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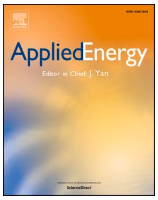

Sustainable aviation fuel from ethanol: Techno-economic analysis and life cycle analysis☆

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HIGHLIGHTS

- Various options for emission reduction in corn-derived SAF pathways are studied.
- Environmental benefits are assessed through standard LCA methods, while TEA analyzes the economic implications.
- The investigated scenarios involve the calculation of marginal abatement costs.
- Strategiesto significantly reduce emissions from SAF production are explored using ETJ pathways.

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ABSTRACT

Sustainable aviation fuel (SAF) is crucial for improving energy security, enhancing domestic production, and reducing carbon emissions in the aviation sector. Among various SAF production technologies, the ethanol-to-jet (ETJ) pathway is a promising option due to its economic viability and technological maturity. This study integrates a techno-economic analysis (TEA) and a life cycle analysis (LCA) to evaluate emissions reduction strategies for SAF production *via* the ETJ pathway, considering use of ethanol derived from both corn grain and corn stover. Conventional corn grain-derived ETJ fuel reduces greenhouse gas (GHG) emissions by 22 % compared to fossil jet fuel, with potential reductions of 26 %–96 % when incorporating renewable energy sources, with a 6 %–32 % increase in the minimum fuel selling price (MFSP). Corn stover-derived ETJ achieves a 77 % GHG reduction but with higher MFSPs compared to corn grain ETJ. Carbon capture and storage (CCS without considering the cost for piping and sequestration, only compression) reduces the emissions of corn grain-derived ETJ by up to 32 gCO_2e/MJ and enables negative emissions for corn stover-derived ETJ, with MFSP increases ranging from 1 % to 22 %. While carbon capture and utilization (CCU) increase ethanol yield by 47 %, it raises MFSPs by 54 % due to high electricity demand. Sustainable farming practices provide only limited carbon intensity (CI) reductions individually but do offer cumulative benefits when combined. These findings highlight the trade-offs between cost and environmental impact, providing insights to optimize SAF production strategies and support aviation sector goals for emissions reduction.

1. Introduction

The International Civil Aviation Organization (ICAO) has pledged to reduce carbon emissions from the aviation sector mainly through requiring the use of sustainable aviation fuels (SAFs) [1–3]. U.S. SAF production capacity has increased from 1.9 million gallons (7.2 million liters) in 2016 to 16 million gallons (60 million liters) in 2022, 26 million gallons (98 million liters) in 2023, and 93 million gallons (352 million liters) had been produced and imported through September 2024; however, these amounts are significantly lower compared to the jet fuel totals consumed by major U.S. airlines [4–6]. Over the past decade, significant research and development (R&D) effort has resulted

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in a large portfolio of feedstock conversion pathways for SAF production, of which eleven are approved by ASTM International to ensure technical performance and safety in aviation operation [7]. These pathways support efforts to meet SAF grand challenges targeting producing 35 billion gallons (132 billion liters) per year in the U.S. by 2050 [4], using domestically available feedstocks while invigorating the bioeconomy.

The ASTM-approved alcohol-to-jet (ATJ) conversion process for aviation includes both ethanol-to-jet (ETJ) and isobutanol-to-jet pathways, and allows for blending up to 50 % ATJ with conventional jet fuel (ASTM D7566) [7,8]. This pathway presents significant potential for contributing to U.S. SAF demand. The current technology readiness level (TRL) of ATJ technology is at level 6 to 7 (approaching commercialization) [9]. Multiple companies have pilot/demonstration plants and offtake agreements with increasing numbers of commercial airlines. LanzaJet pioneered the ETJ technology with its first commercial plant, Freedom Pines Fuels in Georgia, USA. The plant is in the commissioning and startup phase and is expected to produce up to 10 million gallons per year (MGY) of SAF and renewable diesel annually [10]. Another U.S. SAF producer *via* ATJ, Gevo, secured a contract from the Oneworld alliance to supply 200 MGY of SAF to major airports in California over five years starting in 2027 [11]. Recently, Summit Next Gen announced plans for a 250-MGY, ethanol-derived SAF facility in the U.S. Gulf Coast region using Honeywell UOP's ETJ technology, which is expected to become operational in 2025 [12].

Total ethanol production capacity in the U.S. reached 18 billion gallons in 2024, which was produced mainly from corn grain [13]. Ethanol produced from food crops is called first-generation (Gen 1) ethanol. Increased efficiency in corn farming practices and ethanol refining technology has reduced production costs and life cycle greenhouse gas (GHG) emissions (or carbon intensities [CIs]) over time while meeting the growing fuel market demand [14]. Second-generation (Gen 2) ethanol production converts the cellulosic portion of biomass feedstocks (*e.g.*, agricultural residues such as corn stover) into ethanol. Cellulosic fiber in the corn kernel is also considered a form of cellulosic biomass feedstock, and commercial deployment of corn fiber to ethanol technology (called Gen 1.5) is growing at a rapid pace in the U.S. [15].

SAF producers can leverage the established ethanol industry: 187 distributed ethanol production facilities across the U.S. [16]. The current U.S. gasoline blend market accounts for approximately 98 % of total U.S. ethanol production and reached the so-called "blend wall" in 2015, indicating market saturation of E10 (10 % ethanol blend) across the fuel supply [17]. Moreover, it is projected that electrification of the vehicle fleet and the improved engine efficiency of light-duty vehicles will reduce the consumption of both gasoline and its corresponding ethanol component, which will affect the ethanol blending demand in the on-road transportation sector accordingly [18]. Based on the total U.S. corn ethanol nameplate capacity, 2.2–3.5 billion gallons of surplus ethanol capacity is projected in 2030 [19]. Diverting the surplus ethanol production capacity to SAF production will provide a near-term opportunity for the aviation industry to support SAF demand.

Gen 1 ethanol presents moderate to low GHG reduction potential compared to other SAF production pathways, given its farming-related emissions, induced land use change (ILUC) emissions, and ethanol production emissions [20,21]. However, a study showed that the CI of corn ethanol (withouth ILUC) in the U.S. has been reduced from 58 gCO_2e/MJ in 2005 to 45 gCO_2e/MJ in 2019 due to increased corn grain and ethanol yield with reduced fertilizer use and energy consumption [14]. Further emissions reduction technologies can be applied to lower carbon emissions associated with corn ethanol and SAF pathways [22].

Various emissions reduction strategies can make Gen 1 ethanol low-carbon SAF production. Fig. 1 illustrates the major life cycle stages of the corn ethanol supply chain and the carbon emissions reduction technologies studied. Corn farming accounts for the largest share (50 %) of total emissions, followed by emissions from ethanol plants (45 %) [23]. Reducing emissions from these two life cycle stages would significantly lower the CIs of both corn grain ethanol and SAF. Adopting specific farming practices such as reduced/no tillage, application of livestock manure, and growing cover crops during fallow seasons could significantly reduce the life cycle GHG emissions of corn- or corn stover-

