

SAF: a promising approach to meet growing jet fuel demand

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HIGHLIGHTS

- Cross-comparison of technical, economic, and sustainability metrics is quantified.
- HEFA (non-algae) has the lowest cost (~\$3/gge) if with low-cost feedstocks.
- Fischer-Tropsch has the lowest carbon intensity, estimated at 5.5 g CO₂e/MJ SAF.
- HEFA ranks best but has issues with its feedstock supply.
- All pathways except corn grain alcohol-to-jet reduce emissions >50% vs. fossil Jet A.

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ABSTRACT

SAF provides a promising approach to aid the rising jet fuel demand from increased travel around the world and reduce the lifecycle emissions from the aviation sector. Although the feasibility of SAF pathways has been demonstrated through economic and environmental metrics quantification, the models used to quantify these variables have a high degree of variability in terms of accuracy and thereby reliability. To understand how to adopt and commercialize SAF, we need to harmonize these process models and assess metrics and technical limitations related to their production technologies. We find the production cost of SAF using hydro processed fatty acids and esters (HEFA), Fischer-Tropsch (FT), and alcohol-to-jet (ATJ) to be \$3–\$6/gallon gasoline equivalent (gge) and life cycle emissions to be lower than Jet A, except for ATJ using corn grain (≤25%). HEFA utilizing oil feedstocks has the lowest production cost (~\$2.9/gge) and highest jet yield (>150 gge/dry ton), while FT has the largest emission reduction (94%) compared to fossil jet. A unique contribution of this study is a comparative analysis of metrics related to SAF processes across technical, economic, and sustainability aspects. A cross-comparison of these metrics shows HEFA using fats, oils, and grease have the most favorable ratings, while HEFA using algae and ATJ using corn stover have more neutral and unfavorable ratings, respectively. These ratings can be improved by implementing the right combination of practical and technological advancements.

1. Introduction

The travel demand is anticipated to increase over the next decades, which will lead to an increase in Jet A demand, potentially impacting the supply chain of the aviation sector given its high reliance on finite resources like fossil fuels. As such, it is important to consider alternative carbon feedstocks such as biomass and waste alongside conversion pathways to address the growing jet fuel demand. In addition, the

aviation sector accounts for 2.8% of the total greenhouse gas (GHG) emissions globally [1] and 3% of total GHG emissions in the United States (U.S.), translating to 252 million tons of carbon dioxide (CO₂) emissions annually [2]. Sustainable Aviation Fuels (SAF) are a promising near-term, feasible, and scalable strategy to meet the growing commercial aviation fuel demand along with mitigating GHG emissions [3]. SAFs are low-carbon substitutes that can be either blended with petroleum-jet fuels or used as drop-in fuels, while easily integrating with

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existing infrastructure [4]. Moreover, SAFs address many of the challenges associated with current battery technologies and hydrogen utilization in the context of aviation [5]. Moreover, issues associated with short-range flight restrictions, low energy density, and safety concerns can also be addressed using SAF [6].

Although a shift to SAFs has the potential to decrease the emissions from commercial aviation [7], research has shown the costs of producing SAF to be higher than jet fuels [8], owing to high feedstock costs that contribute to approximately 50% of the production cost for many SAF conversion processes [9]. These costs can be reduced using second or third generation feedstocks for producing SAF [10]. Techno-economic modeling also highlights the capital intensity of SAF technologies, with capital investments contributing between 40% and 81% to the total fuel cost of certain pathways [11]. In addition, varying fuel yield, limited feedstock availability, and low technical maturity of SAF conversion pathways delay the adoption and commercialization of SAF technologies [12]. Technical advances in the areas of feedstock production and the feedstock-to-fuel conversion process are necessary to make SAF more economically viable. To address this, policies and incentives (e.g., U.S. Renewable Fuel Standard [13] or Sustainable Skies Act [14,15], European Union ReFuelEU [16], Brazil's *RenovaBio* program [17]) for advancing the commercialization and economic viability of SAF are in place or being proposed. For example, in the EU, the Fit-for-55 policy package includes the ReFuelEU Aviation initiative, which mandates increasing percentages of SAF blends through 2050 [18], with a growing number of adopted and proposed national mandates [19]. Additionally, collaborative efforts between governments and industry have resulted in a recent increase in offtake agreements between airlines and SAF producers [20] (see SI for the summary of offtake agreements). Given the growing interest in the production, utilization, and distribution of SAFs, understanding the feasibility of SAF technologies is essential to meet the growing fuel demand and mitigate potential supply chain disruptions.

To date, the feasibility of SAF pathways has been evaluated through the quantification of different economic and environmental metrics primarily by applying techno-economic analysis (TEA) [21] and life cycle analysis (LCA) [22]. The validity and accuracy of these analyses are highly dependent on the fidelity of the models or methods used to quantify the mass and energy balance of the system. Despite an extensive body of literature on the sustainability of SAFs performed for individual pathways (e.g., aqueous phase reforming pathway [23], alcohol-to-jet [24], hydroprocessed fatty acid pathway from waste oils [25], or using first and second generation feedstocks [26]), most analyses focus on performing either a TEA [27] or LCA [28] without considering multi-dimensional cross-comparison of technical, economic, and sustainability metrics. A recent study on integrated assessment of SAF focuses on three parameters to understand the economic viability, market readiness, and sustainability impacts through qualitative analysis, although the analysis was only focused on a specific region [29]. Similarly, Kim et al. [30] performed a multicriteria decision analysis considering only TEA and LCA as a focus for only two carbon dioxide to SAF technologies without considering ASTM approved pathways. Okolie et al. [31] recently published an analysis that evaluates multiple SAF production pathways to rank their performance based on selected economic, environmental, and technology metrics through a multi-criteria decision analysis considering equal weightage. However, this study includes pathways which are not ASTM certified and did not consider synergistic effects of all the metrics under each umbrella (e.g., SAF blending limitation, return on investment, water consumption, process yield, fossil energy consumption, etc.), the impacts of which can be non-trivial on commercialization and adoption of SAF.

The lack of holistic assessments of SAF pathways affects its commercialization and adoption. In this research, we quantify the essential metrics associated around cost and carbon intensity for selected ASTM approved SAF pathways and assess synergistic effects of key variables across technology, economic, and environmental

considerations that could help catalyze the adoption of SAF. These results will aid stakeholders in identifying the improvements that SAF production pathways will require for meeting performance targets [32]. In addition, a unique contribution of this work is harmonization of process modeling assumptions to perform the analyses and the cross-comparison of metrics associated with SAF production across technology, economic, and sustainability aspects for several ASTM approved SAF pathways.

2. SAF process scenarios

ASTM has approved eleven SAF pathways with blending levels from 5% to 50% [33]. Various SAF conversion pathways have been adopted by multiple industries and airline carriers to reduce CO₂ emissions by 50% from the 2005 baseline [34]. While Fisher-Tropsch (FT) synthesis of synthetic paraffinic kerosene (SPK) was the first pathway to get ASTM approval, there is a fast-tracking review process assisted by the Federal Aviation Administration that provides expedited approval for new processes. In addition, advanced SAF pathways, currently in the Research and Development phase are also being considered for approval which include SAF from alcohol deoxygenation [35], plastics derived crude oil [36], used cooking oil [37], CO₂ via renewable electricity [38], CO₂ via syngas [39], and municipal solid waste conversion via catalysis [40]. Table S1 of the SI has detailed information on all ASTM approved processes.

