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Process analysis and techno-economic comparison of aviation biofuel production via microbial oil and ethanol upgrading

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ABSTRACT

The transport sector is the largest source of greenhouse gases in the EU after the energy supply one, contributing approximately 27% of total emissions. Although decarbonization pathways for light-duty transport are relatively well established, heavy-duty transport, shipping and aviation emissions are difficult to eliminate through electrification. In particular, the aviation sector is strongly dependent on liquid hydrocarbons, making the development of sustainable aviation fuels (SAFs) a critical priority for achieving long-term climate targets. This study evaluates four biomass-to-liquid pathways for producing jet-like SAF from lignocellulosic biomass: (1) triacylglycerides (TAGs) production from syngas fermentation, (2) TAGs production from sugar fermentation, (3) ethanol production from syngas fermentation, and (4) ethanol production from sugar fermentation. These pathways are simulated using Aspen Plus™, and the mass and heat balances obtained are used to assess their technical performance (e.g., carbon utilization, energetic fuel efficiency) and techno-economic viability (e.g., production cost, capital investment). Pathway (4) demonstrated the highest jet fuel selectivity (63%) and total carbon utilization (32.5%), but at higher power demands. Pathway (1) was self-sufficient in energy due to internal syngas utilization but exhibited lower carbon efficiencies. Cost analysis revealed that microbial oil-based pathways were restrained by higher hydrogen demands and lower product selectivity compared to ethanol-based routes. However, with advancements in microbial oil production efficiency and reduced water usage, these pathways could become competitive.

1. Introduction

Global warming and climate change are considered among the most crucial concerns that threaten the survival of humanity and ecosystems on earth. To prevent the catastrophic consequences of exceeding 1.5 °C global warming, zero-emission technologies must be rapidly deployed at a commercial scale [1]. The increasing global emphasis on climate change mitigation, driven by international agreements such as the Paris Agreement, has placed the aviation and maritime sectors under intense inspection due to their growing contributions to greenhouse gas (GHG) emissions. Without significant intervention, aviation emissions could reach 21.2 Gt CO₂ by 2050, with over 10 billion annual passengers [2], while maritime CO₂ emissions could increase by up to 250 % compared to 2012 [3].

Transportation is the second sector after energy with the largest GHG emissions [4–6] and it remains the only sector in the EU where emissions have increased over the past 30 years [5,7]. Unlike the road and railway transports that can eliminate their emissions through electrification, the

aviation sector must rely only on the development of sustainable fuels with similar properties to the fossil-derived ones. This is the only way for long distance flights to be carbon neutral since there is no alternative technology at high altitudes than the aircraft turbo engine [8]. In the maritime sector, advanced biofuels offer the advantage of maintaining existing vessel infrastructure and operations while being safer than gaseous and explosive fuels [9].

Biofuels have emerged as a promising strategy to decarbonize sectors like transport, with the International Energy Agency (IEA) predicting that they could supply up to 27 % of total transport fuels by 2050 [10]. In aviation, Sustainable Aviation Fuels (SAFs) are particularly crucial for reducing emissions, as aircraft engines require fuels that meet strict specifications similar to fossil-derived jet fuel. Among the currently approved SAF pathways, Hydroprocessed Esters and Fatty Acids (HEFA) dominate commercial production due to being the only market-proven and cost-competitive option [11]. However, HEFA faces significant challenges, such as the limited availability and high costs of feedstocks like used cooking oil (UCO) and animal fats, which also offer the greatest environmental benefit. These constraints, combined with concerns over

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Nomenclature*Abbreviation List*

AD	Anaerobic Digestion
ATJ	Alcohol to Jet
BPC	Biofuels Production Cost
BtL	Biomass to Liquid
CAPEX	Capital Expenditure
CEPCI	Chemical Engineering Plant Cost Index
CU	Carbon Utilization
CW	Cooling Water
DFBG	Dual Fluidized Bed Gasifier
EFE	Energetic Fuel Efficiency
FCI	Fixed Capital Investment
GHG	Greenhouse Gas
HDT	Hydrotreatment
HEFA	Hydroprocessed Esters and Fatty Acids
HHV	Higher Heating Value
HMF	Hydroxymethylfurfural
IEA	International Energy Agency
LCA	Life Cycle Assessment
LP	Low Pressure
LT-HP	Low Temperature – High Pressure
NREL	National Renewable Energy Laboratory

NRTL	Non-random two-liquid
OPEX	Operating Expenditures
PSA	Pressure Swing Adsorption
RED	Renewable Energy Directive
SAF	Sustainable Aviation Fuel
ST	Steam Turbine
TAG	Triglyceride
TCI	Total Capital Investment
TDIC	Total Direct and Indirect Cost
TIC	Total Installed Cost
UCO	Used Cooking Oil
WGS	Water-Gas Shift
WWTP	Waste Water Treatment Plant

Subscript

th	thermal
e	electrical
SYN-HDT	biomass gasification to SYNGas to TAGs HyDroTreatment pathway
SUG-HDT	biomass hydrolysis to SUGars to TAGs HyDroTreatment pathway
SYN-ATJ	biomass gasification to SYNGas to Alcohol to Jet pathway
SUG-ATJ	biomass hydrolysis to SUGars to Alcohol to Jet pathway

the GHG reduction potential of some first-generation biofuels, raise skepticism about HEFA's long-term sustainability. Consequently, there is growing interest in alternative technologies that can use more abundant and sustainable biomass feedstocks, such as lignocellulosic residues.

Over the next two decades, advanced feedstock types (i.e. marginal crops, biogenic residues, wastes, algae) and technologies are expected to mature, addressing the feedstock limitations of HEFA and contributing to the scale-up of advanced biofuels production [8]. One of the promising feedstock types that is expected to support advanced oil in the HEFA based route is microbial oil, which is commonly defined as lipids that are accumulated by oleaginous microorganisms that are able to accumulate intracellular oil at more than 20 % of their cell dry weight [12]. The composition of that type of oils has strong similarities with those of vegetable oils and can potentially be a promising source of feedstock for HEFA based plants. Some studies in the literature investigate the economic feasibility of using microbial oil as feedstock for SAF production: Karamerou et al. showed that the microbial oil production cost from 1G feedstock (sugarcane) can range from \$1.2–\$1.81/kg depending on scale, and productivity [13]. Recently, Marchesan et al. revealed that the SAF production cost of SAF from microbial oil from the same substrate is between \$1.83 and \$3.00 per liter [14]. There are various C-sources that can be used as substrates for lipids production from yeast fermentation, such as acetate [15], sugars (glucose) and glycerol [16]. If the production of such substrates is performed with feedstocks that are eligible with Annex IX of Renewable Energy Directive (RED) II [17], the final aviation and marine biofuels can be considered as sustainable. The rate of effectiveness and cost-competitiveness compared to other advanced biofuel pathways needs further investigation.

Another pathway for producing SAF is the Alcohol-to-Jet (ATJ) process, where alcohols, primarily ethanol, are upgraded catalytically to jet fuel through consecutive dehydration to olefins, oligomerization, and hydrogenation. The two main ATJ routes involve either ethylene oligomerization or the Guerbet reaction [18,19]. A critical comparison between these two options shows that ethylene-based oligomerization is superior to the Guerbet reaction in jet fuel production [20]. For that pathway, the most critical aspect from a technical and economic point of

view is the efficient production of bioethanol from advanced biomass feedstock. There are two primary pathways for bioethanol production: the hydrolysis-fermentation route, where biomass is first broken down with chemicals and enzymes and then fermented by microorganisms like yeast to produce ethanol, and the gasification route, in which biomass-derived synthesis gas (a mix of H₂, CO, and CO₂) is fermented by bacteria to produce ethanol [21]. From the economic point of view, various studies of the ATJ route report minimum selling prices ranging from 0.88 to 0.93€/L for 1G ethanol use as feedstock [22], 1.49 €/L when advanced feedstock such as corn stover is employed [23], and higher up to 2.5 €/L for cases that agricultural residues is used as initial feedstock for ethanol synthesis [24]. Regardless of the origin of ethanol, its cost plays the most significant factor (>90 %) at the formulation of jet fuel breakeven price [23,25].

Despite increasing interest in sustainable aviation fuels (SAFs), most techno-economic work to date has focused on either (a) ethanol upgrading pathways (Alcohol-to-Jet, ATJ) or (b) microbial oil production from first-generation feedstocks, but rarely compares these routes on the same technical and economic footing using lignocellulosic feedstocks. To place our analysis in context we compared representative techno-economic studies across the main SAF pathways (Table 1). The literature shows detailed TEAs for ATJ that identify ethanol feedstock costs as the dominant driver (Yao/Tao 2017) [22,23], and several recent TEAs and industry reports for syngas fermentation (Regis et al. 2023) [21] and commercial demonstrations of gas-fermentation ATJ (Lanza-Tech/LanzaJet) [26,27]. In contrast, techno-economic studies of microbial oils (Karamerou et al., Marchesan et al.) [13,14] have mainly considered 1G feedstocks or a limited set of scenarios and emphasize the sensitivity of final lipid costs to productivity, extraction energy and scale. This motivates the present study's direct, side-by-side TEA of ethanol-based ATJ and microbial-oil upgrading using the same lignocellulosic feedstock and consistent costing assumptions, which — to the best of our knowledge — has not been reported previously. Addressing this gap will reveal whether differences in final SAF cost are driven mainly by fundamental conversion chemistry and mass-balance constraints or by uncertain economic assumptions (CAPEX/OPEX, water use, scale-up effects), and therefore where technological R&D should be prioritized.

Table 1

Summary of representative techno-economic assessments (TEAs) and reviews across major SAF pathways (ATJ, HEFA, FT/PtL, syngas fermentation, microbial oils), highlighting feedstocks, scale & key findings.

Study (Year)	Pathway / Focus	Feedstock	TRL / Scale	Key Findings
Karamerou et al. (2021) [13]	Microbial lipids (oleaginous yeasts) TEA	1G sugars (sugarcane)	Pilot / modelling	Lipid cost $\approx$ 1.2–1.8 €/kg; scale & productivity critical
Marchesan et al. (2025) [14]	Microbial oil $\rightarrow$ HEFA upgrading	Sugarcane (1G)	Pilot assumptions	SAF cost varies with assumptions; feedstock important
Yao et al. (2017) [22] / Tao et al. (2017) [23]	Alcohol-to-Jet TEA	Corn grain, corn stover, sugarcane	Detailed plant TEA	Ethanol feedstock cost dominates ATJ SAF price
Regis et al. (2023) [21]	Syngas fermentation $\rightarrow$ ethanol TEA	Switchgrass (lignocellulose)	Conceptual modelling	Syngas cleanup & integration key for ethanol economics
LanzaTech / LanzaJet (2021–2023) [26,27]	Gas fermentation ethanol $\rightarrow$ ATJ (industrial demo)	Industrial off-gases, woody residues	Commercial demo	Industrial validation of gas-fermentation ATJ pathway
Wang et al. (2022) [28]	FT-to-jet / PtL TEA	Various biomass / syngas	TEA comparison study	FT can yield high efficiencies; cost depends on syngas
Collis et al. (2022) [29]	FT from steel-mill gases TEA & LCA	Steel-mill off-gas	Simulation / TEA / LCA	FT SAF viable from industrial gases; emissions reduced
Detsios et al. (2024) [30]	Gasification-driven BtL TEA	Lignocellulosic biomass	Conceptual modelling	Gasification concepts benchmark BtL costs
Gallego-García et al. (2022) [31] / Gallego-García et al. (2023) [32]	Yeast-based microbial oil review	Lignocellulosic sugars / wastes	Review / lab-scale studies	TAG recovery & cell disruption are major cost drivers
Renegar et al. (2024) [33]	Microbial oil TEA scenarios (<i>meta-analysis</i>)	Multiple scenarios	Scenario analysis	Large scenario study; microbial oil economics sensitive to scale
NREL SAF State-of-Industry (2024) [34]	HEFA, ATJ, FT state-of-industry report	Multiple feedstocks	Industry report	Authoritative TEA guidance for HEFA/ATJ/FT
Cortés-Peña et al. (2024) [35]	Microbial oil processing & extraction review	Bioenergy crops / engineered oilcane	Review / lab & modelling	Extraction energy & cost critical for TAG recovery

This study introduces four biomass-to-liquid (BtL) pathways for producing drop-in biofuels for aviation, integrating thermochemical and biochemical processes. These pathways include (1) biomass gasification followed by syngas fermentation to acetate, which is then converted to microbial oil and hydrotreated to produce jet fuel; (2) biomass hydrolysis to sugars, followed by fermentation to microbial oil and subsequent hydrotreatment; (3) biomass gasification with syngas fermentation to ethanol, upgraded through the Alcohol-to-Jet (ATJ) process; and (4) biomass hydrolysis, sugar fermentation to ethanol, and conversion to jet fuel via the ATJ process. These routes leverage lignocellulosic biomass (wheat straw), a non-food, advanced feedstock, aligning with the sustainability criteria set by CORSIA [36] and the EU's RED II [17].

The aim of this study is to assess the performance of these four pathways, the second of which is presented for the first time, in terms of technical (i.e. product yield, carbon utilization, and overall energy efficiency) and techno-economic point of view (i.e. cost production, specific capital investment). As the microbial oil pathways are less mature than the ethanol-based one, this research provides the first

comprehensive techno-economic assessment of SAF production at an industrial scale from microbial oil derived from advanced feedstock and benchmarks its competitiveness against ATJ. Moreover, the detailed process integration and the respective cost estimation and assessment enable the extraction of useful findings on how these novel pathways can be more competitive and to what extent. By bridging this research gap, this study contributes to the development of scalable and cost-effective alternatives to HEFA, helping the aviation sector meet its long-term decarbonization goals. The novelty of this study lies in its comprehensive evaluation of microbial oil pathways for SAF production, providing a unique comparison with the established ATJ process at an industrial scale, which has not been previously explored in the literature.

