

## Economic Assessment of Power to Liquid Using SMR with Direct Air Capture

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**\*Keywords :** SMR, PtL, SAF, SOEC, DAC, Fischer-Tropsch

### 1. Introduction

SAF (Sustainable aviation fuel) is the fuel production technology to replace fossil fuel with fuel from low carbon emitting process. International Air Transport Association (IATA) committed to achieve carbon neutrality until 2050. IATA represented the SAF as the most impactful solution, which can reduce 65% of emission for the flight [1]

South Korea has introduced policies to expand SAF use as part of its net-zero strategy. The Ministry of Trade, Industry and Resources (MOTIR) and the Ministry of Land, Infrastructure and Transport (MOLIT) announced that blending 1% SAF into aviation fuel will become mandatory by 2027. The blending ratio will increase to 3-5% by 2030 and 7-10% by 2035. MOTIR also proposed tax credits of 25% for facility investment and 40% for R&D expenditures [2]

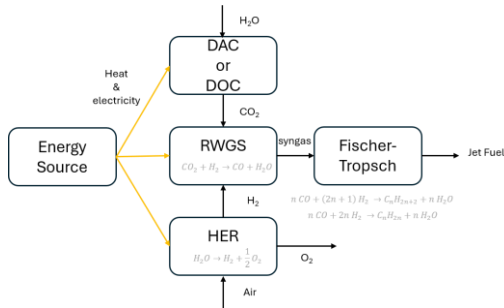
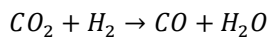


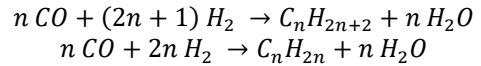
Fig. 1. Process flow diagram of PtL with Fischer-Tropsch reaction for SAF production

The PtL (Power-to-Liquid) is the emerging technology to overcome limitations for other SAF production methods. This method above requires hydrogen and carbon to produce syngas. Green hydrogen can be produced by HER (Hydrogen Evolution Reaction) such as PEM (Proton Exchange Membrane), AWE (Alkaline Water Electrolysis) or SOEC (Solid Oxide Electrolysis Cell). Carbon is usually captured by DAC (Direct Air Capture) technology.



Carbon dioxide and green hydrogen are converted into mixture of the carbon monoxide and remaining

unreacted hydrogen, called syngas by the RWGS (Reverse Water-Gas Shift) process.



The syngas is converted into a mixture of alkane and alkene as the product of Fischer-Tropsch process. This exothermic reaction occurred under 150 – 300 °C with cobalt or iron catalysis [3]

Rolls-Royce proved that commercial aircraft engine is 100% compatible for using SAF. Thus, there is no obstacle for using SAF in terms of engine technology side [7, 8] March, 2026, Rolls-Royce and Equilibriion announced collaboration to conduct TEA (Techno-economic Assessment) for using SMR based SAF production [6] This study will conduct an economic assessment of PtL technology combined with SMR developed in Korea.

Thus, this study estimates cost of carbon dioxide under similar PtL system boundary. Based on the estimation of Direct Air Capture (DAC) carbon dioxide cost, the cost of SAF fuel in Korea are estimated.

### 2. Methods and Results

In this paper, the authors estimated the cost of hydrogen produced based on the Korean-type SMR, the cost of carbon obtained through DAC processes, and the subsequent processing costs incurred during the RWGS and Fischer-Tropsch synthesis. Based on these estimates, the unit production cost per liter of aviation fuel was calculated, and a Monte Carlo sensitivity analysis was conducted using the variables involved in this calculation process. Furthermore, these results were compared with the unit prices of aviation fuel produced via PtL technologies reported in other domestic literature, as well as the prices of aviation fuel produced using non-PtL SAF technologies

#### 2.1 Unit Cost of Hydrogen Production Based on Domestic SMRs

The previous study compared three methods of hydrogen production based on domestic SMR That study evaluated and compared hydrogen production via AWE (Alkaline Water Electrolysis), PEM (Proton Exchange Membrane), and SOEC (Solid Oxide Electrolysis Cell) processes using large-scale nuclear power plants and