Fig. 1 illustrates the process pathways considered in this analysis with variations across feedstocks for nine SAF process technology scenarios. These include 1) woody biomass based Fischer-Tropsch (FT) Synthesis; 2) fats, oils, and grease (FOG), 3) all vegetable oils, 4) fats & grease, and 5) algae based Hydroprocessed Esters and Fatty Acids (HEFA); 6) corn grain based alcohol-to-jet (ATJ) via ethanol intermediate and 7) isobutanol intermediate; 8) cellulosic biomass based alcohol-to-jet (ATJ) via ethanol intermediate and 9) isobutanol intermediate. This study aims to fill the data gaps related to process technology, economics, and sustainability with synergistic effects, in order to gain a consistent understanding of ASTM-approved SAF pathways.

3. Methods

3.1. Techno-economic analysis

Our analysis of the economics of SAF production pathways includes a conceptual process design for developing a detailed process flow diagram based on research or commercial data, rigorous material and energy balance calculations via process modeling framework like Aspen Plus [41], capital and operating cost estimations via an in-house model using Excel-based spreadsheets. These sets of data are utilized for performing a discounted cash flow rate of return analysis based on a fixed set of economic model assumptions (see Table 1) to estimate the minimum fuel selling price (MFSP). The financial assumptions considered in this study are based on “nth plant” assumption, representing matured and commercialized process that reflects the best estimate of SAF production costs, thus assuming lower risk, optimized operation, and established supply chain [42]. It is acknowledged that the financial assumptions that have been taken into consideration are inherently prone to uncertainty and possess the potential to undergo modifications throughout the conclusive phase of project management, particularly concerning a distinct technology that is being implemented in particular environments.

To quantify the SAF production costs, we carried out a detailed techno-economic analysis based on Aspen Plus process design models. The conversion rates and processing parameters were modeled based on in-house bench and pilot-testing experimental data as well as real-world industrial data for specific units. Sahir et al. [43] was used as a benchmark for FT process, State of Industry Report [44] for FOG based HEFA process, Atnoorkar et al. [45] for algae based HEFA process, and Tao

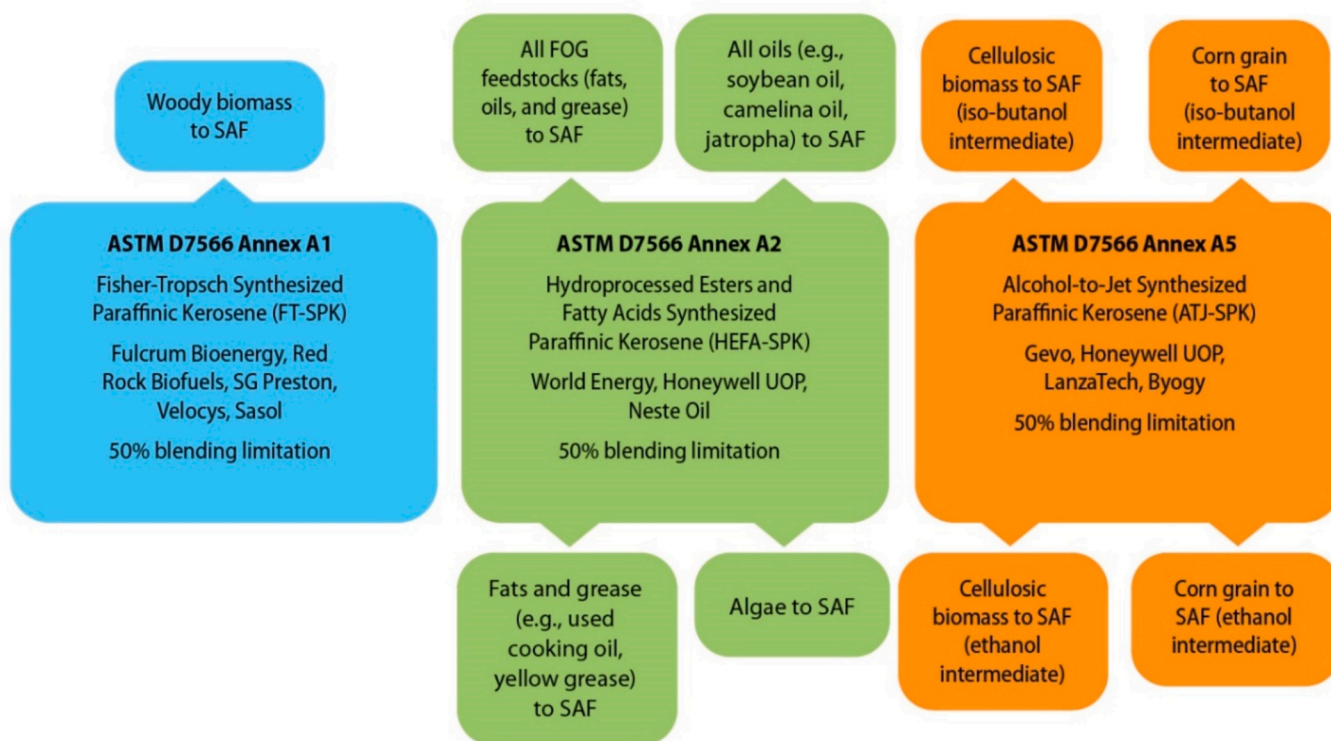


Fig. 1. Process scenarios under three SAF ASTM approved pathways considered for cross-comparison of metrics.

Table 1
Key assumptions in economic analysis for the SAF pathways.

Parameter	Value
Discount rate (%)	10
Plant economic life (years)	30
Equity financing (%)	40
Loan interest rate (%)	8
Loan term (years)	10
Construction time (years)	3

et al. [46] for ATJ processes. The overall process efficiency (or on-stream factor) is assumed to be 90% (7884 operating hours per year), which is consistent with other techno-economic analysis design reports [47]. For a given set of conversion parameters, material and energy balance and flow rate information is generated using Aspen Plus process simulation software, which is used to determine the size and cost of the unit equipment. We then apply an installation factor to determine the installed capital costs and add direct (e.g., warehouse, site development, and additional piping), indirect (e.g., project contingency, field expenses, construction feed, and permits), and other cost parameters (e.g., land and working capital) to determine the total capital investment. See Table S2 in the SI for detailed economic assumptions.

The variable operating costs (e.g., cost of raw materials, energy, and coproducts) associated with the fuel production technologies are also estimated based on material and energy balance calculations using Aspen Plus process simulations. While all the hydrocarbon fuels (gasoline, diesel, jet) are considered as main products (converted to gallon gasoline equivalent [gge]), all the non-hydrocarbon coproducts (e.g., corn oil, polyurethane) are assumed to be sold at market selling price in the variable operating cost calculations. We also consider the cost of labor based on the salaries of personnel employed at the facility. Ninety percent of the total salaries is added for labor burden, and 3.0% of the total installed capital is designated for maintenance (which includes expenses on cleaning) [48]. Property insurance and taxes account for

0.7% of the total capital investment. The combination of costs associated with labor, maintenance, and insurance makes up the fixed operating costs. All costs are adjusted to 2020 dollars using the Plant Cost Index from *Chemical Engineering Magazine* [49], the Industrial Inorganic Chemical Index from SRI Consulting [50], and labor indices provided by the U.S. Department of Labor Bureau of Labor Statistics [51].