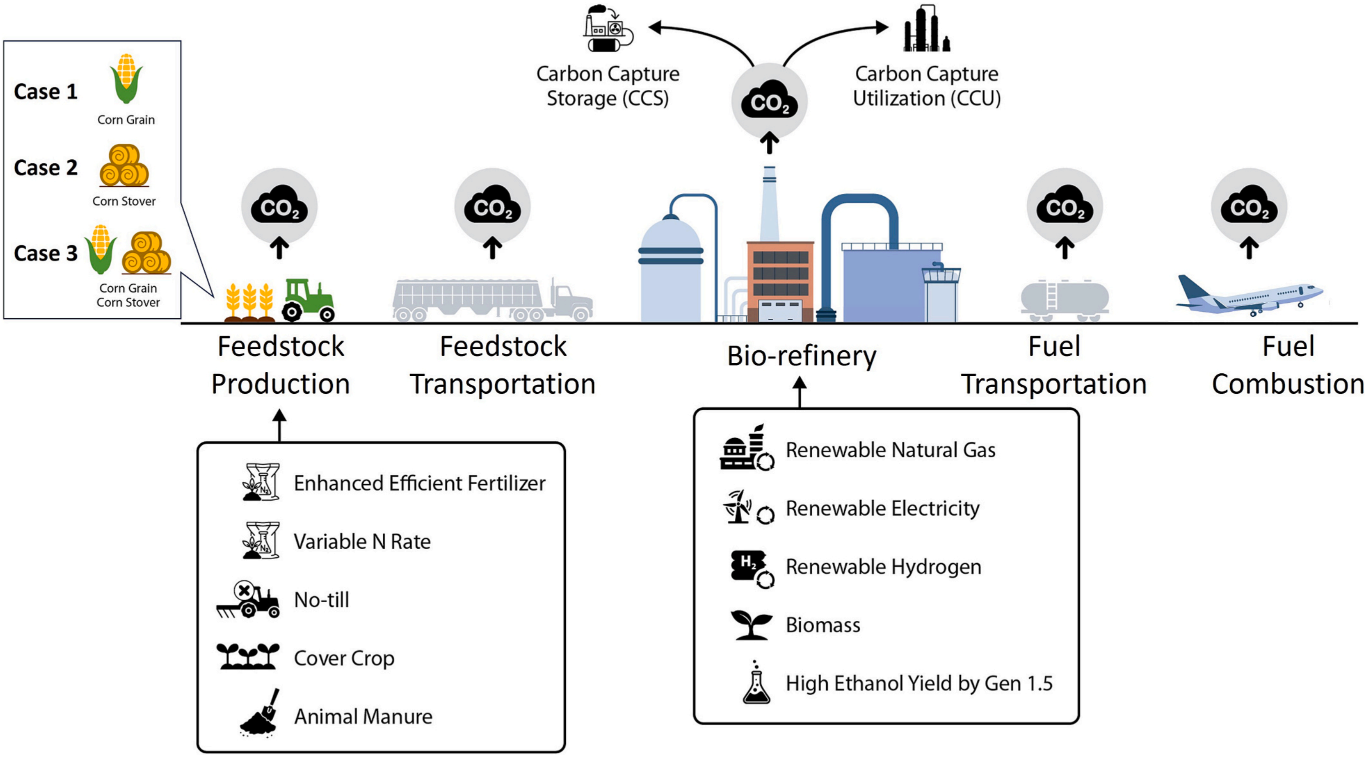

Fig. 1. Major emissions sources in the corn ethanol supply chain and emissions reduction technologies.

derived ethanol [24]. In addition, as emissions in the ethanol refining stages are generated mainly from process fuel combustion and CO_2 from fermentation, replacing process energy with low-carbon energy sources and integrating carbon capture and storage (CCS) or carbon capture and utilization (CCU) technologies into existing facilities will significantly reduce emissions.

Adopting emissions reduction technologies tends to reduce CIs at the expense of increased fuel production costs. To fully understand the potential trade-off between emissions reduction and increased cost for SAF production *via* ETJ, we conducted a techno-economic analysis (TEA) and a life cycle analysis (LCA) of Gen 1, Gen 2, and Gen 1.5 ethanol-derived SAFs with various options. Although studies have presented the environmental impacts of ethanol production, no studies have comprehensively evaluated the economic and environmental impacts of all Gen 1, Gen 2, and Gen 1.5 ETJ pathways. This study uniquely integrates various ethanol feedstock approaches and comprehensive strategies within consistent frameworks, enabling direct comparison of technology options and optimal SAF production solutions. CCS, CCU, renewable energy integration, and sustainable farming practices are strategies implemented with consistent methodological frameworks and datasets.

Understanding both the TEA and LCA implications will help ongoing R&D efforts to advance ETJ technologies and accelerate the commercialization and scale-up of SAF production. Key factors influencing the balance of economic development and environmental protection in transportation and infrastructure planning are identified by this research through a comparison of ETJ project strategies. This comparative analysis informs future research and policy on sustainable, equitable transportation and infrastructure planning.

2. Methodology

2.1. Baseline ETJ Pathways

Three cases were evaluated (as illustrated in Fig. 1): Case 1 is a corn ethanol (Gen 1) process integrated with the ETJ upgrading unit. Case 2 assumes corn stover conversion to ethanol (Gen 2), followed by ETJ upgrading. Case 3 presents an integrated Gen 1 and Gen 2 biorefinery where both corn grain and stover harvested from the same cornfield are converted into ethanol in an integrated facility. The ethanol is then upgraded to SAF, along with other hydrocarbon fuels.

In the Gen 1 ETJ baseline case (Case 1), only corn grain is harvested, while corn stover is left in the field. Dry milling with corn oil extraction for corn ethanol production was selected as the baseline technology because more than 90 % of U.S. ethanol refineries are dry mill plants, and most (>95 %) extract corn oil [19]. Fossil natural gas (NG) and the U.S. electric grid mix are used to meet process heat and electricity demand, respectively. Hydrogen (H_2) used for ETJ upgrading is from steam methane reforming (SMR) of fossil NG. The ETJ upgrading unit is assumed to be co-located and integrated with the Gen 1 ethanol production facility.

For the Gen 2 ETJ baseline case (Case 2), 30 % of the available corn stover is harvested, which is considered a sustainable removal rate that does not significantly degrade soil organic carbon (SOC) [25]. Corn stover is then pretreated, hydrolyzed, and fermented to produce ethanol. Residue from the fermentation process (*i.e.*, lignin) is dewatered, dried, and combusted in a combined heat and power (CHP) unit to generate heat and electricity that support both the corn stover-to-ethanol and ethanol-to-fuel processes. Light hydrocarbons (C1–C3) produced by the ethanol upgrading process are burned in the CHP unit along with lignin to avoid energy loss. For Case 2, the ethanol facility can meet its total energy demand with the CHP unit's combustion of residual lignin, biogas from onsite anaerobic digestion of tillage, and light hydrocarbons from the ethanol upgrading unit. Therefore, this conversion process emits only biogenic carbon emissions. Moreover, excess electricity generated from the CHP unit can be considered a coproduct, generating emissions credits by displacing grid electricity.

In the integrated Gen 1 and Gen 2 ETJ baseline case (Case 3), the corn grain and stover would be harvested from the same cornfield. The collection ratio for corn stover is assumed to be 30 %. As in Case 2, a CHP unit using biomass residues from corn stover ethanol production is used to provide heat and electricity. The integrated Gen 1 and Gen 2 facility assumes co-locating a 100 MGY Gen 1 ethanol and a Gen 2 facility with a baseline stover capacity of 594 dry tons/day followed by the ETJ process. Detailed process descriptions of each baseline pathway are provided in the supplementary information (SI, section S1).

2.2. Technology options

To reduce the CI of the baseline ETJ pathway, multiple technology options were considered. Table 1 describes the low-carbon scenarios evaluated, which include switching fossil-based process energy to renewable sources, adding CCS or CCU, and bolting on corn kernel fiber conversion (Gen 1.5).

The technologies evaluated in this study were selected based on their TRLs, relevance to ongoing research, and potential for near- to medium-term deployment in ETJ fuel production systems. We focused on strategies that have either been demonstrated at commercial scale (*e.g.*, CCS and corn kernel fiber conversion) or are at advanced development stages with growing interest from industry and academia (*e.g.*, renewable hydrogen integration and CCU). This selection aims to reflect realistic implementation pathways and provide actionable insights for scaling SAF production through ETJ technologies.

Combustion of NG as process energy accounted for the major GHG emissions (79 %) in ethanol production [23]. Replacing NG with renewable natural gas (RNG) or biomass can reduce this emissions burden. Replacing grid electricity with renewable electricity and replacing NG SMR H_2 with renewable H_2 could reduce the emissions, as well.

CCS is a mature technology deployed at several dry mills in the U.S. [26–28]. In this study, we assume that the CO_2 transportation pipelines are constructed and operated by other entities, incurring no additional capital costs for the ETJ facility. Thus, only expenses for CO_2 purification and compression to meet pipeline quality are included in the cost of fuel produced in biorefineries. For CCS, two options are considered in this study: (1) capturing high-purity fermentation CO_2 only and (2) capturing both fermentation CO_2 and low-purity CHP flue gas (applicable for Cases 2 and 3).

CCU technologies for converting CO_2 into ethanol are available at various TRLs. These include hydrogenation of CO_2 and electrochemical reduction of CO_2 [29,30]. Gas fermentation is one of the near-commercial CCU technologies patented by LanzaTech [31]. Huang et al. [32] showed the significant emissions reduction potential of this technology in converting an ethanol refinery's CO_2 into ethanol, although the economic viability is still contingent upon significant technological advancements.

Corn kernel fiber ethanol technologies have matured and been deployed in the U.S. The fiber content of corn kernels is about 10–12 wt %, so it is a valuable source of cellulosic sugar that typically ends up in the co-produced distiller's dried grains with solubles (DDGS) in conventional dry mills [33]. Due to the corn kernel fiber's lower lignin content, its pretreatments require milder process conditions than other high-lignin cellulosic feedstocks. Depending on the conversion technologies, 3 %–10 % increases in ethanol yield from dry mills have been reported *via* corn fiber fermentation compared to Gen 1 [34]. Multiple companies have patented Gen 1.5 technologies based on *in-situ* or *ex-situ* technology [35,36]. *In-situ* technology uses additional cellulase enzymes mixed in the fermenter to biologically convert the cellulosic portion of the corn fiber into ethanol along with starch. Dupont and Novozymes [37] produce novel enzymes specifically for the fiber conversion. However, ethanol yield is higher for the technologies that use a separate (*ex-situ*) fiber-to-ethanol conversion train [38]. These two cases are intended to increase ethanol yield from the same corn grain inputs.