Table I : Values utilized for calculation for carbon cost form DAC process

|                                                 | Value |               |       | unit                                  | Ref  |
|-------------------------------------------------|-------|---------------|-------|---------------------------------------|------|
|                                                 | Low   | Mid           | High  |                                       |      |
| LT-DAC CO <sub>2</sub> capture rate, $M_{CO_2}$ |       | 1,000,000     |       | t-CO <sub>2</sub> /y                  | [8]  |
| Specific thermal energy use, $q_{DAC}$          | 1.100 | 1.200         | 1.800 | kWh <sub>th</sub> /kg-CO <sub>2</sub> | [9]  |
| Specific electricity use, $e_{DAC}$             | 0.182 | 0.250         | 0.375 | kWh <sub>e</sub> /kg-CO <sub>2</sub>  | [9]  |
| CAPEX, $CAPEX_{DAC}$                            | 0.200 | 0.524         | 0.786 | USD/(kg-CO <sub>2</sub> /y)           | [8]  |
| Sorbent cost, $C_{sorbent}$                     |       | 8.00          |       | USD/kg                                | [8]  |
| Sorbent replacement period                      |       | 5             |       | y                                     | [8]  |
| Annualized sorbent-replacement cost             |       | 4.4% of CAPEX |       | USD/(kg-CO <sub>2</sub> /y)           | [8]  |
| Discount rate, $i$                              | 8.0   | 10.0          | 12.0  | %                                     | [10] |
| PtL plant life, $n$                             |       | 20            |       | y                                     | [10] |

SMRs in South Korea [7]. Although AWE possesses high technological maturity, it proved inefficient due to the increased voltage required by ohmic loss and the bubble effect at high current densities. The PEM method incurred higher costs due to the use of precious metal catalysts and membranes.

Table II : LCOH from Korean type SMR under 70bar condition [7]

|      | Operating mode   | P5   | Mid  | P95  |
|------|------------------|------|------|------|
| AWE  | Electricity-only | 5.1  | 5.75 | 6.41 |
| PEM  | Electricity-only | 4.88 | 5.5  | 6.12 |
| SOEC | Electricity+Heat | 3.69 | 4.15 | 4.62 |

\*unit : 2024 USD/kg H<sub>2</sub>

In contrast, the SOEC method was reported to effectively leverage the advantages of nuclear energy, as utilizing process heat can significantly reduce the electrical power requirement, thereby demonstrating a high hydrogen production yield. The results summarized in the aforementioned study also indicated that the SOEC method exhibited the best economic performance. However, because this study assumed that the hydrogen production facility is co-located with the subsequent RWGS (Reverse Water Gas Shift) facility, long-distance hydrogen transmission costs were excluded. Consequently, the pure hydrogen production costs of 3.61 USD/kg, 4.07 USD/kg, and 4.54 USD/kg were applied as the P5, Mid, and P95 values, respectively [7]

## 2.2 Unit Cost of Carbon Sources Based on Korean SMR

The KEEI (Korea Energy Economics Institute) derived the electricity generation costs for specific Korean-type SMRs, as presented in Table III [11] In this study, the target power generation cost (LCOE) for the Korean-type SMR was set to 65 USD/MWh or below, and the target construction cost was set to 3,500 USD/kWe or below. Accordingly, the Low, Mid, and High values for the electricity price applied in this study were established as 0.056 USD/kWh, 0.074 USD/kWh, and 0.089 USD/kWh, respectively.

Table III : Korean type SMR electricity price estimation from KEEI [11]

| Construction scenario<br>(construction cost) | Discount<br>rate 3% | Discount<br>rate 7% | Discount<br>rate 10% |
|----------------------------------------------|---------------------|---------------------|----------------------|
| Base 3,500 USD/kW                            | 56.2                | 74.5                | 89.1                 |
| NOAK 5,134 USD/kW                            | 64.0                | 90.1                | 112.4                |
| FOAK 8,460 USD/kW                            | 79.9                | 124.4               | 159.8                |

\*unit : USD/kWh

## 2.3 Unit Cost of Carbon Dioxide Produced via the DAC Method

This method captures dilute carbon dioxide from the atmosphere using sorbents. Because the concentration of carbon dioxide in the air is extremely low, large-scale blower systems are required. In this study, following the reference, the low-temperature solid-sorbent VTSA method was adopted. This approach utilizes porous solid filters coated with amine-based chemicals that selectively bind to carbon dioxide molecules. The core mechanism, known as Vacuum-Temperature Swing Adsorption (VTSA), operates by alternating between increasing the temperature and decreasing the pressure to cyclically capture and separate carbon dioxide.