After the total capital investment, variable operating costs, and fixed operating costs are determined, a discounted cash flow rate of return analysis is typically used to determine MFSP (in terms of dollar (\$) per gge) at a discount rate of 10%. The detailed methods are described in previously published design report from the National Laboratory of the Rockies (formally National Renewable Energy Laboratory) [52]. Due to the variability of process designs, product and coproduct balances, and the uncertainty of process performances, it is necessary to use a bio-refinery analysis concept, such as techno-economic analysis, to understand these SAF conversion technologies. This methodology will be utilized across all ASTM-approved pathways considered here.

3.2. Life cycle analysis

LCA is performed to estimate the carbon intensity and fossil energy use for the SAF technologies evaluated in this study. Mass and energy balances from the Aspen Plus model are used in conjunction with data from the Greenhouse Gases, Regulated Emissions, and Energy use in Technologies (GREET) model [53] and existing literature.

In defining the system boundary for life cycle modeling, we adopt the recommendations described in Prussi et al. [54], which group feedstocks into main product, byproduct or waste/residue. Depending on the group the feedstock falls in, the system boundary could vary as indicated in Fig. S1 of the SI. When a main product such as soy oil is used as feedstock, upstream emissions associated with producing the product (including emissions from planting soybean, fertilizer application and harvesting) as well as the embodied energy and emissions associated with the inputs used in the fuel conversion processes are all accounted for. On the other hand, if the feedstocks are categorized as byproduct (e.

g., tallow) or waste (e.g., used cooking oil) or residues (e.g., logging residue, agricultural residue), emissions associated with producing the main product (e.g., beef, corn, lumber) are not allocated to the byproducts or waste/residues because the purpose of the economic activities is to produce the primary products. As such, for these types of feedstocks (i.e., byproduct, waste, residues), we use a “marginal” approach, which accounts for the additional effects resulting from collection and transportation of the feedstock, pre-treatment and conversion of feedstocks to SAF. The definition of system boundary is consistent with LCA methodology adopted by CORSIA [55].

GHG emissions from potential land use change (LUC) induced by growing feedstock for biofuel production are taken into account for energy crops such as corn and soybeans. Data on LUC is derived from GREET for crops grown and harvested in the U.S. However, no LUC effects are assumed for algal biomass because land used for open ponds is expected to be marginal rather than farmland in agricultural use for growing food crops.

The feedstock modeled for the HEFA process includes soy oil, distillers corn oil (DCO), used cooking oil and animal fats (tallow, in particular). Soy oil is derived from dedicated soybean grown for SAF production and is considered a main product, while feedstocks including DCO, used cooking oil and animal fats are treated as byproducts or wastes. For example, no GHG emissions associated with livestock production (e.g., during cattle growth) or slaughtering processes are allocated to animal fats, as we consider animal fats a “waste” material from livestock production. However, energy used to collect and process animal fats prior to their conversion to SAF is allocated entirely to feedstock.

Corn and corn stover are the feedstocks modeled for the ATJ processes via either ethanol or isobutanol. Corn is modeled as a main product, whereas corn stover is considered a residue from growing corn. The LCA analysis accounts for energy use and emissions due to additional fertilizer (N, P, K) inputs needed to compensate for the loss of nutrients from corn stover harvesting in addition to the energy inputs and emissions from harvesting and transporting corn stover.

Similarly, woody biomass used for the FT conversion process is assumed to be sourced from logging operations and therefore is treated as a residue. Emissions resulting from residue loading, chipping and transportation are taken into account in LCA modeling.

As discussed earlier, the technologies modeled for SAF production in this analysis are at various TRLs. Even for a given technology, configurations of process designs could vary significantly. In modeling the SAF conversion processes, our LCA uses the material and energy inputs and outputs data from Aspen Plus to develop an energy and emission inventory. When the conversion processes produce more than one energy product (e.g., jet fuel, renewable diesel, naphtha), an energy-based approach is applied to allocate emissions among the main product and byproduct(s) in proportion to each energy product's contribution (in terms of its energy content) to the total energy output from the production system. Given the profound impact on LCA results of methodological choice in dealing with co-products, we present another set of results using a hybrid approach. If the system produces non-fuel byproducts such as animal feed, electricity, we apply a displacement approach (also referred to as system expansion) to assign credit to the main product by assuming that the by-product(s) will displace functionally equivalent products in the market and therefore avoid the energy and life cycle burdens associated with producing the replaced products.

The functional unit for life cycle modeling is 1 megajoule (MJ) of fuel for aviation applications. All results are reported on a full fuel life cycle basis from feedstock production to conversion to final use of jet fuels to facilitate a consistent comparison between synthetic jet fuels and their petroleum-derived counterparts.

3.3. GREENSCOPE analysis

The Gauging Reaction Effectiveness for the ENvironmental Sustainability of Chemistries with a Multi-Objective Process Evaluator (GREENSCOPE) methodology was developed by the Environmental Protection Agency's researchers [32,56]. It is a sustainability tool for process evaluation and design. Sustainability is assessed by employing a set of indicators categorized in four areas: economic-based, environmental-based, material efficiency-based, and energy-based (Fig. 2). The strength and uniqueness of the methodology are demonstrated through the definition of best-target and worst-case limits for each of the indicators (dimensionless scale) [57]:

$$\text{Sustainability\%Score} = \frac{(\text{Actual} - \text{Worst})}{(\text{Best} - \text{Worst})} \times 100\%$$

Here, the best target represents 100% sustainability, and the worst-case scenario represents 0% sustainability. The sustainability reference values or scores allow for a direct assessment of the process sustainability status and for assessing how far the process is from achieving a more desirable sustainable state (i.e., potential). We have selected indicators of interest, which represent only a subset of the entire GREENSCOPE indicators. Based on GREENSCOPE guidelines or default values, we have also identified and selected the best case (100% sustainability) and worst case (0% sustainability) scenarios to establish the sustainability scale for each indicator. As part of the future study, we will continue to further refine the GREENSCOPE sustainability indicators for better assessment. Additionally, we will also engage researchers and stakeholders to establish the sustainability scale for specific indicators.

In this study, we have implemented the GREENSCOPE framework for the sustainability performance assessment to produce SAF via the selected pathways. The system boundary is gate-to-gate. As opposed to the life cycle assessment or supply chain sustainability analysis, in which the entire system beyond the manufacturing facility is assessed, the focus of GREENSCOPE sustainability assessment using GREENSCOPE is on gate-to-gate where the process developer has a firsthand opportunity to exert any design changes, excluding the jet fuel production process's upstream and downstream processes [58]. The resulting gate-to-gate GREENSCOPE sustainability assessment will identify the sustainability ‘hot spots’ (areas that have room for further improvement) of the process under consideration. GREENSCOPE encompasses economic parameters and results (including production costs and revenues), and material and energy flow (such as biomass feedstock, releases, ancillary inputs, and process energy). Additionally, physicochemical, thermodynamic, and toxicological properties are also required to calculate life cycle indicators, with the potential data sourced detailed in [56,58]. A subset of the GREENSCOPE indicators pertinent to these processes was selected

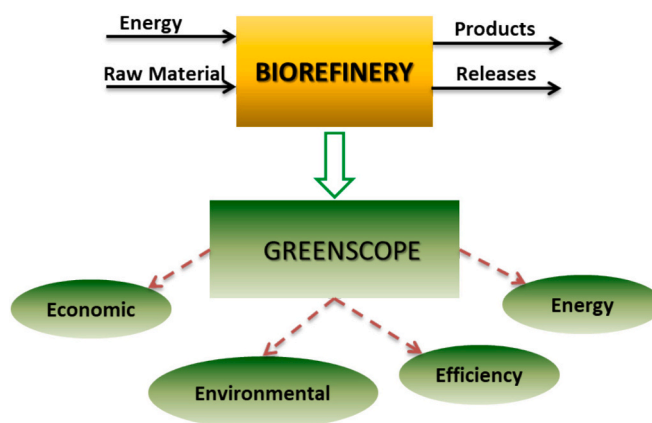


Fig. 2. Implementing GREENSCOPE for sustainability performance assessment of SAF pathways.

based on sustainability score variability across processes which include resource energy efficiency, mass intensity, respiratory effect potential, and ecotoxicity to aquatic life potential. Considering that some of the indicators would not be expected to be of interest for the processes studied, specific indicators to evaluate were chosen. See Table S13 of the SI for input information on all process scenarios.

