically readily available in industrial settings. In contrast, POX, in addition to methane, necessitates a source of oxygen or air, which adds complexity to feedstock supply within the industrial complex.

Furthermore, addressing environmental concerns is of paramount importance. SMR requires attention to the associated CO_2 emissions, especially if these are of non-biogenic origin. Implementing carbon capture and utilization (CCU) or storage (CCS) technologies is essential for mitigating these emissions when using fossil natural gas. Instead, in the case of biomethane, the utilization of these technologies represents a kind of BECCS/U pathway, i.e. BioEnergy with Carbon Capture and Storage or Utilization.

The possibility of utilizing existing refineries in Europe to implement the three routes described in the article presents both opportunities and challenges. Europe currently has 89 operational refineries and 35 closed ones [48], as shown in Fig. 15 (more details are provided in Table A1, in the Supplementary Data section). On one hand, leveraging existing infrastructure can offer significant economic advantages, as it avoids the substantial capital investment required for building entirely new facilities. Additionally, retrofitting existing refineries can accelerate the adoption of these pathways, potentially addressing the pressing need for cleaner and more sustainable energy sources. However, it is essential to consider that the scale of existing refineries may not always align with the optimal size for the proposed routes in terms of economics and environmental performance, and that the FT is not deployed at scale in the EU.

Striking the right balance between utilizing existing infrastructure and potentially building new ones, appropriately sized facilities will be a crucial step in deploying the full potential of these routes while maintaining economic and environmental viability. Although larger refineries tend to have better economies of scale and potentially superior environmental performances, smaller facilities, like a 1000-barrel-per-day (bpd) Fischer-Tropsch (FT) plant, are today technically feasible and less impacting on the socioeconomic context, and realised in existing underexploited refinery fields (brown fields). Indeed, over the past few years, the development of smaller GTL plants has been a relevant subject-matter for innovation and nowadays technology for small-scale FT plants has been developed [49] [50]. Small-scale GTL technology has capacities ranging from 50 bpd to 5000 bpd [51]. For instance, Velocys is developing a 1000 bpd modular system to produce diesel and naphtha at an estimated investment cost 100,000 USD/bpd [37] [52]. Other examples [50] of companies providing small-scale GTL facilities

Fig. 15. Map of existing refineries in EU [48].

are: CompactGTL [53] [49], INFRA technology [54], Gas Technologies LLC, INERATEC, GasTechno Energy & Fuel from the USA [55], and Primus [49].

As for methanol, small-scale plant technologies are also under development: for instance, Haldor Topsoe, jointly with Modular Plant Solutions (MPS), has designed and engineered a small-scale methanol plant (215 t/d), namely "Methanol-To-Go™".

Compared to large-scale applications, small-scale GTL FT plants have logistical advantages, reduced capital cost, as well as a good flexibility to utilize a greater variety of carbon-containing materials as feed [56], including stranded natural gas (flared gas), landfill gas, biogas, or biomass and residual wastes [25]. These advantages have been confirmed by professionals on the Global Gas Flaring Partnership (GGFR) committee at the World Bank, who investigated small-scale GTL technology thoroughly [57].

In line with the ReFuelEU Aviation initiative [8], to attain a target of 5% SAF use for all flights leaving from EU airports by 2030, an estimated 2.3 Mt. of SAF would be required: afterwards, flights departing from EU airports will need to use SAF for 32% and 63% of their jet fuel consumption by 2040 and 2050, respectively. It is estimated that the overall demand for aviation fuel in the EU would reach approximately 46 Mt. in 2040 and 45 Mt. in 2050. If the proposed SAF blending mandate is implemented, the projection indicates a need for roughly 14.8 Mt. of SAF annually by 2040 and approximately 28.7 Mt. by 2050.

As regards Maritime, methanol is gaining attention as a cleaner marine fuel option due to its potential to reduce emissions of pollutants and its carbon-neutral nature when produced from sustainable biomass. In terms of projections, according to Chemical Market Analytics by OPIS [58], the demand for methanol as marine bunker fuel is expected to increase significantly by 2050, from approximately 0.3 Mt. today to about 7.8 Mt. in 2050.

