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Sustainable Aviation Fuels Production via Biogas Reforming and Fischer-Tropsch Integrated with Solid Oxide Electrolysis

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ABSTRACT

Sustainable aviation fuels (SAFs) can be pivotal, gradually replacing fossil kerosene and lowering carbon emissions without changing the existing infrastructure. One of the pathways to produce SAFs is through the Fischer-Tropsch synthesis (FTS) process. The present work proposes an integrated process of sustainable aviation fuel production from biogas through a reforming process, Fischer-Tropsch (FT), and a solid oxide electrolysis (SOEC) process. Aspen Plus v14 is used to build an integrated kinetic process model for biogas reforming, FTS and hydrocracking. The technical evaluation is assessed with several key performance indicators, such as carbon efficiency and process efficiency. In addition, two scenarios are investigated in this study for H_2 supply from SOEC before and after reforming. The output products consist of kerosene and diesel since the tail gas and naphtha are recycled to the reformer to maximize SAF production. The simulation results show that the carbon efficiency of the integrated process is between 96.3% and 96.5%. Meanwhile, the process efficiency is between 40.1% and 40.9%. The process efficiency can be further improved by investigating the options for heat integration, with subsequent economic and environmental analysis to determine the production cost of SAFs and the CO_2 reduction potential compared to conventional aviation fuel. In addition, projection cost analysis is needed to determine the decline in the cost of fuel production in the future.

Keywords: sustainable aviation fuels, biogas reforming, Fischer-Tropsch process, solid oxide electrolysis

1. INTRODUCTION

The aviation industry is essential for the fast and efficient transportation of people and goods, making it crucial for international business and tourism. However, this sector contributes greenhouse gas (GHG) emissions significantly, releasing around one billion tons of CO_2 annually—about 2.5% of global energy-related CO_2 emissions. One of the strategies to achieve carbon neutrality in the aviation sector is the adoption of Sustainable Aviation Fuel (SAFs) [1].

A viable method for producing SAFs is the Fischer-Tropsch (FT) process. This method converts syngas into liquid fuels whose composition depends on pressure, temperature, syngas composition, and catalyst type. The FT synthesis can occur at low temperatures (LTFT) and high temperatures (HTFT). The LTFT process is operated at 210–260 °C with a cobalt catalyst, which produces long-chain hydrocarbon. Meanwhile, the HTFT process is operated at 310–340 °C with an iron catalyst, which generates short-chain hydrocarbons [2].

The syngas, which is a mixture of CO, H_2, CO_2, and H_2O, can be produced from a thermochemical conversion process at a high temperature of 900 °C with several routes: reverse water gas shift, steam reforming, and autothermal reforming, with the primary feedstock is natural gas or biogas along with steam or hydrogen. Biogas is an attractive resource because it has carbon sources from methane and CO_2, which can be transformed into syngas through steam reforming process [3]. In addition, due to the awareness of Power-to-X (PtX) technologies, this can expand to green hydrogen production from the electrolysis process (e.g., solid oxide electrolysis), which can fulfill the syngas requirement for the FT process [4].

