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Research Article

Techno-economic Analysis and Life-Cycle Analysis of Renewable Diesel Fuels Produced with Waste Feedstocks

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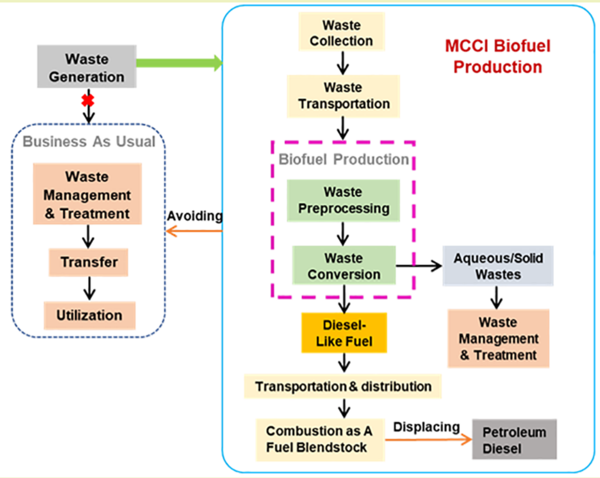

ABSTRACT: Wet waste feedstocks represent an important category of resources that could be utilized to produce biofuels. Diversion of the wet waste resources from going through conventional waste management practices to utilization as feedstocks for energy production also benefits from avoided cost and pollutant emissions of waste management and disposal. This study investigates the economic and environmental implications of producing bioblendstocks for mixing controlled compression ignition engines from two waste-to-fuel pathways: hydroprocessed esters and fatty acids (HEFA) from yellow grease and swine manure hydrothermal liquefaction (HTL) followed by biocrude upgrading. Detailed process models were developed for both pathways, which informed the techno-economic analysis and life-cycle analysis. Conventional swine manure management practice was also modeled in detail as the business-as-usual scenario for the swine manure HTL pathway. The estimated minimum fuel selling prices were \$1.22/gasoline liter equivalent (GLE) and \$0.94/GLE for the yellow grease to HEFA and swine manure HTL pathways, respectively. The life-cycle greenhouse gas (GHG) emissions of the two pathways were 11.2 and −33.3 g of CO_2e/MJ, respectively, for the yellow grease to HEFA and swine manure HTL pathways. The credits of avoided emissions from conventional swine manure management were the main reason for the negative GHG emissions of the swine manure HTL pathway. The marginal GHG emissions abatement costs were estimated to be \$116−\$270/tonne CO_2e and \$5−\$103/tonne CO_2e for the yellow grease HEFA and swine manure HTL pathways, respectively, for a diesel price ranging between \$0.5/GLE and \$0.9/GLE. Since the yellow grease HEFA pathway is already commercialized, it can benefit from the \$200/tonne carbon credit in the California Low Carbon Fuel Standard market, which could help the yellow grease HEFA pathway to achieve near-zero marginal GHG emissions abatement cost.

KEYWORDS: *Waste-to-energy, Greenhouse gas emissions, Marginal abatement cost, Renewable diesel, Minimum fuel selling price, Counterfactual scenarios*

INTRODUCTION

The transportation sector is one of the largest contributors of greenhouse gas (GHG) emissions in the U.S., accounting for 28% of total U.S. GHG emissions in 2018.[1] Biofuels have been regarded as an effective means of mitigating global warming, not only because the carbon uptake during biomass growth offsets the GHG emissions from vehicle operation but also because they may also have improved fuel properties compared to petroleum-derived fuels and offer benefits such as enhanced fuel economy.[2]

Heavy-duty diesel vehicles using mixing controlled compression ignition (MCCI), the most common ignition and combustion strategies for heavy-duty diesel engines, contribute significantly to the emissions of GHG, oxides of nitrogen (NO_x), and particular matter (PM) and are subject to stringent emission standards.[3] Producing MCCI fuel blendstocks from terrestrial biomass holds promise to make alternative fuels with favorable MCCI fuel properties, such as high cetane number[4] and low aromatics,[5] that could help curb engine-out NO_x and PM emissions, which could help to meet increasingly stringent emission regulations and bring about reduction in emission aftertreatment costs and eventually vehicle ownership costs.[3] Meanwhile, wet waste feedstocks, such as animal manure and fats, oils, and greases (FOG), represent another important category of resources that could be utilized to produce MCCI

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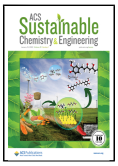

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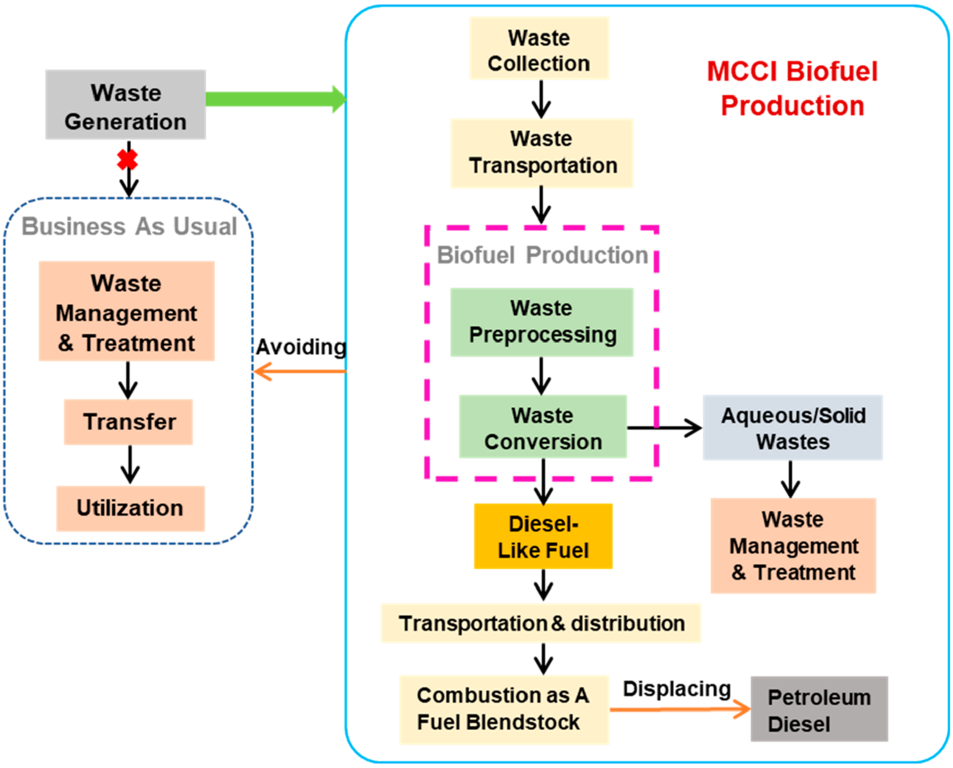


Figure 1. System boundary of TEA and LCA of shifting waste feedstocks from BAU to MCCI fuel production.

bioblendstocks due to its abundant availability.[6] Skaggs et al.[7] estimated that with conversion by hydrothermal liquefaction (HTL) and upgrading, the wet waste resource availability in the United States could be converted to jet fuel that is equivalent to about 24% of the U.S. demand in 2016.