Table 1
ETJ Cases with Various Technology Options.

Cases		Description
Case 1	Case 1.0	**Base case**: Gen 1 ETJ with fossil NG and grid electricity
	Case 1.1.1	Switching process fuel from NG to **dairy manure-derived RNG**
	Case 1.1.2	Switching process fuel from NG to **forest residue**
	Case 1.2	Replacing grid electricity with **renewable electricity**
	Case 1.3	Replacing fossil NG-derived H_2 using **renewable H_2**
	Case 1.4	Adding **CCS** for CO_2 from fermentation
	Case 1.5	Converting captured fermentation CO_2 into ethanol (**CCU**) **using renewable electricity**
	Case 1.6.1	Adding ***in situ* Gen 1.5**
	Case 1.6.2	Adding ***ex situ* Gen 1.5**
	Case 1.7.1	Practicing **conservation tillage (no-till)**
	Case 1.7.2	Using **variable nitrogen fertilizer application rate**
	Case 1.7.3	Applying **enhanced-efficiency fertilizer**
	Case 1.7.4	Growing winter **cover crops**
	Case 1.7.5	Applying **livestock manure**
Case 2	Case 2.0	**Base case**: Gen 2 ETJ with fossil NG and grid electricity
	Case 2.1.1	Adding **CCS for CO_2 from fermentation**
	Case 2.1.2	Adding **CCS for CO_2 from fermentation and CHP flue gas**
	Case 2.2	Replacing fossil NG-derived H_2 with **renewable H_2**
	Case 2.3	Converting captured fermentation CO_2 into ethanol (**CCU**) **using renewable electricity**
	Case 2.4.1	Growing winter **cover crops**
	Case 2.4.2	Applying **livestock manure**
Case 3	Case 3.0	**Base case**: Integrated Gen 1, Gen 2, and ETJ with fossil NG and grid electricity
	Case 3.1.1	Switching process fuel from NG to **forest residue**
	Case 3.1.2	Switching process fuel from NG to **dairy manure-derived RNG**
	Case 3.2.1	Using **grid electricity** for electricity deficit rather than NG CHP
	Case 3.2.2	Using **wind electricity** for electricity deficit rather than NG CHP
	Case 3.3	Replacing fossil NG-derived H_2 with **renewable H_2**
	Case 3.4.1	Adding **CCS for fermentation CO_2**
	Case 3.4.2	Adding **CCS for CO_2 from fermentation and CHP flue gas**
	Case 3.5	Converting captured fermentation CO_2 into ethanol (**CCU**) **using renewable electricity**
	Case 3.6.1	Adding ***in situ* Gen 1.5**
	Case 3.6.2	Adding ***ex situ* Gen 1.5**
	Case 3.7.1	Practicing **conservation tillage (no-till)**
	Case 3.7.2	Using **variable nitrogen fertilizer application rate**
	Case 3.7.3	Applying **enhanced-efficiency nitrogen fertilizer**
	Case 3.7.4	Growing winter **cover crops**
	Case 3.7.5	Applying **livestock manure**

Detailed process descriptions for both *in-situ* and *ex-situ* Gen 1.5 technologies are documented in the supplementary information (S2).

We also considered various current and emerging technologies that can support more sustainable farming practices. The list includes conservation tillage, variable nitrogen (N) fertilizer application rates, enhanced-efficiency nitrogen fertilizer use, crop rotations that include off-season and fallow season cover crops, and animal manure application.

Conservation tillage (no-till) is used for minimal or no soil disturbance, often in combination with residue retention, crop rotation, and use of cover crops. It lowers on-farm fuel consumption and enhances soil carbon sequestration. On the other hand, it might cause increased fertilizer and pesticide use to maintain crop yields.

Applying variable nitrogen fertilizer application rates is a management strategy that divides the fields into subsections and determines the right fertilizer application rates based on soil test results. It may reduce direct and indirect on-field N_2O emissions while lowering on-farm fuel consumption. Enhanced-efficiency fertilizer aims to slow the release of nutrients for crop uptake or alter the conversion of nutrients to other forms that may be less susceptible to losses. As a result, it is effective in reducing fertilizer-induced N_2O emissions.

Crop rotation with winter cover crops is implemented to reduce nutrient leaching to surface/subsurface waters, improve SOC stock, and provide agronomic benefits to subsequent cash crops. Finally, livestock manure applied to soils can provide nutrients that substitute for synthetic fertilizers and help sequester carbon in the field. However, transporting manure from animal feeding operations to farms for land application results in additional fuel use and associated environmental impacts.

2.3. *Life cycle analysis*

For environmental metrics, the life cycle GHG emissions (or CI) of ethanol-derived SAF pathways are compared with the reference petroleum jet fuel production pathway with a CI of 89 gCO_2e/MJ [20]. The system boundary of ETJ pathways includes the entire supply chain of SAF production, including feedstock production (*e.g.*, corn farming including ILUC), feedstock transportation, ethanol production, the ETJ process, fuel transportation and distribution, and fuel combustion.

We implemented the pathways into the Research and Development (R&D) Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) 2024 model developed by Argonne National Laboratory to analyze the CI of each SAF case [39]. GREET is an LCA model that includes major fuel production pathways, enabling a comprehensive analysis. Life cycle inventories and major assumptions for corn farming, ethanol production, and ETJ upgrading are presented in the supplementary information (S4). Because we assume the ethanol and SAF production to be co-located, ethanol transportation is excluded.

For Gen 2, emissions burdens from energy/chemicals used in corn farming and ILUC are allocated only to corn grain, not corn stover, given that corn stover is considered a by-product of corn farming. Instead, the GHG emissions associated with the supplemental fertilizer needed to compensate for the nutrients removed with the corn stover are accounted for (*i.e.*, 4.3 gCO_2e/MJ).

Biogenic CO_2 emissions are assumed to be carbon neutral, as the carbon released during combustion originates from atmospheric CO_2 absorbed during biomass growth. ILUC GHG emissions for corn ethanol-derived SAF were estimated at 9.0 gCO_2e/MJ based on the R&D GREET 2024 default value [39], while we also present the ILUC of 25.1 gCO_2e/MJ estimated by ICAO to illustrate the impact of different ILUC assumptions [20].

2.4. *Techno-economic analysis*

For the TEA, the minimum fuel selling price (MFSP) was calculated using the discounted cash flow rate of return method. MFSP is the fuel selling price required to achieve a net present value of zero at a specific internal rate of return after taxes. The process models provide rigorous material and energy balance calculations for equipment sizing, capital cost estimation, and operating cost calculations.

Capital costs are estimated using the detailed vendor quotations from the 2011 design report by the National Renewable Energy Laboratory (NREL) [40] and the U.S. Department of Agriculture's (USDA's) corn dry mill model [41]. Total capital investment is calculated using established direct and indirect overhead cost factors (*e.g.*, installation, contingency). Energy and material costs are obtained from various market data, published literature, and government reports. A detailed description of the operating cost assumptions is provided in the supplementary information (S3 and Tables S3–S4).

All costs are adjusted to 2023 U.S. dollars using the *Chemical Engineering* Plant Cost Index, the Industrial Inorganic Chemical Index from SRI Consulting [42], and the labor indices provided by the U.S. Department of Labor Bureau of Labor Statistics [43]. The financial assumptions used in this study are based on nth plant economics (*i.e.*, the technology is mature, and similar technology is being operated at a sufficient number of plants), as presented in the supplementary information (S3 and Table S2). The assumed lifetime of the facility is 30 years, with 3 years of construction and a 6-month startup period. We assumed 40 % equity financing with a 10 % internal rate of return.

The process modeling of ethanol and SAF production was carried out in Aspen Plus software, which features rigorous thermodynamic calculations for conventional and nonconventional chemical plant unit operations. The modified process model of a corn grain dry mill developed by USDA is used as the front-end process [41]. The scale of the original model is expanded from 40 MGY to 100 MGY to reflect the capacity of recent dry mills in the U.S. [13]. We have updated the ethanol yield (from 2.83 to 2.86 gal/bushel) and energy requirements of various process units based on a recent industrial survey [14,39].

The biochemical cellulosic ethanol model from NREL [40] is used for the front-end process of the Gen 2 model. The ETJ upgrading model is adapted from a previous NREL study in which the SAF upgrading unit was developed by Oak Ridge National Laboratory [44,45]. The integrated facility leverages Gen 1 and Gen 2 models connected to a single SAF upgrading unit and a shared CHP unit. The integrated facility requires an additional energy supply for the CHP unit, which is calculated in the model. Process simulation models are further detailed in the supplementary information (S2). Note that only the compressor cost is added to the capital costs for the CCS case. Pipeline construction and other auxiliary equipment costs are not considered in this study.