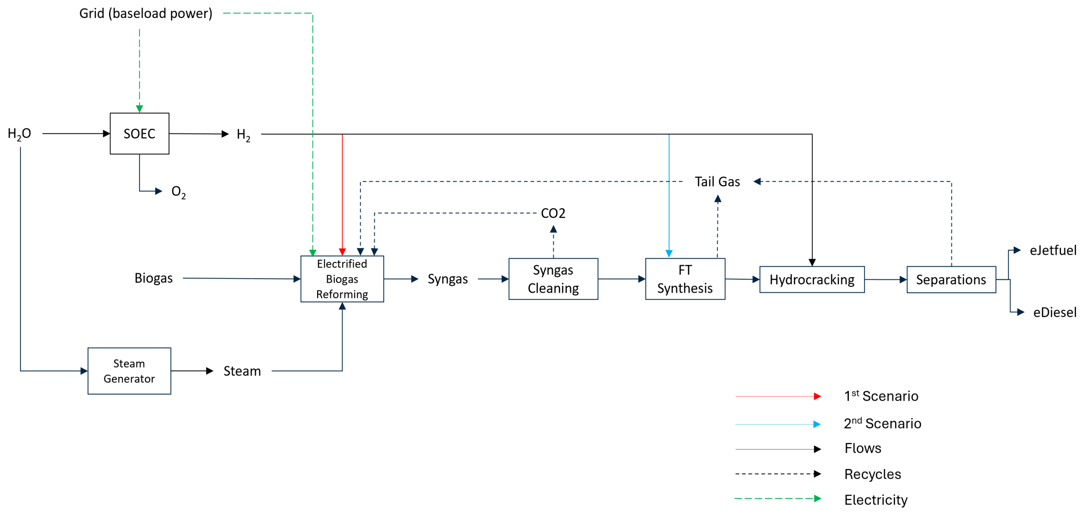


Figure 1. Schematic of the system.

Existing studies in process modeling of sustainable aviation fuel through the Fischer-Tropsch process typically focus on a CO_2 source from flue gas and ambient air. For instance, Paulsen et al. performed techno-economic assessments of jet fuel production integrated, reverse water gas shift (RWGS), Fischer-Tropsch, and electrolysis process with CO_2 source from ambient air through high-temperature direct air capture (HTDAC). It demonstrated that the energy efficiency is up to 39% with specific energy consumption of up to 156 $\mathrm{MJ/kg_{Jet\ fuel}}$ [4]. In another CO_2 source, Marchese et al. conducted the process modeling of integrated RWGS and co-electrolysis process with the Fischer-Tropsch process to produce the liquid fuels with CO_2 source from biogas through MEA absorption. The results show that plant efficiency is 75.8% for co-electrolysis and 70.1% for RWGS [5]. However, these studies do not utilize the methane from biogas as the input to maximize the yield of liquid fuels.

This work aims to develop a rigorous process model of SAF production through the FT process with solid oxide electrolyzer and electrified biogas reforming, which utilize the CH_4 and CO_2 from biogas as the primary feedstock and the output products consisting of kerosene and diesel. Hydrocracking is employed to crack the wax, and the resulting tail gas and naphtha are recycled to the reformer to maximize the fuel yield. Kinetic models are developed for all reactors (reformer, FT, and hydrocracking) and validated with experimental data.

2. METHODOLOGY

2.1. Process description

The integrated process model is developed for SAF production via the Fischer-Tropsch process with syngas sources generated from electrified biogas reforming. Two scenarios are investigated in this study. In the first scenario, biogas, steam, and hydrogen from SOEC are input to the steam reforming reactor. Biogas and steam are fed into the reforming reactor, with the additional required hydrogen being input before the FT reactor in the second scenario. The first and second scenarios are presented in Fig. 1.

2.2. Process Simulation

The process simulation is developed using Aspen PLUS v14 with Peng-Robinson (biogas reforming and electrolysis), Soave-Redlich-Kwong (Fischer-Tropsch and hydrocracking), and E-NTRL (syngas cleaning) EOS's, as the thermodynamic models. The Aspen simulation workbook (ASW) is employed to solve the complex kinetic model of FT and solid oxide electrolyzer cell (SOEC). The process models developed in this study are illustrated in Fig. 2 (biogas reforming) and Fig. 3 (FT process with hydrocracking and separation).

2.2.1 Electrified Biogas Reforming

The electrified biogas reforming along with steam input to produce the syngas was simulated in multi-tubular plug flow reactor (PFR) at P = 20 bar and T = 950 °C. Electrified reformer employs resistance heating to replaces the fired heater, with heating elements powered by an external electricity source to heat the reactor. In terms of energy efficiency, the electrified reformer demonstrated better efficiency compared to conventional fired reformers [3]. A commercial $Ni\text{-}CeO_2/MgAl_2O_4$ catalyst is selected with LHHW kinetic model that combine steam methane reforming, CO_2 reforming, and water gas shift (WGS) reactions developed by Park et al. [6].