Given the nature of wet waste resources that requires dedicated waste management practices to collect, store, treat, and dispose of the waste, shifting the waste resources from going through conventional waste management practices to utilization as feedstocks for energy production may represent an avoided cost of waste management and disposal. About 61% of the total sewage sludge, 27% of the total manure, and 7% of the total food waste may be available at negative prices, while FOG is more commoditized with its price determined by market demand.[8] Thus, the use of wet waste resources as feedstocks in advanced bioenergy processes represents an opportunity to recycle organic waste material into renewable energy and at the same time offset the cost and environmental impact of their disposal via more conventional practices, such as landfilling, anaerobic digestion (AD), or incineration.

Diverse conversion technologies, such as HTL, gasification, and hydro-processing, are available to convert waste feedstocks into liquid fuels. A commercial pathway to produce liquid fuels from waste feedstocks is hydroprocessed esters and fatty acids (HEFA) production from oil feedstocks such as used cooking oil. HEFA jet fuel was approved by the American Society for Testing and Materials (ASTM) in 2011. Diamond Green Diesel has the largest renewable diesel production in North America which produces 290 million gallons (1098 million liters) of renewable diesel per year.[9] Expansion is underway to increase its production to 400 million gallons annually in 2021.[9] Key cost drivers for a biorefinery converting waste oils to HEFA (jet/diesel) include oil price, conversion plant capacity, fatty acid profile, the addition of a hydrocracker, and the type of hydroprocessing catalysts.[10]

HTL can process high moisture feedstocks without pretreatment, and the resulting HTL biocrude intermediate tend to be more stable with lower oxygen contents and high energy content, compared with the bio-oil intermediate from pyrolysis.[11] Economic studies based on the 2020 state of technology reported the price of sewage sludge-derived hydrocarbon fuels at \$1.2/gasoline liter equivalent (GLE) and the ongoing research and development can potentially reduce the price to <\$0.8/GLE by 2022.[12]

Previous analyses of the environmental impacts of several waste-to-fuel pathways have determined a range of potential GHG emissions reductions. Seber et al.[13] reported a range of life-cycle GHG emissions between 12 and 17 g of CO_2e/MJ for HEFA diesel fuel produced from waste cooking oil. de Jong et al.[14] reported life-cycle GHG emissions of 28 g of CO_2e/MJ for a similar system. In comparison, HEFA fuel derived from oil feedstocks (e.g., soybean, palm, etc.) is estimated to have much higher life-cycle GHG emissions of between 40 and 58 g of CO_2e/MJ.[14−16] This is because using wet wastes such as waste cooking oil for biofuels production avoids the emissions from the cultivation of oil feedstocks. Bora et al.[17] estimated that HTL of poultry litter led to a 16% reduction in life cycle GHG emissions compared to the conventional land application. Tao and You[18] compared the life-cycle GHG emissions of slow pyrolysis, fast pyrolysis, and HTL for biofuel production from dairy manure, but the study did not compare with the emissions from the business-as-usual (BAU) waste management process which could generate a great amount of GHG emissions. It is thus important to take into account such GHG "credit" from the avoided BAU emissions when evaluating the environmental impacts of waste-to-fuel pathways.

Given the resource availability, potential economic advantage, and possible environmental benefits of shifting wet wastes to bioenergy production and infrastructure compatibility, this work used detailed techno-economic analysis (TEA) and life-cycle analysis (LCA) to evaluate the economic viability, environmental performance, and scalability of utilizing two waste-to-fuel pathways for MCCI bioblendstock production: HEFA diesel from yellow grease and renewable diesel from swine manure HTL followed by upgrading. The impact of BAU waste management practices was also carefully considered. Detailed process engineering models were developed to address the minimum fuel selling price (MFSP), life-cycle GHG emissions, fossil energy use, NO_x and PM emissions, and water consumption. The TEA and LCA results offer insights into how these bioblendstocks compare with conventional fuels on a cost and environmental basis and inform estimates of the potential benefits they may bring if introduced to the transportation sector in large volumes. In addition to reporting the base case results, sensitivity analysis was also performed to identify important cost and environmental impact drivers that can be addressed in future research and development of these bioblendstocks.

METHODOLOGY AND DATA

This study aims to quantify the net cost and sustainability impacts of diverting the waste resources from conventional waste management and treatment practices to producing MCCI bioblendstocks. We evaluated the net impacts of costs, energy consumption, and emissions by incorporating the impact of the avoided emissions from a BAU scenario, or a counterfactual scenario, where the waste undergoes treatment, followed by possible utilization of the treated waste for land application or landfilling, into a renewable diesel production scenario where the waste resources are used to produce renewable diesel bioblendstocks. Figure 1 shows the system boundary of the TEA and LCA with consideration of the implications of counterfactual scenarios.

Techno-economic Analysis. Detailed process models were developed for two waste-to-fuel energy pathways based on experimental results: (1) yellow grease to HEFA diesel and (2) renewable diesel from swine manure HTL and biocrude upgrading. A brief discussion of the technology readiness level of the two pathways are included in Section "Technology Readiness Level" in the Supporting Information. The mass and energy balances from the process model were integrated with a financial model to evaluate the economic performance of the two pathways (see Tables S11 and S12). Specifically, capital and operating costs, which were estimated from the mass and energy balances, were used in a discounted cash flow analysis to determine the MFSP needed to meet a 10% internal rate of return when the net present value is set to zero. Table 1 summarizes the primary economic assumptions for the "nth-plant" method employed in this study. This method does not account for special financing, equipment redundancies, large contingencies, and long startup times since it assumes several plants have already been built and are operating.

MCCI Fuel from Yellow Grease to HEFA. Yellow grease is essentially rendered used cooking oil (restaurant grease) that meets the following specifications: free fatty acids maximum of 15% and moisture, impurities, and unsaponifiables of less than 2% with 1% maximum water.[19]

The HEFA conversion technologies consist of hydrotreating, deoxygenation, isomerization, and hydrocracking, and they are at a relatively high maturity level and are commercially available. These processes are commonly used in today's refineries to produce transportation fuels. This study modified the base model developed in a previous study[10] and major unit operations including hydrogenation, propane cleave, hydrocracking and hydroisomerization, and product fractionation to primarily produce diesel range hydrocarbon fuels.

Table 1. Key Assumptions for the Techno-economic Analysis

assumption	value	assumption	value
cost year of analysis	2016	plant life (y)	30
project contingency (%)	10	construction period (y)	3
indirect cost factor (% of TIC)	60	maintenance/overhead (% of labor and supervision)	90
direct cost factor (% of TIC)	18.5	start-up time (y)	0.5
working capital (% of FCI)	5	stream factor (%)	90
depreciation period (y)	7	internal rate of return (%)	10
equity financing (%)	40	income tax rate (%)	21

Material and energy balance and flow rate information were generated using Aspen Plus[20] process simulation software, assuming a feed rate to the biorefinery of 200 000 dry tonne of yellow grease per year, which represents about 20% of the total annual yellow grease availability in the United States.[6] Data from process simulation were used to size and cost process equipment as well as compute raw material and other operating costs. The TEA model reasonably estimates a commercial-scale production cost of HEFA diesel. Table S4 summarizes key process model assumptions of the yellow grease to HEFA conversion.

