

Comparative Techno-Economic Analysis of Next Generation

Sustainable Aviation Fuels

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ABSTRACT

This study compares four different scenarios for sustainable aviation fuel (SAF) production using techno-economic analysis (TEA) to assess the Levelized Cost of SAF (LCoSAF). The SAF pathways assessed are: (i) Methanol-to-Jet sourcing carbon from post-combustion carbon capture (MTJ-PCC), (ii) Methanol-to-Jet sourcing carbon from biomethane (biomethane-MTJ), (iii) Hydrothermal Liquefaction of sewage biosolids (HTL), and (iv) Lignocellulosic biomass Fast Pyrolysis bio-oil (FP).

The TEA methodology draws on real-world feedstock and process descriptors and imposes elemental mass balances across critically reviewed unit processes, producing aviation turbine fuel with properties modeled to be within ASTM D4054 specification limits. The results show that SAF produced from lignocellulosic biomass fast pyrolysis has the highest potential, with an LCoSAF of 746 €/t. In comparison, the LCoSAF for Methanol-to-Jet (PCC), Methanol-to-Jet (biomethane), and Hydrothermal Liquefaction of sewage biosolids are 1,109, 2,263, and 5,153 €/t, respectively.

Keywords: Sustainable Aviation Fuel, Techno-economic Analysis, Methanol-to-Jet, Fast Pyrolysis, Hydrothermal Liquefaction, Levelized Cost of SAF.

NONMENCLATURE

Abbreviations

SAF	Sustainable Aviation Fuel
MTJ	Methanol-to-Jet
PCC	Post-combustion Carbon Capture
HTL	Hydrothermal Liquefaction
FP	Fast Pyrolysis
TEA	Techno- Economic Analysis
CAPEX	Capital Expenditure
OPEX	Operational Expenditure
LCoSAF	Levelized Cost of Sustainable Aviation Fuel

LPG	Liquefied Petroleum Gas
EC	Equipment Cost

1. INTRODUCTION

In the effort to achieve net zero by 2050, much attention has been paid to the carbon emissions of the transport sector, which accounts for about a fifth of total carbon emissions [1]. The aviation industry also accounts for about 11.6% of the carbon emissions of the transport sector [2]. In addition, according to forecasts, the demand for commercial aviation will triple by 2070, which has increased attention to decarbonizing this sector [3].

Replacing conventional fossil aviation fuels with Sustainable Aviation Fuels (SAFs) is the main method to decarbonize aviation industry. SAFs are a renewable or circular-carbon, drop-in substitute for conventional aviation fuels, and are approved for use by the aviation OEMs under the stringent specifications of ASTM D7566 [4], following the evaluation practice set out in ASTM D4054. At present, eight SAF types (technically termed synthetic blending components) have been approved for use when blended with conventional fossil-derived blending components, such as Jet A. [4].

A significantly larger number of SAF types will be required to meet European Union and international deployment targets. The introduction of a new feedstock, a novel conversion process, or a distinct fuel property specification constitutes a new SAF type, each of which requires approval from aviation OEMs prior to use.

As both the evaluation, development and production costs of a new SAF are considerable, the deployment of new SAF types depends heavily on strong financial investment. For such investment to be manifested, it is important to have production cost estimates that are both objective, comparative and technically well informed [5]. Reliable techno-economic analyses (TEAs)

bring together the factors that influence SAF cost in a transparent and evidenced based manner. TEA can provide a clear picture of the likely cost of SAF production and allows different pathways to be compared on the same basis, i.e. “*Levelized Cost of SAF*”.

In this study, a techno-economic analysis is performed for four “next-generation” SAF types that are currently under development but not yet approved for use, although approval is anticipated following the completion of the necessary due diligence.

The investigated pathways include Methanol-to-Jet carbon source from both Post-combustion Carbon Capture (MTJ-PCC), and from biomethane (Biomethane-MTJ), Hydrothermal Liquefaction (HTL) of sewage biosolid, and Lignocellulose biomass fast pyrolysis (FP) of forestry residues.