3.4. Synergistic effect of quantitative metrics

Complementing the methodological frameworks for techno-economic analysis, life cycle assessment, and sustainability evaluation outlined in Sections 3.1, 3.2, and 3.3, this section delineates the key variables and parameters considered to evaluate synergistic interactions across technological, economic, and environmental dimensions. Beyond quantitative metrics, we also assess qualitative parameters across these dimensions to provide a comprehensive comparative evaluation of SAF production pathways.

3.4.1. Feedstock availability

Productivity, defined as the annual production of feedstock in a specific region, is a critical metric that affects the commercial and economic feasibility of SAF production, with feedstock availability being influenced by factors such as site preparation, weed control, and fertilization [43]. The feedstock sourcing, preprocessing logistics, and delivery need to be dependable and meet the minimum quality requirements (e.g., critical material attributes such as physical and chemical properties) for the relevant conversion processes. To determine the most efficient production and use of SAF, it is important to consider a feedstock's availability and supply-demand dynamics, including competition with other fuel markets like renewable diesel.

3.4.2. Technology maturity

Technology maturity is evaluated using the Technology Readiness Level (TRL) scale, which assigns a score from 1 to 9. A score of 1 indicates the observation of basic principles, while a score of 9 indicates the complete demonstration of the process system [44]. The DOE has issued a Technology Readiness Assessment Guide [59] which states: "A successful project is a project that satisfies its intended purpose in a safe, timely, and cost-effective manner that would reduce life-cycle costs and produce results that are defensible to expert reviewers."

3.4.3. Economics

Economics can be measured in several ways, including production costs, capital costs, return on investment (ROI), payback period, and internal rate of return (IRR). Production costs can be estimated as \$/gge. For the MFSP, it indicates the production cost of SAF is inclusive of a fixed internal rate of return when the net present value is zero. The total capital investment includes the equipment cost along with other direct (e.g., warehouse, site development, pipeline, etc.) and indirect costs (e.g., proratable expenses, field expenses, start-up costs, permits). ROI, payback period, and IRR are performance measures used to evaluate the profitability of an investment, which are closely related to each other (refer to Section 2 of the SI for details).

3.4.4. Sustainability

Sustainability measurements are defined in the form of carbon intensity (usually considering a functional unit per energy basis), assuming cradle-to-grave lifecycle boundary. For example, the carbon intensity of fossil-based Jet A is 89 g CO₂e/MJ fossil jet [54]. Additionally, sustainability is measured using the GREENSCOPE tool that employs a set of indicators categorized in four metrics: economic-based, environmental-based, material efficiency-based, and energy-based, to evaluate a sustainability score for process evaluation and design [32,56]. The detailed description of the GREENSCOPE methodology can be found in the SI.

4. Results

4.1. Comparison of production costs and carbon intensity

Fig. 3 shows the summary of TEA and LCA modeling results conducted by the authors for the nine process scenarios discussed here. The HEFA process provides the highest fuel yield from starting feedstock for both SAF and renewable diesel applications. The MFSP of SAF from the HEFA process (except algae) scenarios ranges from \$2.90/gge to \$3.00/gge (in 2020\$). Feedstock is the largest contributor to SAF's production cost, accounting for 68%–70% of overall MFSP. Utilizing fats and grease as feedstock provides the lowest carbon intensity of 20.9 g CO₂e/MJ of SAF, a reduction in life cycle GHG emissions of 77% compared to conventional jet fuel. For algal-HEFA, the carbon intensity is highest at 36 g CO₂e/MJ SAF, a reduction of 60% compared to conventional jet fuel, and the MFSP for the process increases to \$4.53/gge, specific to an algae conversion biorefinery configuration including co-production of polyurethane (PU) from a portion of algal lipids which garners substantial co-product credits. Algal biomass feedstock cost remains a primary contributor to MFSP and carbon intensity for the algal-HEFA pathway. For this pathway in particular, we stress that MFSP and carbon intensity can vary widely depending on assumptions for algal feedstock composition and decisions on conversion configuration and inclusion of co-products (PU was selected as an example case here, but other options are available).

In the FT synthesis pathway, syngas production from various ranges of feedstock plays an important role in fuel production. The MFSP of SAF from the FT process utilizing woody biomass is estimated to be \$2.95/gge, with capital costs contributing up to 55% of the overall MFSP. The carbon intensity for this pathway is lowest among all scenarios at 5.5 g CO₂e/MJ SAF, a reduction of up to 94% compared to conventional jet fuel.

The cost of SAF from ATJ-based process scenarios ranges from \$3.14–\$5.59/gge for corn and cellulosic-based feedstock scenarios via C2-C4 intermediates. The overall MFSP for corn grain feedstock with an ethanol intermediate is the lowest among the four process scenarios. While feedstock contributes to 66%–71% of MFSP for corn grain, the capital costs contribute the maximum (39%–43%) to overall MFSP where cellulosic feed is utilized. The carbon intensity is estimated to be 23.4 g CO₂e/MJ SAF and 29.7 g CO₂e/MJ SAF for lignocellulosic biomass feedstocks based ATJ process, where ethanol and isobutanol are produced as intermediates, respectively. Corn grain ATJ for both intermediates have high carbon intensities (67.1 g CO₂e/MJ SAF for ethanol intermediate and 72.1 g CO₂e/MJ SAF for isobutanol intermediate), close to conventional jet fuel, indicating additional strategies would be required for these SAF conversion scenarios to lower the GHG emissions. It should be noted that these costs are shown in 2020\$ and are subject to change based on inflation which can impact the MFSP value significantly. Moreover, technological advancement and its commercial adoption may also impact the capital and operating overall costs. SI provides in-depth information on the process, economics, sensitivity analysis, sustainability, and commercial readiness for all discussed scenarios.

4.2. Cross comparison across different metrics

To compare various SAF process technology scenarios, we examine the following five variables: capital costs, feedstock availability, mass intensity (total mass fed divided by total mass out, GREENSCOPE), resource energy efficiency (energy content of products divided by feedstock, GREENSCOPE), and process yield, within the context of overarching feedstock, technology, economic, and sustainability considerations, illustrated in Fig. 4. Detailed definitions for each variable can be found in SI (Table S3).