2. Concept description

The production processes of the four investigated concepts are shown in Fig. 1. To evaluate the concepts on equal terms, the same feedstock is

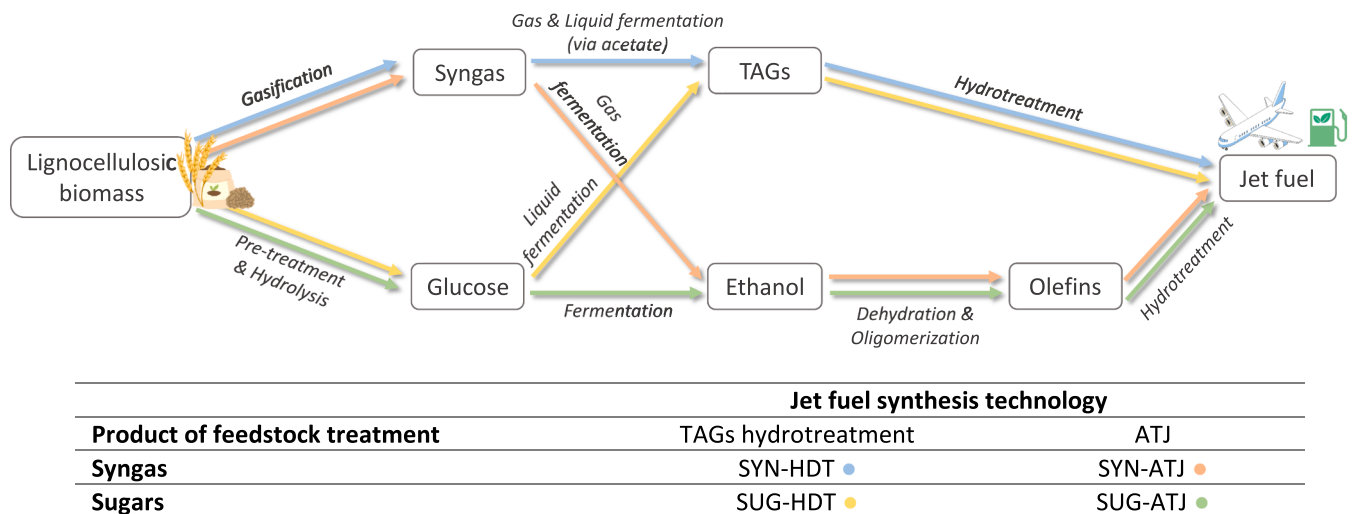


Fig. 1. Block flow diagrams of the four investigated concepts. Each pathway is identified by a sequence of two words: the first word indicates the product of the biomass treatment (gasification/hydrolysis) and the second word specifies the main process for the jet fuel synthesis.

considered, i.e. lignocellulosic biomass from agricultural residues. All routes lead to the same final product (jet-like fuel) and side-products (naphtha, diesel).

2.1. Route SYN-HDT: Jet fuel from microbial oil through syngas

The biogenic solid feedstock is converted into high-quality syngas in a dual fluidized bed gasifier. This type of gasifier operates at atmospheric pressure using steam as the gasification agent. The heat required for the endothermic reactions comes from combusting a part of the produced char, with the heat transferred to the gasifier via hot sand from the oxidizer reactor. The resulting syngas serves as the substrate for the gas-phase fermentation under anaerobic conditions, using acetogenic bacteria (*M. thermoacetica*) to produce acetate. In the second biological step, liquid-phase fermentation is carried out using oleaginous yeast (*Y. lipolytica*) that metabolizes the acetate into Triglycerides (TAGs) at aerobic conditions. Both fermentation processes are conducted under mild conditions, i.e. 30–60 °C and atmospheric or slightly elevated pressure (1–5 bar). After extracting the TAGs from the cells, they are processed into paraffinic jet-like fuel through hydrotreatment and hydrocracking, producing light-ends and diesel as by-products. This concept has already been presented in previous studies [30,37]. The flowsheet for this route is seen in Fig. 2.

2.2. Route SUG-HDT: Jet fuel from microbial oil through glucose/xylose

The biogenic feedstock is firstly pretreated with dilute acid and then converted into sugars (mainly glucose and xylose) through enzymatic hydrolysis. During these steps, cellulose and hemicellulose are broken down to their monomers (glucose, xylose, arabinose, galactose, rhamnose and manose), while HMF (Hydroxymethylfurfural) and furfural are also produced as byproducts. Lignin is also separated and sent to a combustion unit for energy recovery. The sugars are routed to an aerobic fermenter, where oleaginous yeast uses them as a substrate to produce intracellular TAGs. After extracting the TAGs from the cells, they are

finally transformed into paraffinic fuels in the same way described at Route SYN-HDT. This complete production process is presented in this study for the first time. The flowsheet for this route is seen in Fig. 3.

2.3. Route SYN-ATJ: Jet fuel from ethanol through syngas

In this pathway, syngas is produced through biomass gasification as described in the SYN-HDT route. It is then directed to an anaerobic reactor, where acetogenic bacteria (*C. autoethanogenum*) use it as a substrate to synthesize ethanol as an extracellular product. After distillation, the ethanol is further converted into drop-in jet fuel through the ATJ process. In this process, ethanol is dehydrated to ethylene, which undergoes oligomerization over heterogeneous nickel catalysts at low temperatures and high pressure (120–230 °C and 35 bar) to form olefins in the C4–C20 range. Finally, the olefins are hydrotreated to produce paraffins, resulting in a mixture of paraffinic fuels that are separated by distillation into light ends, jet fuel, and diesel. This concept is inspired by the LanzaTech – LanzaJet processes, which have been successfully implemented at a commercial scale [26,27]. The flowsheet for this route is seen in Fig. 4.

2.4. Route SUG-ATJ: Jet fuel from microbial oil through glucose/xylose

This pathway processes the biomass feedstock similarly to Route SUG-HDT, converting it into sugars. These sugars are then introduced into an anaerobic fermenter, where engineered *Zymomonas mobilis* bacteria convert glucose and xylose into extracellular ethanol. The ethanol is then separated from the broth through distillation and converted into paraffinic fuels through the same process described in Route SYN-ATJ, involving dehydration, oligomerization, and hydrotreatment. The flowsheet for this route is seen in Fig. 5.

3. Model description

The process models were developed in the commercial software

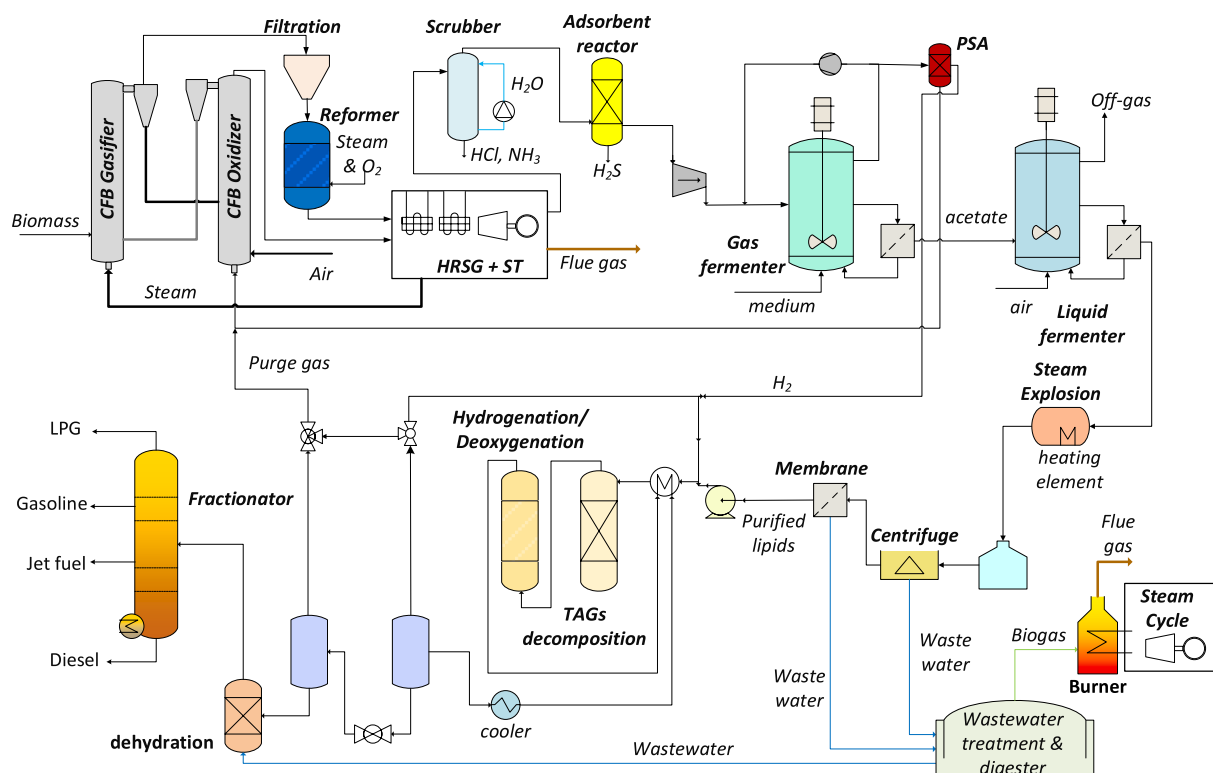


Fig. 2. SYN-HDT flowsheet.

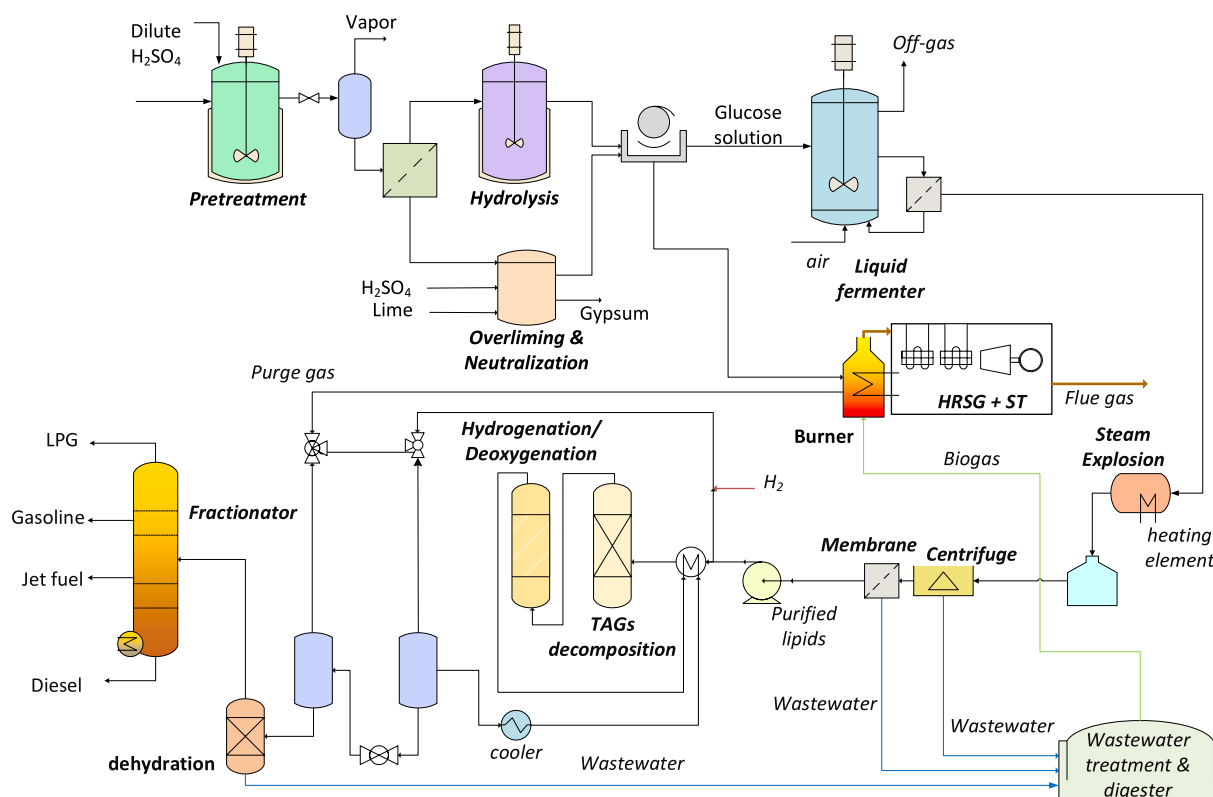


Fig. 3. SUG-HDT flowsheet.

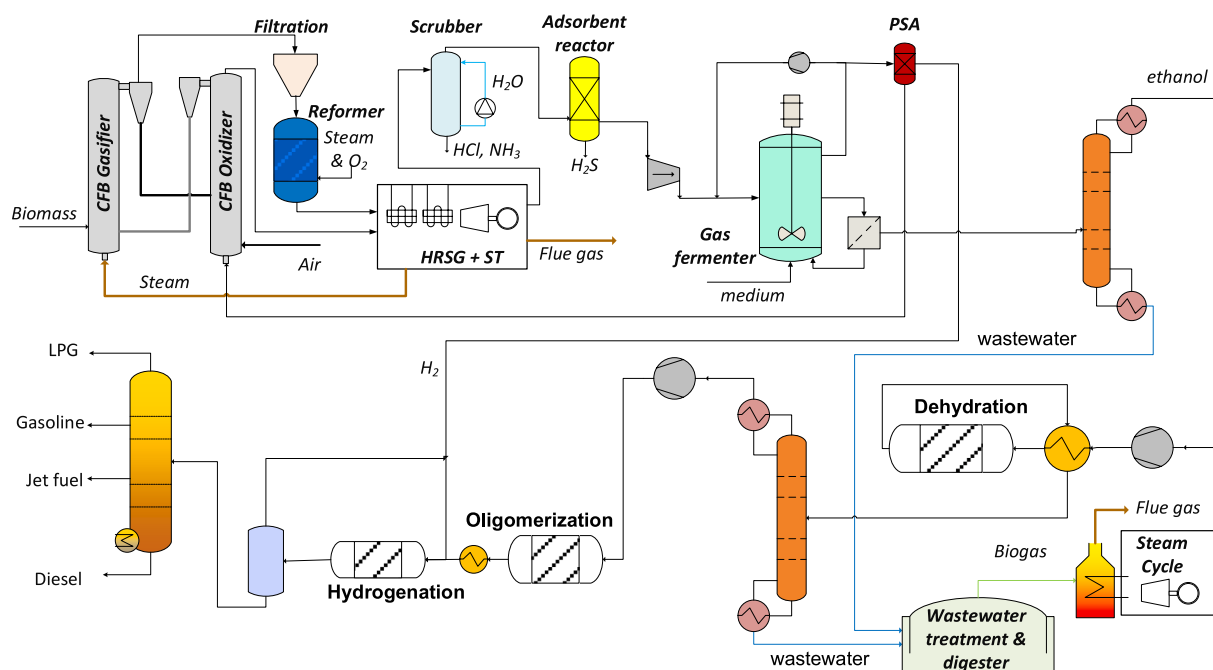


Fig. 4. SYN-ATJ flowsheet.