2.5. Marginal Abatement Costs

Marginal abatement costs (MACs) represent the cost of mitigating one tonne of GHG emissions using various technology options. It is a useful metric that shows the economic and emissions trade-offs for adopting the various technologies. The MAC is defined as the difference in fuel price divided by the emissions reduction:

$$\text{Marginal abatement cost} = (\text{MFSP}_{\text{SAF}} - \text{fossil jet fuel price}) / (\text{CI}_{\text{fossil jet}} - \text{CI}_{\text{SAF}})$$

In this study, the reference fossil jet fuel price is set at \$2.5/GGE (Gasoline gallon equivalent), and the fossil jet CI ($\text{CI}_{\text{fossil jet}}$) is set at 89 $\text{gCO}_2\text{e/MJ}$. The MACs are calculated with the MFSP and CI values of each SAF case (MFSP_{SAF} and CI_{SAF}, respectively).

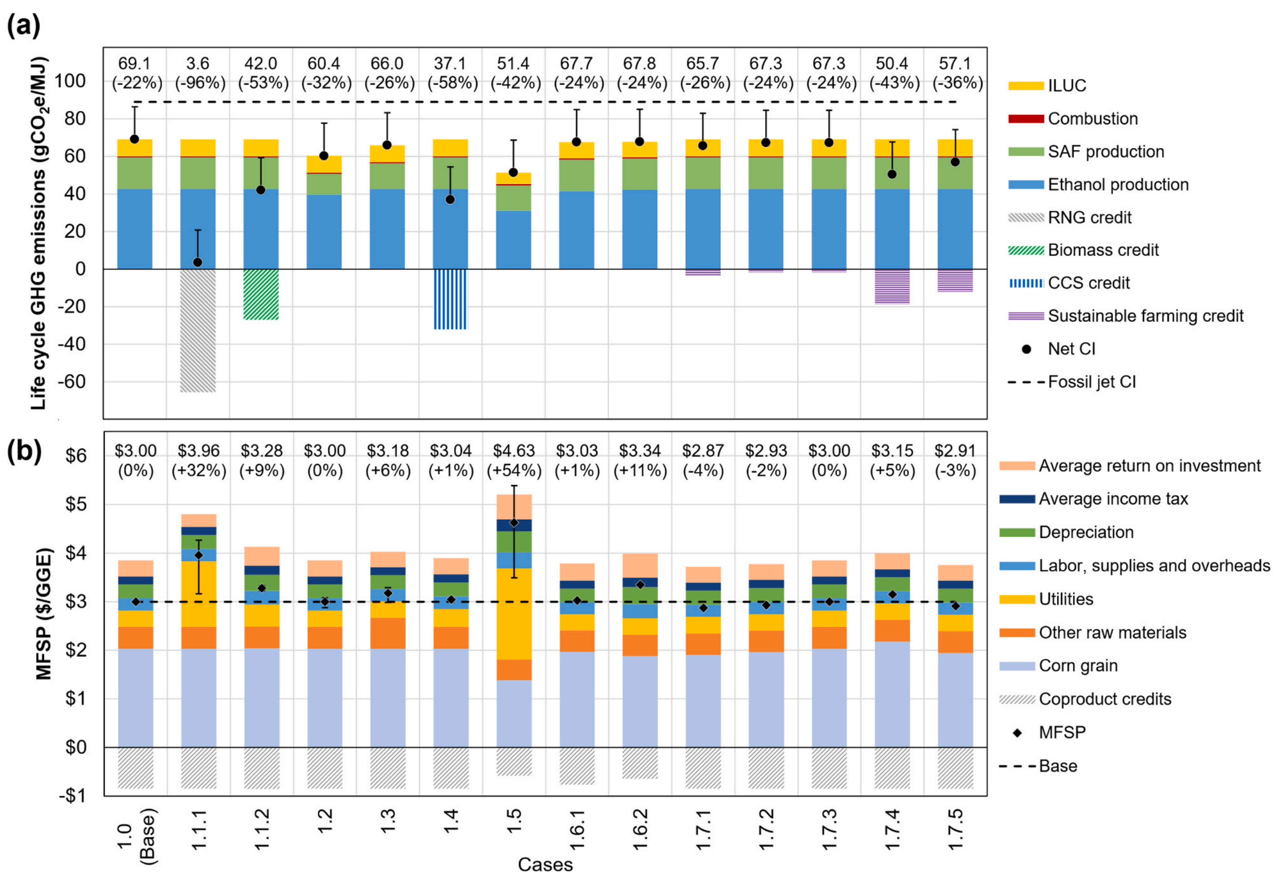

Fig. 2. (a) GHG emissions for the Gen 1 ETJ pathways. (b) Cost contributions to MFSP for Gen 1 low-carbon scenarios. Case 1.0: Gen 1 baseline; 1.1.1: Switching process fuel from NG to dairy manure derived RNG; 1.1.2: Switching process fuel from NG to biomass (forest residue); 1.2: Renewable electricity; 1.3: Renewable H_2; 1.4: CCS; 1.5: CCU for ethanol production with renewable electricity; 1.6.1: Adding *in situ* Gen 1.5; 1.6.2: Adding *ex situ* Gen 1.5; 1.7.1: Conservation tillage; 1.7.2: Variable N rate; 1.7.3: Enhanced-efficiency fertilizer; 1.7.4: Cover crops application; 1.7.5: Manure application. The error bars represent the cases' net CIs using a CORSIA ILUC value of 25.1 $\text{gCO}_2\text{e/MJ}$.

3. Results and discussion

Case 1. Gen 1 ETJ.

The life cycle GHG emissions of the Gen 1 ETJ pathways are presented in Fig. 2(a). The baseline SAF from Gen 1 corn grain ETJ has total emissions of 69.1 gCO_2e/MJ, where 51.7 gCO_2e/MJ are from ethanol production (including corn farming, ILUC, and ethanol fermentation). ETJ upgrading accounts for 16.7 gCO_2e/MJ. The Gen 1 ETJ shows 22 % lower GHG emissions than the fossil jet reference (89 gCO_2e/MJ).

The evaluated technologies show 24 %–96 % lower GHGs than the CI for petroleum jets. For example, when process fossil NG used in the baseline is replaced by dairy manure-derived RNG (Case 1.1.1) or biomass (Case 1.1.2), GHG emissions are estimated at 3.6 and 42.0 gCO_2e/MJ, respectively; emissions reductions relative to the fossil jet reference are 96 % and 53 %, respectively. The major GHG emissions reduction using biomass is led by carbon-neutral biogenic CO_2 emissions. In addition to the biogenic CO_2 benefits, use of dairy manure-derived RNG provides emissions credits that would have otherwise been emitted by diverting manure from business-as-usual waste management practices generating significant fugitive methane emissions.

Replacing grid electricity with renewable electricity (Case 1.2) in both ethanol and ethanol-to-fuel production provides a 8.8 gCO_2e/MJ reduction compared to the baseline case, which contributes to a 32 % GHG reduction relative to the fossil jet. Using renewable H_2 (Case 1.3) instead of fossil NG-derived H_2 provides a 3.1 gCO_2e/MJ GHG reduction from the baseline, which contributes to about 26 % of GHG emissions reduction from the fossil jet reference.

CCS (Case 1.4) achieves a considerable emission reduction by sequestering CO_2 captured from Gen 1 ethanol fermentation. The GHG emissions are 32 gCO_2e/MJ lower than the baseline, equivalent to a 58 % reduction compared to the fossil jet fuel reference. For the renewable electricity-driven CCU option (Case 1.5), the GHG emissions reduction from the baseline is 18 gCO_2e/MJ, which represents the combined CI for ethanol from both corn and CO_2. While emissions reduction benefits per MJ of hydrocarbon fuels are lower with CCU than with CCS, note that CCU generates additional ethanol production from CO_2: 0.47 MJ for 1 MJ of corn grain ethanol production.

Gen 1.5 processes integrated into a Gen 1 facility contribute 1.5 and 1.3 gCO_2e/MJ reductions from the baseline for *in-situ* (Case 1.6.1) and *ex-situ* (Case 1.6.2) technologies, respectively. The corresponding reductions compared to the fossil jet fuel reference are about 24 % for both cases.

Adoption of sustainable farming practices contributes to GHG emissions reduction in feedstock production. Variable N rate (Case 1.7.2) and enhanced-efficiency fertilizer (Case 1.7.3) contribute 1.8 gCO_2e/MJ reductions for both cases, mainly due to lower N_2O emissions from the soil. Conservation tillage (Case 1.7.1), cover crops (Case 1.7.4), and manure application (Case 1.7.5) contribute 3.4, 18.7, and 12.1 gCO_2e/MJ reductions, respectively, mainly due to their ability to boost SOC in the soil, which provides a carbon sequestration credit. Note that the impact of multiple sustainable farming practices may be stacked. If all impacts from the sustainable farming practices are aggregated, emissions reductions are estimated at 38 gCO_2e/MJ.