In terms of sector-specific demands, according to the EU Reference Scenario 2020 [59], the projected energy demand for international aviation is expected to reach 41,846 ktoe by 2030 and 44,375 ktoe by 2050. Simultaneously, the energy demand for international maritime transport is estimated to be 45,966 ktoe by 2030 and 55,939 ktoe by 2050.

As regards the Italian context, the EU Reference Scenario 2020 [59] still indicates that the energy demand for international aviation is expected to be approximately 4000 ktoe by 2030 and 4600 ktoe by 2050. Additionally, the energy demand for international maritime transport is projected to reach approximately 2400 ktoe by 2023 and 2700 ktoe by 2050.

Examining the biomethane potential production, today 3 billion cubic meters (bcm) are produced in the EU-27, while biogas production reaches 15 bcm [47]. In response to the EU renewed commitment to accelerating biomethane production, the Gas for Climate [47] study, through a comprehensive analysis, has estimated a biomethane potential from anaerobic digestion in the EU-27 by 2030 to reach 38 bcm. The top 5 countries driving this growth include France, Germany, Italy, Poland, and Spain. The primary feedstocks contributing to this potential are manure (33%), agricultural residues (25%), sequential cropping (21%), and industrial wastewater (over 10%). Looking further ahead, the estimated biomethane potential for 2050 is an impressive 91 bcm in the EU-27. Once again, the top 5 countries leading this expansion are France, Germany, Italy, Poland, and Spain. The key feedstocks expected to drive this growth see a largely leading role of sequential cropping (47%), then manure (19%), agricultural residues (17%), and industrial wastewater (over 10%). Moreover, there is the potential to unlock even more biomethane by considering additional feedstocks, such as biomass sourced from marginal or contaminated land and seaweed, as outlined in the REPowerEU plan. Additionally, renewable methane, produced from renewable electricity and biogenic CO_2 captured during biogas upgrading, along with landfill gas, can further contribute to this promising potential.

In the specific case of Italy, as per the Gas for Climate report [47], the potential production of biomethane from anaerobic digestion was estimated to be approximately 5.6 bcm by 2030, increasing to an estimated 8.2 bcm by 2050.

The potential of biomethane as a raw material for the three pathways explored in this study is, therefore, remarkable. Indeed, based on the results from our modelling, and considering the European scenario, via the GTL-FT route, at 2030 it is potentially possible to cover 9% of the demand for kerosene-based jet fuel with SAF produced from this pathway, provided the reforming technology is POX. On the other hand, if the reforming technology were SMR, it could cover 4% of the 2030 demand. Alternatively, opting for the GTL-F_ATJ route would cover about 11% of the jet fuel 2030 demand. When considering methanol as maritime fuel, the GTL-MeOH route could meet approximately 56% of the 2030 demand for maritime fuels using POX as the reforming technology and 25% using SMR as the reforming technology.

In the context of projected fuels demand for the year 2050, the GTL-FT route emerges as a promising solution. This approach has the potential to address 19% of the demand for kerosene-based jet fuel with SAF, contingent on utilizing POX as the reforming technology. Conversely, if SMR were the chosen reforming technology, it could cover 9% of the demand. Turning to alternative routes, opting for the GTL-F_ATJ route would contribute to approximately 25% of the jet fuel demand.

Shifting focus to maritime fuel options, the GTL-MeOH route, employing POX as the reforming technology, has the capacity to fulfil an impressive 105% of the demand for maritime fuels. Meanwhile, using SMR as the reforming technology would cover 48%.

Figs. 16 and 17 show the European energy fuel demand (EJ) within the aviation and maritime sectors, along with the potential production of SAF and MeOH as per the suggested value chain, highlighting the investigated pathways.

In the 2030 Italian scenario, the GTL-FT pathway has the potential to roughly cover 13% of the demand for kerosene-based jet fuel with SAF if employing POX as the reforming technology. However, with SMR as reforming technology, it could only meet 6% of the demand, even though it simultaneously generates another valuable product, i.e. hydrogen. Alternatively, choosing the GTL-F_ATJ route would cover approximately 18% of the jet fuel demand.

