Evaluating Impacts of Sustainable Aviation Fuel Production with CO2-to-Fuels Technologies on High Renewable Share Power Grid

Preprint

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Evaluating Impacts of Sustainable Aviation Fuel Production with CO_2-to-Fuels Technologies on High Renewable Share Power Grid

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***Abstract*— This paper investigates the impact of Sustainable Aviation Fuel (SAF) production using CO_2-to-Fuels technologies on a future power grid with a high share of renewable energy. We focus on understanding the implications of the 2050 SAF production goal on the U.S. power system's long-term planning, encompassing generation, transmission, and cost analysis. Via the Regional Energy Deployment System (ReEDS) model, we developed a detailed SAF electricity demand model based on a low-temperature electrolysis-syngas fermentation-ethanol pathway. Four SAF target scenarios which aim to meet 10%, 15%, 20%, and 27% of SAF demand by 2050. These scenarios are exhaustively simulated to assess their impact on the power grid. Our results reveal that increasing SAF demand will result in higher electricity requirements, as well as expanded generator and transmission capacities, leading to an overall rise in system costs. However, these impacts are manageable within the broader context of U.S. capacity expansion plans. This study provides valuable insights into incorporating the CO_2-to-Fuels electricity demand model and other carbon capture technologies into power system planning, emphasizing their significance in shaping a sustainable energy future.**

Keywords— Capacity Expansion Model, Carbon Capture, Electrolysis, Sustainable Aviation Fuel, CO_2-to-Fuel Technology.

I. INTRODUCTION

The imperative for global decarbonization is reshaping industries and accelerating the transition towards more sustainable forms of energy. In the U.S., the 2050 zero greenhouse gas (GHG) emissions goal is proposed, which could be achieved via investment in sustainable infrastructure, public transit, and renewable power generation, among others [1]. The transportation sector is a major GHG emitter, accounting for 29% of total U.S. GHG emissions in 2021 [2]. Among all transportation subsectors, the aviation sector contributed to approximately 8% of the U.S. transportation sector's GHG emissions and about 2% of nation's total GHG production in 2021 [2]. Unlike other transportation subsectors which can be decarbonized by using batteries or hydrogen fuel cell powertrain technologies, the technical and economic challenges of aviation electrification open the opportunity for CO_2-to-fuels technology using clean power sources. One product with the potential to substitute current fossil-based jet fuel with a significantly lower carbon impact is Sustainable Aviation Fuels (SAF).

SAF refers to fuels that are produced from biomass or waste resources, such as the CO_2 waste stream that is otherwise emitted into the atmosphere. The chemical characteristics of SAF are similar to traditional jet fuel [3], allowing it to be blended with traditional jet fuel to a certain degree without the need for modification or adaptation of the aircraft engines and delivery and storage infrastructure. The U.S. government has set a goal to produce 35 billion gallons per year by 2050 [4]. Among the various pathways to produce SAF, CO_2-to-fuels technologies which utilize the low-cost electricity generated from clean energy such as wind, solar, and hydro, can offer a novel and economical approach to reduce life-cycle GHG emissions. Moreover, such SAF facilities using CO_2-to-fuels technologies can serve as demand response devices to the power grid, and hence, provide multiple benefits such as optimizing renewable energy utilization, reducing need for peaking power plants, and enhancing grid stability and reliability.

Recently, there has been growing interest in understanding the impact of carbon capture technologies on power system planning. The works [5-7] have developed constraints to model the operating constraints of carbon capture power plants in capacity expansion models. The authors of [8] proposed an integrated model to optimize centralized biogas plants in long-term planning. However, these studies primarily focus on carbon capture technologies as components of power plants and assess their impacts within small-scale systems. The role of carbon capture technologies as a demand factor in the large-scale power system remains less explored. Moreover, the modeling representation of CO_2-to-fuels technologies, which link electricity, hydrogen, and CO_2 sectors, still requires further development and clarification.

