Environmental and economic tradeoffs of feedstock usage for liquid fuels and power production

by

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Submitted to the Department of Aeronautics and Astronautics in partial fulfillment of the requirements for the degree of

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Abstract

The thesis is divided into two parts – 1) assessing the energy return on investment for alternative jet fuels, and 2) quantifying the tradeoffs associated with the aviation and non-aviation use of agricultural residues. We quantify energy return on energy investment (EROI) as one metric for the sustainability of alternative jet fuel production. Lifecycle energy requirements are calculated and subsequently used for calculating three EROI variants. $EROI_1$ is defined as the ratio of the lower heating value (LHV) of the liquid fuel produced, to lifecycle (direct and indirect) process fossil fuel energy inputs and fossil feedstock losses during conversion. $EROI_2$ is defined as the ratio of fuel LHV to total fossil fuel energy input, inclusive of the fossil energy embedded in the fuel. $EROI_3$ is defined as the ratio of fuel LHV to the sum of renewable and non-renewable process fuel energy required and feedstock energy losses during conversion. We also define an approximation for $EROI_1$ using lifecycle CO_2 emissions. This approach agrees to within 20% of the actual $EROI_1$ and can be used as an alternative when necessary. Feedstock-to-fuel pathways considered include jet fuel from conventional crude oil; jet fuel production from Fischer-Tropsch (FT) processes using natural gas, coal and/or switchgrass; HEFA (hydroprocessed esters and fatty acids) jet fuel from soybean, palm, rapeseed and jatropha; and advanced fermentation jet (AF-J) fuel from sugarcane, corn grain and switchgrass. We find that $EROI_1$ for conventional jet fuel from conventional crude oil ranges between 4.9–14.0. Among the alternative fuel pathways considered, FT-J fuel from switchgrass has the highest baseline $EROI_1$ of 9.8, followed by AF-J fuel from sugarcane at 6.7. Jet fuel from oily feedstocks has an $EROI_1$ between 1.6 (rapeseed) and 2.9 (palm). $EROI_2$ differs from $EROI_1$ only in the case of fossil-based jet fuels. Conventional jet from crude oil has a baseline $EROI_2$ of 0.9, and FT-J fuel from NG and coal have values of 0.6 and 0.5, respectively. $EROI_3$ values are on average 36% less than $EROI_1$ for HEFA pathways. $EROI_3$ for AF-J and FT-J fuels considered is 50% less than $EROI_1$ on average. All alternative fuels considered have a lower baseline $EROI_3$ than conventional jet fuel.

Using corn stover, an abundant agricultural residue, as a feedstock for liquid fuel or power production has the potential to offset anthropogenic climate impacts associated with conventional utilities and transportation fuels. We quantify the environmental and economic opportunity costs associated with the usage of corn stover for different applications, of which we consider combined heat and power, ethanol, Fischer-Tropsch (FT) middle distillate (MD) fuels, and advanced fermentation (AF) MD. Societal costs comprise of the monetized attributional lifecycle greenhouse gas (GHG) footprint and supply costs valued at the shadow price of resources. The sum of supply costs and monetized GHG footprint then provides the societal cost of production and use of corn stover for a certain application. The societal costs of conventional commodities, assumed to be displaced by renewable alternatives, are also calculated. We calculate the net societal cost or benefit of different corn stover usages by taking the difference in societal costs between corn stover derived fuels and their conventional counterparts, and normalize the results on a feedstock mass basis. Uncertainty associated with the analysis is captured using Monte-Carlo simulation.

We find that corn stover derived electricity and fuels reduce GHG emissions compared to conventional fuels by 21-92%. The mean reduction is 89% for electricity in a CHP plant, displacing the U.S. grid-average, 70% for corn stover ethanol displacing U.S. gasoline and 85% and 55% for FT MD and AF MD displacing conventional U.S. MD, respectively. Using corn stover for power and CHP generation yields a net mean societal benefit of \$48.79/t and \$131.23/t of corn stover, respectively, while FT MD production presents a mean societal benefit of \$27.70/t of corn stover. Ethanol and AF MD production from corn stover result in a mean societal cost of \$24.86/t and \$121.81/t of corn stover use, respectively, driven by higher supply costs than their conventional fuel counterparts. Finally, we note that for ethanol production, the societal cost of CO_2 that would need to be assumed to achieve a 50% likelihood of net zero societal cost of corn stover usage amounts to approximately $\sim$\$100/tCO_2, and for AF MD production to $\sim$\$600/tCO_2.

Thesis Supervisor: Steven R.H. Barrett
Title: Assistant Professor of Aeronautics and Astronautics

Acknowledgments

A poet, named Kabir, once said:

Guru gobind dou khade, kaake lagoon paay?
Balihari guru aapne gobind diyo batay

I face both God and my guru - whom should I bow to first?
I first bow to my guru because he's the one who showed me the path to God.

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1. Introduction

Alternative jet fuels have the potential to diversify energy sources for aviation beyond petroleum [1]. In the case of using biomass-derived alternatives, they can contribute to mitigating aviation's impact on climate change [2], which has been estimated at $\sim$3.5% of total anthropogenic radiative forcing [3]. While alternative jet fuel use is currently small relative to conventional fossil fuel use (<0.01% of total jet fuel consumption in the US in 2013, for example [4]), national and international bodies have introduced goals for alternative fuel usage, which are aimed at facilitating large scale adoption of alternative jet fuels. The International Air Transport Association (IATA) targets 10% alternative fuel use in global aviation by 2017 [5], and the US Federal Aviation Administration (FAA) has a goal of one billion gallons of alternative fuel consumption by 2018 (5% of domestic jet fuel consumption) [6]. 21 of the 36 billion gallons of alternative fuel production mandated by the Renewable Fuels Standard in the US for 2022 could come from renewable jet fuel [7].