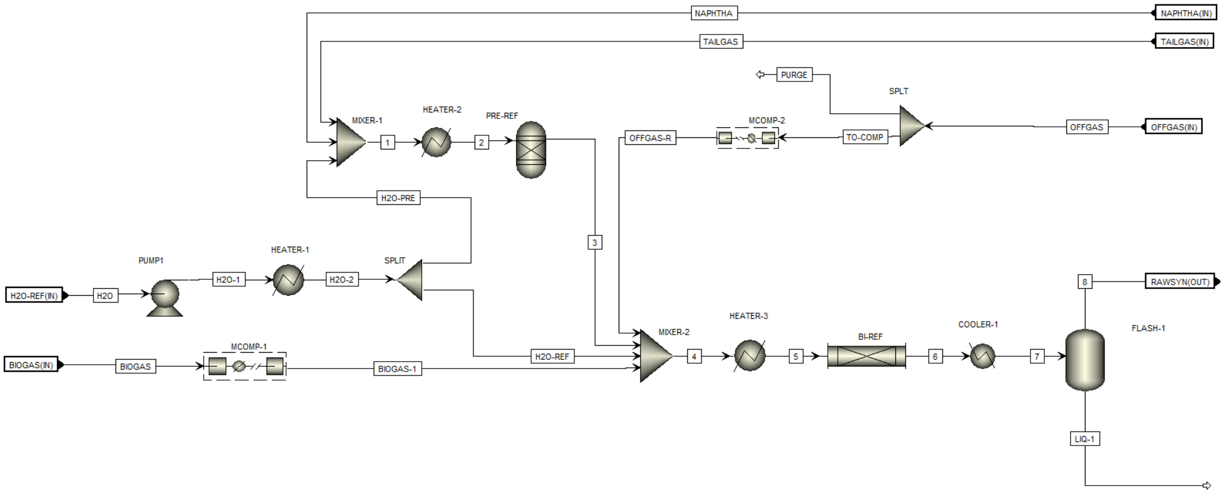
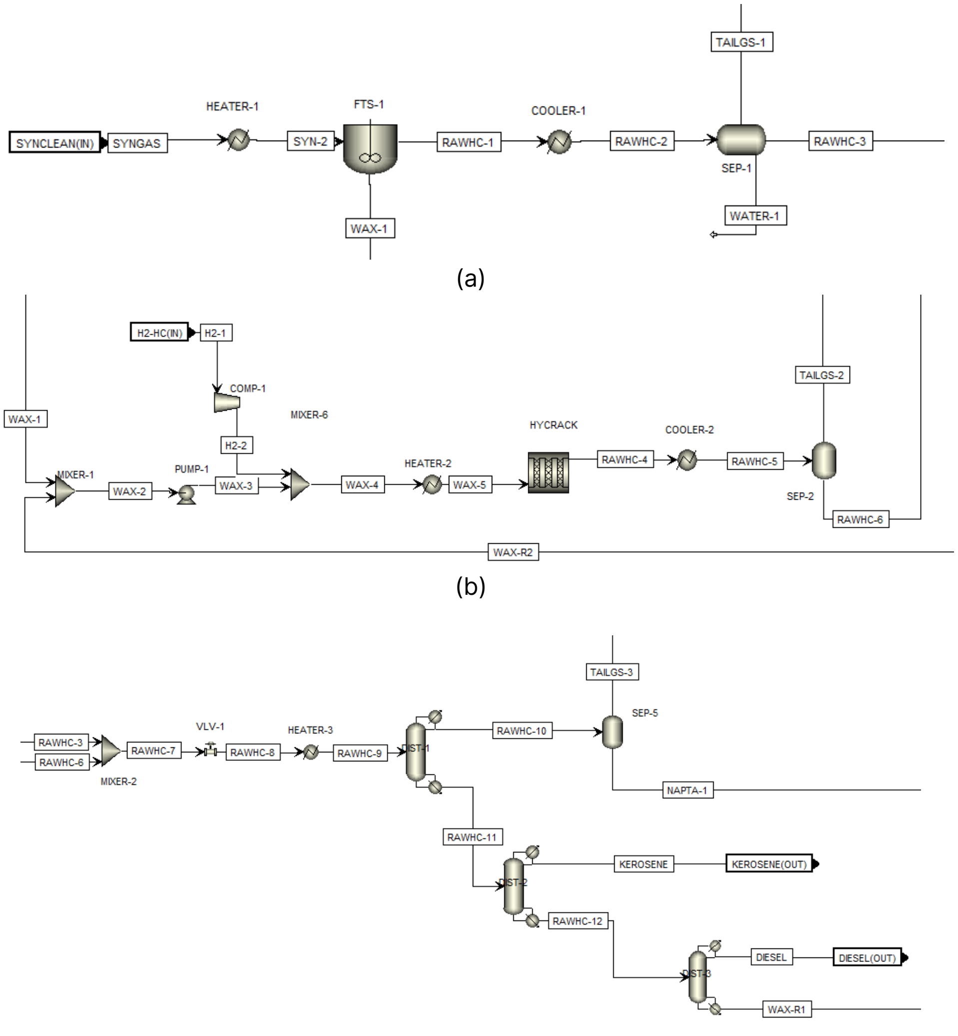