In this paper, we focus on understanding the impacts of achieving 2050 SAF production goal on power system long-term planning, which includes generation, transmission, and analysis of system price and cost. The primary contribution of this papers are as follows:

1) Introduce the SAF facility design and distribution methods corresponding to a selected CO2-to-SAF pathway, including the Electrochemical CO2-to-CO, Syngas Fermentation, and Ethanol-to-Jet steps.

2) Develop a detailed SAF facility demand model based on this pathway with both hydrogen electrolysis and pathway energy

consumption demand, and embed the model in the power system capacity expansion model – ReEDS [9].

3) Develop four SAF target scenarios to achieve 10%, 15%, 20%, and 27% of the 2050 SAF production target, and exhaustively assess the system-wide impacts, including changes in installed capacity, total electricity generation, transmission capacity build-out, and total system costs in the contiguous-scale U.S. power grid.

4) Comprehensively illustrate the system impact of SAF demands, highlighting the challenges and potential pathways for integrating SAF production into the national energy strategy and sustainable energy utilization, providing guidance for policymakers and system planners.

energy inputs for the pathway are multifaceted, including the electricity required for electrolysis for hydrogen production, CO_2-to-CO electrolysis, SAF plant operations, and heat for the purification processes of ethanol and jet fuel.

For the LTE-SF-ETS pathway, the total carbon efficiency from CO_2 to fuel is 87%. This includes a 96% conversion rate of CO_2 to ethanol during syngas fermentation, utilizing hydrogen H_2 and CO. The carbon loss encountered during the ethanol upgrading pathway is minimal. Energy inputs for CO2U technologies come from hydrogen (produced via electrolysis), electricity, and natural gas. The energy efficiency of hydrocarbon production through this pathway stands at 40%. The remaining energy is allocated to cooling processes,

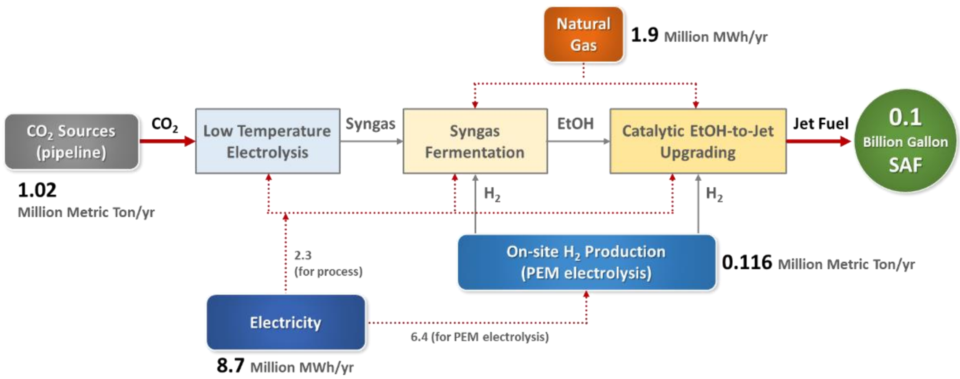

Figure 1. Low temperature electrolysis-syngas fermentation-ethanol to SAF pathway and 1000MW SAF facility design with on-site hydrogen production.

II. CO_2-TO-SAF PATHWAY AND FACILITY DESIGN

In this section, we briefly introduce the selected CO_2-to-SAF production pathway and describe the corresponding SAF facility design and facility distribution.

Low temperature electrolysis-syngas fermentation-ethanol to SAF (LTE-SF-ETS), illustrated in Figure 1, is a three-step CO_2-to-SAF process beginning with an electrochemical CO_2-to-CO, followed by syngas fermentation and ethanol-to-jet conversion [10]. Compared with other CO_2-to-SAF pathways, this pathway selectively maximizes the SAF production without any other hydrocarbon coproducts, which is more economic and sustainable. The initial step in this pathway involves the electrochemical reduction of a CO_2 source into a CO mixture. This process is facilitated by low-temperature elctrolyzers, such as alkaline and polymer electrolyte membrane (PEM), using catalyst materials typically comprising silver (Ag), gold (Au), palladium (Pd), and zinc (Zn). In the electrolyzer's cathode, CO_2 is absorbed and reduced to CO, utilizing electrons derived from water oxidation at the anode. The resulting CO/CO_2 mixture is subsequently combined with hydrogen (H2) for syngas fermentation. This stage employs acetogenic microorganisms, such as C. ljungdahlii and C. auto-ethanogenum [11], to produce ethanol and other byproducts under optimal operating conditions, including specific temperature and pH levels. The ethanol generated in the second step can then be dehydrated to form ethylene, using catalysts like silica-alumina. This is followed by oligomerization, which transforms ethylene into higher and more complex olefins. Various catalysts, including commercial Ziegler–Natta catalysts and sulfonic resins, are used in this process, culminating in hydrogenation to create the hydrocarbon complexes found in jet fuel products [12]. The