MCCI Fuel from Swine Manure HTL. A detailed process model was developed using Aspen Plus[20] for a 100 dry tonne per day swine manure hydrothermal liquefaction (HTL) plant. Assuming 90% uptime, such an HTL plant processes 32 781 dry tonne of swine manure per year, which represents 0.4% of the total annual recoverable manure in the United States.[6] The centralized upgrading plant was assumed to process biocrude transported from multiple manure processing HTL plants in a region, receiving 10 times the biocrude produced by one 100 dry tonne per day HTL plant. The centralized upgrading plant thus had a biocrude feed capacity of 144 million liters per year. This configuration and the selected plant scale are consistent with the previous analysis of sewage sludge HTL.[21] A block flow diagram representing major process steps for the manure HTL pathway is given in the Supporting Information (Figure S1). Key process model assumptions of this pathway are summarized in Table S5.

Life-Cycle Analysis. The material and energy flows from the process models informed the LCA of the two waste feedstock pathways. The LCA system boundary includes the waste feedstock collection and transportation, biorefinery conversion, and bioblendstock transportation and combustion in a vehicle (Figure 1). The greenhouse gases, regulated emissions, and energy use in technologies (GREET) model[22] as released in 2020 was used to conduct LCA. The GREET model, publicly available and developed with the support of the U.S. Department of Energy, is a tool for the LCA of fuels and vehicle technologies and permits users to investigate energy and environmental impacts that are addressed in this analysis.

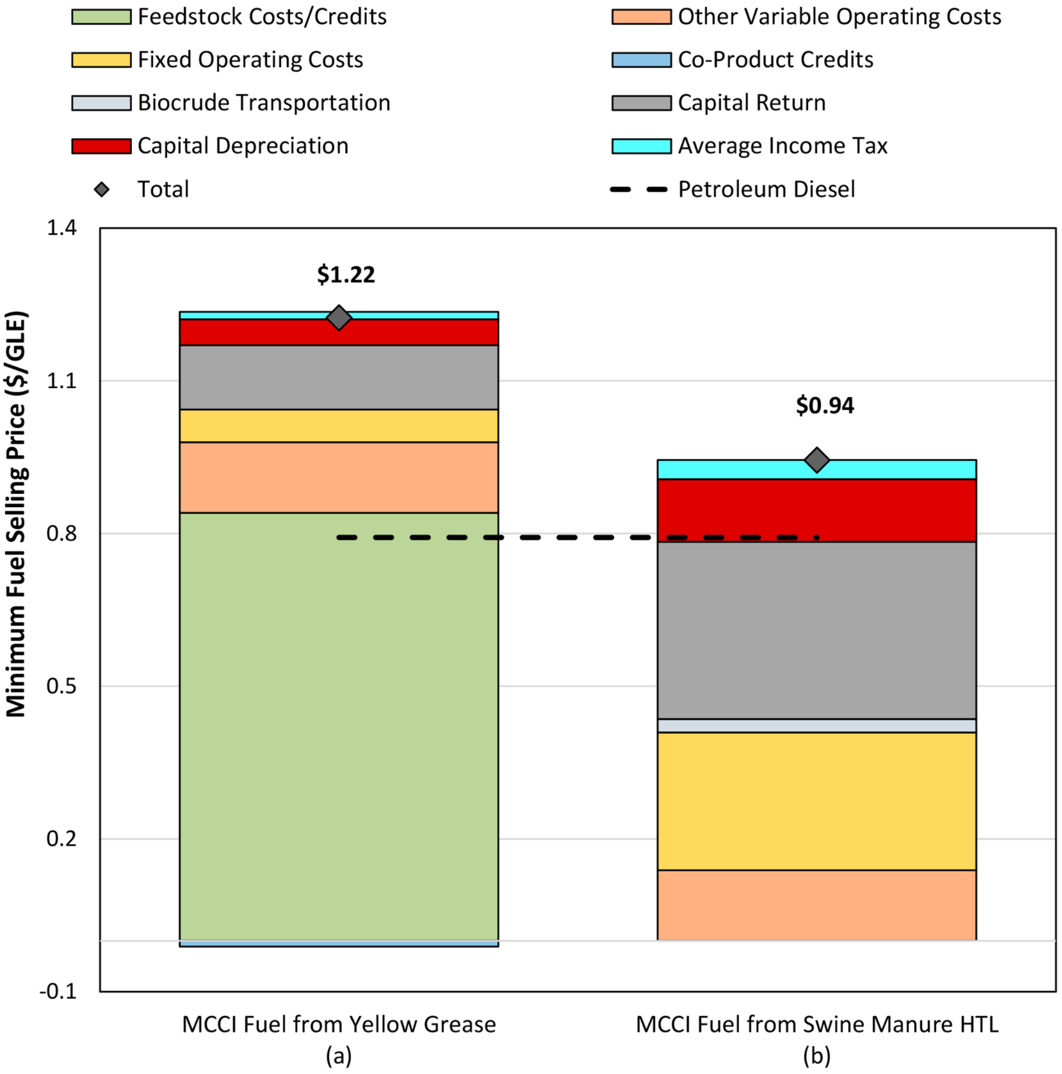


Figure 2. Cost breakdown of the minimum fuel selling price for MCCI fuel produced from (a) yellow grease and (b) swine manure HTL, in comparison to the diesel price of $0.79/GLE.[27]

Given the target use of the bioblendstocks as fuels for MCCI diesel vehicles, this study used per mega-joules (MJ) as the functional unit for both bioblendstocks. The yellow grease to HEFA pathway coproduces about 5% propane by energy output as another energy product. The swine manure HTL pathway coproduces about 24% naphtha by energy output as an additional energy product. An energy-based allocation method was applied at the system level to allocate the energy, emission, and water consumption burdens between the diesel bioblendstock and the coproduct for both pathways. Detailed LCA assumptions, including management of waste streams and carbon sequestration by solid waste landfilling, are discussed in more detail in the section "Life Cycle Assessment Assumptions" in the Supporting Information.

Counterfactual Scenario. Swine manure is high in nitrogen and moisture. In the counterfactual scenario, it requires proper management to prevent surface and groundwater contamination, protect the health of livestock and the public, and utilize manure nutrients for enhancing soil. Typical manure management practices involve storage, handling, treatment, and utilization to manage manure nutrients and achieve the above-mentioned goals. Major swine manure management systems currently adopted in the U.S. include deep pits, anaerobic lagoons, liquid/slurry storage, and application to pastures, as listed in Table S6. During swine manure management, a fraction of the carbon in manure is converted to CH_4-rich biogas, which typically contains 60−70% CH_4,[23] which is a potent GHG. Such emissions are avoided if swine manure is used to produce MCCI bioblendstock; thus, they are accounted for as emission credits in the LCA. Detailed assumptions regarding the counterfactual scenario of the swine manure HTL pathway are discussed in the section "Renewable Diesel from Swine Manure HTL" in the Supporting Information.