$$LCOC = \frac{CRF \cdot CAPEX_{DAC} + OPEX_{fixed} + C_{sorbent}}{M_{CO_2}} + e_{DAC} \cdot P_e + q_{DAC} \cdot P_{th}$$

In the *LCOC* equation, *LCOC* denotes the levelized CO<sub>2</sub> supply cost. *CRF* is the capital recovery factor; *CAPEX<sub>DAC</sub>* and *OPEX<sub>fixed</sub>* denote the DAC capital expenditure and fixed operating cost, respectively. *C<sub>sorbent</sub>* is the annualized sorbent-replacement cost. *M<sub>CO<sub>2</sub></sub>* is the annual mass of CO<sub>2</sub> captured. *e<sub>DAC</sub>* and *q<sub>DAC</sub>* are the specific electricity and thermal-energy consumptions, respectively. And *P<sub>e</sub>* and *P<sub>th</sub>* are the unit prices of electricity and heat, respectively.

The opportunity cost coefficient between heat and electricity was derived by referencing the St. Alban-Lyon plant in France, which supplies 320 MW<sub>th</sub> of heat at 100°C. In this case, 1 MWe of electricity generation capacity is sacrificed to supply every 5 MW<sub>th</sub> of heat. If the Korean-type SMR operates under similar conditions, the equivalent heat price ratio relative to the electricity production price, denoted as  $\lambda_{th}$ , was calculated to be 0.2.

$$P_{th} = \lambda_{th} \cdot P_e$$

Furthermore, for a clear economic evaluation, the CRF (Capital Recovery Factor), which accounts for the discount rate, was calculated as shown in the following equation to annualize the initial investment cost over the project's lifetime

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1}$$

Here,  $i$  is the discount rate and  $n$  is the project lifetime.

From the values listed on Table II, the unit cost of carbon dioxide was calculated. The Low, Base, and High supply costs of carbon dioxide calculated through this process were 0.05480 USD/kg-CO<sub>2</sub>, 0.12086 USD/kg-CO<sub>2</sub>, and 0.19232 USD/kg-CO<sub>2</sub>.

#### 2.4 Estimation of SAF Unit Production Cost via the PtL Process

The PtL process produces carbon monoxide from carbon dioxide and hydrogen via RWGS(Reverse Water-Gas Shift). Syngas, a mixture of unreacted hydrogen and the carbon monoxide produced from the RWGS process, is converted into synthetic crude oil via the Fischer-Tropsch process. This is then refined and separated to yield SAF, along with the by-products naphtha and diesel

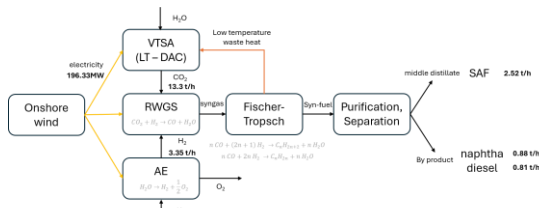


Fig. 2. Material flow diagram based on the reference literature [10]

The figure above illustrates the amounts of hydrogen and carbon dioxide used in each process, as presented in the reference. Based on this, it can be seen that 5.278 kg of carbon dioxide and 1.329 kg of hydrogen are required per 1 kg of SAF, respectively. Furthermore, the paper states that 5.57 MW out of the total 196.33 MW of power is consumed in the RWGS process. From this, it can be deduced that 2.21 kWh of specific refinery electricity is required per 1 kg of SAF [10]

$$LCOSAF = C_{H_2} + C_{CO_2} + C_{elect} + CAPEX + OPEX - R_{byproduct}$$

The fixed O&M cost was assumed to be 3% of the annualized value obtained by dividing CAPEX by the CRF.

$$OPEX = \frac{1}{CRF} \times CAPEX_{levelized} \times 0.03$$

Using the values in Table IV, the LCOSAF was calculated.

#### 2.5 Result Analysis

##### 2.5.1 Result from Monte Carlo method

The LCOSAF results derived from the Monte Carlo analysis with 100,000 samples are presented in the figure below.