Methanol-to-Jet is currently in the advanced stages of OEM evaluation through the ASTM D4054 where methanol is converted into liquid hydrocarbons via catalytic oligomerization followed by hydroprocessing [6]. The methanol used can be derived from synthesis gas, which can originate from various sources such as biomass gasification, renewable hydrogen with captured CO₂, or reforming of methane or biomethane [7].

Hydrothermal liquefaction (HTL) is a thermochemical process that converts wet biomass into bio-crude under moderate temperature (250–400 °C) in a water-rich environment [8] producing bio-crude that contains hydrocarbons (C₅–C₃₀) and oxygenated compounds. This bio-crude is upgraded into hydrothermal liquefaction synthetic paraffinic kerosene (HTL-SPK) through hydrodeoxygenation, hydroisomerization, and fractional distillation [9].

Fast pyrolysis (FP) is a thermochemical conversion process in which biomass is rapidly heated in the absence of oxygen to produce bio-oil, a very complex mixture of highly functionalized oxygenated hydrocarbons. Operating at moderate temperatures (400–600 °C) and with residence times typically under two seconds, the process achieves high bio-oil yields. The bio-oil requires extensive upgrading to remove all oxygen content to produce the complex mixture of (C₆–C₂₀) hydrocarbons required for SAF [10]. In this study forestry residue derived fast pyrolysis is studied.

2. METHODOLOGY

The methodology to assessing the levelized cost of SAF is as follows: First, the SAF production unit processes are presented. A detailed elemental mass flow is derived to account for the conversion of feedstock to product,

allowing quantitative estimate of the energy and supplemental raw material quantities required (e.g. hydrogen), in addition to the LCA of the carbon intensity of the SAF produced [11]. Then, the associated supply chain configuration and principal economic parameters are systematically described for each pathway. Finally, the TEA arithmetic is applied to estimate the final production cost is reported.

2.1 System Boundaries and Supply Chain

Figures 1 illustrate the supply chains of the MTJ-PCC, biomethane-MTJ pathways, FP, and HTL. The system boundary extends from feedstock transportation point to the SAF transportation to the airport. Processes such as storage at the airport and feedstock production are outside of the scope of analysis for the reason that the results produced should be fairly comparable for each SAF type analyzed.

In all scenarios energy is supplied using electricity and the SAF production capacity is considered 1,000,000 tonnes SAF/year. To allow for comparability economic cost parameters of Finland are considered for all scenarios.

Additionally, for FP and HTL scenarios a transportation distance of 100 km is considered to transfer the forestry residue and sewage biosolids to the SAF production facility.

This study use the mass and energy balance modeled by Mannion et al. [11] for scenarios exactly consistent to the system boundary set out above. From the work of Mannion et al. The MTJ-PCC ,biomethane-MTJ, HTL and FP scenarios use 1,813 GWh/year, 2,646 GWh/year, 1,655 GWh/year, and 718 GWh/year of electricity, respectively.

2.2 Techno-economic analysis

2.2.1 CAPEX

In the first step of economic analysis, capital expenditure (CAPEX) is calculated. Fixed costs include Equipment Cost (EC) and other capital expenses during construction. Equipment Cost for all required equipment is calculated using Equation 1. Equation 1, reduces the imprecision of this estimate by exploiting the concept of normalizing the Equipment Cost to the known equipment cost of existing installations that are similar. [12].

$$\frac{EC_{\text{this study}}}{EC_{\text{ref case}}} = \left(\frac{Capacity_{\text{this study}}}{Capacity_{\text{ref case}}} \right)^{SF} \quad (1)$$

$EC_{\text{this study}}$, $Capacity_{\text{this study}}$, $EC_{\text{ref case}}$, and $Capacity_{\text{ref case}}$ are the equipment cost of the this study, the main feed capacity of this study, the equipment cost of the reference case and the main feed capacity of the reference case, respectively. Additionally, the economy of capacity change is considered using Scaling Factor (SF). SF in this study is 0.67 based on the data from the literature [13]. Table 1 shows the initial number for equipment cost calculation.