Aspen PlusTM. The simulation results are validated against the provided literature data and serve as conceptual models. While they provide valuable insights into process performance, uncertainties may arise due to variations in experimental conditions and inherent model assumptions. The simulations were performed at full scale assuming a fuel heat input of 220 MW_{th} on a HHV basis for all the examined cases, using wheat straw as the selected lignocellulosic feedstock. The selected plant

size of 220 MW_{th} reflects a typical median scale for European bio-refineries, aligning with studies that show the sustainable availability of biomass in the region supports such large-scale deployments [38]. In fact, the enabled biomass conversion technologies offer the feature of feedstock flexibility, especially that of gasification and various lignocellulosic feedstock types can be used, ensuring the sustainable supply and continuous operation of the plant. The selection of straw pellets as

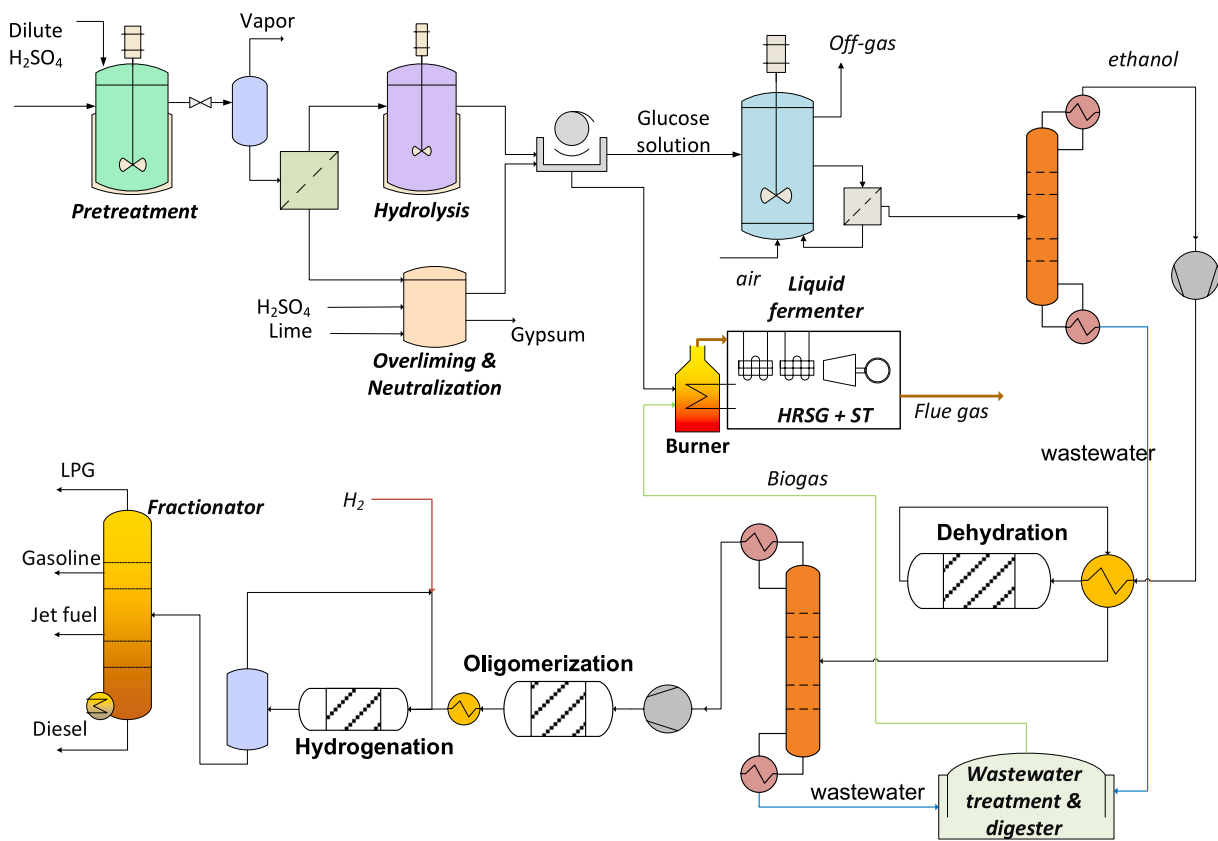


Fig. 5. SUG-ATJ flowsheet.

the common feedstock for all case studies is done for benchmarking the pathways on equal terms and does not preclude the use of other biogenic residues and waste found in abundance in Europe, such as forest and agricultural residues [39,40].

3.1. Feedstock properties

The primary specifications of the feedstock are presented in Table 2. The higher heating value (HHV) of the feedstock is 16MJ/kg and its flow rate in all BtL plants is 49140 kg/h. (Fig. 6).

For routes SUG-HDT and SUG-ATJ, the feedstock was defined as a mixture of conventional solids (lignin, cellulose, xylan, arabinan, galactan, mannan, ash) and liquids (water, extractives). The chemical formula, as well as the physical property data (such as molecular weight, density, heat capacities, enthalpy of formation, acentric factor, critical temperature, pressure and volume) for the biomass components, like cell mass, hemicellulose, enzymes were extracted from the NREL (National Renewable Energy Laboratory) Aspen Plus database for biofuel components [44]. For routes SYN-HDT and SYN-ATJ, the feedstock was defined based on its proximate and ultimate analysis since it was

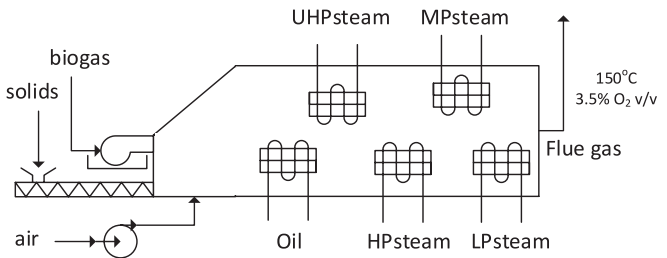


Fig. 6. General scheme of heat recovery system from combustibles burning.

considered a non-conventional solid.

The standard cubic equation of state Peng-Robinson was selected as the property method for all models. To compensate for the poor job that equations of state generally do at predicting liquid density, the Peng-Robinson (PENG-ROB) property method in Aspen Plus™ uses the American Petroleum Institute (API) method for pseudocomponents and the Rackett model for real components to calculate liquid molar volume. The Peng-Robinson model has also been extended to handle polar

Table 2
Composition and analysis of the selected feedstock (wheat straw) [41–43].

Composition (% db)							
Lignin	Cellulose	Xylan	Arabinan	Galactan	Mannan	Extractives	Ash
19.0	42.0	21.0	3.0	1.7	0.8	6.5	6.0
Proximate analysis (%)							
Moisture	Fixed Carbon		Volatile Matter		Ash		
9.7	19.7		75.8		6.0		
Ultimate analysis (%)							
Ash	Carbon	Hydrogen	Nitrogen	Chlorine	Sulfur	Oxygen	
6.0	46.21	5.96	0.34	—	0.006	41.484	

components and non-ideal chemical systems. For biological processes like gas and liquid fermentation and anaerobic digestion, the NRTL (Non-Random Two-Liquid) method is used due to the prevalence of oxygenated and polar molecules. This method works well under the mild temperature and pressure conditions typical of these operations. Across all models, the compressors' isentropic efficiency was set at 85 %, while the pumps' efficiency at 70 %.

The pathways analyzed involve well-established biochemical and thermochemical conversion processes, and no novel hazardous compounds are introduced beyond those typically present in biofuel production. While certain intermediates (e.g., syngas, ethanol, and triglycerides) have associated handling risks, their safety considerations align with existing industrial standards and should be objective for future work that focuses on risk assessment addressing storage, transport, and operational safety concerns [45].

The following paragraphs provide a detailed description of the models' sub-processes. The reactions and main conditions, as well as the input parameters for these processes are summarized in the [Supplementary material](#).

3.2. Biomass pretreatment and hydrolysis

The model of this process comprises two main parts: the dilute acid pretreatment of the lignocellulosic material (and the subsequent detoxification and neutralization procedure of the liquid hydrolysate) and the enzymatic hydrolysis of cellulose. All the processes are modelled as stoichiometric reactors (RStoic) with specific reaction stoichiometry. For modelling purposes, starch, cellulose and hemicellulose (xylan, arabinan, galactan, mannan) polymers are represented by their monomers. As a first step, the lignocellulosic material is mixed with water to obtain an H₂O/feedstock mass ratio of 2.8, and sulfuric acid is added to the produced slurry to reach a concentration of 2 % w/w. The reactor's product undergoes solid/liquid separation through a pneumapress pressure filter. The separated hydrolysate liquor is cooled and fed to the overliming tank. Solid Ca(OH)₂ is added to the tank to react with the H₂SO₄ and raise the pH of the liquid. The effluent stream is then sent to the neutralization reactor, where H₂SO₄ is added to neutralize the solution by reacting with the excess of Ca(OH)₂. The design of the pneumapress pressure filter, the overliming tank and the subsequent neutralization tank was based on NREL's previous studies [46,47]. During the neutralization reaction, gypsum (CaSO₄·2H₂O) is formed, which is then removed through hydrocyclone and rotary drum filtration. The solid fraction deriving from the pneumapress pressure filter is mixed with water to reach a H₂O/solids mass ratio of 13 and sent to the cellulose hydrolysis reactor. After cellulose hydrolysis, the produced slurry is filtered to separate the solids. The solid/liquid separation was modelled as a simple splitter block assuming 100 % recovery of fermentable liquids [48,49].

3.3. Glucose and xylose fermentation to TAGs

The scope of this process is the synthesis of TAGs via fermentation, using as substrate the derived glucose and xylose solution from the biomass pretreatment and hydrolysis process. More specifically, this solution is sent to the aerobic fermenter, where oleaginous yeast consumes the sugars to produce biomass and intracellular TAGs. Triolein (C₅₇H₁₀₄O₆), tripalmitin (C₅₁H₉₈O₆), trilinolein (C₅₇H₉₈O₆) and tristearin (C₅₇H₁₁₀O₆) are selected as the representative TAGs produced during the lipid accumulation phase. The reactions that represent the biomass formation phase, and the reactions that represent the lipid production phase, are based on [31,50]. The conversion rates of the reactions are selected in such a way that the subsequent decomposition of TAGs simulates the optimum lipid content [51] and the fatty acid distribution, as reported in the literature [30].

3.4. Biomass gasification

For the implementation of the gasification and the reforming reactions, equilibrium models have been used, while for kinetically and hydrodynamically controlled phenomena that cannot be predicted with the rules of chemical equilibrium (e.g. unconverted solid carbon, formation of gaseous hydrocarbons), fitting of selected parameters with experimental data was followed. The selected parameters and the fitting of the model are based on previous Dual Fluidized Bed Gasifier (DFBG pilot) tests [52,53]. For the DFBG unit, a gasifier operating with 100 % steam and an oxidizer operating with air are considered. Char, as well as gas fermenter's off-gases and light gases from the hydrotreatment unit, are used as fuel sources for the oxidizer. Filtration of syngas takes place at gasifier outlet temperature, while the filter ashes are also directed to the oxidizer. The syngas cleaning train was modeled to include particulate filtration, tar removal, and sulfur scrubbing, following design assumptions from NREL techno-economic design report [54]. A mixture of sand and calcium carbonate was used to represent the bed material. The governing reactions in the gasifier are the steam gasification reaction, the Water-Gas Shift (WGS) reaction, the Boudouard reaction, the homogeneous gas reactions that form hydrocarbons and the partial combustion reactions. The catalytic reformer operates under autothermal conditions with the addition of air as the oxidation medium, and steam as the reforming agent.

3.5. Gas and liquid fermentation (syngas to TAGs)

This part includes the syngas fermentation for the production of acetate and the acetate fermentation for the production of TAGs. The reformed syngas from the biomass gasification section is sent to the anaerobic fermenter where syngas fermentation takes place. A stoichiometric reactor was used to simulate this stage of the process. The reactor operates at 55°C since the optimal temperature range for *Moorella thermoacetica*, the acetogenic bacterium considered in this study, is 55 – 60°C [55], and at slightly elevated pressure to achieve higher solubility of the reacting gases in the liquid phase. For modelling purposes, the acetate, which is the real product of gas fermentation, is represented by acetic acid (C₂H₄O₂). Additionally, it was considered that the H₂ and CO utilization of the syngas inlet stream by the bacteria is 80 % and 90 %, respectively. The selected values are based on literature data [56]. The remaining unconverted gas is utilized at the oxidizer of the gasification unit and depending on the pathway, it provides the necessary hydrogen for the hydrotreatment processes via pressure swing adsorption (PSA). The dilute acetate solution deriving from the gas fermenter is sent to the liquid fermenter to be converted into biomass and intracellular lipids by oleaginous yeast. Triolein (C₅₇H₁₀₄O₆), tripalmitin (C₅₁H₉₈O₆), trilinolein (C₅₇H₉₈O₆) and tristearin (C₅₇H₁₁₀O₆) are selected as the representative TAGs produced during the lipid accumulation phase. The reactions that represent the lipid production phase are based on [30]. After the double-stage fermentation process, the fermentation broth containing the cells undergoes certain purification steps in order to extract the lipids from the yeast cells. Microbial oil is assumed to be recovered through cell disruption (via enzymatic hydrolysis) followed by solvent extraction. However, for simplicity reasons, these steps are omitted from the model.