generation of excess electricity, combustion losses (including flue gas cooling), and losses in electrolyzer efficiency. The hydrogen electrolyzer efficiency considered here is 51.45 kWh/kg in 2050, i.e., to produce 1 kg H_2, 51.45 kWh power is required. In this work, we assume the capacity of a single SAF plant is 1000 MW with on-site hydrogen production by PEM electrolysis. This SAF facility design is illustrated in Figure 1. To capture 1.02 million metric ton (MMT) CO_2 and achieve 102 million-gallon SAF production per year, 8.7 million MWh electricity is required in which 6.4 million MWh is for PEM electrolysis for generating green hydrogen and 2.3 million MWh is for all the other energy consumptions of SAF facility.

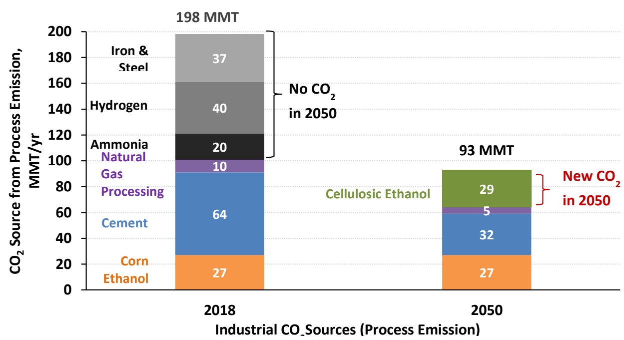

Figure 2. Potential industrial CO_2 sources (2018 CO_2 source data [13]).

In 2050, the estimated total CO_2 sources is 93 MMT/year without considering the direct air capture (DAC). These are the high- and medium- purity CO_2 sources of process emissions from selected industries including corn ethanol, natural gas processing, cement, and cellulosic ethanol. The projected potential CO_2 sources in each industry is illustrated in Figure 2.

Assuming all the CO_2 sources are utilized to generate SAF production, it will lead to 9.3 billion-gallon SAF per year. This can contribute to around 27% of the 35 billion-gallon SAF production goal in 2050, which in turn, requests 793.2 million MWh electricity demand. Since the CO_2 demand is 8.6 time larger than the hydrogen demand in the SAF facility, we distribute the SAF facility demand to locations that are close to the CO_2 sources including the corn ethanol, natural gas (NG) processing, cement, and cellulosic ethanol industries, and the refinery facilities of jet fuel production. To meet the optimal 27% SAF goal, 103 SAF facilities among the entire U.S. power grid are selected as illustrated in Figure 3. The capacity, location, and number of selected SAF facilities will be modeled as inputs to the SAF demand model introduced in Sec. III.

III. SAF Demand Model in Capacity Expansion Model

In this section, we introduce the SAF production demand model and embed it in ReEDS. ReEDS is the flagship capacity expansion model developed by NREL for the long-term planning of power sector. ReEDS models the evolution and operation of generation, transmission, and end-use demand technologies under a set of given input assumptions. ReEDS relies on system-wide least cost optimization to estimate the type and location of future generation and transmission capacity. The model combines two optimization modules with a simulation module representing electricity supply and end-use energy service demand, respectively [9]. For variable generation (VG) and storage technologies, ReEDS uses a dispatch algorithm to estimate the capacity credit and a statistical calculation to estimate the level of curtailment for VG units.