Unlike swine manure, more than 60% of which was estimated to be available at negative prices for utilization that avoids manure management, yellow grease is widely recovered from restaurants and rendering plants and sold to biorefineries in the U.S. to produce biodiesel or renewable diesel at a high community price,[8] given its quality for use as a feedstock for fuel production. The market price of yellow greases was estimated to be ~$600/dry tonne.[24] The California Low Carbon Fuel Standard (LCFS) that mandates a carbon intensity reduction of the transportation sector in

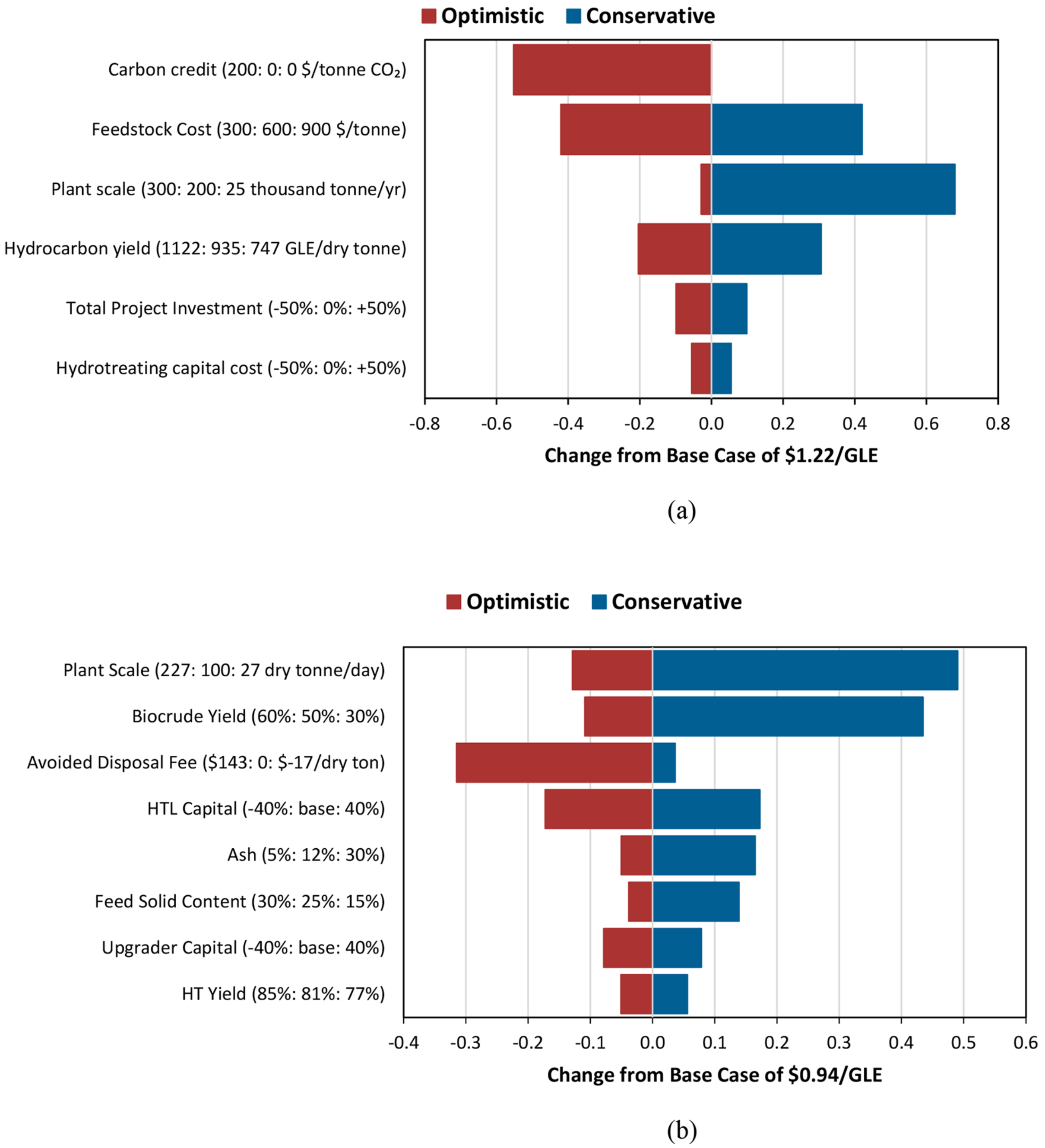


Figure 3. MFSP sensitivity analysis results for MCCI fuel produced from (a) yellow grease and (b) swine manure HTL.

California creates a strong incentive for using yellow grease to produce biodiesel and renewable diesel fuels. As a result, about 36% of the U.S. renewable diesel production in 2019 was estimated to have used yellow grease as a feedstock.[25] Driven by the strong demand for alternative diesel fuels in the heavy-duty transportation sector, it is assumed that yellow grease will continue to be in high demand as a biofuel feedstock, which could avoid the need for managing yellow grease at wastewater treatment plants. Therefore, this study did not consider any counterfactual scenario impacts of using yellow grease for MCCI bioblendstock production.

Sensitivity Analysis. *Process Assumptions.* To identify key drivers of the TEA and LCA results, parameters were varied to understand their impacts on the economic and environmental results. A detailed discussion of the rationales for the selected parameter values in the base case, the optimistic scenario, and the conservative scenario for the two pathways can be found in the section "Sensitivity Analysis Assumptions" in the Supporting Information.

For the yellow grease to HEFA pathway, the cost sensitivities on feedstock price, plant size, capital cost, and hydrocarbon yields were assessed. Table S9 lists the key technical and economic assumptions for the sensitivity analysis of the yellow grease to HEFA pathway.

For the manure HTL pathway, the impacts of feedstock price, plant size, hydrotreating yield, etc. were assessed. Altering some of these parameters (e.g., hydrotreating yield and feedstock ash content, etc.) would change the overall material and energy balances of the conversion processes. For instance, a high HTL feed solid content can improve the biocrude yield. Table S10 lists the key technical and economic assumptions for sensitivity analysis.

Alternative Counterfactual Scenarios for Swine Manure HTL. Considering the great impact of the counterfactual scenario on the life-cycle GHG emissions, two possible variants of the counterfactual scenario were also investigated to reflect the variabilities in handling the CH_4-rich biogas from the manure management systems. In the first case (referred to as Case C1 hereafter), 100% of the manageable CH_4 is assumed to be flared for mitigating CH_4, a potent greenhouse gas. Such an assumption would reduce the GHG credits (and thus increase the life-cycle GHG emissions) for the MCCI bioblendstock because the avoided GHG emissions from the conventional manure management systems are decreased.