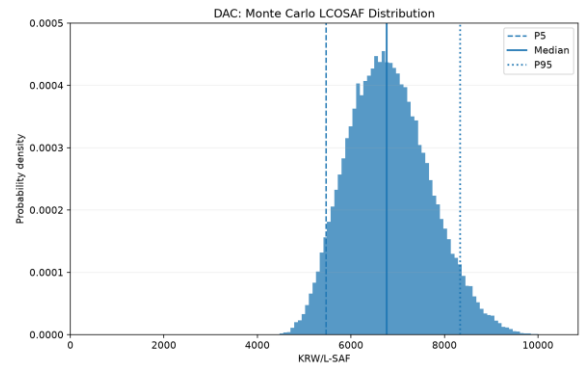


Fig. 3. The LCOSAF distribution from Monte Carlo

Table V : Summary of LCOSAF (Levelized Cost of SAF) calculation

|     | Low   | Mid   | High  |
|-----|-------|-------|-------|
| DAC | 6.139 | 6.225 | 6.297 |

\*unit : USD/kg-SAF

The results from the MC analysis also represented with box plot and violin plot as shown in Fig.4.

Table IV : Values utilized for calculation for PtL process (RWGS & FT)

|                                    | Value   |         |           |           |              |
|------------------------------------|---------|---------|-----------|-----------|--------------|
|                                    | Low     | Mid     | High      | unit      | Ref          |
| Efficiency of PtL process          | 22.60   | 28.06   | 52.20     | %         | [14, 16, 17] |
| Refinery CAPEX sensitivity         | 40.630  | 58.040  | 87.060    | £ million | [10]         |
| Refinery capacity scaling exponent |         | 65.0    |           | %         | [10]         |
| Naphtha price                      | 0.595   | 0.674   | 0.786     | USD/kg    | [14]         |
| Diesel price                       | 436.290 | 938.170 | 1,187.970 | KRW/L     | [15]         |
| Diesel density                     | 0.815   | 0.825   | 0.835     | kg/L      | [16]         |

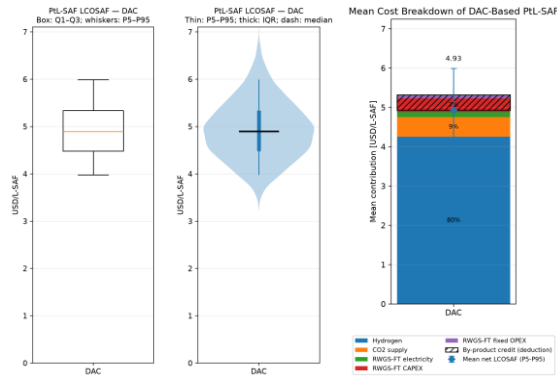


Fig. 4. The LCOSAF results illustrated in (a) box plot, (b) violin plot, and (c) cost breakdown

As a result of the analysis, the SAF production cost for the DAC method was determined as shown in Table V. According to the cost breakdown in Fig. 4, over 80% of the total costs were incurred during the hydrogen production process, while 9% originated from carbon dioxide production. However, it was observed that the energy consumption and CAPEX associated with the RWGS and FT processes were relatively minor, accounting for a combined total of less than 10%. Furthermore, revenue generated from the sale of by-products, such as naphtha and diesel, was found to contribute significantly to reducing the overall production unit cost.

### 2.5.2 Sensitivity Analysis

An OAT (One-At-a-Time) sensitivity analysis was conducted to determine the range within which the LCOSAF results can vary in response to changes in each variable.

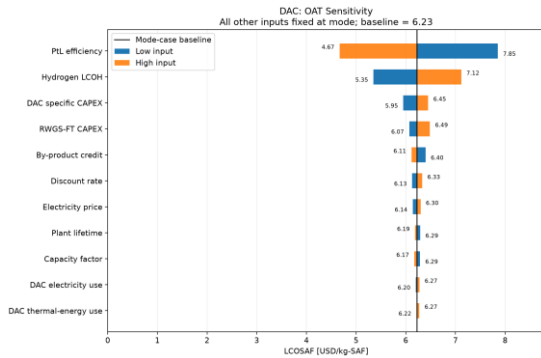


Fig. 5. OAT sensitivity analysis

To cross validate the OAT results, an SRRC (Standardized Rank Regression Coefficient) sensitivity analysis was also conducted based on the carbon dioxide production method.