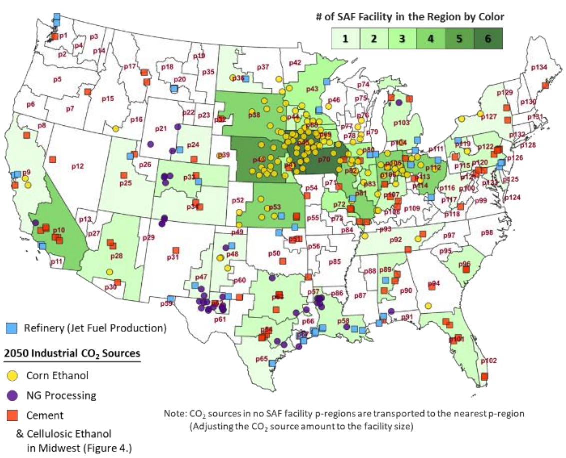

Figure 3 SAF facility distribution in the U.S. power grid.

For the selected pathway stated in Sec. II, SAF production can be modeled by two separate processes. The first process is hydrogen electrolysis process that consumes electricity to produce hydrogen. The second one is jet fuel fermentation and synthesis process that consumes electricity, hydrogen, and other inputs such as CO_2 and heat, to produce SAF. To reduce carbon emission associated with SAF production, renewable power generation from solar and wind will be prioritized for the first electrolysis process because it has more flexibility. The second process relies heavily on electrochemical reactions, meaning that it has less flexibility during operation.

We propose the SAF production model contains the following constraints:

$$\varphi_{r,t}^{\mathrm{ELE}} P_{r,h,t}^{\mathrm{ELE}} = D_{r,h,t}^{\mathrm{ELE}} \quad (1)$$

$$\varphi_{r,t}^{\mathrm{SAF}} P_{r,h,t}^{\mathrm{SAF}} = D_{r,h,t}^{\mathrm{SAF}} \quad (2)$$

$$P_{r,h,t}^{\mathrm{SAF}} = \tau_{r,t}^{\mathrm{SAF}} D_{r,h,t}^{\mathrm{HYD}} \quad (3)$$

$$\mu_{r,t}^{\mathrm{ELE}} C_{r,t}^{\mathrm{ELE}} \leq P_{r,h,t}^{\mathrm{ELE}} \leq C_{r,t}^{\mathrm{ELE}} \quad (4)$$

$$\mu_{r,t}^{\mathrm{SAF}} C_{r,t}^{\mathrm{SAF}} \leq P_{r,h,t}^{\mathrm{SAF}} \leq C_{r,t}^{\mathrm{SAF}} \quad (5)$$

$$8760 \vartheta_{r,t}^{\mathrm{SAF}} C_{r,t}^{\mathrm{SAF}} \leq \sum_{h \in \mathcal{H}} P_{r,h,t}^{\mathrm{SAF}} \quad (6)$$

$$\sum_{h \in \mathcal{H}} D_{r,h,t}^{\mathrm{SAF}} = E_{r,t}^{\mathrm{SAF}}, \sum_{h \in \mathcal{H}} D_{r,h,t}^{\mathrm{ELE}} = E_{r,t}^{\mathrm{ELE}} \quad (7)$$

where $P_{r,h,t}^{\mathrm{ELE}}$ and $P_{r,h,t}^{\mathrm{SAF}}$ denote the electricity power for the first electrolysis process and the second SAF production process of region r at hour h in year t, respectively. $\varphi_{r,t}^{\mathrm{ELE}}$, $D_{r,h,t}^{\mathrm{ELE}}$, $\varphi_{r,t}^{\mathrm{SAF}}$, and $D_{r,h,t}^{\mathrm{SAF}}$ denote the efficiency and the product mass of electrolysis and SAF production process, respectively. $\tau_{r,t}^{\mathrm{SAF}}$ is the coefficient connecting the hydrogen mass input mass and SAF production power. $C_{r,t}^{\mathrm{ELE}}$, $\mu_{r,t}^{\mathrm{ELE}}$, $C_{r,t}^{\mathrm{SAF}}$, and $\mu_{r,t}^{\mathrm{SAF}}$ represent the installed electrolysis and SAF production capacity and minimum loading level at region r in year t, respectively. $\vartheta_{r,t}^{\mathrm{SAF}}$ denotes the minimum capacity factor for SAF production process because it is generally not flexible. $E_{r,t}^{\mathrm{SAF}}$ denotes the required annual SAF production at region r in year t.