In the second variant of the counterfactual scenario (referred to as Case C2 hereafter), manure is utilized for renewable electricity generation via anaerobic digestion (AD). Case C2 represents the trend of utilization of manure for bioenergy production via AD. Right now, only about 1% of the U.S. pig farms install dedicated AD systems to collect and utilize the CH_4-rich biogas for the production of energy, such as electricity and heat.[26] In Case C2, a mixed plug-flow anaerobic digester was used to maximize CH_4 production, for which the CH_4 yields and energy usage are listed in Table S8. The CH_4-rich biogas is purified and combusted in a combined heat and power (CHP) plant. After meeting the on-site heat and power demand, excess electricity is sold to the grid to displace the U.S. average generation mix. Case C2 represents a competing case against renewable diesel production from manure HTL, because the opportunity of producing renewable electricity that could displace much more emission-intensive generation of electricity from a mix of fossil and renewable resources is foregone if the manure is used to produce renewable diesel instead. Therefore, Case C2 is expected to generate the highest GHG emissions from renewable electricity generation, compared to the base case counterfactual scenario and the counterfactual scenario where 100% of the CH_4 is flared.

RESULTS AND DISCUSSION

TEA Results. *MCCI Fuel from Yellow Grease to HEFA.* Per dry tonne yellow grease feedstocks, the production of hydrocarbon fuel is 935 GLE and total hydrocarbon fuel production is about 144 million GLE per year. When assuming \$600 per tonne yellow grease (dry basis), the predicted MFSP was \$1.22/GLE (Figure 2a). The feedstock contribution to overall MFSP was about 69% based on the annual 200 000 dry tonne/y HEFA facility (Figure 2(a)). Total project investment was \$206 million, contributing 16% of fuel production cost. The other costs were from hydrogen consumptions in the oil upgrading steps, catalysts costs, additional utility costs, and fixed operating costs. Utilities must be purchased for the HEFA facilities unless there is an on-site boiler and CHP plant.

MCCI Fuel from Swine Manure HTL. The MFSP shown in Figure 2b was calculated based on the lower heating value of all the hydrocarbon products (gasoline- and diesel-range). The estimated MFSP for this pathway was \$0.94/GLE. This pathway had a total installed capital investment of \$293 million, including \$210 million for ten 100 dry tonne per day HTL plants and \$83 million for the centralized biocrude upgrading plant. The feed/HTL reactor effluent heat exchanger in the HTL plants was the most capital-intensive equipment, corresponding to 35% of the total installed capital cost while the whole upgrading plant only accounted for 28% of the total installed capital cost. The operating costs were dominated by fixed operating costs, feedstock, and utilities (shown as other variable operating costs in Figure 2b). Fixed operating costs totaled \$0.27/GLE, including labor, maintenance, etc. Utilities and chemicals consumed in the HTL plant contributed 72% of other variable operating costs. Biocrude production cost accounted for 70% of the total cost (see biocrude cost breakdown in Figure S4). Therefore, efforts to reduce the HTL plant equipment cost and operating cost are critical to reducing the fuel MFSP.

Sensitivity Analysis. Figure 3a shows sensitivity analysis results around key economic and technical assumptions for the yellow grease to HEFA pathway. Each bar on the tornado chart represents a single point sensitivity in the parameter that is varied. The feedstock cost, plant scale, hydrocarbon yield from the HEFA process, total project investment, and hydrotreating capital cost all had a significant impact on MFSP. Since feedstock cost contributed over 60% of the total cost, it had the most significant cost impact as shown in Figure 3a. California's Low Carbon Fuel Standard (LCFS) currently has a carbon credit price of \$200 per tonne of CO_2 for low-carbon transportation fuels,[28] which has driven up the demand for animal fats and used cooking oil in biodiesel and renewable diesel production. If such a carbon credit is considered, the MFSP will be reduced by \$0.55/GLE of cost. When the HEFA plant scaled down from 200 000 dry tonne per year to 25 000 dry tonne per year which was based on the resource analysis performed by Milbrandt et al.,[6] the MFSP increased by 56% to \$1.90/GLE, due to unfavorable economies of scale. When the hydrocarbon yield was reduced by 20%, from 935 to 747 GLE/dry tonne feedstocks, the MFSP increased by 25%. Varying total project investment by ±50%, the MFSP varies by 8%. Varying hydrotreating capital cost by ±50%, the MFSP varies by 4%.

Figure 3b shows the sensitivity analysis result around key economic and technical assumptions for MCCI fuel production from swine manure HTL. As shown, the HTL plant scale, which was varied between 27 and 227 dry tonne swine manure per day, had the greatest impact on the MFSP. A 227 dry tonne per day HTL plant scale could reduce the MFSP by \$0.13/GLE while the small scale (27 dry tonne per day) was economically infeasible due to the unfavorable economies of scale. When the biocrude yield was 30%, the MFSP increased to \$1.38/GLE. The MFSP dropped by \$0.027/GLE if the feedstock credit (avoided disposal fee) increased by \$10/dry tonne. Following the feedstock credit, when decreasing the total HTL capital investment by 40%, the MFSP dropped to \$0.76/GLE. The results suggest that given a larger HTL plant size for the economy of scale and considering a tipping fee for removing waste from the hog farms, the MFSP could be significantly reduced.

Feed ash and solid content also could cause more than a \$0.13/GLE change in the MFSP. The greatest contributor to the MFSP change was from HTL biocrude production when changing the variables such as HTL plant scale, biocrude yield, HTL capital cost, and feed ash content. This was because the capital costs and operating costs for the biocrude production area accounted for 58% and 47% of the total capital costs and operating costs for this pathway, respectively. However, the HTL feed solid content had slightly greater impact on the aqueous phase treatment cost than the biocrude production