Figure 2. Process Simulation of Biogas Reforming



(a)

(b)

(c)

Figure 3. Process Simulation of (a) Fischer-Tropsch with (b) Hydrocracking and (c) Separation

2.2.2 Solid Oxide Electrolyzer

The solid oxide electrolyzer cell (SOEC) unit is modeled as the stoichiometric reactor at 750 °C and P = 1.15 bar with an H_2O conversion of 60%. The fraction of hydrogen produced from the electrolyzer is recycled back to the stack, and it is adjusted by design specifications so the steam concentration in the feed of the stack is at 90%. The modeling of the electrolytic cell, which is applied in the Aspen Plus stoichiometric reactor, is assisted by the Aspen simulation workbook (ASW). The detailed mathematical model of electrolytic cells is presented by AlZahrani and Dincer [7].

2.2.3 Fischer-Tropsch and Hydrocracking

A low-temperature Fischer Tropsch (LTFT) with a cobalt-based catalyst is employed in the process model from the syngas with an H2/CO ratio of around 2.1. The process is modeled in a slurry-bubble column reactor (SBCR) with an operating pressure of 20 bar and a temperature of 230 °C [8]. The SBCR can be modeled as the continuous stirred tank reactor (CSTR) in Aspen Plus, assisted by the Aspen simulation workbook. In general, the reaction follows this highly exothermic reaction:

$$CO + 2H_2 \rightarrow -(CH_2)- \ +H_2O \qquad \Delta H = -150\frac{kJ}{mol} \quad (1)$$

The term of $-(CH_2)-$ is described as the monomer product through the polymerization process, and the water is a side product of the process. The FTS process is modeled based on chain growth probability and the olefin/paraffin ratio which is presented by Todic et al. with CO conversion per pass = 52.5% [8].

A heavier hydrocarbon in wax produced from the FT reactor is sent to a hydrocracking process to maximize the jet fuel yield. The hydrocracking model with silica-alumina catalyst was simulated in the plug-flow reactor at P = 30 bar and T = 367 °C, assisted by the Aspen simulation workbook. The hydrocracking kinetic model is based on the study by Bhutani et al., 2006 [9].

2.2.4 Additional processes

There are additional processes besides reforming, SOEC, and the FT process, e.g., CO_2 capture, pre-reforming, and distillation columns, which are needed for a comprehensive evaluation of the biogas-to-jet fuel process.

Syngas cleaning is employed to remove CO_2 from the syngas, which is recycled back into the reforming reactor. The MEA absorption process, a well-established industrial process, is used, with a CO_2 recovery of 90% and specific heat consumption of 3.5 MJ per kg-CO_2 [10].

The raw synfuel from FT and hydrocracking are sent to three stages of distillation columns to separate the tail gas, naphtha, kerosene, diesel, and wax at atmospheric conditions. The tail gas and naphtha are recycled back to the pre-reforming reactor which is operated at P = 20 bar and T = 400 °C and simulated in Gibbs reactor at adiabatic conditions to produce additional CO and H_2 from C_{2+}. The wax is sent to the hydrocracking reactor along with wax from the FT process.