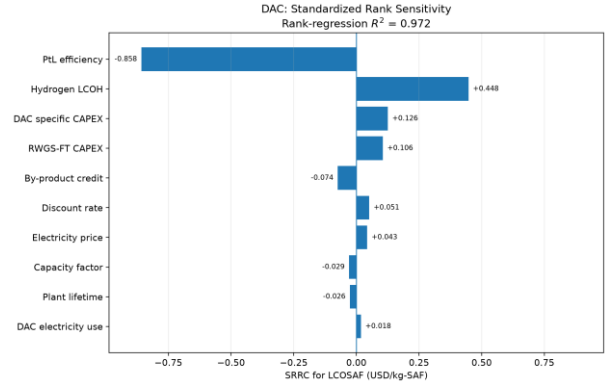


Fig. 6. SRRC sensitivity analysis

Based on the OAT and SRRC sensitivity analyses, LCOSAF was found to be most strongly influenced by the efficiency of the PtL process. In fact, under highly efficient conditions, the LCOSAF values were observed to decrease by up to 25.04%.

As shown in Fig. 5, the LCOSAF was observed to depend relatively heavily on the hydrogen LCOH due to its relatively low carbon dioxide production cost.

However, it was observed that the results exhibited relatively low sensitivity to the CAPEX of the DAC and RWGS-FT facilities compared to the cycle efficiency and hydrogen production cost.

### 2.6 Result Comparison

SAF prices reported in the literature were reviewed and compared with the results obtained in this study. Table VI summarizes the production costs of SAF generated via the PtL process. Table VII details the costs of producing SAF using biogenic or waste carbon feedstocks instead of the PtL pathway.

Table VI : PtL cost comparison with other PtL methods in literature

| Label                         | CO <sub>2</sub> source   | H <sub>2</sub> source | Synthesis  | Energy source         | Original cost   | Cost metric          |
|-------------------------------|--------------------------|-----------------------|------------|-----------------------|-----------------|----------------------|
| Rojas-Michaga (2023) [10]     | LT-DAC                   | AWE                   | RWGS-FT    | Offshore wind/grid    | 5.16 £/kg;      | MJSP                 |
| Peacock et al. (2024) [8]     | LT-DAC                   | SOE                   | RWGS-FT    | Nuclear/renewable     | 239 USD/bbl     | LCOF                 |
| Paulsen et al. (2024) [8]     | HT-DAC                   | AEC/SOEC              | RWGS-FT    | Electricity           | 4.45–6.32 €/L   | MFSP                 |
| Kim et al. (2026) [17]        | CO <sub>2</sub> -derived | SOEL                  | RWGS/SOEL  | Renewable electricity | 3.71–5.72 USD/L | Unit production cost |
| Sendlhofer et al. (2026) [18] | CO <sub>2</sub> -based   | Electrolysis          | FT/MtJ/EtJ | Region dependent      | 2.8–8.2 USD/kg  | NPC                  |
| This study                    | LT-DAC                   | SOEC                  | RWGS-FT    | SMR                   | P5–Median–P95   | LCOSAF               |

Table VII : PtL cost comparison with other SAF method in literature [19]

| Label               | CO <sub>2</sub> source             | H <sub>2</sub> source | Synthesis                        | Low  | Mid  | High |
|---------------------|------------------------------------|-----------------------|----------------------------------|------|------|------|
| HEFA: yellow grease | Biogenic or waste feedstock carbon | -                     | HEFA                             | 0.66 | 0.91 | 1.24 |
| HEFA: tallow        | Biogenic or waste feedstock carbon | -                     | HEFA                             | 0.79 | 1.06 | 1.42 |
| FT: MSW             | Biogenic or waste feedstock carbon | -                     | Fischer-Tropsch from MSW         | 0.95 | 1.15 | 1.39 |
| HEFA: soybean oil   | Biogenic or waste feedstock carbon | -                     | HEFA                             | 0.87 | 1.19 | 1.6  |
| AF: sugarcane       | Biogenic or waste feedstock carbon | -                     | Advanced fermentation            | 1.1  | 1.47 | 1.96 |
| FPH: corn stover    | Biogenic or waste feedstock carbon | -                     | Fast pyrolysis + hydroprocessing | 1.02 | 1.52 | 2.1  |
| AF: corn grain      | Biogenic or waste feedstock carbon | -                     | Advanced fermentation            | 1.3  | 1.66 | 2.1  |
| APP: woody biomass  | Biogenic or waste feedstock carbon | -                     | Aqueous phase processing         | 1.73 | 2.07 | 2.48 |
| AF: herbaceous      | Biogenic or waste feedstock carbon | -                     | Advanced fermentation            | 2.16 | 2.51 | 2.92 |
| This study          | LT-DAC                             | SOEC                  | RWGS-FT                          | 3.96 | 4.87 | 5.94 |