Regarding the use of methanol as maritime fuel, the GTL-MeOH pathway could exceed the demand for maritime fuels (about 152% coverage) when using POX for reforming. This provides ample room for other methanol applications. If employing SMR as the reforming technology, the production of MeOH as maritime fuel through this pathway would cover approximately 69% of the demand for maritime fuels.

In the foreseen Italian scenario for 2050, the GTL-FT pathway with

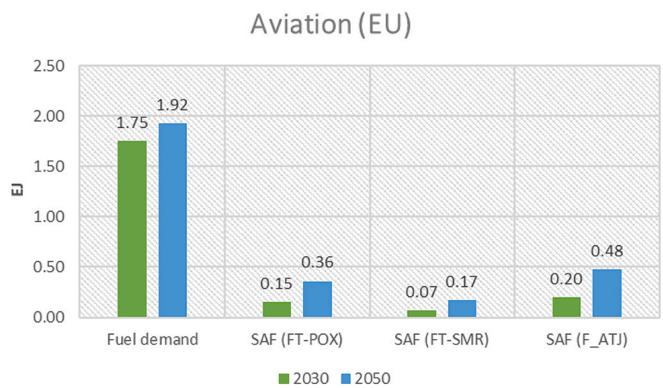

Fig. 16. 2030 and 2050 European fuel demand in the aviation sector (EJ) and potential production of SAF according to the different value chains.

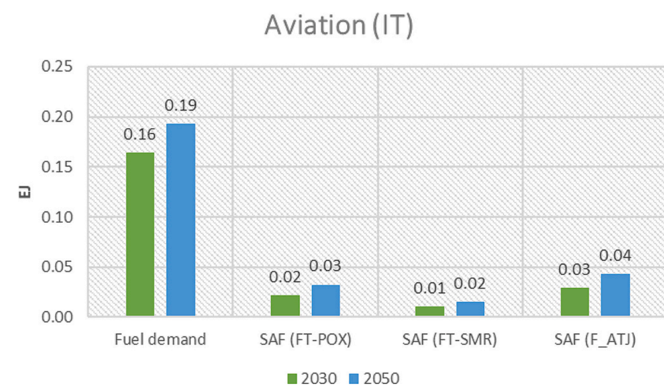

Fig. 18. 2030 and 2050 Italian fuel demand in the aviation sector (EJ) and potential production of SAF according to the different value chains.

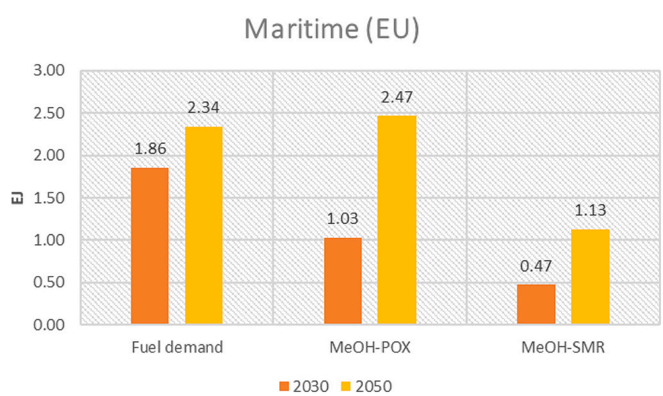

Fig. 17. 2030 and 2050 European fuel demand in the maritime sector (EJ) and potential production of MeOH according to the different value chains.