3.6. Microbial oil hydrotreatment

This part of the process refers to the hydrotreatment of the produced TAGs to obtain the targeted jet-like fuel. Initially, the decomposition of the representative TAGs is taken into account to simulate the fatty acid distribution that contains palmitic acid (C₁₆H₃₂O₂), oleic acid (C₁₈H₃₄O₂), stearic acid (C₁₈H₃₆O₂), and linoleic acid (C₁₈H₃₂O₂). Total conversion of the triglycerides into acids and propane (C₃H₈) is assumed at a temperature of 370 °C [57] and 140 bar. The H₂:TAGs mass ratio is set to 0.09 according to [58].

Then an equilibrium reactor is employed for the simulation of the hydrotreating reactor involving hydrogenation, deoxygenation and reduction reactions. The yield of the product is established based on the equilibrium state of the reactions taking place within the reactor [37]. The temperature selected for this reactor is 370 °C [57].

Following this, hydrocracking and isomerization are employed to break down long-chain paraffins into shorter, branched hydrocarbons, enhancing the fuel's properties, especially for jet fuel. Hydrocracking is simulated at conditions of 340 °C and 140 bar, ensuring the breakdown of heavier hydrocarbons into the desired jet-range products (C8–C16) [58]. The TAGs are converted into approximately 65–73 wt% n-paraffins and 24–33 wt% iso-paraffins [58]. To account for this, an isomerization step is simulated using a stoichiometric reactor.

Appropriate catalytic system selection is assumed for maximization of the jet fraction. The reaction conversions were carefully chosen to simulate the paraffinic composition of the three fuel fractions. This selection is based on relevant literature studies on the production of jet-like and diesel-like fuels from hydrotreated oils [58]. The hydrotreated microbial oil is then separated from the gas phase (unreacted hydrogen, light hydrocarbons, produced CO/CO₂) and sent to a Flash Separator in order to retrieve the targeted drop-in biofuels. The fractionation part of the process is modelled employing two distillation columns where naphtha, jet and diesel fractions are separated. The light gases produced during the process are recycled and utilized as supplementary fuel in other process stages where additional energy is required. The unreacted hydrogen is recycled back to these stages.

3.7. Syngas fermentation to ethanol

This part includes the syngas fermentation for the production of ethanol. The reformed syngas from the biomass gasification section is sent to the anaerobic fermenter where syngas fermentation takes place. A stoichiometric reactor is used to simulate this stage of the process. The reactor operates at 37 °C since it is the optimal temperature for the growth of most ethanol-producing acetogenic bacteria (*Clostridium autoethanogenum*) [59], and at slightly elevated pressure to achieve higher solubility of the reacting gases in the liquid phase. The reactions that represent microbial growth are based on [30], while the reactions that refer to the production of acetic acid (side product) and ethanol are based on [21]. It is considered that the H₂ and CO utilization of the syngas inlet stream by the bacteria in each pass is 80 % and 90 %, respectively. The selected values are based on literature data [56]. The conversion rates are based on optimum conversions of CO and H₂ found in literature [60]. The remaining unconverted gas is utilized at the oxidizer of the gasification unit.

3.8. Glucose and xylose fermentation to ethanol

The scope of this process is the synthesis of ethanol via fermentation, using the derived glucose and xylose from the biomass pretreatment and hydrolysis process as substrates. More specifically, this glucose/xylose solution is sent to the anaerobic fermenter where bacteria (engineered *Zymomonas mobilis*) convert glucose and xylose into biomass and ethanol [61,62]. The reactions for the cell growth and the ethanol production phase, as well as the conversion rates of these reactions, are based on [62].

3.9. Alcohol-to-Jet (ATJ) process

The ATJ process consists of three main reactive stages: dehydration, oligomerization and hydrogenation, followed by a separation zone [63].

3.9.1. Ethanol dehydration to ethylene

In the first reactive stage of the ATJ process, ethanol is dehydrated at 450 °C and 11.4 bar to achieve 99.5 % conversion to ethylene. The reactor setup consists of four tubular adiabatic reactors connected in

series, each containing a catalyst bed. The overall ethanol conversion in this stage is assumed to be around 99.5 %. In Aspen PlusTM, the reactions are modeled using a Stoichiometric Reactor (RStoic). Following this stage, the ethylene produced is directed through a turbine, reducing its pressure to 3 bar. This pressure drop is essential for efficient separation of ethylene in a distillation column, which is modeled using the RadFrac unit, designed to recover 99 % of the ethylene [63,64].

After this step, the ethylene is compressed to reach a higher pressure of 35 bar for the oligomerization process. This is achieved through multistage compression, utilizing a pressure ratio of 3.3 across three stages, resulting in intermediate pressures of 3.3 bar and 10.8 bar before reaching the final pressure of 35 bar. Between each compression stage, the gas is cooled down to 38 °C using intercoolers, and any condensed water is removed in a knock-out drum, modeled as a flash in Aspen PlusTM [64]. The ethylene oligomerization process requires the introduction of ethylene with a purity ranging from approximately 99 vol% to 99.95 vol% [65].

3.9.2. Ethylene oligomerization

The recovered ethylene is then directed to the second reactive stage, where it undergoes oligomerization into products within the C4–C20 range over heterogeneous nickel catalysts under low temperature and high pressure (LT-HP) conditions of 120 °C and 35 bar, achieving an ethylene conversion level of 99 % and a selectivity of 97 % for the desired products. In Aspen Plus, the reactor is modeled using the RStoic unit, while the reactions are based on [63,66]. The olefins generated from ethylene oligomerization are directed into a secondary oligomerization reactor, where they undergo further oligomerization into higher-chain-length olefins. This stage employs an Al-SBA-15-supported Ni catalyst along with a LiAlH₄ co-catalyst, and operates at a higher temperature of 230 °C compared to the initial oligomerization step, with the reactions based on [67]. The conversion rates for these stoichiometric reactions are estimated based on the anticipated hydrocarbon fractions [23].

3.9.3. Hydrotreatment

The final step for the production of paraffinic fuels is the olefins hydrotreatment, while a total conversion of the alkenes to alkanes is assumed [18]. A hydrogen-to-olefins ratio of 4:1 is employed in this process. The hydrocarbon mixture is routed to one flash separator and two distillation columns for the separation of light gases, naphtha, jet fuel, and diesel.

3.10. Wastewater treatment and biogas synthesis

In this study, the treatment of effluent streams is considered. Since the water volumes used in the examined pathways are significant, particularly in hydrolysis or fermentation-based processes, wastewater management cannot be outsourced and must be integrated into the overall plant design. A simplified approach for power requirements is adopted, using the detailed model from [62], as a reference. Specifically, the required air mass flow for the aerobic part of the treatment is set at 55 % of the wastewater flow, and a compressor is used (discharge pressure: 1.7 atm, isentropic efficiency: 0.7). Moreover, it is assumed that 40 % of the water is evaporated and released to the atmosphere from the reverse osmosis unit. Additional details about the process can be found in [62]. The clean water is considered when calculating the fresh water required to meet the overall process water demands. For biogas synthesis via anaerobic digestion (AD), the model follows the approach of [68], aiming to convert all organic compounds into CO₂ and CH₄, without violating stoichiometric principles.

3.11. Heat integration and utilities

A common strategy for all the examined cases is adopted regarding the way that heat and cooling demands at each process are fulfilled. At

first, the characteristics of the steam utilities that are employed to cover the heat demands at the endothermic processes through steam condensation or to recover the excess heat at the exothermic ones are determined the same for all cases (see [Supplementary Material](#) for details). Moreover, cooling water and chilled water are used for the unexploited heat and refrigerant medium for low-temperature cooling duties. Finally, a heating oil is employed for very high temperature demands.

3.11.1. Steam generation

Apart from the steam generated during the exothermic reaction processes, combustible side streams like lignin and the biogas produced in the AD are burned to generate steam (and heating oil where necessary). The heat duty for the heat exchangers is configured such that steam (and heating oil) generation matches the respective process demands. Additionally, surplus low-pressure (LP) steam is produced from the excess heat and utilized as a by-product to generate additional revenue.

3.11.2. Cooling tower

The cooling tower is an important part of the plant that secures the constant inlet temperature of the cooling water but a considerable amount of water is released to the atmosphere and should be taken into account in the water management analysis. The cooling tower is modeled as a Flash unit, where water at a temperature of 30 °C mixes with ambient air and is partially evaporated so that it achieves the desired temperature according to utility specifications for cooling water (see [Supplementary Material](#) for details). The amount of water is determined to maintain adiabatic conditions. For the cooling tower operation, three pumps are employed: one for feeding cooling water (CW) to the tower ($\Delta P = 0.717$ bar), another for draining water ($P_{out} = 1.5$ bar) and mixing it with make-up water, and a third for distributing the final stream back to the plant ($P_{out} = 5.2$ bar). Additionally, an induced draft fan operates at $P_{out} = 1.0$ bar.

4. Economic assessment methodology

For the economic analysis, the under examination cases are compared against the biofuels production cost (BPC, expressed in €/MWh) and the minimal selling price of the produced jet fuel fraction.

The methodology for the calculation of the equipment cost and the assumptions for Total Capital Investment (TCI) and OPEX estimation follows. The equipment cost of each component is estimated based on an “nth plant” assumption, using corresponding equipment costs from the literature according to the following equation:

$$C_i = C_o \left(\frac{S_i}{S_o} \right)^f \quad (1)$$

In this study, the scaling parameter f is 0.6 for all equipment units. The parameters for all equipment cost estimation for all examined cases are summarized in [Supplementary material – S.Table 4](#). The Total Installed Cost (TIC) calculation is based on the installation factor n_{istb} which is multiplied by the respective equipment cost. This includes the purchased equipment, erection, piping, site improvements, instruments, control systems, and final installation/integration.

$$IC_i = n_{ist} C_i \quad (2)$$

The reference year is 2020, using the average annual CEPCI (Chemical Engineering Plant Cost Index) value (596.2) [69] (see [Supplementary material – S.Table 4](#)). This reference year was chosen to ensure consistency across all modeled pathways and comparability with widely cited techno-economic assessments in the literature, many of which also benchmark to 2020 cost indices. While more recent years would reflect current price increases, updating to later indices (e.g. years 2024–2025) would require rescaling of all cost inputs and could introduce

inconsistencies with the techno-economic assumptions and external benchmark data sets. Additionally, the period of 2021–2023 was strongly affected by pandemic-related supply-chain disruptions, the Russia–Ukraine war, and resulting energy price volatility, which several macroeconomic analyses have identified as sources of exceptional instability in production and commodity costs [70–73]. In contrast, 2020 provides a more stable and consistent baseline across all pathways and aligns with many widely cited TEA studies and reports that also use this year as a benchmark (e.g., [34,74,75]). Importantly, the purpose of this work is to compare pathways under the same boundary conditions, and thus the relative differences between process routes remain valid irrespective of the chosen reference year. If desired, absolute production costs may be escalated to more recent years using standard chemical engineering cost indices without altering the comparative conclusions of this study significantly.

Regarding the novel equipment and units, such as gas and liquid fermenters that are not yet available at commercial scale, the same cost estimation approach is adopted for the gas fermentation units in both ethanol and acetate production using syngas as a substrate (SYN-ATJ and SYN-HDT, respectively). For lipid production in the SYN-HDT and SUG-HDT scenarios, the unit cost estimation is based on a previous study for similar application [30], in which certain figures from the literature and appropriate correlations for the reactors number and volumes have been considered [37]. Similarly, the cost estimation of the lipids recovery part was based on techno-economic studies from processes with same configuration for the extraction and purification of the desired product [76].

The indirect costs that include engineering, contractors, legal fees, etc. are set as 89 % of the Total Purchased Equipment Cost. The contingencies are assumed 10 % of the sum of total direct and indirect costs (TDIC), and the sum of them (contingencies and TDIC) constitutes the fixed capital investment (FCI). The total capital investment (TCI) for each case is the sum of FCI with the working capital, which is defined as 10 % of the FCI [77,78].

The parameters for the operational cost calculation such as O&M and insurance are considered as a portion of the FCI [79]. The assumptions made for the economic evaluation are summarized in [Supplementary material](#). The feedstock cost has a critical contribution to the overall cost assessment (24–28 % of total cost, as seen below in [Section 5.4](#)). The price of 70€/t is taken from [80] as the average price of straw in the last trimester of 2024. As for the hydrogen cost, it also plays a considerable role yet with no great importance on the final fuel price formulation for the cases that external H₂ are required for the hydrotreatment process (4.7 % – 11.9 % for the SUG-based cases). Despite the projections for a gradual decrease of its price, it was considered the current value of green H₂ from IRENA's report for conservative purposes [81].

5. Results and discussion

5.1. Main process simulation results

The heat and mass balances for the entire production processes were analyzed, and the performance of the four pathways was evaluated based on the key factors listed in [Table 3](#).

Energetic Fuel Efficiency (EFE) indicates the fraction of the chemical energy in the initial feedstock that is retained in the final fuel products. Carbon Utilization (CU), on the other hand, represents the percentage of the carbon in the original feedstock that is effectively converted into the final fuels.

The results reveal distinct differences among the four pathways (SUG-HDT, SYN-HDT, SUG-ATJ, SYN-ATJ) in terms of fuel yield, energy efficiency, and hydrogen demand. SUG-ATJ shows the highest liquid fuel mass yield (0.10) and overall yield (0.16), with the strongest focus on jet fuel production, as 63 % of its products are jet fuel. However, it requires the highest external power consumption (10.07 MW), which makes it energy-intensive despite its impressive yield. This results from

Table 3

Main process results from the four case studies.