Fig. 2(b) compares the cost contributions to MFSP for Case 1, which is broken down into feedstock costs, fixed costs (labor, supplies, and overhead), variable costs (utilities and other raw materials), coproduct credits, capital depreciation, income tax, and average return on investment.

The estimated MFSP for the base case (Case 1.0) is $3.00 per GGE. Replacing NG with RNG (Case 1.1.1) increases the MFSP by 32 % due to the higher purchase prices of livestock manure-derived RNG. The price assumptions for the RNG are given in the Supplementary Information (Table S4), where the RNG price is more than 7 times the NG price. Note that RNG price can vary significantly based on the source and the plant's geographic location. We have considered the complete replacement of NG with RNG; however, RNG might have resource limitations regionally. Replacing NG with biomass (Case 1.1.2) increases the MFSP by 9 %.

Using renewable electricity for the entire facility (Case 1.2) results in $2.88–$3.08/GGE depending on renewable electricity prices, as shown in Fig. 2(b). The base renewable electricity price is assumed to be equal to grid electricity ($0.07/kWh) with a range of $0.02 to $0.10/kWh. In the regulated U.S. electricity market, electricity price is typically a fixed number, regardless of the electricity source [46]. In 2023, renewable electricity accounted for 23 % of total electricity production in the U.S. [47]. Therefore, the availability of renewable electricity for a specific location needs to be considered and would require further investigation.

Using renewable H_2 for the ethanol-to-fuel unit (Case 1.3) produces a 6 % increase in the MFSP if the H_2 price is $4.5/kg. Prices of renewable H_2 can vary from $1/kg to $6.25/kg based on the U.S. Department of Energy's (DOE's) Hydrogen Analysis (H2A) proton exchange membrane (PEM) electrolysis model [48]. As a result, the MFSP varies from $2.99 to $3.29.

The addition of a CCS unit (Case 1.4) increases the MFSP by 1 %. The increase in MFSP comes primarily from the additional energy costs for CO_2 capture and compression. The costs of transporting and injecting CO_2 into deep storage sites are not considered, as we assume these are outside of biorefinery fences.

Converting CO_2 into ethanol *via* the CCU unit (Case 1.5) shows a 54 % increase in MFSP. The CO_2-to-ethanol conversion process requires significant energy for the H_2 and CO electrolysis process. The variable operating costs increase by 58 % from the base case (Case 1.0). This significant increase in MFSP occurs because the additional ethanol output could not offset the operating and capital costs for the CCU unit. As a result, MFSP varies from $3.49 to $5.38/GGE, depending on the variations in electricity prices.

In-situ Gen 1.5 (Case 1.6.1) increases the MFSP slightly, while the MFSP for *ex-situ* Gen 1.5 (Case 1.6.2) is 11 % higher than the base case, mainly because of the higher capital expense for *ex-situ* conversion of corn fiber to ethanol. Ethanol yield improvement in *ex-situ* conversion cannot offset the capital expense.

Employing various sustainable farming practices (Cases 1.7.1–1.7.5) might affect the corn production cost, resulting in feedstock price variations. Conservation tillage (Case 1.7.1) could reduce the corn price by 6.4 %, reducing the MFSP by 4 %. Application of variable N rate fertilization techniques (Case 1.7.2) reduces the MFSP up to 2 %. Enhanced-efficiency fertilizer (Case 1.7.3) has an insignificant impact on the corn price; hence, the MFSP is almost identical to the base case. Crop rotation with winter cover crops (Case 1.7.4) increases corn production cost by 7 %, leading to a 5 % increase in the MFSP. Using animal manure as a fertilizer replacement (Case 1.7.5) might decrease the MFSP by 3 %.

Case 2. Gen 2 ETJ

The GHG emissions of Gen 2 ETJ pathways are presented in Fig. 3(a). The baseline case (Case 2.0) has total life cycle GHG emissions of 20.2 gCO_2e/MJ fuel, which is about 77 % lower than the fossil jet reference case (89 gCO_2e/MJ). Low-carbon options can provide further emissions reductions to decrease the CIs, ranging from −111.1 to 17.1 gCO_2e/MJ and representing a 225 % to 81 % reduction, respectively, from the fossil reference case.

Unlike the Gen 1 case, where only fermentation CO_2 can be captured, CCS options for Gen 2 (Cases 2.1.1 and 2.1.2) provide 32 and 131 gCO_2e/MJ carbon credits for capturing CO_2 from fermentation only and from both fermentation and the CHP unit, respectively. Consequently, adopting CCS options can significantly reduce the total GHG emissions for the Gen 2 ETJ pathway, achieving net-negative emissions. Using renewable H_2 for SAF upgrading (Case 2.2) leads to a 3.1 gCO_2e/MJ reduction and contributes to a total reduction of 81 % compared to the fossil reference. For the CCU option (Case 2.3), the ethanol stream produced from captured CO_2 is combined with Gen 2 ethanol for SAF upgrading. Renewable electricity is used in the CCU plant, and renewable H_2 is used for SAF upgrading. Because the CCU case utilizes

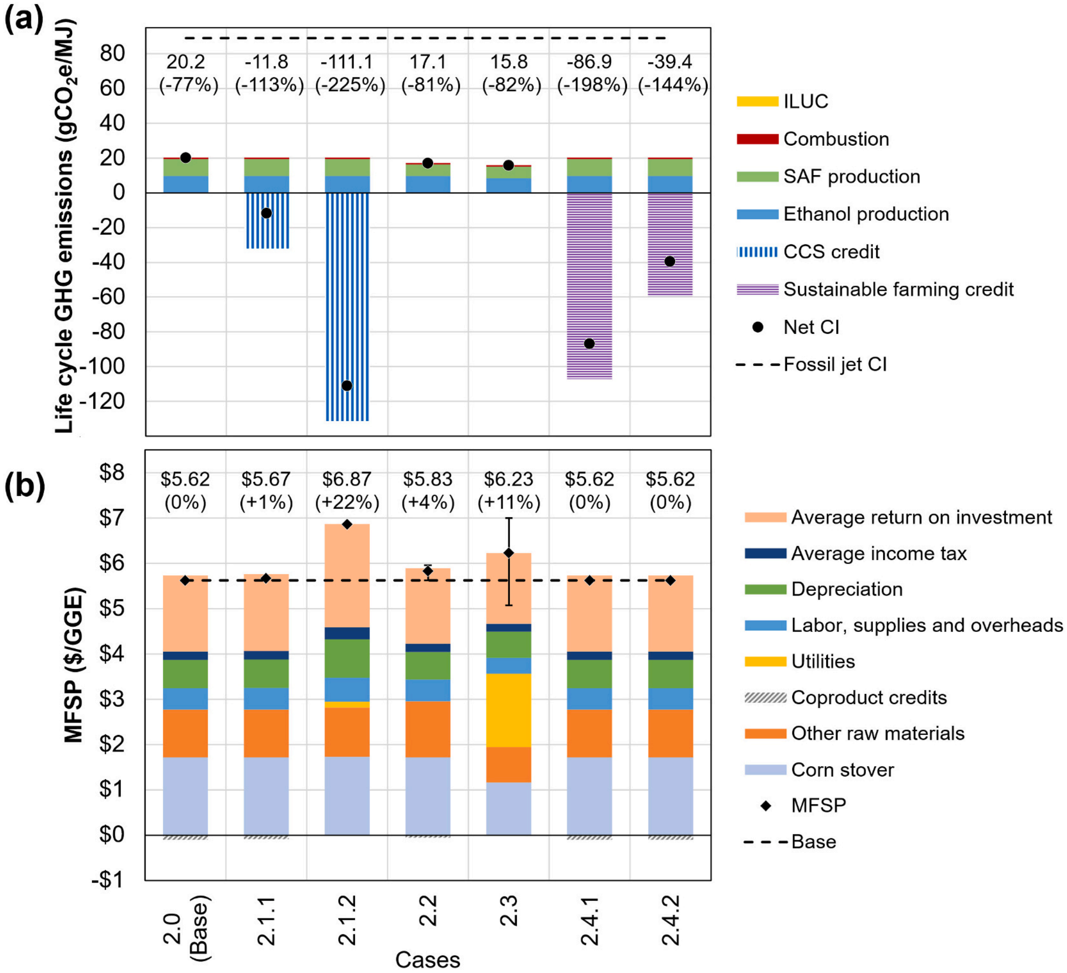

Fig. 3. (a) GHG emissions for the Gen 2 ETJ baseline scenario and low-carbon options. (b) Cost contributions to MFSP for Gen 1 low-carbon scenarios. Case 2.0: Gen 2 ETJ baseline; 2.1.1: CCS using fermentation CO_2; 2.1.2: CCS using both fermentation and CHP CO_2; 2.2: renewable H_2 for SAF upgrading; 2.3: CCU with fermentation CO_2 for SAF production; 2.4.1: sustainable farming practices with cover crops application; 2.4.2: sustainable farming practices with manure application.

renewable electricity (0 gCO_2e/kWh), it does not increase total GHG emissions compared to the baseline, leading to reduced GHG emissions per MJ of SAF production due to additional 47 % ethanol compared to the base case.