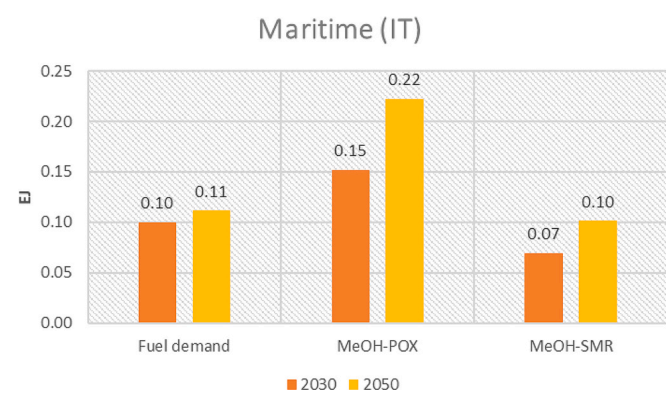

Fig. 19. 2030 and 2050 Italian fuel demand in the maritime sector (EJ) and potential production of MeOH according to the different value chains.

POX could potentially fulfil about 17% of the demand for kerosene-based jet fuel with Sustainable Aviation Fuel (SAF). At the same time, with SMR as the reforming technology, it could meet 8% of the demand, while simultaneously generating a valuable amount of hydrogen. An alternative route, the GTL-F_ATJ pathway, is estimated to cover around 22% of the jet fuel demand. Focusing on maritime fuel applications, the GTL-MeOH pathway, with POX as the reforming technology, could exceed the demand for maritime fuels, providing extensive coverage at approximately 198%. This surplus creates opportunities for various methanol applications. In contrast, using SMR as the reforming technology, the production of MeOH as maritime fuel through this pathway is anticipated to cover around 91% of the demand for maritime fuels.

Fig. 18 and Fig. 19 show the European energy requirements in the aviation and maritime sectors, quantified in EJ. They also provide the potential production of SAF and MeOH based on the proposed value chain, outlining the diverse pathways under examination.

Summarizing, Table 8 recaps the products generated by each of the studied pathway per MJ_{CH4} at inlet, offering a comprehensive view, beyond the contribution to Aviation and Maritime only.

In fact, while the GTL-FT route (10,000 bpd unit) predominantly delivers Naphtha (219 t/d), Kerosene (222 t/d, here assumed for Aviation use), Diesel (95 t/d) and Waxes (474 t/d) and the GTL-MeOH (2000 t/d) only Methanol (for Maritime), the GTL-F_ATJ (1000 t/d of products) offers Jet Fuel (700 t/d), Gasoline (100 t/d) and Diesel (200 t/d). With additional H_2 production, in the case of the SMR route.

Processes should therefore be selected on the base of the political priorities: the allocation of the current and future available biomethane will be decided on sector priorities, and policies/regulations will follow accordingly. For instance, if green hydrogen generation is to be prioritized against the contribution to Aviation and Maritime, the SMR route

Table 8
Liquid Fuels and Hydrogen produced from each pathway (MJ/MJ_{CH4}).

		Fuels	H_2
GTL-FT	POX	0.454	0
GTL-FT	SMR	0.207	0.666
GTL-MeOH	POX	0.682	0
GTL-MeOH	SMR	0.312	0.666
GTL-F_ATJ	POX	0	0
GTL-F_ATJ	SMR	0.188	0.660

could be preferred. Otherwise, POX will offer more volumes to Aviation or Maritime, for the same given amount of biomethane.

Finally, it is worth to observe that, from a strict energy viewpoint, while POX is an exothermal reaction which generates thermal energy (even if presenting risks of explosions) recoverable in the process itself, SMR is an endothermal route which requires thermal energy feeding.

Finally, focusing on the 2030 target, based on the stated EU and IT potential, the number of 1 MWe equivalent AD units necessary to serve each pathway is summarized in the following Table 9, together with the potential max contribution to the expected EU and IT demand at that year.

5. Conclusions

This research addressed three different advanced biofuel production pathways for the aviation and maritime sectors based on sustainable biogas from decentralized farm-level anaerobic digestion.

Based on the outcomes of the modelling work, the number of biogas facilities necessary to feed a 10,000 bpd GTL Fischer-Tropsch synthesis

Table 9
Potential max contribution of each pathway to 2030 EU and IT objectives, and nr of 1 MWe AD units necessary per process route.