	SYN- HDT ●	SUG- HDT ●	SYN- ATJ ●	SUG- ATJ ●
Feedstock (kg/h)	49,140	49,140	49,140	49,140
Products (kg/h)	5259	7330	6801	7927
- Light (kg/h)	1200	1714	1702	1906
- Jet fuel (kg/h)	2221	3131	4310	5023
- Diesel (kg/h)	1838	2484	788	999
Liquid fuel mass yield (Jet/ Feedstock)	0.05	0.06	0.09	0.10
Overall mass yield (Products/ Feedstock)	0.11	0.15	0.14	0.16
Mass fraction (Jet/Products)	0.42	0.43	0.63	0.63
Carbon utilization – Total (%)	21.7	29.2	28.0	32.5
Carbon utilization – Jet (%)	9.2	13.9	16.0	20.7
Energetic Fuel Efficiency – Total (%)	28.4	40.7	39.0	45.8
Energetic Fuel Efficiency – Jet (%)	11.8	19.6	22.5	29.4
Hydrogen demand (kg/h)	381.6*	360.0	115.2*	147.6
Power demands (MWe)	0.00	2.67	5.04	10.07

*extracted from syngas

the energy requirements of the ethanol dehydration and oligomerization steps, which involve additional hydrogenation and compression duties. Furthermore, compared to the syngas-based routes, the SUG-ATJ pathway has lower internal energy self-sufficiency, which increases the need for external electricity supply.

SYN-HDT, on the other hand, is self-sufficient in power, meeting all its electricity requirements through the steam turbine (ST) unit. This makes it energy-efficient compared to SUG-ATJ. It also has a relatively lower hydrogen demand (381.6 kg/h), which is supplied by the DFBG unit, highlighting the advantage of syngas-derived hydrogen for this pathway. However, SYN-HDT has lower overall yields (0.11) and poorer carbon utilization (22 %), as well as a lower jet fuel mass fraction (42 %).

Similarly, SYN-ATJ is also partially self-sufficient in power, as it covers part of its energy needs through the ST unit. It performs better in terms of hydrogen demand (115.2 kg/h) compared to SYN-HDT, and it also benefits from syngas-derived hydrogen from the DFBG unit. Despite its relatively lower power demand compared to SUG-ATJ, SYN-ATJ shows strong performance in jet fuel production, with 63 % of its output being jet fuel, and a carbon utilization rate of 16 %.

Another feature that is mainly associated with the environmental impact of the proposed pathways is the water use and specifically the demands for fresh process and cooling water. While a wastewater treatment plant is considered for all cases, the treated water is not sufficient. Simulation results reveal that the majority of those requirements are for the replenishment of the cooling water that is released to the atmosphere from the cooling tower. The specific total water demands for SYN-HDT, SUG-HDT, SYN-ATJ and SUG-ATJ are 51.2, 36.3, 46.0 and 30.7 m³ per t of produced biofuels. The sugar production based pathways have comparatively lower freshwater requirements because lower cooling water needs are required due to the operation of the hydrolysis and fermentation reactors at low temperatures. There is certainly potential for reducing of the cooling water flows that will lead to a more environmentally friendly approach of water management and should be studied in future.

The SUG-HDT pathway requires significant hydrogen (360 kg/h), but its power consumption is more moderate (2.67 MW). However, it underperforms in jet fuel production, with a jet fuel mass fraction of 43 % and a carbon utilization rate of 29 %, which are both lower than the ATJ pathways.

Although the SUG-ATJ pathway demonstrates the highest jet fuel yield and carbon utilization, its considerably higher external power demand (10.07 MW) underlines the need for further investigation into

process optimization strategies to mitigate environmental impacts associated with high energy consumption. This results from the energy requirements of the ethanol dehydration and oligomerization steps, which involve additional hydrogenation and compression duties. Furthermore, compared to the syngas-based routes, the SUG-ATJ pathway has lower internal energy self-sufficiency, which increases the need for external electricity supply.

In summary, SUG-ATJ emerges as the most efficient pathway for jet fuel production, despite its high power consumption, while SYN-ATJ provides a good balance between energy self-sufficiency and solid performance in jet fuel production. The gasification based (SYN-) pathways (SYN-HDT and SYN-ATJ) are more energy-efficient due to their reliance on syngas-derived hydrogen from the DFBG unit and power generation from the ST unit, though SYN-HDT still lags in terms of fuel yield and carbon efficiency. SUG-HDT offers moderate hydrogen demand and power consumption but is less effective in producing jet fuel compared to the ATJ pathways.

5.2. Carbon balances

The carbon flow across the four investigated pathways is illustrated in the following figures (Fig. 7, Fig. 8, Fig. 9 & Fig. 10). Only the primary sub-processes are depicted, while the Waste Water Treatment Plant (WWTP) and boiler have been excluded for simplicity.

The carbon balances reveal that the SUG-ATJ pathway achieves the highest carbon utilization, with 20.7 % of the initial carbon converted into jet fuel. In this pathway, the most significant carbon losses occur in the lignin and solid residues stream after biomass hydrolysis (35.1 %) and in the liquid fermenter's off-gases (16.7 %). Conversely, the pathways with the lowest carbon utilization are SYN-HDT (9.2 %) and SUG-HDT (13.9 %), both of which involve microbial oil production. These pathways experience significant carbon losses in the liquid fermenter's off-gases during TAG production, ranging from 18 % to 28 %, which remain devalorized. Additionally, pathways employing the DFBG technology, SYN-HDT and SYN-ATJ, also suffer substantial carbon losses, with approximately 40 %–50 % of the carbon emitted through the oxidizer's flue gases. Carbon in wastewater streams of the four pathways ranges from 4 % to 15 %, with SUG-HDT showing the highest proportion at 15.3 %. These wastewater streams are treated in WWTPs, enabling biogas production and the recycling of clean water back to the process.

It should be mentioned that the carbon that is not finally ended at the produced fuels is released as CO₂ at gaseous streams, either at flue gases or fermentation off-gases. In all cases, apart from the scrubbed CO₂ from the ethanol recovery unit, the CO₂ concentration is low and a purification unit is required in case of further utilization as feedstock for synthetic fuels production. The only exception is the considerable 9.2 % of CO₂ from the ethanol recovery at the SYN-ATJ that is at > 99 % purity.

5.3. Energy analysis results

5.3.1. Utilities

In all cases (Table 4), the heating demands at different temperature levels are covered and a surplus of low enthalpy steam is generated from the rest available heat that can be sold externally. Especially in TAG based pathways, a small amount of higher quality steam can be produced from the recovered heat at hydrocracking process. Moreover, the gasification based pathways have considerably higher demand for cooling water, especially due to the syngas temperature decrease before gas fermentation. Finally, the requirement for refrigeration is observed only at the SYN-HDT case for the effective separation of light gases (mainly C3) from the crude hydrocarbon stream after hydrotreatment.

5.3.2. Energy balances

The following Sankey diagrams (Figs. 11–14) illustrate the distribution of energy content (in MW) across each input and product, as well as the energy flow through the different processes of each pathway.

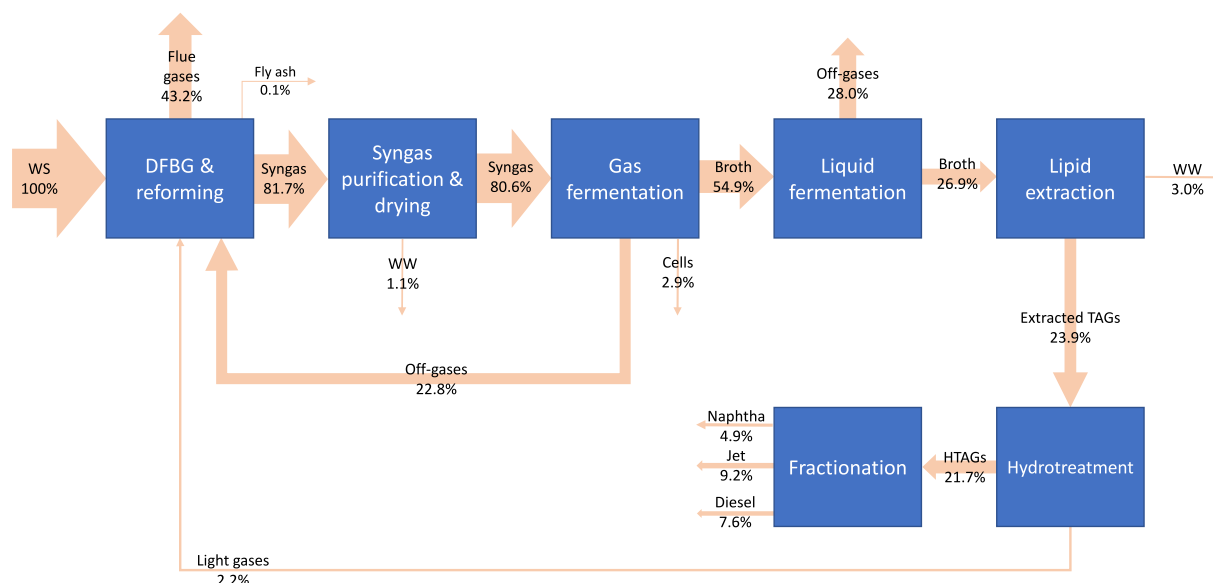


Fig. 7. Carbon balance (% of Initial Carbon) of the SYN-HDT pathway.

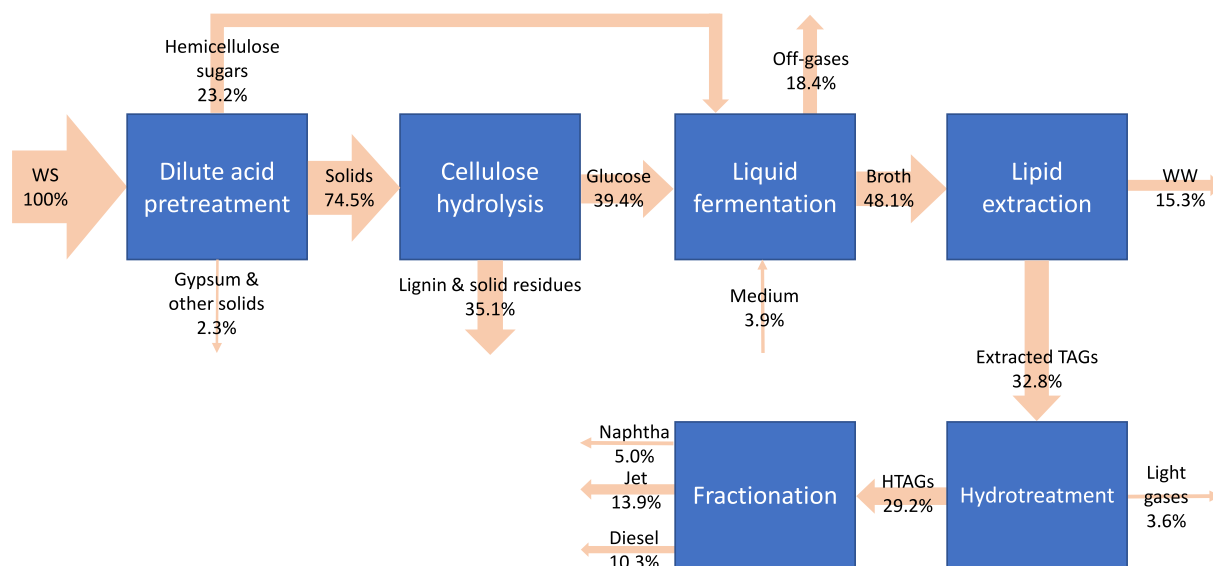


Fig. 8. Carbon balance (% of Initial Carbon) of the SUG-HDT pathway.

The SYN-HDT pathway starts with biomass gasification via the DFBG process, where 223.85 MW of biomass is converted into syngas, a high-thermal-energy gas. This syngas is directed to the steam turbine (ST) system, where its thermal energy is converted into electricity. High-temperature flue gases generated during the process are recycled back into the DFBG unit to enhance energy efficiency. During syngas fermentation, off-gases, acetate, and hydrogen are produced and fully utilized: off-gases are recycled to the DFBG, acetate is transformed into TAGs through liquid fermentation, and hydrogen is used in the hydrotreatment (HDT) process. This recycling of off-gases and flue gases improves energy utilization and reduces overall losses. The HDT stage in this pathway requires heating, hydrogen, and electricity—both hydrogen and electricity being self-generated within the system. Major biofuels outputs from the HDT process include jet fuel (28.77 MW) and diesel (24.48 MW). By effectively recycling energy through combustion to produce high-thermal-energy flue gases and utilizing by-products, this pathway optimizes energy efficiency. However, despite these measures, notable energy losses still occur due to waste streams. Finally yet

importantly, as it makes clear from Fig. 11, more than half of the feed-stock heat content is converted into non-exploitable heat that must be removed for the effective operation of the whole plant, making the cooling tower as a major component of the system, though it does not take part directly in the production process. The processes with the highest cooling demands are the two fermenters. Moreover, the cooling loads from the condenser at the Steam Plant are also considerable.

The SUG-HDT pathway encompasses several stages, beginning with biomass hydrolysis, where the majority of the energy input (223.85 MW) is derived from the biomass itself, supplemented by heating. During this stage, biomass is converted into sugars (a valuable intermediate directed toward fermentation) and lignin (a by-product that can be combusted to generate flue gases with high thermal energy), alongside the production of waste. Following hydrolysis, the process transitions to fermentation and hydrotreatment. The HDT stage is recognized as the most energy-intensive, requiring hydrogen (14.11 MW), heating (1.77 MW), and electricity (1.10 MW), emphasizing the high energy demands of this catalytic process. This stage plays a pivotal role in

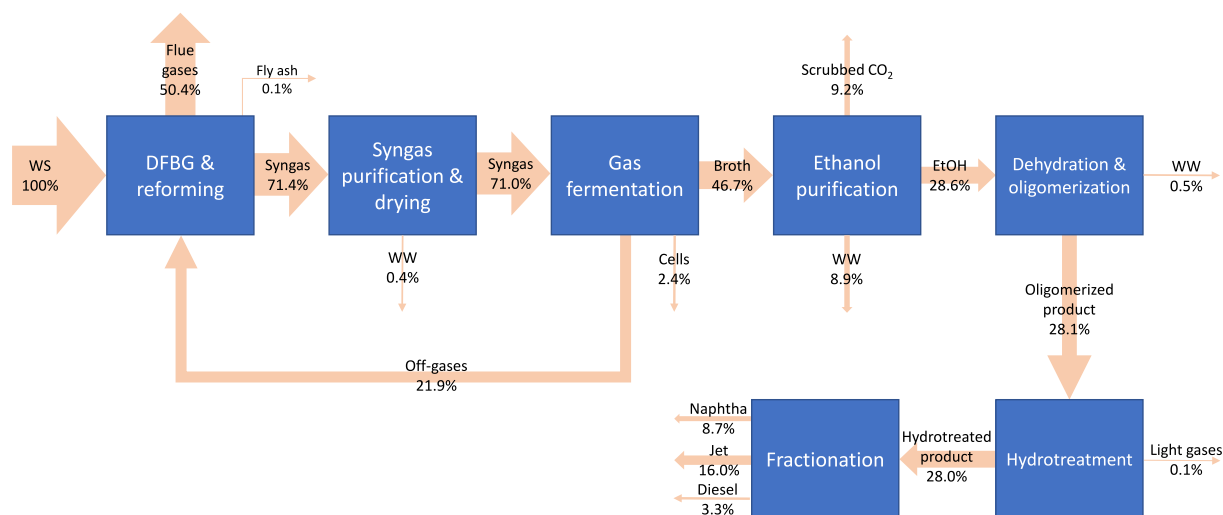


Fig. 9. Carbon balance (% of Initial Carbon) of the SYN-ATJ pathway.