Table 1- The equipment cost of each scenario based on equation 1

Scenario	Ref Case		This Study		Ref.
	Capacity (kt/y)	Equipment cost (M€)	Capacity (kt/y)	Equipment cost (M€)	
MTJ-PCC	241 (CO ₂)	216	6,666 (CO ₂)	1,993	[14]
Biomethane-MTJ	71 (biomethane)	216	3,070 (biomethane)	2,023	[14]
HTL	334 (sewage biosolid)	10	11,200 (sewage biosolid)	105	[15]
FP	730 (solid residue)	120	6,850 (forestry residue)	571	[16]

Table 2 provides other important parameters and their estimation formula. Also the cost needed for each parameter is reported for all scenarios in this study.

The CAPEX can be calculated using the following equation:

$$CAPEX = \text{Equipment Cost} + \sum_{j=1}^{12} j \quad (2)$$

Table 2 Typical parameters used for CAPEX estimation as a function of equipment cost (EC)

j	CAPEX items	Estimation
Total direct plant costs (D)		
1	Equipment installation	0.47 × Equipment Cost
2	Instrumentation and control	0.36 × Equipment Cost
3	Piping	0.68 × Equipment Cost
4	Electrical	0.11 × Equipment Cost
5	Buildings	0.18 × Equipment Cost
6	Yard improvements	0.10 × Equipment Cost

j	CAPEX items	Estimation
7	Service facilities	0.55 × Equipment Cost
Total indirect plant costs (I)		
8	Engineering and supervision	0.33 × Equipment Cost
9	Construction expenses	0.41 × Equipment Cost
10	Legal expenses	0.04 × Equipment Cost
As a function of total direct and indirect costs (D + I)		
11	Contractor's fee	0.05 × (D + I)
12	Contingency	0.10 × (D + I)

The Annualized Capital Cost (ACC) helps convert the one-time capital cost into an equivalent annual cost over the asset's lifetime, considering the time value of money. Equation 3 is used to calculate the ACC.

$$ACC = CAPEX \times \frac{i(i+1)^n}{(i+1)^n - 1} \quad (3)$$

In the above equation, i is interest rate. Also, n is the project's lifetime.

2.2.2 OPEX

The operational expenditure (OPEX) is divided into two categories: direct OPEX and indirect OPEX. The purchasing and transporting raw materials, labor, utilities, and transporting fuel to the place of use are included in direct OPEX. Labor needed for each facility is estimated using Peters et al. [17]. Table 3 shows the parameters considered for indirect OPEX and how they are calculated [18].

Table 3 Typical parameters for indirect operating expenditure (OPEX) estimation.

ID	OPEX item	Estimation
1	Operating supervision	0.15 × Labor costs
2	Maintenance labor	0.01 × CAPEX
3	Maintenance material	0.01 × CAPEX
4	Operating supplies	0.15 × (2* + 3)
5	Laboratory charges	0.20 × Labor costs
6	Insurance and taxes	0.02 × CAPEX
7	Plant overhead costs	0.55 × (Labor costs + 1 + 5)
8	Administrative costs	0.33 *(7)
Indirect OPEX = $\sum_{1}^8 ID$		

* This numbers presents the item in specific row for example 2 is Maintenance labor cost

Equation 4 is used to calculate LCoSAF. In this equation the co-products are considered as benefits.

$$LCoSAF \left(\frac{\text{€}}{\text{tonne SAF}} \right) = \frac{ACC + OPEX_{\text{Indirect}} + OPEX_{\text{Direct}} - \text{Benefits}}{\text{SAF production capacity(tonne)}} \quad (4)$$

For TEA, some initial numbers are needed. Table 4 illustrates the initial prices.

Table 4 Initial economic parameters applied in the techno-economic assessment

Parameter	Amount	Unit	Ref.
Forestry Residue	50	€/ t	[19]
Biomethane	720	€/ t	[20]
Electricity	80	€/	[21]
Water	3.8	€/ t	[22]
Naphtha	550	€/ t	[23]
Diesel	1,850	€/ t	[24]
Project's lifetime (n)	20	Year	[18]
Transportation unit price	0.08	€/t. km	[25]

1. RESULTS

In this section the economic results are presented and the main economic parameters of different scenarios, including CAPEX, OPEX, and the LCoSAF, are compared to understanding which pathway is more economic.