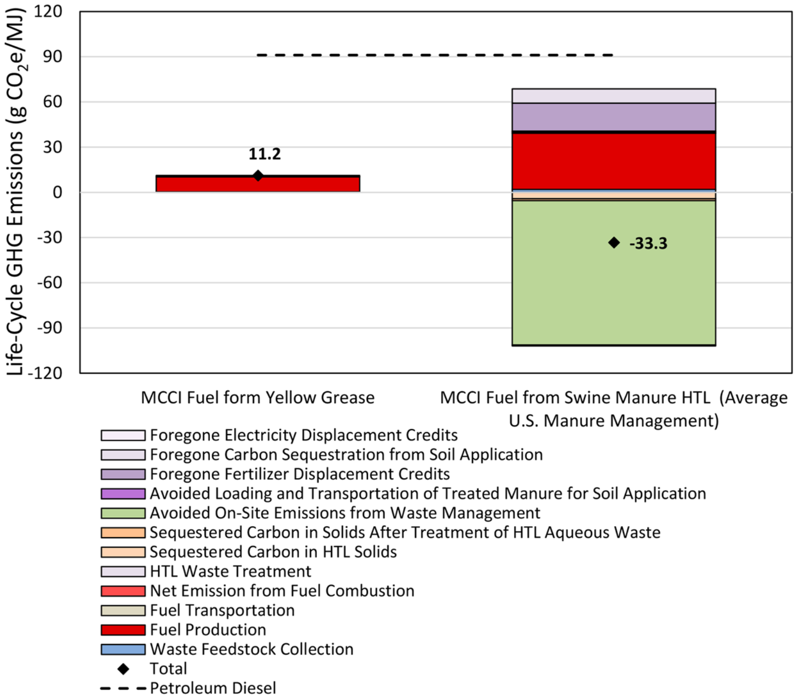
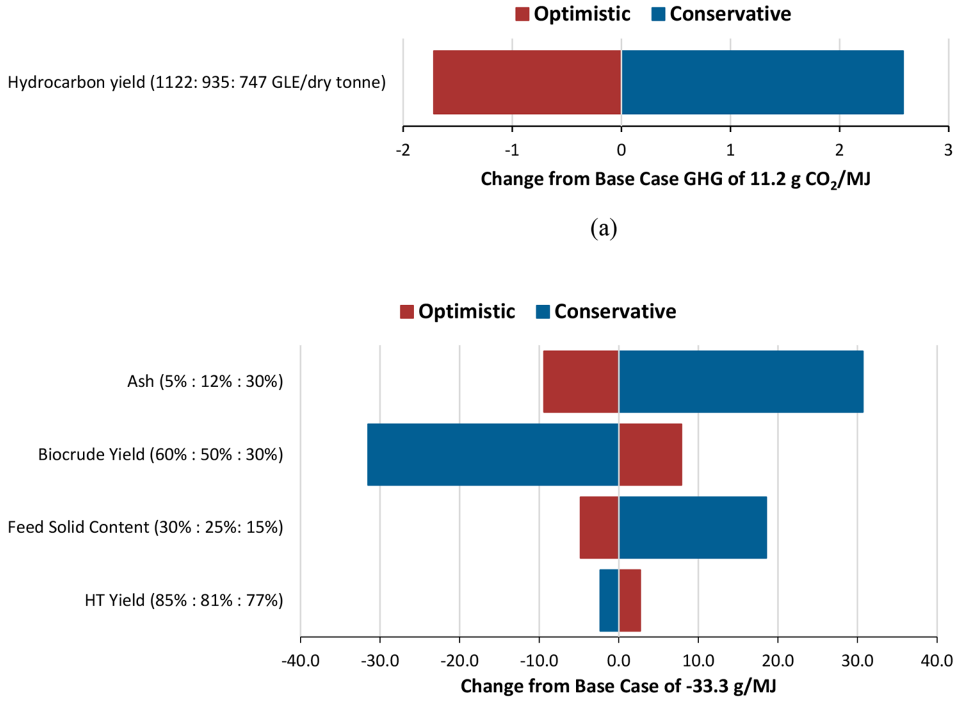


Figure 4. Life-cycle GHG emissions results for MCCI bioblendstocks produced from wet waste feedstocks, in comparison to 91 g of CO_2e/MJ of petroleum diesel.[22]



(a)

(b)

Figure 5. GHG emission sensitivity analysis results for MCCI fuel produced from (a) yellow grease and (b) swine manure HTL.

cost since feed solid dictated the processed aqueous amount. The upgrader capital cost and hydrotreater yield had relatively less impact on the MFSP.

LCA Results. Life-cycle GHG emissions, fossil energy use, NO_x and PM emissions, and water consumption were assessed in this study. GHG results are discussed in detail below, while the other results are included in the Supporting Information.

MCCI Fuel from Yellow Grease to HEFA. Figure 4 shows the life-cycle GHG emissions of the waste-derived MCCI fuels evaluated in this study. The yellow grease to HEFA pathway achieved a GHG emission of 11.2 g of CO_2e/MJ, a 88% reduction relative to petroleum diesel. The GHG emissions were driven by fuel production, which requires a considerable amount of natural gas, electricity, chemicals, and hydrogen

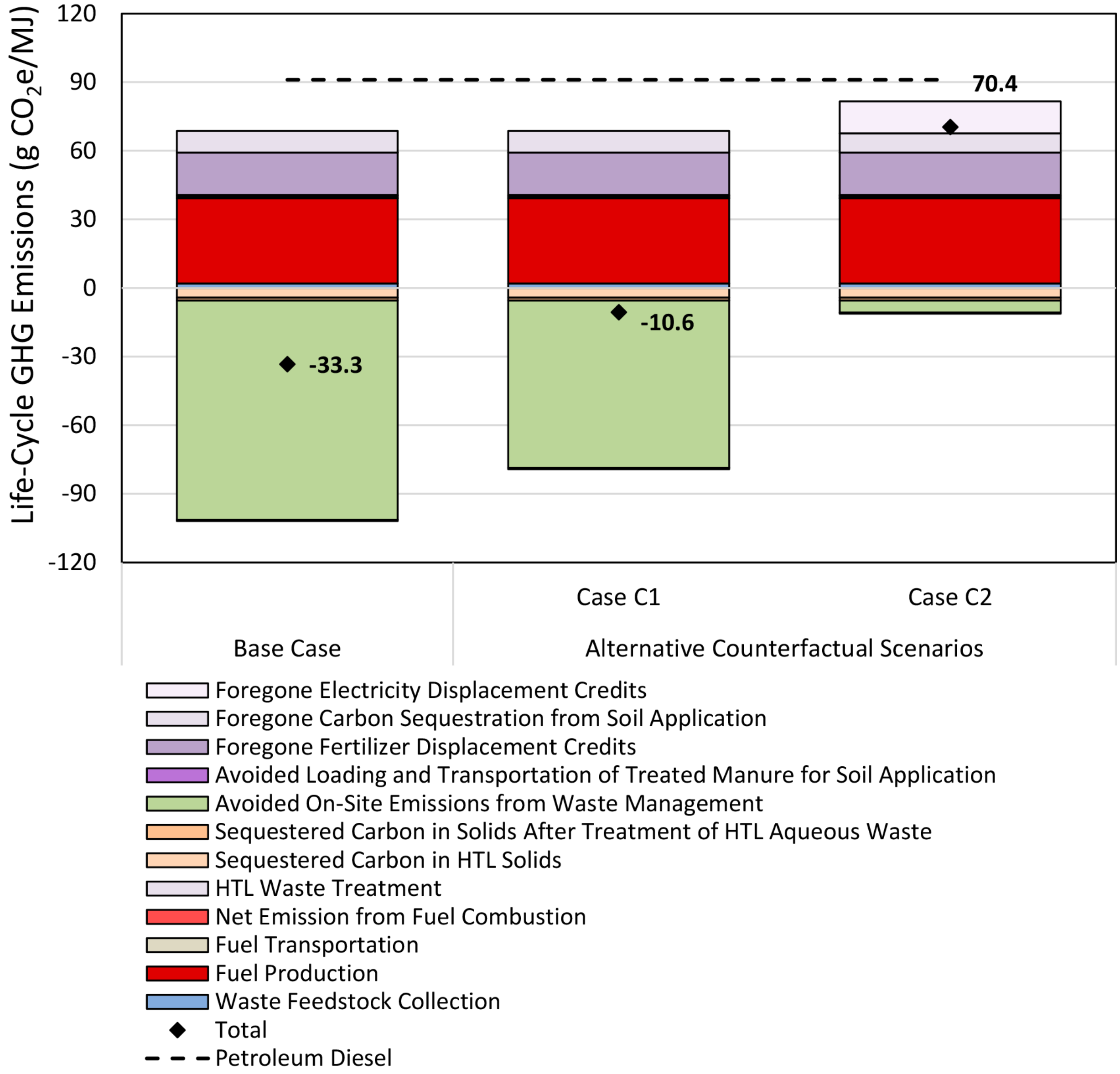


Figure 6. Life-cycle GHG emissions results for MCCI bioblendstocks produced from swine manure via HTL with different counterfactual scenario assumptions, in comparison to 91 g of CO_2e/MJ of petroleum diesel.[22] The base case assumes average U.S. swine manure management practices with 50% of the manageable biogas flared and the remaining vented; Case C1 assumes average U.S. swine manure management practices with 100% of the manageable biogas flared; Case C2 assumes anaerobic digestion for bioelectricity generation in the counterfactual scenario.