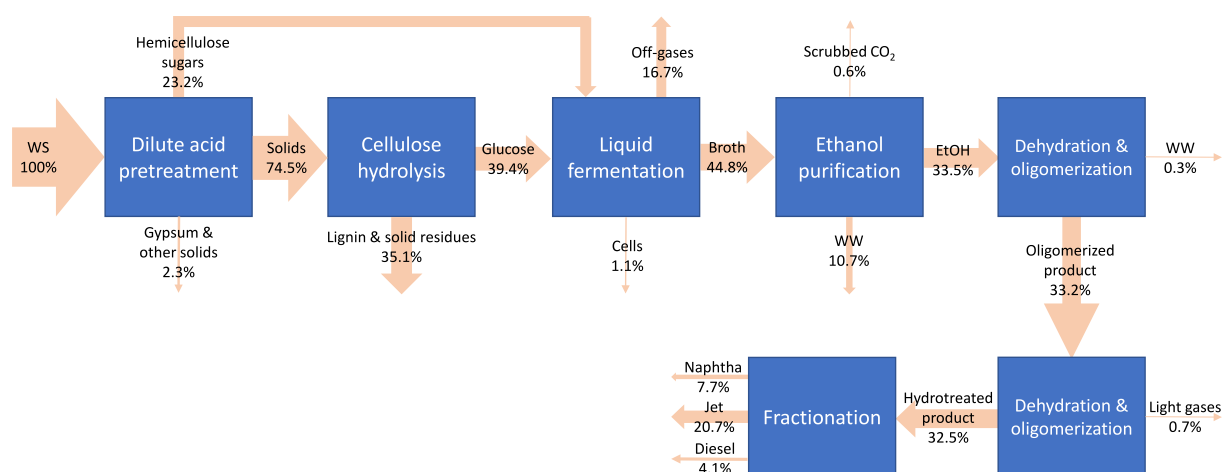


Fig. 10. Carbon balance (% of Initial Carbon) of the SUG-ATJ pathway.

Table 4

Utilities flow in kg/s (*/* stands for “consuming”/“generated”).

Utility name	SYN-HDT	SUG-HDT	SYN-ATJ	SUG-ATJ
Refrigerant	253.2	—	—	—
Chilled water	316.8	2.7	124.4	—
Cooling water	4778.6	2295.3	4480.9	3102.2
Low Pressure steam	0.0/2.0	6.4/35.1	16.7/21.3	20.7/35.9
Medium Pressure steam	0.0/1.3	0.0/0.2	—	—
High Pressure steam	—	0.7/0.7	0.7/0.7	0.7/0.7
Ultra high Pressure steam	0.8/0.8	0.7/0.7	0.5/0.5	0.7/0.7
Oil	—	—	46.5/46.5	54.5/54.5

transforming sugars into biofuels such as jet fuel (42.91 MW), naphtha (16.37 MW), and diesel (33.29 MW). In the WWTP, the organic components of the wastewater are converted into biogas, which is combusted along with lignin in the boiler. Overall, the pathway achieves significant biofuel production, with jet fuel being a particularly prominent output. Process efficiency can be improved through energy recovery mechanisms, such as recycling by-products, and utilizing combustion flue gases and light gases, although considerable energy losses remain evident at various stages.

The SYN-ATJ pathway closely resembles the SYN-HDT pathway, with the key addition of an ethanol conversion stage. Biomass is first gasified into syngas through the DFBG process, which is then fermented

into ethanol. As already said, the fermentation stage is energy-intensive, requiring substantial inputs of electricity (9.85 MW) and heating (33.63 MW), contributing to a total energy consumption of 197.54 MW for this step. The ethanol is subsequently converted into biofuels using the Alcohol-to-Jet (ATJ) process, which consumes hydrogen (4.68 MW) and additional energy for fuel separation. The final biofuel outputs include jet fuel (51.57 MW) and diesel (10.73 MW), with the pathway also recycling off-gases and flue gases back to the DFBG unit to enhance energy recovery and utilization. Despite efficient energy recycling and significant biofuel yields, the process still suffers from energy losses through light gases and waste heat, indicating potential areas for further optimization.

The SUG-ATJ pathway begins with the hydrolysis of biomass to produce sugars, which are subsequently fermented into ethanol. This ethanol is then converted into biofuels, such as jet fuel, through the Alcohol-to-Jet process. A key characteristic of this pathway is the high energy demand during ethanol recovery, requiring significant inputs of heating (30.51 MW), while some electricity (0.08 MW) is consumed for pumps and fermenter operation. Following fermentation, the ATJ process utilizes hydrogen (5.83 MW) and electricity (1.33 MW) to convert ethanol into biofuels. The final biofuel outputs include jet fuel (66.97 MW) and diesel (13.35 MW), along with naphtha (25.43 MW) as an additional valuable product. While the pathway demonstrates effective energy utilization, some energy is lost as waste heat. Energy recovery is

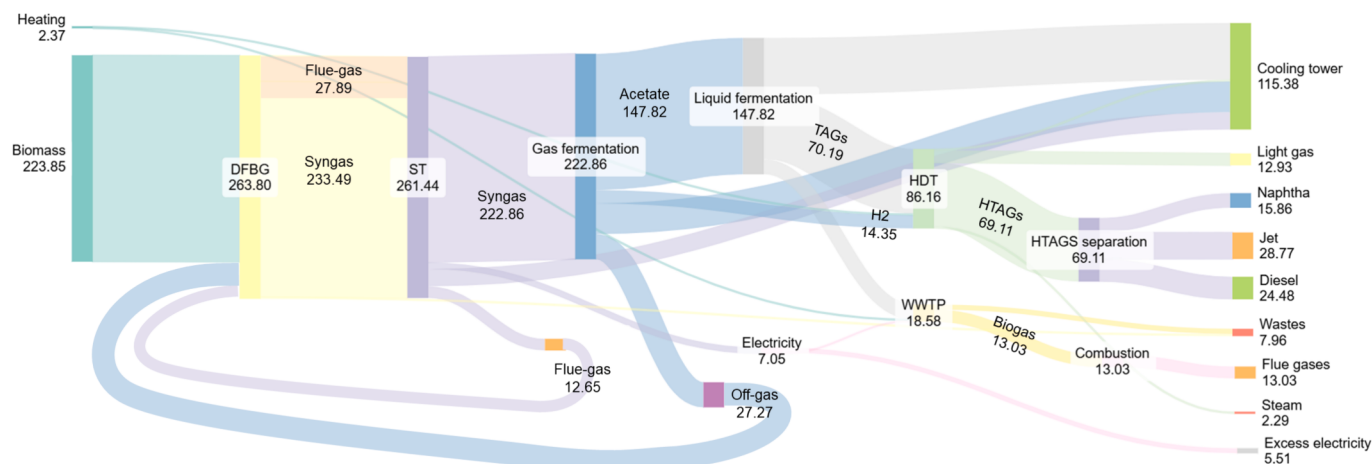


Fig. 11. Energy balance of the SYN-HDT pathway (values in MW).

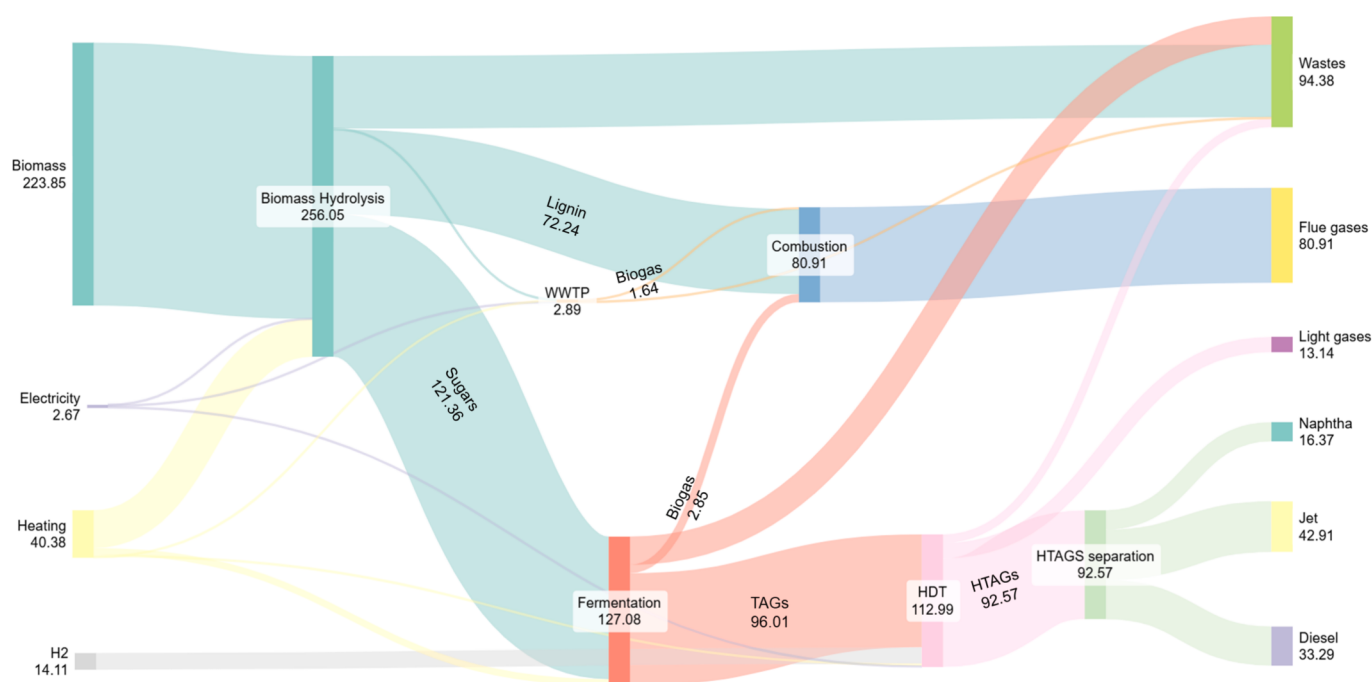


Fig. 12. Energy balance of the SUG-HDT pathway (values in MW).

partially achieved through the combustion process, which generates flue gases with high thermal energy. However, the overall energy efficiency could be enhanced by minimizing waste and improving the conversion efficiency from fermentation to biofuels.

When comparing these four pathways – SYN-HDT, SUG-HDT, SYN-ATJ, and SUG-ATJ – in terms of energy consumption, utilization, and efficiency, several key differences emerge. The SUG-HDT pathway primarily uses biomass hydrolysis followed by fermentation and hydro-treatment, with the latter being the most energy-intensive step. This pathway demonstrates good biofuel yields but significant energy losses in the form of waste and flue gases. The SYN-HDT pathway uses biomass gasification and syngas treatment, with notable recycling of Off-gas and Flue gases, making it more energy-efficient than SUG-HDT in terms of energy recovery. Both SUG-ATJ and SYN-ATJ pathways follow similar processes, with SUG-ATJ using a more direct ethanol conversion, while SYN-ATJ relies on gasification and fermentation to produce ethanol before converting it to biofuels. Both of these pathways consume significant energy during fermentation and Alcohol to Jet conversion, but

the SYN-ATJ pathway benefits from Flue and Off gas recycling, making it more energy-efficient than SUG-ATJ. Overall, while all pathways involve energy-intensive processes, the SYN-HDT and SYN-ATJ pathways generally offer better energy recovery and efficiency due to their recycling mechanisms and syngas treatment processes. However, all pathways still face challenges in optimizing waste handling and reducing energy losses through flue and off-gases.

5.4. Techno-economic analysis results

Table 5 summarizes the installed cost of the units per examined pathway, while Table 6 presents the main costs for the cases under examination. The ATJ scenarios present lower total equipment and capital costs regardless of the pathway for ethanol production. It should be mentioned that the Total Capital Investment estimate for the establishment of such commercial plants has an uncertainty of plus-minus 40 % [82], the influence of that uncertainty is discussed in following paragraph. A more detailed analysis of how capital costs are distributed per

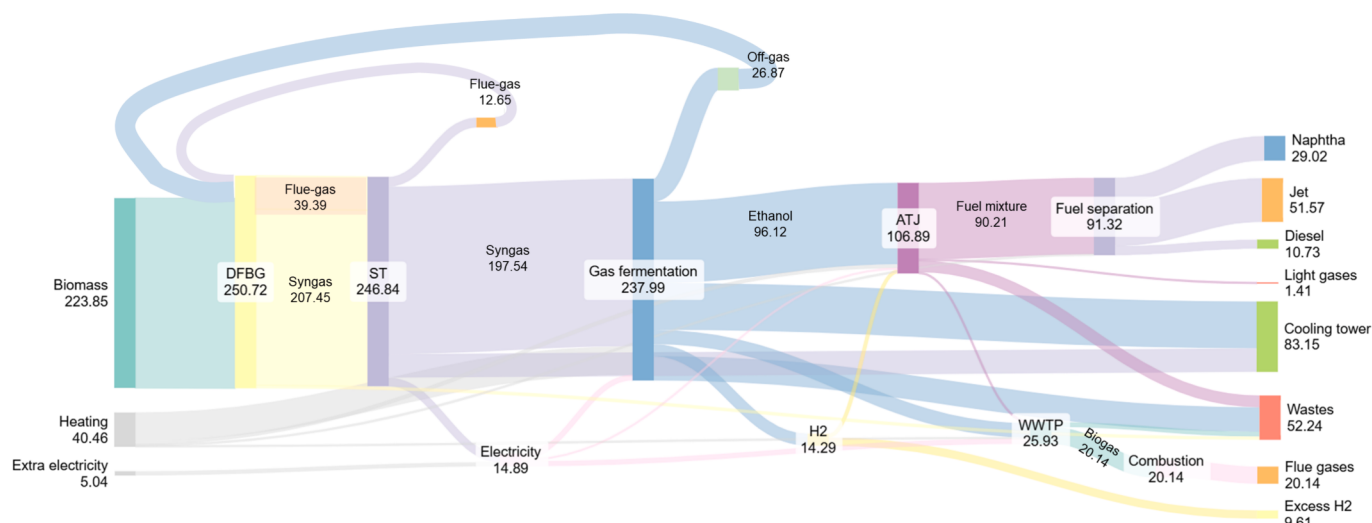


Fig. 13. Energy balance of the SYN-ATJ pathway (values in MW).