In the model, equations (1) and (2) constrain that the hydrogen production and final SAF production are constrained by the electricity power consumptions of the associated electrolysis and SAF production process, respectively. Equation (3) indicates that the SAF production power is limited by the hydrogen intake because hydrogen is considered as a fuel for the SAF production process. Constraints (4) and (5) limit the electricity power of electrolysis and SAF production to their respective installed capacity and technical minimal running levels. Constraint (6) limits the minimum capacity factor for SAF production process. Constraint (7) ensures the SAF production target can be met.

Note that the hydrogen production mass $D_{r,h,t}^{\mathrm{ELE}}$ in (2) does not necessarily equals to the hydrogen intake mass $D_{r,h,t}^{\mathrm{HYD}}$ in (3). This is because the electrolysis process can have a much lower capacity factor and run with higher flexibility to take advantage of renewable power generation. To achieve this, a hydrogen storage system is introduced and modeled as follows.

$$D_{r,h,t}^{\mathrm{ELE}} + D_{r,h,t}^{\mathrm{STR,out}} - D_{r,h,t}^{\mathrm{STR,in}} = D_{r,h,t}^{\mathrm{HYD}} \quad (8)$$

$$0 \leq D_{r,h,t}^{\mathrm{STR,in}} \leq D_{r,h,t}^{\mathrm{ELE}} \quad (9)$$

$$0 \leq D_{r,h,t}^{\mathrm{STR,in}} \leq D_{r,h,t}^{\mathrm{STR,in,max}} \quad (10)$$

$$0 \leq D_{r,h,t}^{\mathrm{STR,out}} \leq D_{r,h,t}^{\mathrm{STR,out,max}} \quad (11)$$

$$S_{r,h,t}^{\mathrm{HYD}} = S_{r,h,t-1}^{\mathrm{HYD}} + \varphi_{r,t}^{\mathrm{STR,in}} D_{r,h,t}^{\mathrm{STR,in}} - \frac{1}{\varphi_{r,t}^{\mathrm{STR,out}}} D_{r,h,t}^{\mathrm{STR,out}} \quad (12)$$

$$S_{r,t}^{\mathrm{HYD,min}} \leq S_{r,h,t}^{\mathrm{HYD}} \leq S_{r,t}^{\mathrm{HYD,max}} \quad (13)$$

where $D_{r,h,t}^{\mathrm{STR,out}}$, $D_{r,h,t}^{\mathrm{STR,out,max}}$, $D_{r,h,t}^{\mathrm{STR,in}}$, and $D_{r,h,t}^{\mathrm{STR,in,max}}$ denote the hydrogen storage mass withdraw and injection and respective upper bounds, respectively. $S_{r,h,t}^{\mathrm{HYD}}$ denotes the hydrogen mass that is stored in the storage at time h. $\varphi_{r,t}^{\mathrm{STR,in}}$ and $\varphi_{r,t}^{\mathrm{STR,out}}$ denote the storage injection and withdraw efficiency, respectively. $S_{r,t}^{\mathrm{HYD,max}}$ and $S_{r,t}^{\mathrm{HYD,min}}$ denote the maximum and minimum hydrogen mass that should be stored in the storage facility, respectively.

Equation (8) constrains the hydrogen mass flow. Constraint (9) indicates the hydrogen storage injection should not be greater than the hydrogen production by electrolysis process. Constraints (10) and (11) limit the storage injection and withdraw to the storage facility capacity. Equation (12) calculates the hydrogen stored in the storage, which is further constrained by the installed capacity of the storage facility by constraint (13). We embedded equations (1) - (13) to ReEDS model for four SAF production target scenarios analysis.