during the HEFA conversion step. GHG emissions from feedstock collection, fuel transportation and distribution, and net fuel combustion were minimal. The life-cycle GHG emissions results and its key drivers agree well with previously published results of 12−17 g of CO_2e/MJ.[13]

MCCI Fuel from Swine Manure HTL. Figure 4 shows the life-cycle GHG emissions results of the swine manure HTL pathway under the base case counterfactual scenario. In this scenario, swine manure is treated by the current average swine manure management in the U.S. We assumed that 50% of the manageable CH_4-rich biogas is flared and the remaining becomes fugitive emissions. The LCA results under two alternative counterfactual scenarios are shown in Figure 6 and discussed in the section "Alternative Counterfactual Scenarios for Swine Manure HTL". The manure HTL pathway had a GHG emission intensity of −33.3 g of CO_2e/MJ in the base case, a 137% reduction relative to petroleum diesel. The low GHG emissions were mainly driven by the avoided CH_4 emissions that would otherwise become fugitive emissions in the counterfactual scenario. The conventional manure management systems could generate a great amount of CH_4 which amounted to −95.8 g of CO_2e/MJ. Fuel production was also a major contributor to the GHG emissions, causing 37.3 g of CO_2e/MJ emissions because HTL requires intensive energy inputs including electricity and natural gas, and HTL biocrude upgrading demands a considerable amount of natural gas for hydrogen production. In the counterfactual scenario, treated manure is used for soil application, which displaces synthetic fertilizers and generates GHG credits. Such credits are foregone if manure is used for HTL instead, leading to 18.5 g of CO_2e/MJ GHG emissions. In addition, the foregone credits from carbon sequestration by soil application of treated manure contributed 9.5 g of CO_2e/MJ.

The counterfactual scenario has a great impact on the life-cycle GHG emissions of manure HTL because on-site CH_4 emissions from conventional waste management systems play an important role. Traditional manure management often causes an emission of a significant amount of CH_4, which is a potent GHG. The avoided emissions from waste management thus often lead to considerable GHG credit for the biofuels produced from waste feedstocks. Similar results have also been noted by other LCA research of biogas and bioelectricity produced from waste feedstocks including wastewater sludge and animal manure.[29,30] In consequence, biofuels produced from manure usually have negative life-cycle GHG emissions by avoiding the CH_4 emissions from traditional manure management.[31,32]

Sensitivity Analysis. *Process Assumptions.* Figure 5a shows the GHG emission sensitivity analysis results for the yellow grease to HEFA pathway. Hydrocarbon yield is the only sensitivity parameter (see Table S9) affecting the GHG emissions. A 20% change in the hydrocarbon yield affected the life-cycle GHG emissions by about 2 g of CO_2e/MJ.

Figure 5b shows the GHG emission sensitivity analysis results for the swine manure HTL pathway. The ash content of swine manure had the greatest impact on the GHG emissions. Relative to a 12% ash content in the base case, 30% of feedstock ash increased the GHG emissions from −33.3 g of CO_2e/MJ in the base case to −2.6 g of CO_2e/MJ. In contrast, the life-cycle GHG emissions were reduced to −42.7 g of CO_2e/MJ when feedstock ash content was 5%. The significant impact of feedstock ash content on the GHG emissions can be explained by two reasons. On one hand, high feedstock ash content causes increased GHG emissions from feedstock collection and fuel production because more manure is required to produce 1 MJ of renewable diesel when the manure feedstock has a high ash content. On the other hand, GHG emissions from counterfactual management of high-ash manure are lower due to a reduced volatile solids content. The credits from avoided counterfactual GHG emissions are therefore reduced if feedstock ash content is high.

The impact of HTL biocrude yield on the GHG emissions was considerable and could be counterintuitive. With a low biocrude yield of 30%, the life-cycle GHG emissions were reduced from −31.5 g of CO_2e/MJ in the base case (a biocrude yield of 50%) to −64.8 g of CO_2e/MJ. This is because a lower biocrude yield means that a larger amount of manure is required to be sourced for the production of 1 MJ of renewable diesel, thus resulting in more GHG emission credits from the avoided counterfactual manure management. Since the avoided counterfactual emissions played a dominating role in the total GHG emissions (Figure 4), the high GHG emission credits at a lower biocrude yield outweighed the slight increase in the GHG emissions from fuel production. As a result, a lower biocrude yield led to reduced life-cycle GHG emissions and vice versa. However, low biocrude yield led to a significant increase in the MFSP (Figure 3b). Therefore, biocrude yield represents a trade-off between the environmental and economic implications. To convert the same amount of feedstock for biofuel production, however, the biofuel yield is critical to reducing both life-cycle GHG emissions and costs of the biofuels.

Feedstock solid content affects the diesel consumption for feedstock collection and transportation, energy (natural gas and electricity) demand for HTL, and quicklime usage for waste treatment. When the feedstock contained 30% solids and 70% moisture, the life-cycle GHG emissions were −38.1 g of CO_2e/MJ, a reduction of 4.8 g of CO_2e/MJ relative to the base case (solid content of 25%). When the feedstock solid content went down to 15% and moisture content increased to 85%, the life-cycle GHG emissions increased significantly to −14.7 g of CO_2e/MJ, an increase of 18.6 g of CO_2e/MJ from the base case.

The hydrotreating yield similarly affected the GHG emissions as the biocrude yield, but with a much smaller impact due to the narrow range considered in the sensitivity analysis. A hydrotreating yield of 77% caused the GHG emissions to be reduced from −33.3 g of CO_2e/MJ in the base case (hydrotreating yield of 81%) to −35.6 g of CO_2e/MJ. When hydrotreating yield was increased to 85%, the GHG emissions experienced an increase of 2.7 CO_2e/MJ relative to the base case. Similar to the sensitivity case of biocrude yields, a low hydrotreating yield leads to reduced GHG emissions due to a higher demand for feedstock sourcing that is shifted from the counterfactual manure management, resulting in more emission credits.