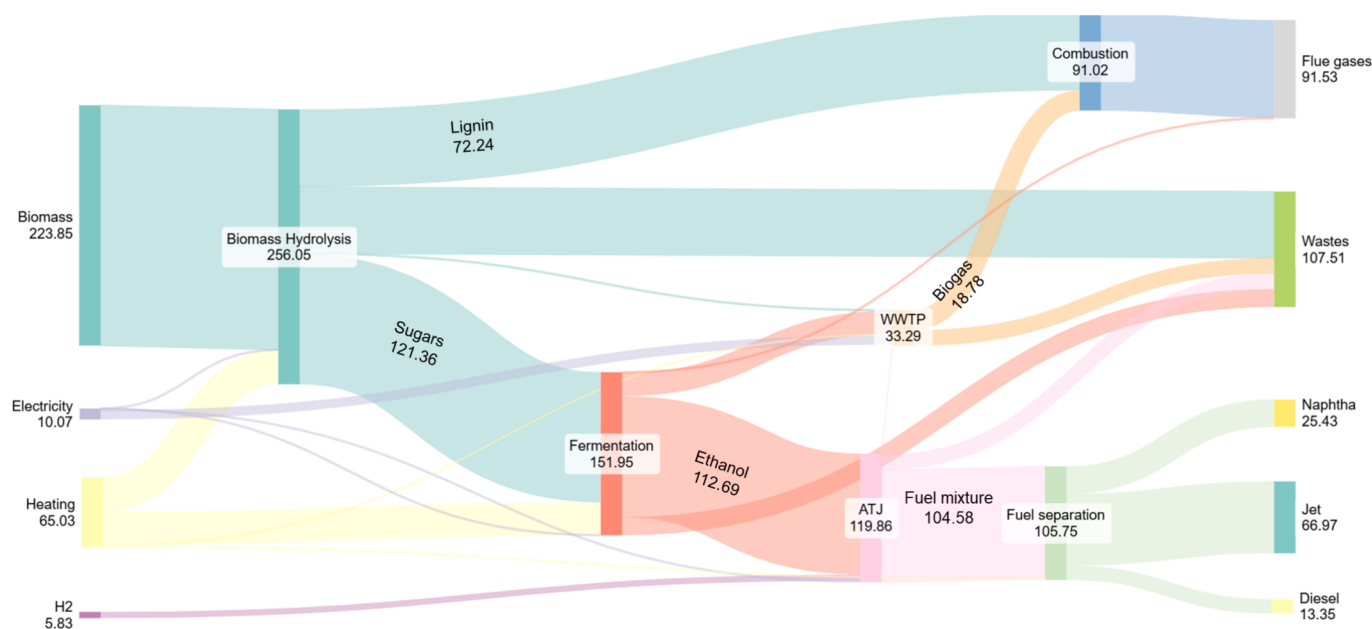


Fig. 14. Energy balance of the SUG-ATJ pathway (values in MW).

unit follows below. On the other hand, the total operational costs for the gasification based fuel synthesis via TAGs (SYN-HDT) are 15 % lower than those of the corresponding ATJ pathway. However, the lower product yield in this case, combined with the high capital costs, are the main reasons for the higher biofuel production cost.

For the microbial oil upgrading pathways (SYN-HDT and SUG-HDT), the estimated minimum selling prices (1.86–3.33 €/L) are comparable to values reported in the literature for microbial oil-derived jet fuel from 1G feedstocks such as sugarcane (1.83–3.00 €/L) [14], highlighting that our results are in close agreement despite being based on advanced biomass resources. In the reference case (SUG-ATJ), the presented analysis yields a minimum selling price of 1.24 €/L, which falls within the range of previously reported values for comparable ATJ configurations (1.49–2.50 €/L) [23,24]. These consistencies with literature values support the validity of the presented methodological framework, underlying assumptions, and cost estimations.

Furthermore, the minimum jet fuel selling price is strongly influenced by the selectivity of the jet fuel fraction that is distilled. As seen in

Table 3, 63 % w/w of the final products from the ATJ technology is jet fuel, whereas only 42 % w/w comes from the TAGs hydrotreatment. It should be pointed out that the analysis is based on relevant experimental campaign that was conducted for the first time, and there is undoubtedly significant room for improvement.

Fig. 15a illustrates the role of each main process in the CAPEX estimation. Regarding the first biomass conversion step, gasification (including gas conditioning) has a capital cost similar to that of pre-treatment and hydrolysis for sugar production. In contrast, the intermediate product synthesis and recovery section plays a key role in determining the final costs, as both the selected intermediate product and the process used for its production can vary significantly. The conversion of glucose into ethanol and microbial oil has the lowest cost, with ethanol production being notably less expensive than any other pathway. Comparing SUG-HDT and SUG-ATJ in terms of the cost of glucose to the intermediates conversion, it seems that the ethanol production path has almost half capital cost than that of TAGs. This is may attributed to the greater fermenters for lipids production that are needed

Table 5
Installed costs (in M€).

Pathway	SYN-HDT	SUG-HDT	SYN-ATJ	SUG-ATJ
handling		16.10		16.10
pretreatment		19.89		19.89
gasification unit*	63.29		63.29	
gas conditioning*	4.06		3.99	
gas fermentation	64.97		63.79	
neutralization & conditioning		5.38		5.38
saccharification/fermentation		16.46		32.92
ethanol recovery			11.81	17.87
ATJ			8.84	9.85
PSA	4.60		4.22	
TAGs production	64.76	38.42		
TAGs recovery**	16.19	19.55		
TAGs upgrading	21.96	28.28		
HRSG + heat exchangers			6.14	
wastewater treatment	55.96	47.01	38.13	46.78
utilities	6.64	6.03	6.81	7.23
boiler	6.13	45.67	7.18	48.66

* Costs for syngas cleaning (particulate/tar/sulfur removal) are included within the gasification and gas-conditioning blocks.

** Costs for cell disruption (via enzymatic hydrolysis) followed by solvent extraction steps were estimated based on analogous processes in microbial lipid production TEAs and are included in the TAGs recovery block.

Table 6
Main cost results.

Pathway	SYN-HDT	SUG-HDT	SYN-ATJ	SUG-ATJ
Total Purchased Equipment Cost (M€)	196.58	158.50	137.17	137.81
Total Capital Investment (M€)	596.86	473.98	415.13	404.33
Total fixed operating costs (M€/y)	21.23	17.17	15.23	14.87
Total Variable Operating Costs (M€/y)	29.89	42.74	44.15	39.91
Total Operating Costs (M€/y)	51.12	59.91	59.38	54.78
Ethanol production cost (€/L)	—	—	0.871	0.667
Lipids production cost (€/L)	1.73	1.08	—	—
HCS production cost (€/L)	1.95	1.25	1.38	1.12
Revenues from co-products (M€/y)	33.13	41.79	26.11	30.58
Jet fuel minimum selling price (€/L)	3.33	1.86	1.67	1.24
Biofuels production cost (€/MWh)	224.77	143.53	157.68	128.17

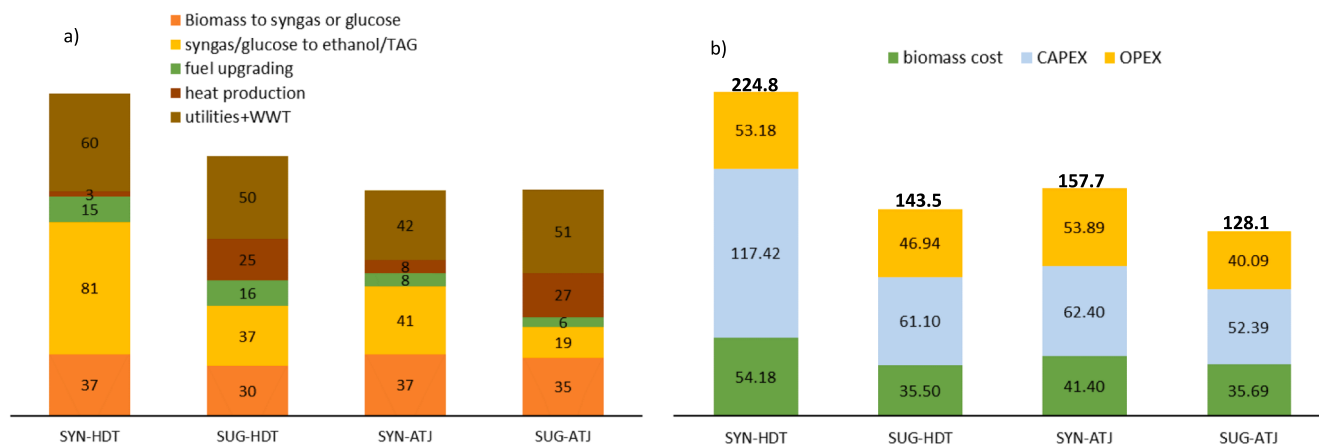
to achieve sufficient gas–liquid mixing as well to the multi-step process for TAGs extraction, recovery and purification (see Table 5). Gas fermentation options, however, are more capital-intensive, particularly the recovery and purification of TAGs. Another important consideration is that the cost of utilities (e.g., cooling systems, wastewater treatment, and biogas production) accounts for a significant portion of the total equipment cost across all cases.

Fig. 15b shows the contribution of capital and operational costs to the determination of the final production cost. In all cases except SYN-TAGs, operational costs (including both OPEX and biomass feedstock costs) play a slightly greater role in determining the final cost. Notably, the biomass cost in glucose-based pathways (SUG-TAG and SUG-ATJ) is lower due to the high EFE rates. External hydrogen for oil hydrotreatment is a significant cost item in the OPEX for the SUG-TAG case, representing 36 % of the total OPEX (compared to 15 % in the SUG-ATJ case), or 17€/MWh in the overall BPC. Potential improvements in the development of oleaginous strains that maximize selectivity for C12–C14 free fatty acids—thereby reducing hydrocracking requirements—could improve the economics of this pathway by saving hydrogen costs, as more than 15 % of hydrogen is consumed in the hydrocracking reactions. Lowering the cost of green hydrogen through technological advancements and policy interventions is crucial, as scaling up green hydrogen technologies is key to addressing climate change and ensuring a sustainable energy future.

Another parameter that affects not only the overall plant configuration but also the operation strategy and economics is the utilization of excess heat and recoverable combustibles. One option is to convert this heat into electricity to meet a significant portion of the power demand. A less capital-intensive approach is to supply this heat as steam to nearby industries or district heating networks. A detailed analysis was conducted to determine under which conditions the former or the latter option is more profitable.

Fig. 16 shows how the utilization of excess heat, either as steam or combined heat and power, along with electricity and steam prices, affects the BPC. The analysis was performed for the SUG-ATJ case. The increase in TCI and OPEX for the case of both heat and power generation is estimated at 3.2 % and 4.7 %, respectively. For steam prices greater than 30€/t, the configuration in which only steam is considered as a utility product proves to be the most beneficial, regardless of electricity costs. It can be seen that for the selected parameters in the base case, the difference between the two configurations is marginal.

Since the examined pathways consist of several consecutive process steps with intermediate products that are progressively upgraded into the final ones (hydrocarbons for transport), a specific analysis is conducted to investigate how the production cost of each intermediate product correlates with the effort to increase its calorific value. Fig. 17a

**Fig. 15.** a) Equipment cost per unit (in M€), b) biofuels production cost (bpc) breakdown (in €/mwh).

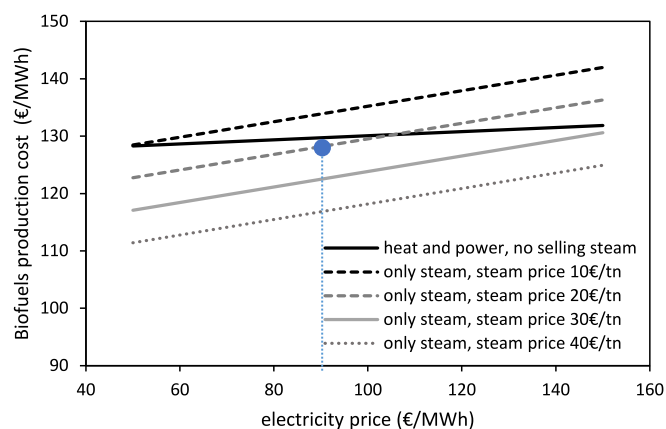


Fig. 16. Impact of excess heat utilization on the biofuels production cost.

illustrates this trend, where ethanol values are derived from the SUG-ATJ pathway, and the remaining values come from the SUG-HDT pathway. The upgrading in energy content is significant when moving from acetic acid to microbial oil, highlighting the importance of the liquid fermentation step and the subsequent downstream processing required to produce a product with improved energy content, along with the associated increases in investment and operational costs. Regarding the final upgrading step for hydrocarbon formulation, the SUG-HDT case shows an improvement in energy content (from microbial oil to hydrocarbon) of 16.3 %, with a corresponding increase in production cost of 5.7 %. In contrast, for the SUG-ATJ case, the energy content increases by 61.2 %, but the respective increase in production cost is 7.3 %, emphasizing the high importance of the upgrading section for this pathway. Fig. 17b clearly shows that the contribution of OPEX to the total production cost increases as the heating value of the targeted product rises. In other words, the most capital-intensive components are concentrated in the early stages of biomass processing.