Cover crops (Case 2.4.1) and manure application (Case 2.4.2) contribute 107 and 60 gCO_2e/MJ reductions, respectively, mainly due to their ability to boost SOC in the soil, which provides a carbon sequestration credit. We also assumed that all SOC credits are allocated to corn stover ethanol. However, discussions are still underway about how to allocate the benefits of an SOC increase between corn stover and corn grain; depending on the allocation method(s) selected, the CIs resulting from these farming practices may be significantly changed.

Fig. 3(b) compares the cost contributions to MFSP for all scenarios. The MFSP for the base case (Case 2.0) is estimated as $5.62/GGE.

The CCS of only fermentation CO_2 (Case 2.1.1) increases the MFSP by 1 %, while the CCS of CHP flue gas in addition to fermentation CO_2 (Case 2.1.2) increases the MFSP by 22 % over the base case. This is because the CCS of CHP flue gas has higher capital and operating costs as it uses an amine scrubbing unit for CO_2 purification.

Higher prices for renewable hydrogen (Case 2.2) increase the MFSP by 4 % compared to fossil-based hydrogen; however, the MFSP can range between $5.63 and $5.96/GGE based on low and high hydrogen cost assumptions.

Retrofitting a CCU unit to the plant (Case 2.3) produces an 11 % increase in MFSP, a result of the high electricity requirements for the H_2 and CO electrolysis process. Additional capital costs for the CCU are mostly offset by additional ethanol production. The MFSP can vary between $5.07/GGE and $7.00/GGE based on variations in renewable electricity prices ($0.02–$0.10/kWh). Therefore, both the MFSP and CI might become lower than the base case if all electricity were to be replaced by renewable electricity at $0.02/kWh.

Deploying sustainable farming practices (Cases 2.4.1 and 2.4.2) has no cost implications, as the farming practices do not affect the economics of corn stover, as illustrated in Fig. 3(b).

Case 3. Integrated Gen 1/Gen 2 ETJ.

Fig. 4(a) presents the GHG emissions results of Case 3, the integrated Gen 1 and Gen 2 ETJ pathways. The Case 3 baseline has a CI of 62.1 gCO_2e/MJ, which is 30 % lower than the fossil jet case's CI and 10 % lower than the Case 1 baseline. Note that all results are presented for combined ethanol production from Gen 1 and Gen 2.

Using biomass to replace fossil NG (Case 3.1.1) provides a 19.9 gCO_2e/MJ emissions reduction compared to the baseline (and a 52 % reduction compared to the fossil jet) due to the biogenic CO_2 emissions credit. RNG (Case 3.1.2) provides biogenic CO_2 credits and avoided emissions credits by diverting manure from business-as-usual dairy manure treatment to RNG production. The total emissions credit using RNG is estimated at −57.4 gCO_2e/MJ, which reduces the CI of this case to 4.7 gCO_2e/MJ.

The use of imported renewable electricity (Case 3.2.2) to reduce external NG inputs to the CHP unit decreases the GHG emissions by 3.0 gCO_2e/MJ. Using grid electricity (Case 3.2.1) does not help reduce GHG

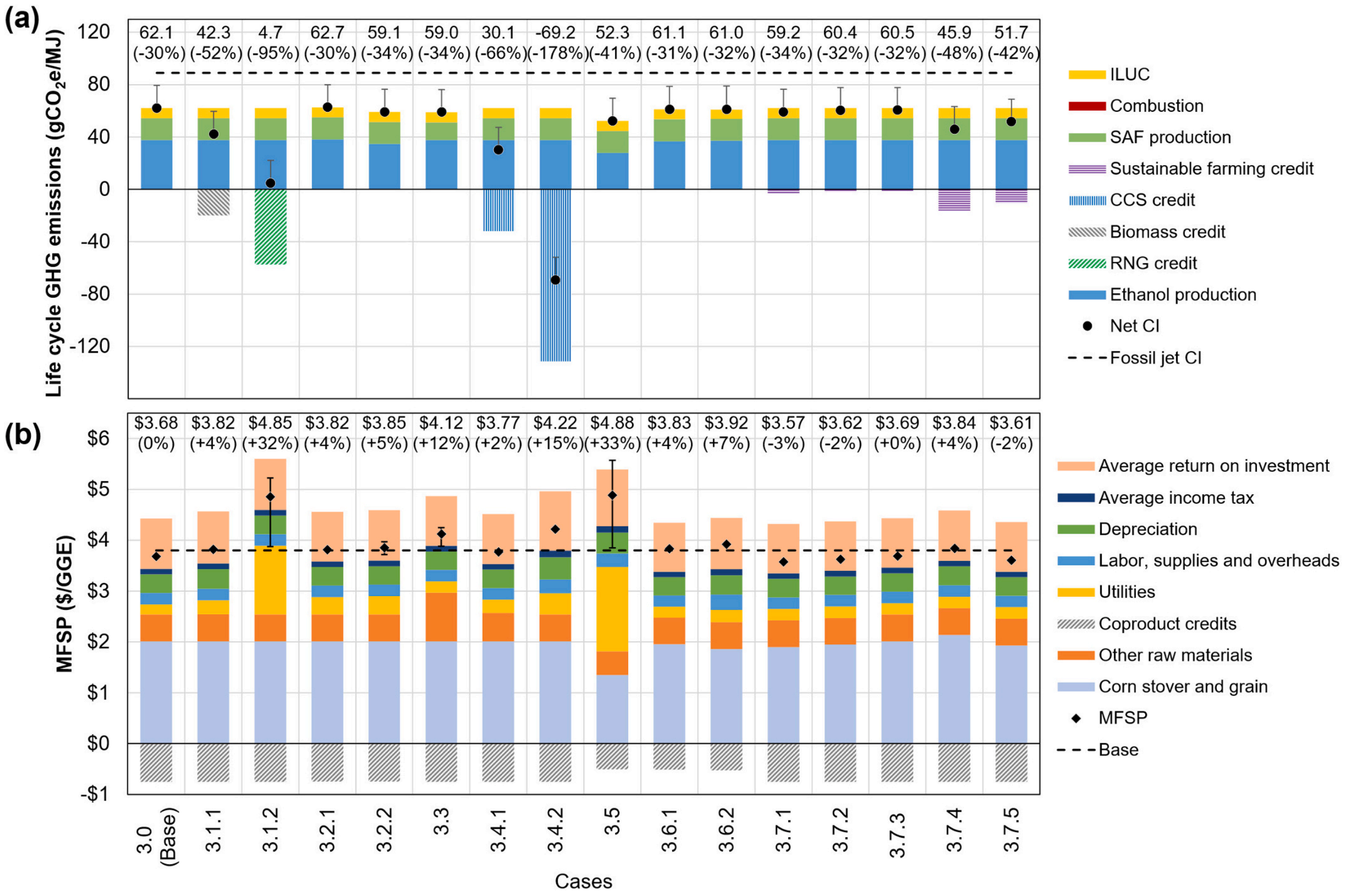

Fig. 4. (a) GHG emissions for Case 3, the integrated Gen 1 and Gen 2 ETJ biorefinery, when Gen 1 and Gen 2 ethanol are considered as a combined gallon. (b) Cost contributions to MFSP for integrated Gen 1/Gen 2 low-carbon scenarios. Case 3.0: integrated Gen 1/Gen 2 baseline; 3.1.1: switching process fuel from NG to biomass (wood chips); 3.1.2: switching process fuel from NG to dairy manure-derived RNG; 3.2.1: importing grid electricity; 3.2.2: importing renewable electricity; 3.3: switching to renewable H_2; 3.4.1: CCS (fermentation CO_2 only); 3.4.2: CCS (CO_2 from both fermentation and CHP); 3.5: CCU (fermentation CO_2) for ethanol production followed by ETJ using renewable electricity and renewable H_2; 3.6.1: with *in situ* Gen 1.5; 3.6.2: with *ex situ* Gen 1.5; 3.7.1: conservation tillage; 3.7.2: variable N rate; 3.7.3: enhanced-efficiency fertilizer; 3.7.4: cover crop applications; 3.7.5: manure applications. The error bars represent the net CIs of the cases using the CORSIA ILUC value of 25.1 gCO_2e/MJ.

emissions; the CI becomes even higher (62.7 gCO_2e/MJ) than the Case 3 baseline CI of 62.1 gCO_2e/MJ. Using renewable H_2 for SAF upgrading (Case 3.3) contributes a 3.1 gCO_2e/MJ reduction from the baseline.