Fig. 4 displays all five metrics analyzed in this analysis, for which the outer vertex represents the preferred outcome for each pathway (see SI

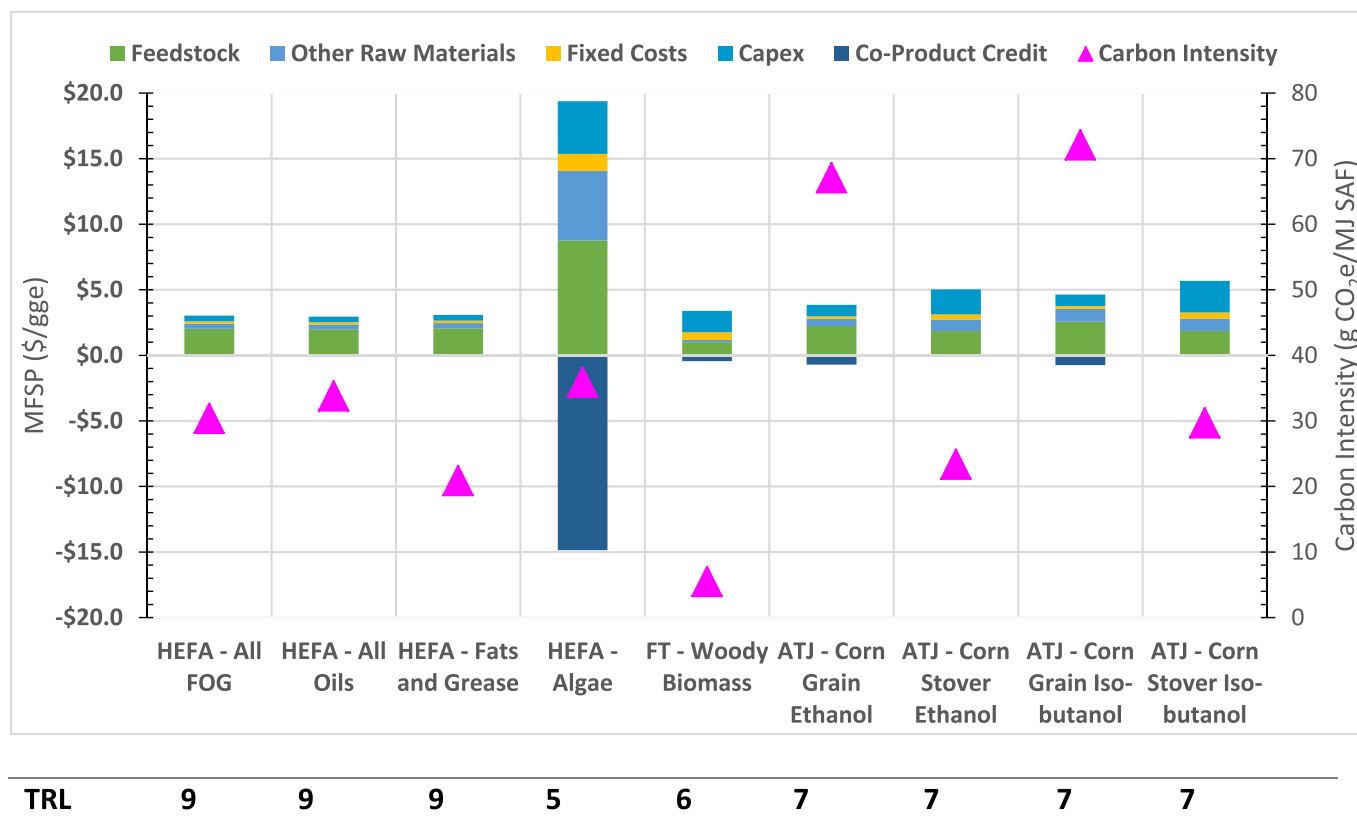


Fig. 3. Summary of techno-economic and life cycle assessment results. MFSP data are illustrated using left x-axis with cost breakdown on feedstock, other raw materials, fixed costs, capital cost (Capex) and co-product credit, while Carbon Intensity is shown on secondary (right) y-axis in terms of $\text{g CO}_2\text{e/MJ SAF}$ as triangles.

for quantitative estimates of all the metrics for process scenarios analyzed here).

Our results indicate HEFA (except algae) stands out across all SAF processes in terms of mass intensity, resource energy efficiency, and yield, with emerging commercial facilities operational around the world. HEFA based on algae incurs high capital costs and requires further technology improvements. HEFA (except algae) and corn grain based ATJ processes are least capital intensive, while remaining processes tend to have high capital required per gge of SAF produced. Thus, for pathways using lignocellulosic biomass feedstocks and algae, not only is securing capital investment critical but also process improvement opportunities for making value added co-product should be considered improving yields, mass intensity or resource energy efficiency.

5. Discussion

Qualitative assessments help address data gaps and uncertainties in SAF technology adoption, enabling commercialization by simulating processes and considering technological, economic, and environmental variables. Therefore, in addition to having the comparison of five selected metrics, the mapping across several metrics will provide analyses insights on process technology evaluations. In this mapping analysis, the metrics are categorized into favorability, neutral or unfavorability criteria bins according to the technology readiness, economic, and sustainability categories, using the methodology similarly in Bartling et al. [47]. These criteria can be defined using either quantitative estimates or subjective measures. Each metric is ranked as favorable, neutral, or unfavorable based on the cutoff criteria. The metrics are represented by the columns, and the rows represent the ASTM-approved SAF pathway variations considered in this study in Fig. 5. These results can be valuable for scientists, engineers, process developers, farmers, investors, and other stakeholders. They can use this

information to compare different metrics related to SAF production. Table S4, S5, and S6 provide a summary of definitions and screening criteria for metrics that are either quantitative or qualitative under technology readiness, economic viability, and sustainability metrics.

Technology readiness metrics are targeting to understand technology performance (performance data, blending limit and SAF use) and scalability (production facilities, TRL and gaps) based on defined targets in Table S4. Our results show a mix of favorability criteria for SAF process scenarios in terms of technology readiness metrics. All processes achieve a favorable rating for allowable blending limits of at least 50%, given by only including ASTM approved pathways in this study. Most processes achieve a favorable rating for accessible data for process modeling. The HEFA-algae process, on the other hand, is unpredictable, thus achieving an unfavorable rating due to limited data, variable feed composition, and different algae production methods, including varying process configurations and co-product selections. There is no commercial data for lignocellulosic based ATJ pathways, but there have been demonstrations [60,61] and proposed plans to produce SAF [62–64] from ATJ, resulting in most of the metrics falling in favorable and neutral bins. In terms of production facilities, HEFA (except algae), FT, and corn grain ATJ scenarios are the only processes with commercial scale facilities or plans to go commercial in the near future [64–69]. This leads to a rating that is either favorable or neutral. On the other hand, there are no eminent commercial plans announced publicly for corn stover ATJ and HEFA utilizing algae feed, resulting in an unfavorable rating [70]. A favorable rating on TRL means that the technologies have a detailed design, and the processes have been demonstrated at a reasonable scale. Except for HEFA, all process scenarios receive a neutral rating for their TRLs. New or low TRL technologies require industries to navigate a learning curve in order to minimize gaps and achieve the best environmental and economic outcomes. Except for algae, HEFA process scenarios satisfy favorable criteria, but other scenarios have notable