Table 5 summarizes the outcomes of the techno-economic analysis for different SAF production pathways. Substantial variation is observed across the assessed methods in terms of CAPEX, OPEX, and LCoSAF.

The biomethane-MTJ and MTJ-PCC pathways show the highest CAPEX, at 9774.8 M€ and 9630.3 M€, respectively, primarily driven by large-scale equipment investments and associated infrastructure. In contrast, HTL requires the lowest investment of 509.4 M€, followed by FP by 2763.0 M€.

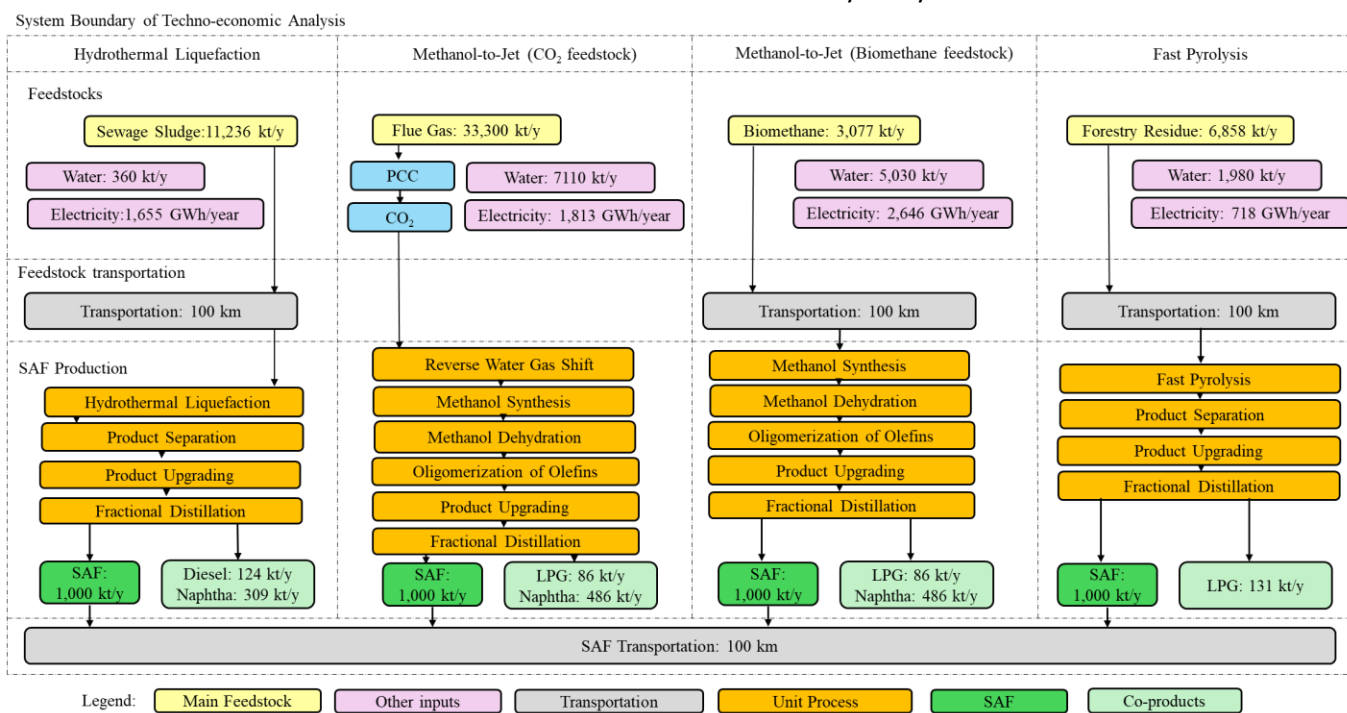


Fig. 1 The supply chain schematic for different scenarios. The numbers from Liam et al. [11]

In terms of co-product benefits, the FP pathway achieves the highest annual income by 592 M€/y, whereas biomethane-MTJ and MTJ-PCC generate considerably lower income from co-products.