2.3. Performance Indicators

The performance indicators from the proposed process are calculated based on the mass and energy balance, as presented below:

- Carbon conversion ratio, also known as carbon efficiency (η_C), is defined as the ratio of the carbon atoms in the hydrocarbon after reforming and the Fischer-Tropsch process relative to carbon atoms in the biogas feedstock, as presented in Eq. (2):

$$\eta_C = \frac{\dot{n}_{C,hydrocarbons}}{\dot{n}_{C,feedstock}} \quad (2)$$

- Hydrogen efficiency (η_H) is defined as the ratio of the hydrogen atoms in the hydrocarbon products relative to the hydrogen atoms in the water for SOEC process, as presented in Eq. (3):

$$\eta_H = \frac{\dot{n}_{H,hydrocarbons}}{\dot{n}_{H,feedstock}} \quad (3)$$

- Process efficiency (η_P) represents the ratio of the energetic content of hydrocarbon products relative to the energetic content of biogas and the total energy input of the system, including the electrified reforming power, SOEC power, and process power consumption, as shown in Eq. (4):

$$\eta_P = \frac{\dot{m}_{hydrocarbon} \times LHV_{hydrocarbon}}{\dot{m}_{biogas} \times LHV_{biogas} + P_{SOEC} + P_{reforming} + P_{process}} \quad (4)$$

3. RESULTS

The integrated modeling of the FT process with electrified biogas reforming considers biogas feedstock volume flow of 45 million m^3/year, and the mole fraction is 60% CH_4 and 40% CO_2. This flow corresponds to 5,544 kg/hr. The validation of the FT process was carried out using mole fraction against the carbon number, as shown in Fig. 4, along with experimental data from Todic et al.[8]. As it can be appreciated there is a good correlation between the model predictions and experimental data for hydrocarbons with up to 15 carbons. Unfortunately, there were no experimental data for long chain hydrocarbons.

Table 1 highlights mass and energy balance of FT fuel process in two scenarios. After recovering and recirculating unreacted CO_2 from the syngas cleaning process via MEA absorption, tail gas, and naphtha from FT and separation process, the hydrocarbon output is 2,132 kg/hr of kerosene and 648 kg/hr of diesel meanwhile in the second scenario, the hydrocarbon output is 2,137 kg/hr of kerosene and 648 kg/hr of diesel. In addition, the total electricity consumption for electrified reforming, SOEC, and other processes in the first and second scenarios are 38.9 MW and 37.9 MW, respectively.

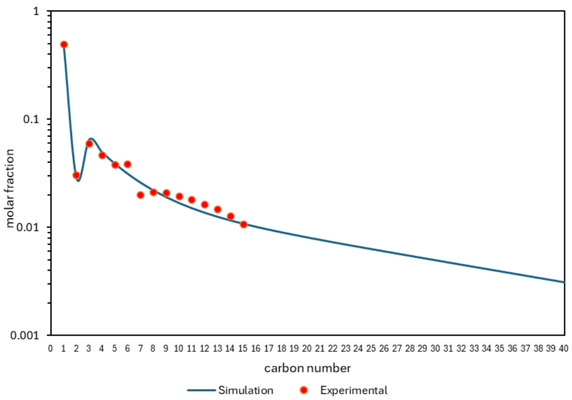


Figure 4. The Molar fraction of FT products with Experimental validation

Regarding energy input, the first scenario requires larger electricity consumption (27.9 MW) compared to the second scenario (27.1 MW) due to the electrified reforming consuming more electricity with hydrogen input sent to reforming. It differs from the second scenario, where hydrogen input is sent directly to the FT reactor to fulfill syngas requirements ($H_2/CO \approx 2.1$) for the FT process. However, in the SOEC, electricity consumption is slightly elevated due to the reaction of hydrogen with CO_2 in the reformer within the first scenario, which consequently reduces hydrogen output. The electricity requirement for electrified biogas reforming is two times higher than that of the SOEC process because the SOEC process is only employed to supply the lack of hydrogen produced from reforming. In addition, the hydrogen requirement for hydrocracking, supplied by the SOEC, is significantly lower than hydrogen requirement for the reforming process.