\*unit : USD/L

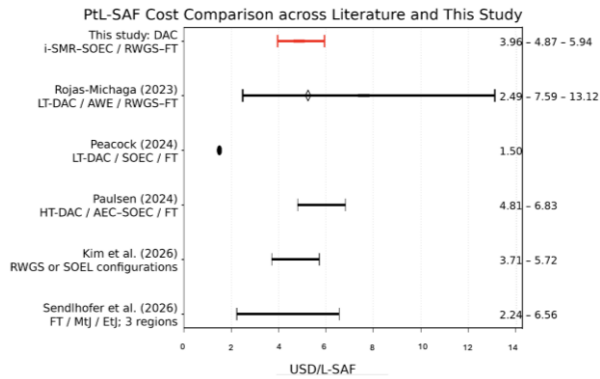


Fig. 7. SAF cost comparison from literature, utilizing PtL

According to Fig. 7, the DAC method utilizing nuclear power is sufficiently competitive compared to other technologies.

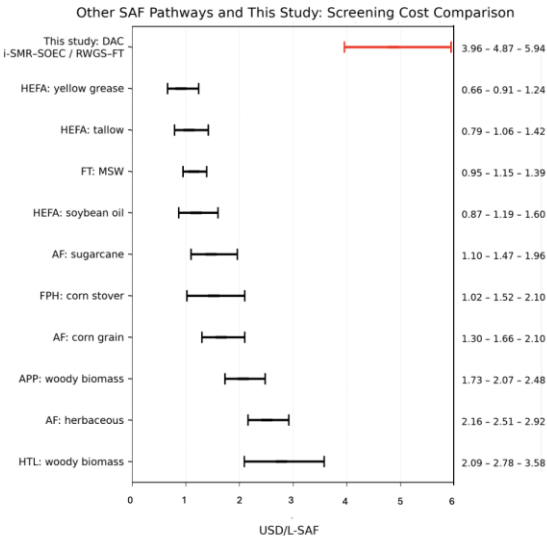


Fig. 8. SAF cost comparison from literature, utilizing other SAF methodologies

According to the conclusions drawn from Fig. 8, the PtL pathway utilizing domestic SMRs does not exhibit

significant competitiveness compared to other SAF production methods. However, South Korea has limited land available for securing large quantities of biomass, and the necessity for large-scale facilities, stemming from the low energy density of other SAF pathways, can pose a barrier to their implementation. Therefore, PtL technology can be considered a viable alternative to overcome these limitations.

### 3. Summary and Conclusions

The production of SAF (Sustainable Aviation Fuel) utilizing the Rolls-Royce SMR has been under consideration. Consequently, this study aimed to evaluate the economic feasibility of producing SAF through a facility utilizing a Korean-type SMR in South Korea. Given the characteristics of SMRs, the SOEC (Solid Oxide Electrolysis Cell) method, which utilizes both heat and electricity to achieve a low production unit cost, was uniformly adopted for hydrogen production. For carbon dioxide capture, DAC (Direct Air Capture) method was selected.

A cost breakdown of the calculated LCOSAF was conducted to examine the specific components constituting the final price. Furthermore, OAT (One-At-a-Time) and SRRC (Standardized Rank Regression Coefficient) sensitivity analyses were cross-validated to determine which factors significantly impacted the resulting values. The results indicated that the efficiency optimization of the PtL (Power-to-Liquid) cycle had the most substantial impact across all cases. Specifically, the LCOH (Levelized Cost of Hydrogen) was a second major cost driver for the DAC method.

Overall, SAF produced through a DAC-PtL system coupled with a Korean-type SMR was competitive with PtL values reported in the literature, although its production cost remained higher than that of several biogenic- and waste-based SAF pathways. Because the economics of DAC-PtL depend strongly on process efficiency, further process optimization could substantially reduce the SAF production cost.

## ACKNOWLEDGEMENT

This work was supported by the Innovative Small Modular Reactor Development Agency grant funded by the Korea Government MCEE (No. RS-2024-00400615)

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