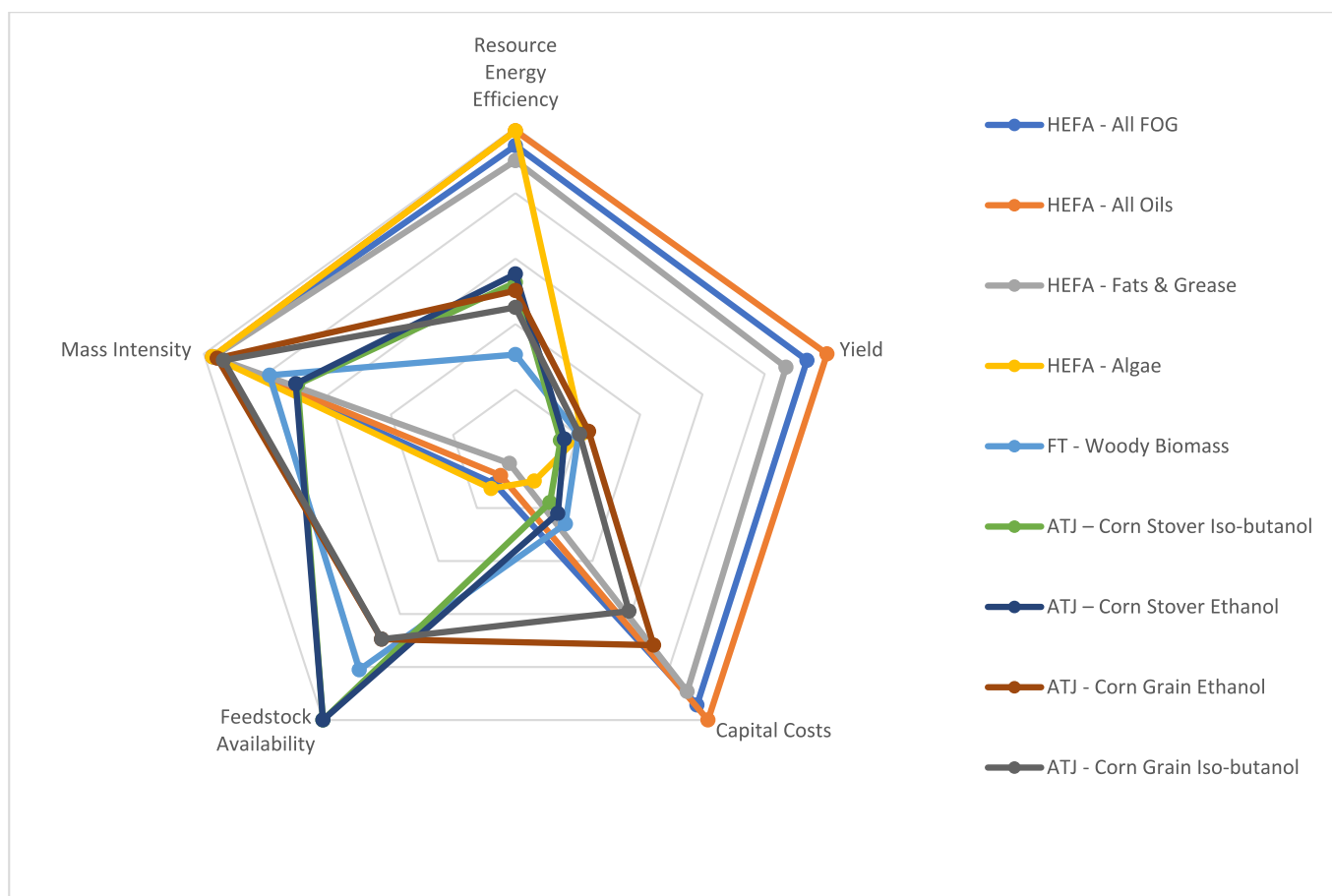


Fig. 4. Cross-comparison of selected SAF process scenarios across different metrics.

gaps, categorizing them as neutral.

Economic metrics include cost metrics (MFSP, ROI, payback period, etc.), dependency on co-products, feedstocks (price and availability) and capital intensity. For the metrics defined under economic viability, a majority fell under the favorable and neutral categories based on the defined targets in Table S5. The baseline MFSP rates for two HEFA scenarios (all feedstocks and all oils) and FT processes are below \$3/gge. All HEFA scenarios, except for algae and corn grain ATJ processes, have a neutral rating with MFSP ranging from \$3–\$4/gge. However, the remaining three process scenarios are unfavorable as their MFSP exceeds \$4/gge. Baseline MFSP is not the only metric for evaluating the economic potential of conversion pathways. SAF processes are being analyzed to understand emerging trends and improvements using economic sensitivity analysis (refer to SI). The favorable rating can be achieved through two process scenarios: HEFA based on fats and grease, and ATJ based on corn grain with an ethanol intermediate. However, the other seven scenarios must enhance certain key parameters to meet the MFSP target of \$2.5/gge (defined in the favorability criteria).

Except for algae-based HEFA, all process scenarios have favorable or neutral ratings on the coproduct dependency metric, with a dependency on co-products of 50% or less. Most processes (FT, corn stover ATJ, and algae HEFA) are capital intensive per gge of product, resulting in an unfavorable rating. However, the remaining process scenarios achieve a favorable or neutral rating with capital costs per gge of product below 10. The production cost of SAF is significantly impacted by the feedstock, so our favorability criteria assumptions are tightly defined to understand its implications. We identified six process scenarios involving HEFA and corn grain ATJ, where feedstocks contribute over 50% to MFSP, placing them in the unfavorable category. While there are options available to reduce feedstock costs (a cost of <\$60/ton is

considered favorable) through the use of alternate waste feed, there are trade-offs to consider between high feedstock/low conversion costs and low- or zero-waste feedstock/high conversion costs.

For feedstock availability, the majority of processes (FT and ATJ) achieve favorable rating with an abundance of woody biomass, agriculture resources (e.g., corn grain, based on the current ethanol production in U.S. [71,72]), and agriculture residues (e.g., corn stover) available for producing SAF [71,73]. For SAF production potential, six SAF scenarios under all feedstocks — HEFA, FT and ATJ — can potentially produce >5 billion gge/year of SAF, achieving a favorable rating, while the remaining three scenarios only achieving neutral rating.

We can determine the investment's profitability by using the payback period and ROI. Among the nine process scenarios, four of them are considered unfavorable (a payback period of <5 years and ROI of >5%/yr is considered favorable). The HEFA scenarios excluding algae offer the best returns. The low price of fossil jet fuel is the reason for this. Thus, for large-scale adoption of SAF from renewable sources, incentives or a premium market may still be necessary. Additionally, further research and development are needed to improve these technologies and make them more mature.

Sustainability metrics include yield, energy intensity, carbon intensity, GHG emission reduction, fossil energy and water consumption, with detailed definitions in SI for each metric. The inputs used to estimate selected GREENSCOPE variables are shown in the SI (Table S6). HEFA, except algae, has the highest yield and is favorable. Other process scenarios achieve neutral favorability criteria, except for corn stover based ATJ pathways.