A sensitivity analysis on critical parameters is performed in order to illustrate their influence on the economic performance of each pathway. As seen from Fig. 18, the capital cost has a great influence especially on SYN-HDT and secondly on SUG-HDT as the most CAPEX demanding cases. Since their main technologies are still at low technology readiness level, they have more prospects of investment cost reduction. Moreover, the biomass feedstock cost is another important factor, and better MSP can be achieved if low cost, yet challenging feedstock types like biogenic residues and biowastes are employed. Gasification is a proven technology that can handle quite effectively such feedstock, making concepts like SYN-HDT and SYN-ATJ improve their economic performance. The electricity price has smaller impact on cases that have relevant low power consumptions (SUG-HDT). Finally, due to the relatively lower selectivity in jet fuel for the TAG bases cases (SYN-HDT and SUG-HDT), the revenues from selling of the side products (LPG, gasoline and Diesel)

play a significant role in the determination of jet fuel breakeven point, highlighting the necessity of improvement in hydrotreatment catalyst towards the maximization of jet fuel fraction yield.

Overall, the structured comparison in Table 7 highlights the trade-offs between the four pathways. The SUG-ATJ route shows the highest carbon efficiency and jet fuel yield, but this advantage comes at the expense of significantly higher external power demand. In contrast, the SYN-HDT pathway benefits from high energy self-sufficiency and relatively low external power needs due to syngas-derived hydrogen, although its overall fuel yield and carbon efficiency remain limited. The SYN-ATJ pathway represents a balanced option, with moderate carbon losses and favorable hydrogen demand compared to the hydro-processing routes. Finally, the SUG-HDT process performs in the mid-range across most categories, but its relatively high water demand may affect its sustainability at larger scale. This structured assessment makes clear that the pathways differ not only in cost but also in their technical and environmental performance, and no single route is superior across all factors.

5.5. Ways for making microbial oil based pathway more competitive

In contrast to ethanol, there are only a few studies on using microbial oil as an intermediate carrier for advanced biofuels production, which are mainly based on first-generation feedstocks or scenario analyses (see Table 1), whereas our study performs a direct comparison of microbial oil and ethanol upgrading from lignocellulosic biomass under consistent assumptions. Although the above analysis shows that ethanol-to-jet pathways offer better performance, this paper highlights certain aspects that need optimization, which could make microbial oil-based pathways more competitive and economically viable. Compared to ethanol fermentation, TAG production is aerobic and requires oxygen, which binds hydrogen and/or carbon and reduces overall efficiency. Potential mitigation strategies include developing more oxygen-efficient microbial strains, coupling with renewable hydrogen supply to compensate for the hydrogen deficit, and improving gas-liquid mass transfer to reduce aeration demand. These measures could improve the competitiveness of microbial oil routes relative to ethanol-based pathways. Fig. 19a illustrates how the biofuels production cost can be reduced through certain realistic improvements in the SUG-TAG process. If the wastewater intake at the WWT plant is reduced by 25 % (e.g., by recycling part of the contaminated water in the process), the cost decreases by 6.5€/MWh. Additionally, further optimization of the biological processes, aimed at achieving a total requirement for fresh process water equal to that of the SUG-ATJ case, is expected to result in a similar reduction in production costs. Finally, the development of more efficient strains in the second fermentation step, which could lead to a 5 % increase in TAGs production compared to the base case, would reduce production costs by approximately 5.8€/MWh. In total, these improvements could lower the cost below that of the SUG-ATJ case, making the SUG-TAG concept a competitive advanced biofuels production option.

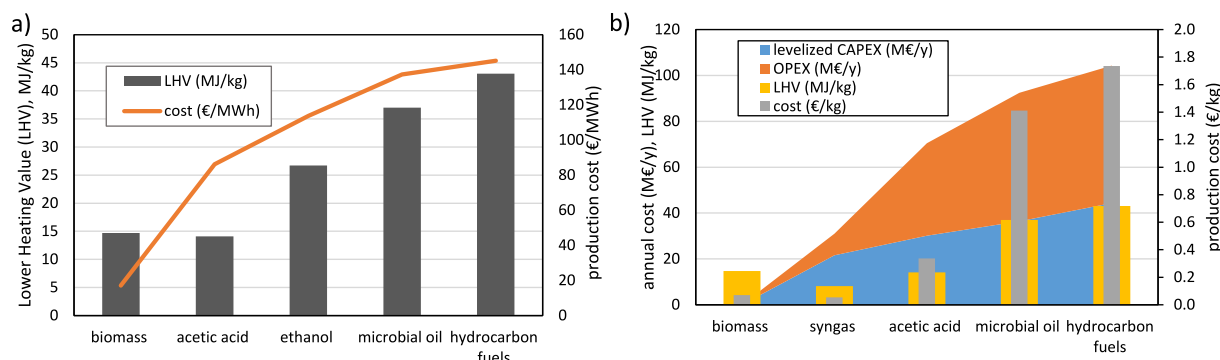


Fig. 17. a) Production cost and heating content of the intermediate and final products, b) cost breakdown of the intermediate and final products.

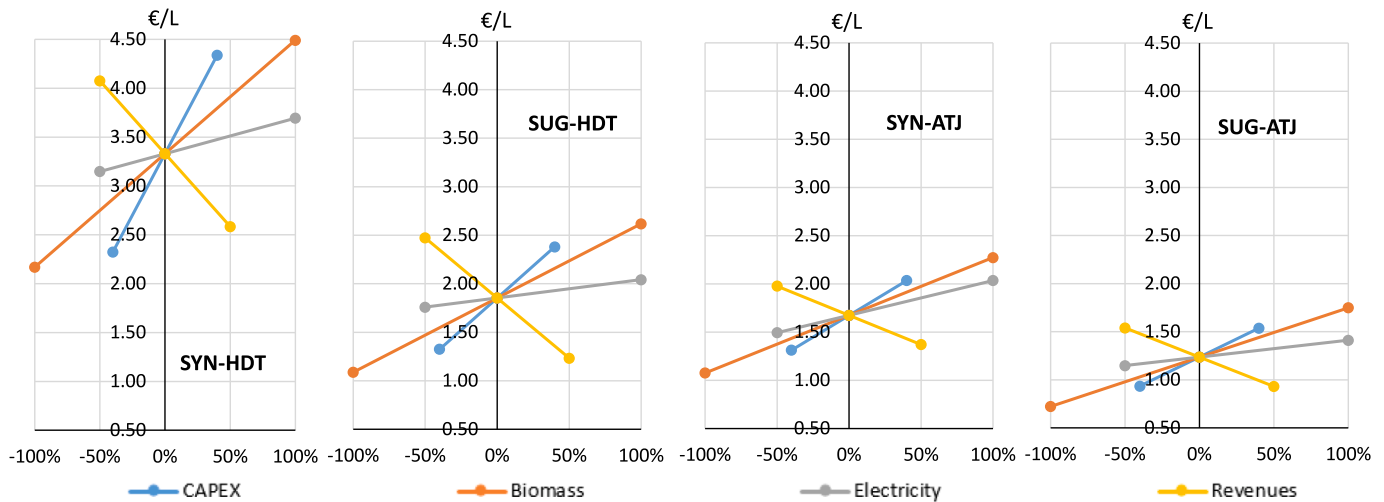


Fig. 18. Sensitivity analysis of jet fuel minimum selling price.

Table 7

Structured comparison of pathway performance with respect to key techno-economic and environmental factors. The qualitative scale ('+' favorable, '0' neutral, '-' unfavorable) is based on relative performance among the four pathways.

Factor	SYN-HDT	SUG-HDT	SYN-ATJ	SUG-ATJ
Energy self-sufficiency	+	0	0	-
Hydrogen demand	0	0	+	-
Carbon efficiency	-	0	0	+
Jet fuel yield	-	0	+	+
Power demand	+	0	0	-
Water demand	0	-	0	+

Regarding the minimum jet fuel selling price, the oil hydrotreatment modeling was based on the only available experimental study on microbial oil hydroprocessing in the literature. However, there is significant potential for further improvements in catalysts to maximize jet fuel selectivity. Fig. 19b shows how the minimum selling price of jet fuel is influenced by the different distributions of hydrocarbon product yields. Catalysts for hydrocracking that can minimize the yield of lighter fractions have a significant beneficial impact on the plant's sustainability when aviation biofuel is the primary desired product.

5.6. Limitations of the study

This study is subject to several limitations. First, many process parameters—particularly for microbial oil fermentation and recovery—are based on laboratory- or pilot-scale data, which may not be directly representative of industrial performance. Scale-up to commercial plants often introduces additional challenges such as contamination risk, reactor hydrodynamics, and process control, which are difficult to capture in conceptual models. Second, long-term continuous operation data are scarce, especially for gas fermentation and aerobic TAG production. The limited number of pilot demonstrations makes it uncertain whether the high yields and productivities reported in batch or fed-batch experiments can be maintained at scale over extended operation periods. Third, some blocks were modeled using standard design assumptions, as discussed in the model description section. While these are consistent with TEA literature, they may not fully capture some aspects such as the variability of sugars / syngas composition from different feedstocks, the potential formation of inhibitory by-products, or the energy penalties associated with advanced cleaning steps. Fourth, capital and operating cost estimates remain uncertain due to scale-up effects and the use of standard cost correlations. These estimates also do not explicitly account for potential reductions through technological learning, supply chain improvements, or policy incentives that could emerge as the sector matures. Finally, broader sustainability aspects such as water footprint, land use impacts, or indirect greenhouse gas

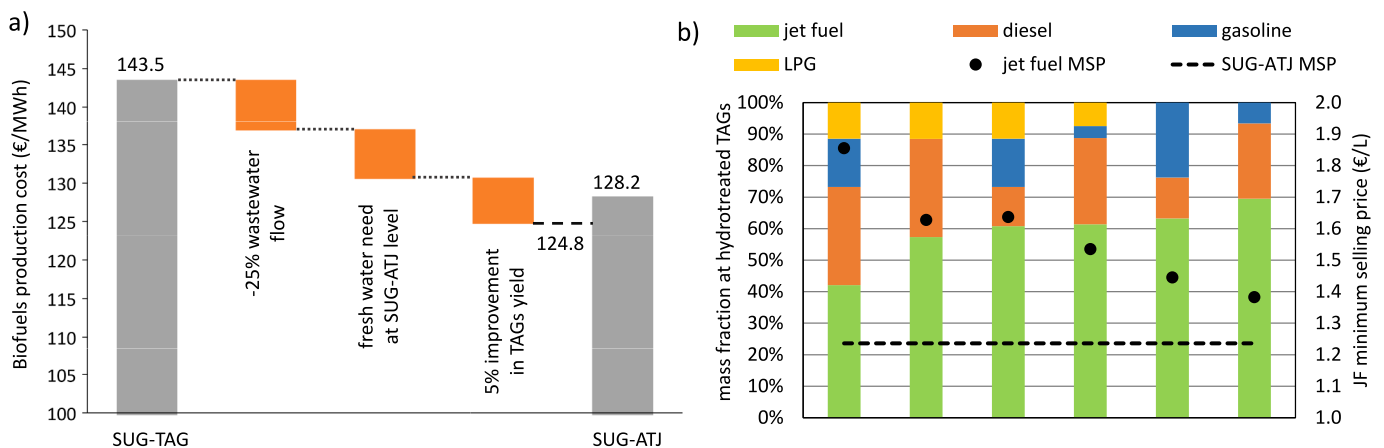


Fig. 19. a) Expected decrease in BPC after advancements in SUG-TAG pathway, b) minimum jet fuel selling price for different selectivities in final products.

emissions were outside the scope of this analysis, but they may influence the relative attractiveness of different pathways in practice. These limitations should be considered when interpreting the results, which are intended to provide comparative insights into the relative performance of pathways rather than precise cost forecasts.

6. Conclusions

This study compared four advanced pathways for lignocellulosic biomass to SAFs production via ethanol and microbial oil intermediates. Ethanol-based Alcohol-to-Jet (ATJ) pathways, particularly SUG-ATJ, achieved the highest jet fuel yield and carbon utilization, with over 60 % jet fuel selectivity. However, its high external power demand highlights the need for process optimization strategies and integration with renewable energy.

Microbial oil pathways (SUG-HDT and SYN-HDT) demonstrate significant long-term potential, with advances in strain engineering and catalyst development likely to improve TAG yields, selectivity, and cost competitiveness. Syngas-based pathways (SYN-HDT and SYN-ATJ) stand out for their energy self-sufficiency, utilizing syngas-derived hydrogen and process heat recovery. However, these pathways face limitations in fuel yield and carbon efficiency due to higher carbon losses and lower jet fuel selectivity. To address the energy and carbon losses, especially in the SYN-HDT pathway, heat integration and waste stream utilization were implemented to enhance process efficiency.

Future study should focus on comprehensive life cycle assessment, water footprint evaluation, and carbon capture and utilization (CCU) to address environmental trade-offs. Further innovations in strain/catalyst optimization are recommended to enhance TAG yields and improve jet fuel selectivity, ultimately lowering production costs. By overcoming current technological bottlenecks and implementing these innovations, microbial oil pathways could emerge as viable alternatives for commercial-scale SAF production, contributing significantly to aviation sector decarbonization. This study fills a critical gap in the literature by conducting a detailed techno-economic analysis assessment of microbial oil pathways at an industrial scale. It also provides valuable insights into SAF development, guiding strategic investments and policy frameworks toward more sustainable and economically viable biofuel technologies.

CRedit authorship contribution statement

Vasiliki Kaperneka: Writing – original draft, Visualization, Software, Formal analysis, Conceptualization. **Leda Maragoudaki:** Writing – review & editing, Software, Data curation. **Konstantinos Atsonios:** Writing – review & editing, Supervision, Project administration, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.fuel.2025.137118>.

Data availability

Data will be made available on request.

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