IV. System Model and SAF Scenarios

In this section, we introduce the system model and the SAF production demand scenarios evaluated in this paper. As stated in Sec. III, we use ReEDS to model the 2020 to 2050 U.S. power system long-term planning problem. ReEDS models the contiguous United States as a 134-node system, where each node represents one balancing area, see Figure 3. The transmission network is aggregated and modeled as 418 transmission interconnected lines representing interfaces between regions. We model the baseline scenario (no SAF demand) with the 100% clean energy electricity by 2035 and the projected net zero GHG emission by 2050 demand growth profile [14]. In this profile, we assume 1) the light-duty vehicle is 100% electric vehicle (EV) in 2050, 2) net zero CO_2 emission after year 2035, 3) DAC is enabled, 4) carbon capture and storage is employed, and 5) hydrogen combustion turbine generator technology is adopted. Other model input and assumptions are consistent with the National Renewable Energy Laboratory 2022 Annual Technology Baseline [15]. TABLE 1 summarizes the four SAF demand scenarios in 2050 built upon the 2050 baseline scenario with different SAF targets.

TABLE 1 Summary of SAF production target scenarios.

Core Scenarios	SAF Process E_{2050}^{SAF} (TWh/yr)	H_2 Electrolysis (MMT/yr)	H_2 Electrolysis E_{2050}^{SAF} (TWh/yr)	CO_2 Capture and Compression (TWh/yr)
27% SAF	213	11	588	12
20% SAF	158	8	436	9
15% SAF	119	6	327	7
10% SAF	79	4	218	5

V. Numerical Results

In this section, we illustrate the capacity expansion results of 2050 U.S. power grid baseline scenario and the proposed four SAF demand targets scenarios. We used ReEDS with GAMS 34.0 on a Windows workstation with 192 GB of RAM and 3.0-GHz processors to execute all scenarios.

Figure 4 demonstrates the total installed capacity and annual generations in 2050 for the baseline scenario. The total generation and installed capacity difference of the proposed four scenarios compared to the baseline is shown in Figure 5 and Figure 6, respectively. As shown in these figures, the additional SAF production will require more generation capacity and more electricity generation to meet SAF production demand. Compared to the baseline case, the increase in total generation and capacity are not very significant. To meet the highest 27% SAF production target in 2050, the electricity generation and generation capacity need to be increased by 884.8 TWh and 383.9 GW, or 7.13% and 6.74%, respectively.

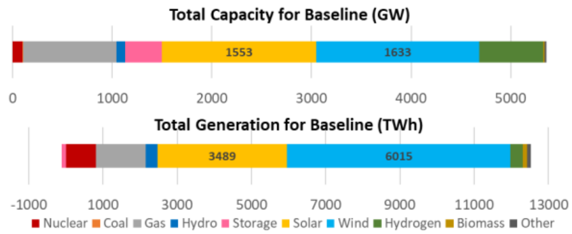

Figure 4 Total installed capacity and generation of 2050 baseline scenario.

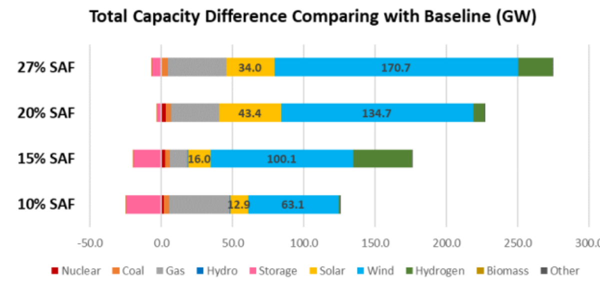

Figure 5 Total generation capacity difference compared to baseline (GW).

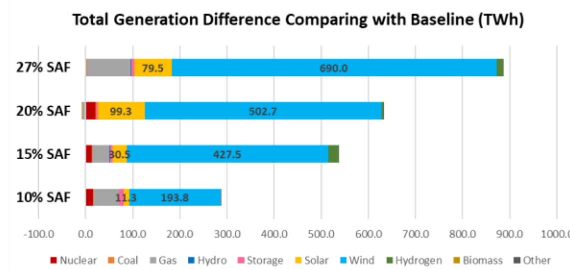

Figure 6 Total generation difference compared to baseline (TWh).