Under energy intensity and fossil energy consumption, HEFA (except algae) and FT processes are favorable (a value <0.015 giga joule/kg is favorable). All ATJ processes except corn grain ATJ via isobutanol

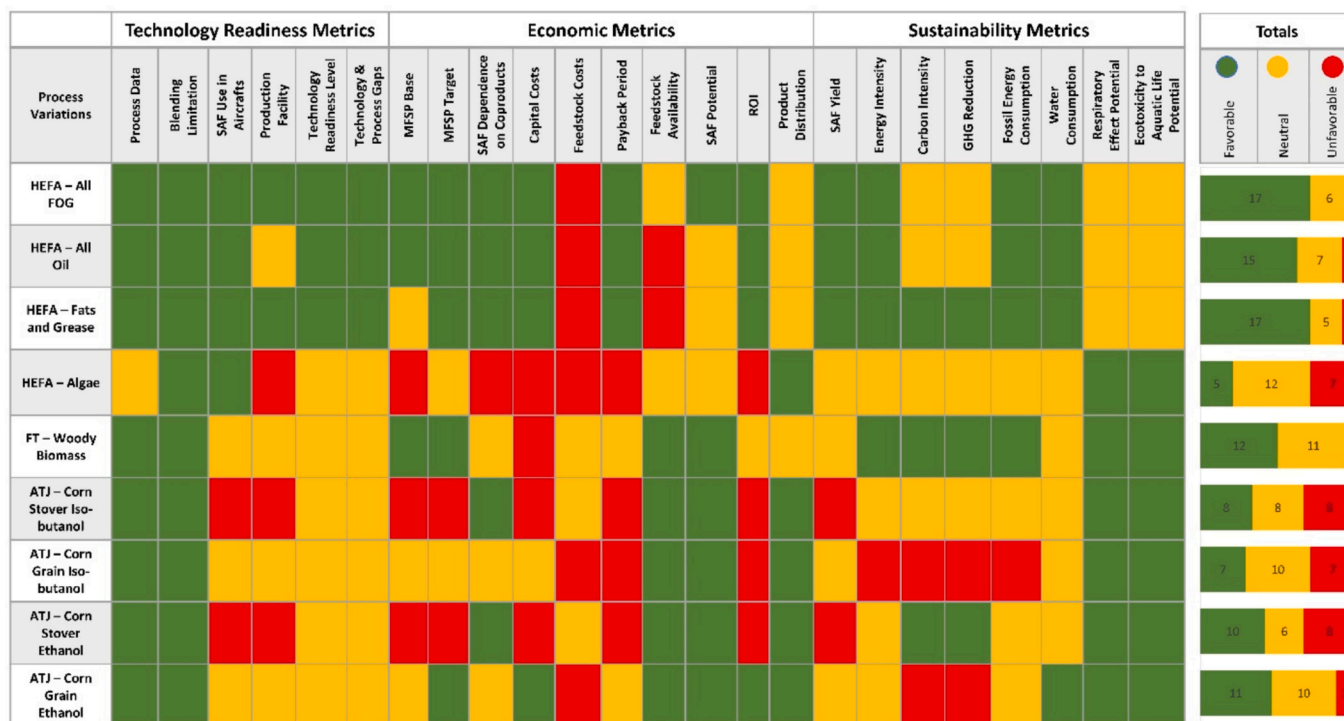


Fig. 5. Summary of mapping results for the nine SAF process scenarios. Results are categorized and compared based on favorability for each metric. Green, yellow, and red boxes represent favorable, neutral, and unfavorable categorization, respectively. The totals (right column with total counts of favorable, neutral and unfavorable) for each favorability ranking for process scenarios are shown in the bar chart. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

intermediate achieve a neutral rating. For carbon intensity and GHG emission reduction, the HEFA, FT, and corn stover ATJ pathways perform better compared to other scenarios. This results in three favorable ratings for carbon intensity and GHG emission reduction. However, corn grain based ATJ scenarios reflect higher carbon intensities and lower GHG emission reduction, making them comparably unfavorable for these metrics.

In terms of process water consumption, the HEFA (except algae) and corn grain ATJ pathways (ethanol intermediate) use the least water per fuel produced and have a favorable rating (considered as <3 gal/gge). All other scenarios are considered neutral. To further evaluate sustainability, we also consider the respiratory effect potential and ecotoxicity to aquatic life potential using the GREENSCOPE methodology. FT and ATJ processes perform better than HEFA processes (except algae) for both metrics. However, HEFA scenarios have a low sustainability score (neutral rating) for ecotoxicity to aquatic life potential and respiratory effect potential (a score > 90% is favorable).

Comparing metrics across different factors provides insights into the most promising SAF pathways in terms of technology readiness, economic viability, and sustainability. In our analysis of nine process scenarios, technology metrics were consistently rated as the most favorable. However, economic and sustainability metrics received a mixture of unfavorable and neutral ratings. The primary obstacle faced by most processes was high feedstock costs, which greatly influenced the MFSP and resulted in a payback period of 10 years or more. As a result, most economic measures were unfavorable. In terms of sustainability, most metrics were neutral, indicating that process scenarios were able to reduce GHG emissions by at least 50% compared to the fossil baseline. However, there is room for improvement in metrics such as yield. The HEFA pathways (except algae) achieved the most favorable ratings due to several reasons not limited to 1) technology already commercialized (TRL of 9), 2) low SAF production costs (close to ~\$3.0/gge), 3) high blending limit with Jet A fuel (50%), 4) low technology and process gaps, 5) low capital costs per unit of product (<3.5 million\$/million

gge), 6) low payback period (<4 years), and 7) high SAF production yield (>270 gge/dry ton feedstock). However, high feedstock costs (>\$500/ton) and low availability (sustained availability of <100 million dry tons/yr) may limit their economic impact and scalability. The ATJ pathway, which utilizes corn grain, have more unfavorable sustainability metrics especially under carbon intensity (72.1 g CO₂e/MJ for isobutanol intermediate and 67.1 g CO₂e/MJ for ethanol intermediate case – which is >43 g CO₂e/MJ score listed under unfavorable bin) and emission reduction (reduction of 19% for isobutanol intermediate and 25% for ethanol intermediate compared to fossil Jet A – which is less than 50% score under the unfavorable bin). Thus, corn grain pathways would require additional efforts to add other options (e.g., carbon capture) to make as compelling a case for meeting the aviation sector sustainability targets. On the other hand, for FT pathways, only one unfavorable economic indicator (capital costs of 12.7 million \$/million gge, which is >10 million\$/million gge score under the unfavorable bin) suggests that they have good potential for large-scale operations once capital investment is secured.

We compared the results using a ternary plot and found that there is a skewed distribution of favorable and neutral ratings for all process pathways in the economic and sustainability metrics, except for HEFA utilizing algae and ATJ pathways with isobutanol as an intermediate. These pathways lean more towards unfavorable ratings (Fig. 6). For technology readiness metrics, all the process pathways lean towards the favorable/neutral side, except for corn stover based ATJ pathways, which have an equal distribution of favorability ratings. In summary, non-algae HEFA and FT processes meet the combined requirements for the favorability criteria defined under each metric. Other pathways may still need additional improvements to create an optimal pathway for catalyzing SAF adoption while meeting cross-dimensional criteria.