Table 1: Key Performance Indicators of the FT fuel

Parameter	1st Scenario	2nd Scenario
Material input (kg/hr)		
Biogas flow rate	5,544	5,544
Process Water	9,674	9,609
Material output (kg/hr)		
Kerosene	2,132	2,137
Diesel	648	648
Energy input (MW)		
Biogas heat flow	27.2	27.2
Electricity input	38.9	37.9
Energy output		
Kerosene	22.2	22.3
Diesel	4.4	4.4
Electricity input (MW)		
Electrified reforming	27.9	27.1
SOEC	8.9	8.7
Compressor	2.01	2.01
Pump	0.07	0.07

The performance indicators assessed in this study, include carbon conversion, hydrogen and process efficiencies. As presented in Fig. 5, the overall (kerosene and diesel) carbon conversion efficiency between the two scenarios is relatively the same, around 96%. The carbon loss is in the purge, associated with CO_2 recirculation from the syngas cleaning process and tail gas recirculation from the FT process. The total hydrogen efficiency is approximately 27%, significantly lower than carbon conversion efficiency, due to the abundance of water lost after water separation from syngas in reforming and syncrude in the FT process.

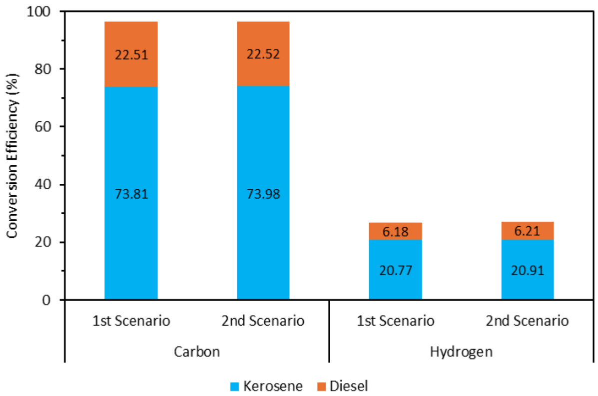


Figure 5. Carbon and Hydrogen Conversion Efficiency from Two Scenarios

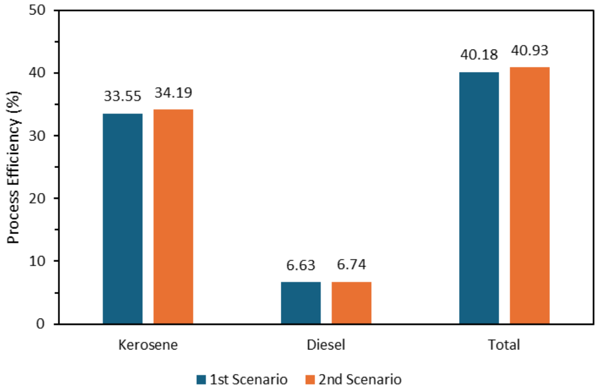


Figure 6. Process Efficiency from Two Scenarios

Overall, the process efficiency as shown in Fig. 6 is calculated at approximately 40% due to the large electricity consumption in electrified reforming and SOEC processes. The comparison between the two scenarios reveals insights into mass and energy balances, particularly focusing on process efficiency of two scenarios. The results show that the second scenario exhibits slightly better overall process efficiency, with stable hydrocarbon production, while slightly reducing total electricity consumption. For further analysis, the developed model featuring the two scenarios needs to incorporate heat integration, which will change the electricity consumption and process efficiency. In addition, economic and environmental assessments are conducted to determine the production cost and carbon reduction potential compared to conventional aviation fuel.

4. CONCLUSION

The study evaluated two scenarios of sustainable aviation fuels (SAFs) production from biogas upgrading and the Fischer-Tropsch process, with focus on carbon utilization, process efficiency, and electricity consumption. Rigorous kinetic process models for all involved processes were developed to enhance the accuracy and flexibility of the evaluation. Based on the developed models, the two scenarios achieve stable production of kerosene and diesel. However, providing hydrogen at the inlet of the FT unit (after the reformer) resulted in lower electricity consumption compared to the scenario where the additional hydrogen required for FT is supplied directly at the reformer. In addition, the carbon conversion efficiency remains high (96%), indicating high carbon utilization for hydrocarbon production.

In future work, the study will expand on economic implications to assess the cost of SAF production compared to conventional aviation fuels. In addition, the environmental impact will be assessed via life-cycle assessment to determine the potential of carbon reduction from the whole process.

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