Two CCS options (Cases 3.4.1 and 3.4.2) provide about 32 and 131 gCO_2e/MJ carbon sequestration credits, respectively, which decreases the CIs to 30.1 and −69.2 gCO_2e/MJ. The CCU option (Case 3.5) that converts captured CO_2 into ethanol followed by ETJ can reduce GHG emissions by 9.8 gCO_2e/MJ compared to Case 3.0 using renewable electricity and renewable H_2.

Introducing Gen 1.5 technology has only a limited impact on the CIs of combined ethanol-derived SAF (1.1 and 1.2 gCO_2e/MJ reduction from the baseline, Case 3.0), mainly due to the small Gen 1.5 ethanol volume share. The volume shares of the ethanol from Gen 1, Gen 2, and Gen 1.5 streams are 84 %, 13 %, and 3 % for the *in-situ* Gen 1.5 case (Case 3.6.1), respectively. The volume shares are 80 %, 12 %, and 8 % for the *ex-situ* Gen 1.5 case (Case 3.6.2). Sustainable farming practices (Cases 3.7.1–3.7.5) reduce the CI by 1.6–16.2 gCO_2e/MJ compared to the base case (Case 3.0) by preserving or adding SOC.

Fig. 4(b) summarizes the cost contributions and MFSP for Cases 3.0–3.7.5. The base case (Case 3.0) MFSP is estimated at $3.68/GGE.

Replacing NG with biomass (Case 3.1.1) increases MFSP by 4 %, while replacing it with RNG (Case 3.1.2) increases it by 32 % because of the high RNG cost ($23.8/GJ). The RNG price can significantly vary based on sources and locations, affecting the estimated MFSP in this study.

Reducing the NG supply to only what is needed to meet the heat demand and importing grid electricity (fossil- or renewable-based) to compensate for the electricity deficit (Cases 3.2.1 and 3.2.2) both serve to increase the MFSP by 4–5 %. As the error bar shows, MFSP ranges between $3.63/GGE and $3.88/GGE when the additional electricity is sourced from renewable sources (Case 3.2.2) due to the variation in renewable electricity costs ($0.02–$1/kWh). In addition, the availability of renewable electricity at the facility location might be a limiting factor on a regional basis.

Using renewable hydrogen (Case 3.3) leads to a 12 % higher MFSP than the base case; however, the MFSP can vary from $3.81 to $4.17/GGE.

The CCS of only fermentation CO_2 (Case 3.4.1) results in a 2 % increase in MFSP, whereas the CCS of both fermentation CO_2 and flue gas CO_2 (Case 3.4.2) might result in a 15 % increase.

High capital costs for the CCU unit and significantly higher utility costs for H_2/CO electrolysis (Case 3.5) result in a 33 % higher MFSP. If renewable electricity is used for the electrolysis process, the MFSP varies from $3.79 to $5.50/GGE, as shown in Fig. 4(b).

The MFSP change for different sustainable farming practices (Cases 3.7.1–3.7.5) varies between −3 % and 4 % compared to the base case.

For the integrated Gen 1/Gen 2 ETJ process, ethanol from Gen 1 accounts for 86.5 % of the total ethanol production, and the rest (13.5 %) comes from Gen 2. All ethanol produced is then upgraded to hydrocarbon fuels.

3.1. Marginal abatement costs

Fig. 5 represents the MAC for all investigated scenarios of the three base ETJ pathways. For Gen 1 ETJ, the MAC of CCU options is significantly higher, followed by the *ex-situ* Gen 1.5 option. However, these technologies require further R&D efforts to reduce capital and operating costs while improving performance that will help reduce emissions even further. The MAC for the CCS of the fermentation CO_2 option (Case 1.4) is below \$100/t CO_2e, showing near-term deployment potential. However, note that pipeline construction and other auxiliary equipment costs are excluded from the TEA whereas the impact of sequestered carbon is included in the LCA system boundary.

The MAC for the Gen 2 ETJ base case (Case 2.0) is significantly higher than the MAC for the Gen 1 ETJ base case (Case 1.0), as it is driven by higher ethanol production costs. Following a similar pattern, the CCU option has the largest MAC, while the CCS of both fermentation off-gas and CHP flue gas has a comparatively lower MAC. Planting cover crops during winter or the fallow season has very high GHG emissions reduction potential without affecting the overall economics.

The MAC for Case 3 scenarios follow a pattern similar to Case 1 scenarios, as more than 85 % of the ethanol in the integrated facility comes from the corn grain instead of corn stover. Using CCU, importing grid electricity, and using renewable hydrogen are the highest MAC options. The lowest MAC comes from the CCS of both fermentation CO_2 and CHP flue gas CO_2. Note that CO_2 compression to pipeline quality is included in this study, while transportation and storage costs are excluded.

3.2. Evaluating the combined impact of multiple strategies for SAF production from the ETJ pathway

Realizing emissions reduction in ETJ pathways requires deploying a portfolio of strategies based on various location-specific parameters. For instance, the availability and cost of renewable energy sources such as RNG or electricity will vary by plant location, resulting in different production costs. While employing a single technology may provide only a small CI reduction for the ETJ pathway, combining multiple technologies can enable greater reductions.

We implemented each emission reduction technology individually and stacked them for the integrated facility. Here we present the MFSP and net CI reductions resulting from this work. Fig. 6 illustrates one example: the combination of strategies adopted for the integrated Gen 1/Gen 2 ETJ pathway (Case 3). Note that such linear combinations may not be feasible for all available techniques. For example, implementing variable N rate techniques may not be possible if animal manure is used for farming.

In this example, four sustainable farming practices (variable N rate, enhanced-efficiency fertilizer, conservation tillage, and cover crop) are adopted along with fuel switching and CCS. The superimposed CI and MFSP plot clearly show the cumulative environmental benefits and cost penalties for adding each technology. The cumulative GHG reduction can reach up to 56 % compared to the fossil jet (89 g CO_2e/MJ) by combining the sustainable farming practices. The final MFSP after adopting these farming practices remains similar to the base case.

Using renewable H_2 provides an additional 3 % GHG reduction at the expense of a 3 % cost increase. Switching from NG to biomass as process fuel indicates a potential GHG reduction of up to 81 % compared to the fossil jet case. The MFSP at this stage becomes \$3.9/GGE. Finally, adding CCS provides net-negative CI with a 117 % reduction. The MFSP for the CCS of fermentation CO_2 is 6 % higher than the base case.

Our analysis shows that adding CCS after switching NG to biomass is the most economically viable option. Although other technology combinations are possible, they are unlikely to substantially reduce emissions without adopting RNG or CCS. This finding is also valid for the Gen 1 case. Gen 2 shows low-carbon SAF potential by including CCS or any single sustainable farming practice due to its initial low emissions compared to the base case.