As a result, the estimated LCoSAF varies widely among the assessed technologies. FP and HTL demonstrate comparatively lower production costs of 746 and 1109.8 €/t SAF, respectively, indicating greater economic viability. Conversely, MTJ-PCC and biomethane-MTJ show significantly higher LCoSAF values at 2263.3 and 5153.7 €/t SAF, respectively. The higher

LCoSAF in MTJ-PCC and biomethane-MTJ may limit their competitiveness under current market conditions.

Figure 2 illustrates the cost structure of different SAF production scenarios. Based on fig. 2 the direct OPEX dominates the overall cost contribution for all pathways, particularly for biomethane-MTJ, which shows the highest operating burden. In contrast, CAPEX is relatively modest compared to OPEX, except in MTJ-based routes where investment intensity is substantial. Among the pathways, FP and HTL stand out with comparatively

lower LCoSAF values, demonstrating more economic results.

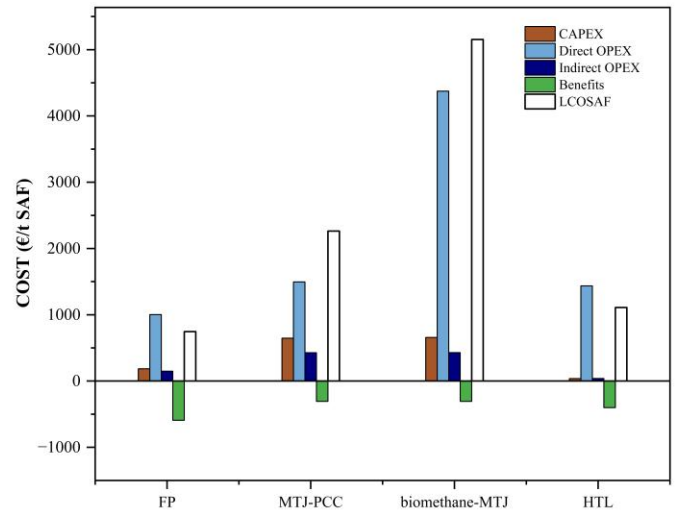


Fig. 2 Cost components, benefits, and LCoSAF for different SAF production pathways.

Table 5 Results of the techno-economic analysis (TEA) for different conversion pathways for sustainable aviation fuel (SAF).

Method	CAPEX (M€)	ACC(M€/y)	Direct OPEX (M€/y)	Indirect OPEX (M€/y)	Benefits (M€/y)	LCoSAF (€/ t SAF)
FP	2763.0	185.7	1003.2	149.1	592.0	746.0
MTJ-PCC	9630.3	647.3	1495.6	427.0	306.7	2263.3
biomethane-MTJ	9774.8	657.0	4374.0	429.6	306.9	5153.7
HTL	509.4	36.8	1436.0	38.1	401.1	1109.8

2. DISCUSSION

This study presented a comparative techno-economic analysis of four sustainable aviation fuel production pathways: methanol-to-jet with post-combustion carbon capture, biomethane to fuel using methanol-to-jet, hydrothermal liquefaction of sewage biosolids, and fast pyrolysis of forestry residues.

The results showed that among the assessed pathways, fast pyrolysis and hydrothermal liquefaction showed the greatest economic potential, with levelized costs of 746 and 1109.8 euro per tonne of sustainable aviation fuel, respectively, driven by comparatively lower capital intensity and favorable co-product benefits. In contrast, methanol-to-jet with post-combustion carbon capture and biomethane derived methanol-to-jet exhibited substantially higher costs of 2263.3 and 5153.7 euro per tonne of sustainable aviation fuel, reflecting their high electricity demand and investment requirements. Direct operating costs were identified as the dominant cost driver across all pathways.

Overall, these findings suggest that thermochemical routes such as fast pyrolysis and hydrothermal liquefaction offer more competitive opportunities for sustainable aviation fuel deployment, while methanol-to-jet pathways may require significant technological advances and supportive policy frameworks to achieve cost competitiveness.

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