6. Conclusions

Identifying key variables related to technology, economics, and

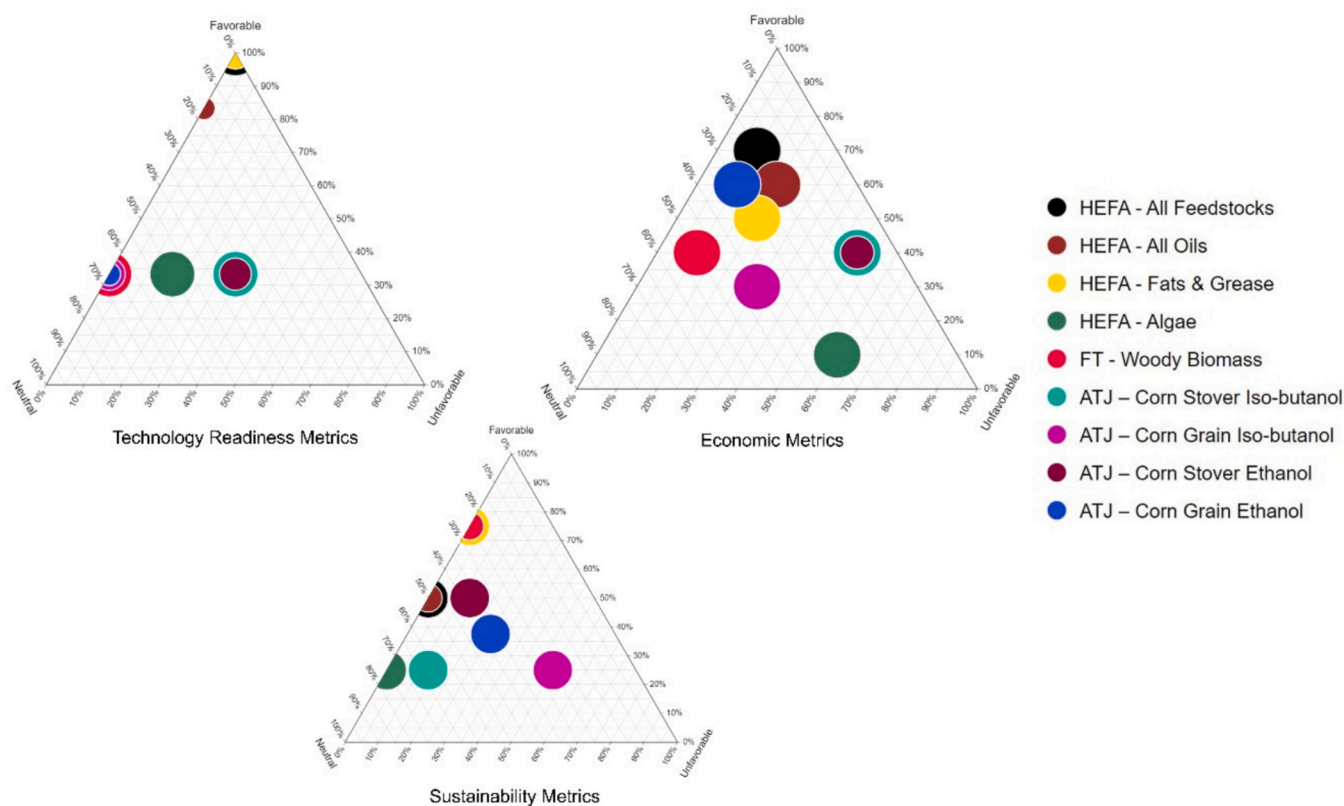


Fig. 6. Comparison of metrics across process scenarios.

environmental sustainability can play a crucial role in promoting the adoption of SAF. These variables can assist stakeholders in recognizing the necessary improvements in SAF production pathways to achieve performance targets. These factors help stakeholders comprehend SAF requirements and potential benefits, enabling them to make informed implementation decisions. This study provides holistic assessments and cross-comparisons of several ASTM approved SAF conversion technologies on major technical, economic, and sustainability metrics, such as yield, economics, availability of feedstock, technology readiness level, fuel production costs, and carbon intensity.

This study demonstrates the strengths and limitations of various SAF production methods, underscoring the importance of additional research and development to enhance their performance and competitiveness compared to fossil-based jet fuels. Of the pathways studied here, the non-algae HEFA process has the highest yield versus other processes and performs best in terms of economics with the lowest MFSP and capital costs per gge of fuel. Note that the corn grain ATJ via ethanol intermediate also has low capital costs. However, the HEFA pathway is challenged particularly by feedstock availability, which can be significantly improved by including algae as a feedstock to increase resource supply for large-scale adoption, in addition to FOG. The substantial availability of agricultural-based feedstock helps ATJ pathways to adopt faster. However, ATJ pathways are generally more challenged in terms of economic metrics compared to HEFA. Lastly, the FT process also holds significant potential by way of enabling the highest reduction in carbon intensity compared to fossil-derived jet fuels.

Most pathways have a carbon intensity lower than conventional jet fuel and have the potential to reduce GHG emissions by more than 50%, except when corn grain is used as the feedstock due to high GHG emissions from land use change. The cost for all the studied pathways ranges from \$3–\$6/gge. However, federal and state biofuel incentives and credits range from \$4–\$6/gge. As a result, investments are slow to be adopted as the biofuel sector is waiting for policy incentives to be implemented to ensure economic viability. To achieve the target of 35

billion gallons of SAF production goal by 2050 set by the SAF Grand Challenge, an estimated capital investment of \$121 to \$324 billion may be required, based on a unit facility size of 100 million gallons of SAF production. Relative to this, the biofuel investment in 2023 was just above \$1 billion, while the total global investment in low-carbon technology was almost \$1.8 trillion [74]. The studied ASTM SAF pathways demonstrate cost competitiveness when aggressive incentives are increased to bridge the price gap with conventional jet fuel. Additionally, the challenge of feedstock availability and sourcing hinders SAF production. This is due to factors such as concentrated feed types in specific locations, inadequate infrastructure for feedstock distribution, and competition with the commodity chemical market for the same feedstock.

This study offers technical, economic, and sustainability metrics that go beyond the traditional cost and emission values. The analysis shows that HEFA with all feedstocks is the most efficient pathway, with most metrics falling into the favorable category. However, HEFA using algae reflects a high number of neutral ratings, indicating further room for improvement in all metrics. The study highlights the importance of considering future feedstock availability for technology adoption and the potential impact of using waste feedstocks in the SAF pathway. Combining key process metrics can speed up SAF adoption and aid decision making. By leveraging advancements in process technology from aviation, biofuel, and agricultural industries, furthering experimental research on conversion technologies, and highlighting the importance of policy incentives, it is possible to work towards an optimal process for economically, technically, and environmentally viable SAF technology.

CRedit authorship contribution statement

Arpit Bhatt: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Ling Tao:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Formal analysis, Conceptualization. **Yimin**

Zhang: Writing – original draft, Methodology, Formal analysis. **Sharon Smolinski:** Writing – original draft, Formal analysis. **Eric Tan:** Writing – original draft, Methodology, Formal analysis. **Bruno Klein:** Writing – original draft, Methodology, Formal analysis. **Matthew Wiatrowski:** Writing – original draft, Methodology, Formal analysis. **David Quiroz:** Writing – original draft, Formal analysis.

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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.apenergy.2026.127894>.

Data availability

Data will be made available on request.

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Glossary

- ATJ: Alcohol-to-Jet
 CO₂: carbon dioxide
 DCO: Distillers corn oil
 FOG: Fats, oil, and grease
 FT: Fischer-Tropsch
 gge: gallon gasoline equivalent
 GHG: Greenhouse gases
 GREENSCOPE: Gauging Reaction Effectiveness for the ENvironmental Sustainability of Chemistries with a Multi-Objective Process Evaluator
 HEFA: Hydroprocessed fatty acids and esters
 IRR: Internal rate of return
 LCA: Life cycle analysis
 LUC: Land use change
 MFSP: Minimum Fuel Selling Price
 MJ: mega joule
 ROI: return on investment
 SAF: Sustainable Aviation Fuels
 TEA: Techno-economic analysis