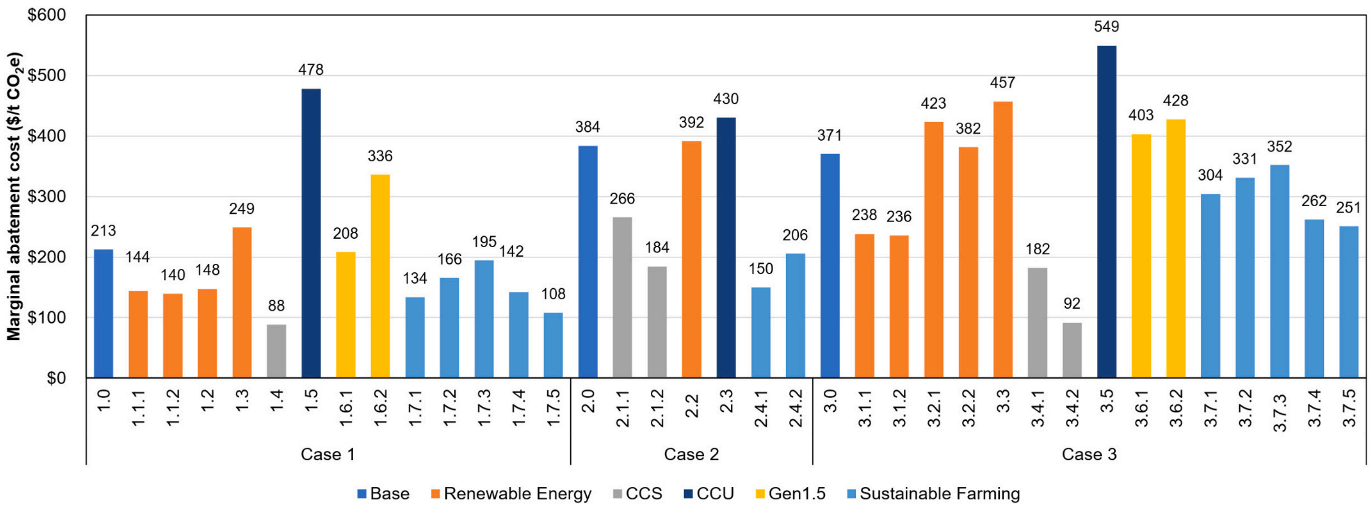

Fig. 5. Marginal abatement cost (\$/t CO_{2e}). Case 1.0: Gen 1 baseline; 1.1.1: switching process fuel from NG to dairy manure-derived RNG; 1.1.2: switching process fuel from NG to biomass (forest residue); 1.2: renewable electricity; 1.3: renewable H_2; 1.4: CCS (compressor cost only, no pipeline cost); 1.5: CCU for ethanol production with renewable electricity; 1.6.1: adding *in-situ* Gen 1.5; 1.6.2: adding *ex-situ* Gen 1.5; 1.7.1: conservation tillage; 1.7.2: variable N rate; 1.7.3: enhanced fertilizer efficiency; 1.7.4: cover crops application; 1.7.5: manure application. Case 2.0: Gen 2 ETJ baseline; 2.1.1: CCS using fermentation CO_2 (compressor cost only, no pipeline cost); 2.1.2: CCS using both fermentation and CHP CO_2 (compressor cost only, no pipeline cost); 2.2: renewable H_2 for SAF upgrading; 2.3: CCU with fermentation CO_2 for SAF production; 2.4.1: cover crop application; 2.4.2: manure application. Case 3.0: integrated Gen 1–Gen 2 baseline; 3.1.1: switching process fuel from NG to biomass (wood chips); 3.1.2: switching process fuel from NG to dairy manure-derived RNG; 3.2.1: importing grid electricity; 3.2.2: importing renewable electricity; 3.3: switching to renewable H_2; 3.4.1: CCS (fermentation CO_2 only; compressor cost only and no pipeline cost); 3.4.2: CCS (CO_2 from both fermentation and CHP; compressor cost only and no pipeline cost); 3.5: CCU (fermentation CO_2) for ethanol production followed by ETJ using renewable electricity and renewable H_2; 3.6.1: with *in situ* Gen 1.5; 3.6.2: with *ex situ* Gen 1.5; 3.7.1: conservation tillage; 3.7.2: variable N rate; 3.7.3: enhanced fertilizer efficiency; 3.7.4: cover crop applications; 3.7.5: manure applications.

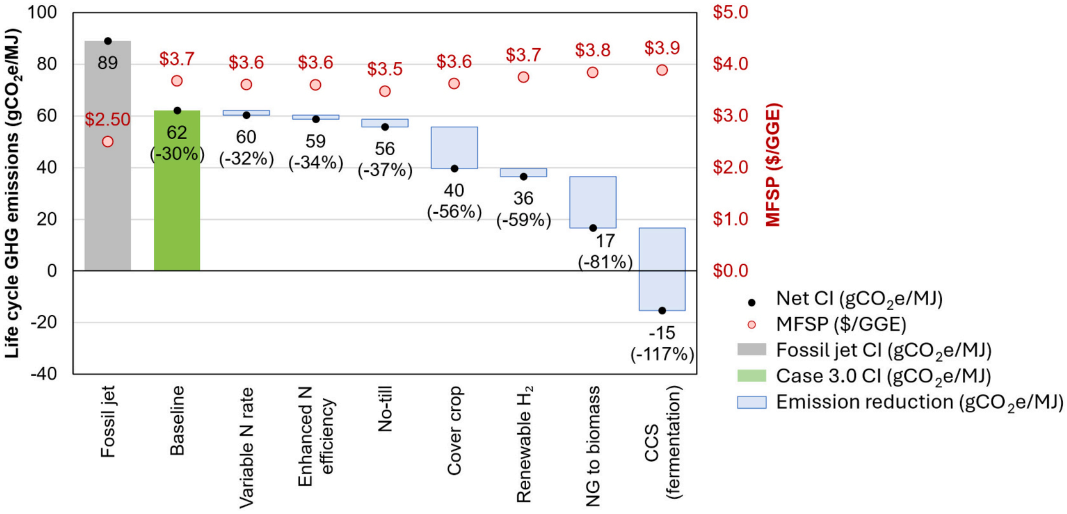

Fig. 6. Combinations of low-carbon options for an integrated Gen 1/2 ETJ facility.

3.3. *Limitations and future work*

While this study provides insights into the economic and environmental trade-offs of SAF production *via* various ETJ pathways, several limitations must be acknowledged.

A major challenge in scaling SAF production is the need for substantial infrastructure development. Expanding SAF deployment will require significant investment in new processing facilities, supply chain logistics, and blending infrastructure at airports. Because these infrastructure requirements are closely tied to regional resource availability and logistical constraints, further research is needed to improve regional supply chain planning and implementation strategies. This effort includes considering the uneven distribution of feedstocks, renewable energy, and supporting infrastructure, as well as how multiple strategies can be combined to optimize economic and environmental outcomes. Strengthening these aspects would enhance the practical feasibility of SAF production. In addition, while the availability and reliability of renewable energy sources are crucial for emissions reduction, their integration into SAF production is highly dependent on regional resource conditions and infrastructure.

Another limitation is the uncertainty in feedstock availability and sustainability. The long-term supply and sustainability of corn grain and stover depend on agricultural practices, land management, and competing broader bioeconomy demands. This study assumed a 30 % stover removal rate based on sustainability constraints identified in previous research [49–51]. However, regional variations in stover availability, soil conditions, and management practices may result in varying sustainable removal rates. Future research should consider spatially explicit modeling to better capture these regional differences.

Assessing the combined effects of multiple emissions reduction strategies is essential for understanding their overall impact on SAF production. While some mitigation technologies can be integrated, others may face technical, economic, or regulatory constraints that limit their compatibility; in some cases, their impacts may not be fully additive. Although Fig. 6 presents aggregated impacts, note that it does not fully capture potential trade-offs, synergies, or implementation challenges when combining multiple strategies. This study focused on the economic and environmental aspects of SAF production; regulatory and policy analysis falls outside the scope of this research.

While this study includes sensitivity analysis for selected cost parameters using error bars, a comprehensive uncertainty analysis was not conducted due to the large number of cases evaluated. A full uncertainty analysis is considered an important area for future work to further assess the robustness of the results. In particular, although the SAF-specific ILUC values used in this study reflect the latest available estimates [39], ILUC remains subject to modeling uncertainty. Continued refinement of land use models will help improve confidence in SAF CI estimates, particularly for Gen 1 pathways.

4. Conclusions

This study provides a comprehensive assessment of ETJ pathways, highlighting the technical, economic, and environmental trade-offs involved in producing SAFs from both corn grain (Gen 1) and corn stover (Gen 2) ethanol processes. The findings show that both Gen 1 and Gen 2 reduce emissions; further improvements can be achievable by combining multiple strategies across the supply chain. Renewable energy inputs and CCS offer the greatest potential for realizing emissions reductions but may require substantial infrastructure and investment. Sustainable farming practices provide more moderate benefits and are easier to adopt on an incremental basis. Gen 2 pathways achieve lower baseline CIs compared to Gen 1 but face scalability and economic challenges. Integrated Gen 1/Gen 2 systems present a balanced approach but require process improvements. Overall, while low-carbon or even net-negative CI SAFs are technically feasible, their success depends on site-specific factors such as energy prices, infrastructure, and supportive policies. Aligning technological development, infrastructure planning, and feedstock management will be essential for ethanol-derived SAFs to contribute meaningfully to aviation emissions reduction.

CRediT authorship contribution statement

Md Mosleh Uddin: Writing – original draft, Data curation, Writing – review & editing, Formal analysis, Conceptualization. **Uisung Lee:** Writing – original draft, Methodology, Data curation, Writing – review & editing, Validation, Formal analysis. **Hui Xu:** Writing – original draft, Formal analysis, Conceptualization, Methodology, Data curation. **Yuan Li:** Writing – original draft, Formal analysis, Investigation, Data curation. **Hoyoung Kwon:** Writing – original draft, Investigation, Methodology, Formal analysis. **Yimin Zhang:** Formal analysis, Investigation, Conceptualization. **Sharon Smolinski:** Validation, Formal analysis, Investigation. **Hao Cai:** Validation, Resources, Supervision, Investigation. **Ling Tao:** Writing – review & editing, Validation, Resources, Methodology, Funding acquisition, Data curation, Writing – original draft, Supervision, Project administration, Investigation, Formal analysis, Conceptualization.

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.2025.126373.

Data availability

No data was used for the research described in the article.

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