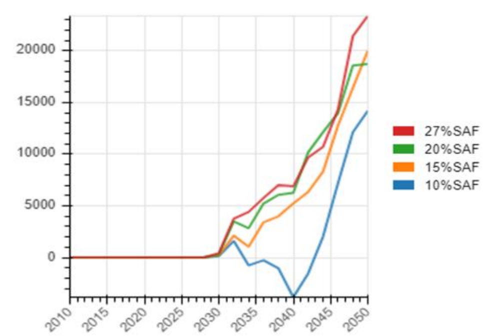

Figure 7 Transmission expansion difference compared to baseline (GW-mile)

Figure 7 shows the difference in transmission capacity expansion compared with the baseline. For 27% SAF scenario, the additional SAF demand results in 23,404 GW-mi new transmission build-out, representing 6% increase. This figure indicates that more transmission capacity will be invested when the SAF production target increases. However, there are some years where a lower SAF production target requires more transmission expansion, and the 10% SAF production target may require less transmission capacity compared to the baseline between 2030 to 2040. This is because the transmission expansion is not only influenced by load growth projection but also influenced by the investment of generating capacities, *i.e.*, capacity, generation type, location, *etc*. Thus, it is reasonable to have some fluctuations in the transmission capacity expansion. Overall, all these SAF production scenarios will have higher transmission capacity in 2050 compared to the baseline.

TABLE 2 compares the total system cost from 2010 to 2050 for all the studied scenarios including capital, operation & maintenance (O&M), fuel, transmission, and transmission O&M costs. We observe that the total system cost increases as the SAF production target increases.

TABLE 2 Comparison of total system cost (Bil $).

	Baseline	10%	15%	20%	27%
Capital	2559.8	2612.5	2627.4	2640.1	2663.8
O&M	1676.5	1694.6	1700.8	1706.0	1715.5
Fuel	666.7	679.6	674.2	674.1	675.5
Transmission	161.3	162.0	166.1	168.8	170.0
Transmission O&M	297.0	298.7	301.7	302.2	303.6
Total	4739.9	4803.8	4831.1	4849.1	4885.8
Total cost % increase	N/A	1.35%	1.92%	2.30%	3.08%

The baseline and 27% SAF scenarios capacity expansion results comparison is summarized in TABLE 3. Overall, the 27% SAF target scenario will increase the generation and transmission capacity buildout as well as the total system costs.

TABLE 3 Comparison of baseline and 27% SAF scenarios.

	Baseline	27% SAF	% Change
Electricity Demand (TWh)	12,413.6	13,298.4	+7.13%
Generating Capacity (GW)	5,688.9	6,072.8	+6.74%
New Transmission Buildout (GW-mi)	421,813	445,217	+5.55%
Total System Cost (Bil $)	4,739.9	4885.8	+3.08%

VI. Concluding Remarks

In this paper, we have explored the impacts of SAF production using CO_2-to-Fuels technologies on a future power grid with a high share of renewable energy. We developed a comprehensive SAF electricity demand model based on a low-temperature electrolysis-syngas fermentation-ethanol pathway and integrated it into ReEDS. This model enabled us to assess the generation, installed capacity, transmission capacity, and system cost impacts across four SAF target scenarios. These scenarios aim to meet 10%, 15%, 20%, and 27% of the SAF demand in the U.S. power grid by 2050. Our findings indicate that an increase in SAF demand will lead to a corresponding rise in electricity demand, generator and transmission capacities, and overall system costs. However, these impacts are within acceptable limits when considered as part of the broader U.S. capacity expansion results. We believe this research offers valuable insights for model developers and policymakers. It underscores the importance of incorporating the CO_2-to-Fuels pathway electricity demand model and other carbon capture technologies into power system planning and analysis. This inclusion is crucial for developing a more comprehensive understanding of carbon capture technologies and ensuring sustainable, efficient cross-sectoral energy systems.

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