		Nr of 1 MWe AD units per pathway	Potential contribution to EU Aviation 2030	Potential contribution to EU Maritime 2030	Potential contribution to IT Aviation 2030	Potential contribution to IT Maritime 2030
GTL-FT	POX	516	9%	–	13%	–
GTL-FT	SMR	1128	4%	–	6%	–
GTL-MeOH	POX	336	–	56%	–	152%
GTL-MeOH	SMR	735	–	25%	–	69%
GTL-F_ATJ	POX	–	–	–	–	–
GTL-F_ATJ	SMR	1126	11%	–	18%	–

plant is estimated at 516 if partial oxidation of methane (POX) is adopted, while it increases to 1128 in case of using steam methane reforming (SMR) technology. This setup produces 222 t/d of kerosene and 95 t/d of diesel. On the other hand, a GTL plant with methanol synthesis would require 336 biogas plants if employing POX and 735 with SMR, yielding 2000 t/d of MeOH. Conversely, a GTL biorefinery based on syngas fermentation and alcohol-to-jet conversion (ATJ) would need 1226 biogas plants, producing 700 t/d of jet fuel, 100 t/d of gasoline, and 200 t/d of diesel. Thereby, GTL technology coupled with Fischer-Topsch synthesis proves to be the most effective option for jet fuel production if limiting the volume of biomethane and the corresponding number of AD plants is the main driver to develop the value chain. Nevertheless, hydrogen production from SMR adds another relevant component to the analysis, which requires proper consideration on a case-specific base.

In the 2030 European context, the Fischer-Tropsch based route may satisfy 4–9% of kerosene-based jet fuel demand, depending on the employed reforming technology, while the alcohol-to-jet route might cover around 11%. Conversely, the methanol-based pathway may meet 25–56% of maritime fuel demand. On the other hand, by 2050, the Fischer-Tropsch pathway could cover 9–19% of jet fuel demand, whereas the alcohol-to-jet option route may contribute by 25% to jet fuel demand. Instead, the methanol-based pathway could meet from 48% to even 105% of the maritime fuel demand.

As regards Italy in 2030, the Fischer-Tropsch route may fulfil 6–13% of kerosene-based jet fuel demand, while the alcohol-to-jet alternative could meet 18%. The methanol-based pathway, instead, could cover 69% of the demand or even exceed it by 52%. On the other hand, by 2050, the Fischer-Tropsch pathway could satisfy from 8 to 17% of jet fuel demand in Italy, while the alcohol-to-jet option 22%. The methanol-based route could cover 91% of the maritime demand, or even exceed it by 98%, depending on the reforming technology adopted.

In addition, these processes provide valuable by-products beyond aviation and maritime sectors, including naphtha, diesel, waxes, hydrogen, and gasoline, making them versatile across industries.

Preliminary investment insights indicate costs of USD 791,970 per t/d for a GTL plant with Fischer-Tropsch technology, USD 130,275 per t/d for a GTL plant based on methanol synthesis, and approximately USD 669,740 per t/d for a GTL plant employing syngas fermentation and alcohol-to-jet conversion. These figures could aid decision-making in implementing these processes.

Using existing refineries in Europe to implement these the three routes presents both opportunities and challenges. Leveraging established refinery infrastructure offers economic benefits and faster adoption of cleaner routes by improving social consensus: in this respect, decoupling biomethane production to conversion is crucial for optimal performance.

Continuous advancements, scaling, and investments are imperative for green transitions. Reliable technologies and long-term stable policies are essential to address regulatory risks, as well as collaboration across sectors and industrial symbiosis are needed.

Current policy and regulatory landscape in EU and IT already allows for the agro-industrial implementation of the proposed value chains, contributing with sustainable biomethane to a diversified offer of sustainable biofuels in all sectors, particularly in the so called hard-to-abate transport fields of aviation and maritime.

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CRediT authorship contribution statement

David Chiaramonti: Conceptualization, Funding acquisition, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Lorenzo Testa:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

David Chiaramonti reports financial support was provided by European Commission. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data have been taken from published research and technical reports, which are referenced in the article and accessible to anyone

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Appendix A. Supplementary data

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