Alternative Counterfactual Scenarios for Swine Manure HTL. Figure 6 shows the life-cycle GHG emissions of the swine manure HTL pathway with alternative counterfactual scenario assumptions, in comparison to the results of the base case which assumes average U.S. manure management for the counterfactual scenario. If all the manageable CH_4 emissions from the counterfactual waste management systems were flared (Case C1), the life-cycle GHG emissions of manure HTL would go up to −10.6 g of CO_2 e/MJ, but it still offers a 112% reduction relative to petroleum diesel, owing to a significant amount of unmanageable CH_4 emissions that were avoided and accounted for as a GHG emission credit of −73.1 g of CO_2 e/MJ.

In Case C2, where the manure undergoes dedicated anaerobic digestion to utilize biogas for electricity generation, the GHG emissions of manure HTL increased significantly to 70.4 g of CO_2e/MJ, which was just 23% lower than petroleum diesel. The emission increase relative to the base case counterfactual scenario is mainly attributed to two reasons. First, the generated biogas was collected and combusted for energy production, almost eliminating fugitive CH_4 emissions that would have been accounted for as emission credits in the base case counterfactual scenario. Second, the credits from displacing the grid electricity were foregone by shifting the manure AD biogas production for electricity generation to manure HTL biofuel production.

TEA and LCA Results Synthesis. To illustrate the economic and environmental performances of the two waste feedstock pathways relative to those of petroleum diesel, the marginal GHG emissions abatement costs of these technologies were estimated based on the TEA and LCA results. The marginal GHG emissions abatement cost for a given pathway is defined as the potential marginal cost relative to the price of petroleum diesel, divided by the potential reduction in emissions relative to those of petroleum diesel, as illustrated in eq 1.

$$\begin{aligned}&\text{marginal GHG emissions abatement cost}\\&\quad= [\text{MFSP of MCCI blendstock (\$ per GLE)} - \text{diesel}\\&\qquad\text{price (\$ per GLE)}]/[\text{GHG of petroleum diesel}\\&\qquad(\text{tonne of CO}_2\text{e perGLE}) - \text{GHG of MCCI fuel}\\&\qquad(\text{tonne of CO}_2\text{e per GLE})]\end{aligned}\tag{1}$$

In eq 1, the MFSP of MCCI blendstocks and GHG of MCCI fuel were estimates by this study, and the GHG of petroleum diesel (91 g of CO_2e/MJ, or 2.9 kg of CO_2/GLE) was obtained from GREET 2020.[22] Figure 7 shows the marginal GHG emissions abatement costs for the two pathways compared to petroleum diesel prices in the last 5 years.[27] The marginal GHG emissions abatement cost of MCCI bioblendstocks produced from yellow grease was between \$116 and \$270 per tonne CO_2e. The GHG emissions abatement cost of renewable diesel from swine manure HTL was as low as \$5 to \$103 per tonne CO_2e because of the dramatic reduction of GHG emissions relative to petroleum diesel. To put this in perspective, California's LCFS currently has a carbon credit price of \$200 per tonne of CO_2e for low-carbon transportation fuels.[28]

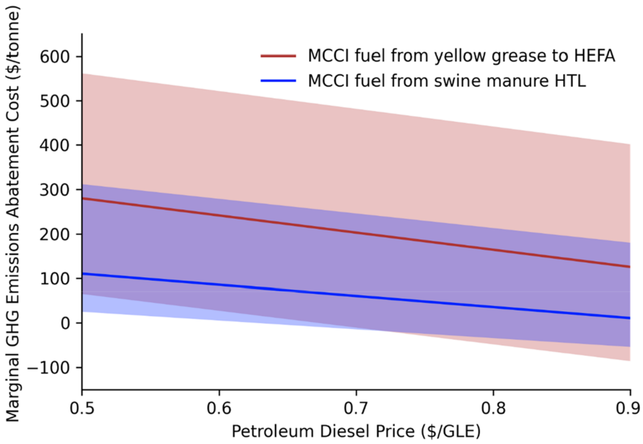


Figure 7. Marginal GHG emissions abatement costs. The shading indicates the boundaries calculated based on the TEA and LCA sensitivity analysis results.

Figure 7 also shows the boundaries of the marginal GHG emissions abatement costs calculated with the maximum and minimum MFSP and GHG emissions estimated in the sensitivity analysis. The estimated marginal GHG emissions abatement cost of the yellow grease to HEFA pathway fell into a wide range because of the wide range of MFSP estimated by the sensitivity analysis. Note that the lower bound of the yellow grease to HEFA pathway, which factors in the \$200 per tonne CO_2 equivalent carbon credit in LCFS,[28] is probably a better reflection of the current market dynamics of the technology, where yellow grease-derived biofuel production receiving the significant LCFS carbon credit has increased the demand for yellow grease for fuel production and driven up its price.[33] The results indicate that yellow grease-derived HEFA could achieve near-zero marginal GHG emissions abatement costs with the current carbon credit.

The marginal GHG emissions abatement costs of MCCI bioblendstocks produced from swine manure HTL are dependent on many factors such as the feedstock cost, counterfactual emission credit, biocrude yields from HTL, and plant size, etc. Figure 7 indicates that this pathway could also achieve near-zero marginal GHG emissions abatement costs under optimiztic conditions (e.g., a significant counterfactual emission credit, a large plant size allowing for economy of scale, optimal biocrude yields, etc.).

Process Scalability. A key challenge of waste-to-fuel scalability is related to the viability of large-scale production because distributed waste resources are a well-known feature for any conversion strategy using a waste resource. The two pathways discussed in this study also face distinct scalability challenges due to resource characteristics, including their location, amount, and quality. A detailed discussion of the scalability of the two pathways are provided in the section "Process Scalability" in the Supporting Information.

■ CONCLUSION

TEA/LCA results of the two waste feedstock pathways highlight their economic and environmental performances and opportunities for improvement. From an economic perspective, the price of waste feedstocks is low and even negative when the cost impact of fuel carbon regulation is considered. Meanwhile, the plant size has a great impact on the MFSP. It is thus critical to develop a robust supply chain for a large-scale waste-to-fuel facility so that production costs could be reduced with economies of scale.

On the environmental side, using waste feedstocks for energy production could offer great GHG emission reduction potentials relative to petroleum diesel fuels. Avoided manure management emissions due to shifting the waste feedstocks to MCCI bioblendstock production could generate great GHG credits for a waste-to-fuel pathway like in the case of the swine manure HTL pathway. No BAU scenario was considered for the yellow grease to HEFA diesel pathway because yellow grease has been utilized for fuel production in an established market. Should the market dynamics of yellow grease as a feedstock for biofuel production change, the cost and environmental impacts of treating yellow grease at wastewater treatment plants should be considered in future analysis.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acssuschemeng.1c06561.

> Renewable diesel from swine manure HTL, technology readiness level, techno-economic analysis assumptions, life cycle assessment assumptions, counterfactual scenario of swine manure HTL (conventional swine manure management), sensitivity analysis assumptions, material and energy balance results, MFSP of the biocrude from swine manure HTL, life-cycle water consumption, fossil energy consumption, NO_x emissions, $PM_{2.5}$ emissions results, and process scalability (PDF)

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Notes

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