Previous studies have assessed the feasibility and sustainability of alternative jet fuels from a production cost perspective [8] and from an environmental perspective, including emissions [9], associated health and economic impacts [10] and impacts on land and water resources [2]. We consider two metrics to evaluate the environmental and economic performance of alternative fuels: energy return on investment (EROI) for alternative jet fuel production and the societal costs of alternative feedstock usage. EROI is the ratio of fuel energy return to the amount of energy required to process and obtain it. It can be used to evaluate the long-term sustainability of producing alternative aviation fuels. Societal costs comprise of the monetized lifecycle GHG footprint, and supply costs for alternative feedstock-to-fuel pathways, valued at the shadow price of resources. We use a societal cost-benefit analysis framework to assess the environmental and economic tradeoffs associated with the use of bioenergy feedstocks for liquid fuels and power production.

2. Energy Return on Investment for Alternative Jet Fuels

2.1 Introduction

EROI is defined as the ratio of fuel energy return, as defined by the product of fuel mass and lower heating value, to the amount of energy required to obtain it [11]. It gives an indication of the extent to which an energy investment pays off in terms of the energy contained in the resulting jet fuel. We compute variants of EROI for alternative feedstock-to-jet fuel pathways and compare the results with those for conventional jet fuel from crude oil. There has been previous research on the EROI of certain biofuels such as corn ethanol [12] and soybean biodiesel [13, 14] but the results are not applicable to aviation. This is because none of these fuels are suited for use in aircraft engines due to incompatible fuel properties, such as increased risk of fire or explosion in the case of ethanol [15], or poor thermal stability and a high freezing point in the case of biodiesel [16].

This study is the first to quantify EROI for a broad range of alternative jet fuel production pathways. Alternative production pathways considered in this analysis include:

1. Hydroprocessed esters and fatty acids jet (HEFA-J) fuel from soybean, rapeseed, palm and jatropha

2. Fermentation and advanced fermentation jet (AF-J) fuel from sugarcane, corn grain and switchgrass

3. Fischer-Tropsch jet (FT-J) fuel from natural gas (NG), coal and switchgrass

The pathways (Figure 2-1) are selected on the basis of near-term viability: Fischer-Tropsch and HEFA fuels have already been evaluated under ASTM D4054 [17] and certified under ASTM D7566 [18]. A subset of the AF-J pathway (alcohol-to-jet fuel) is expected to be one of the next set of pathways to be certified [19].

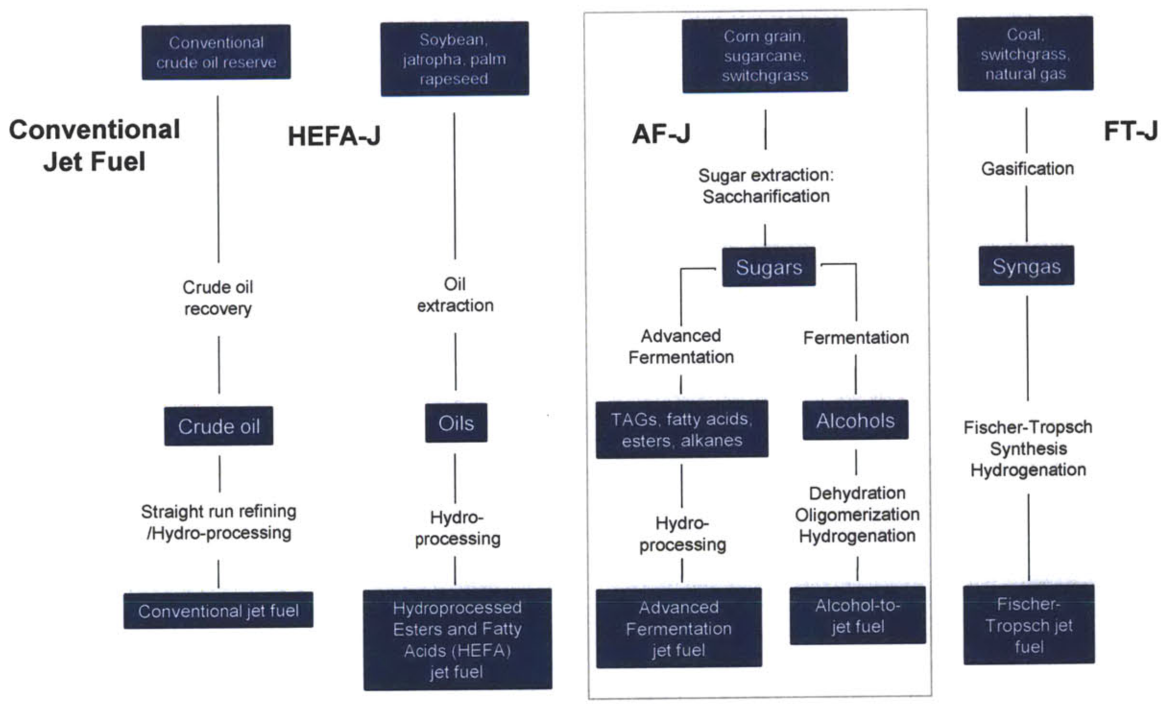

Figure 2-1: Feedstock-to-jet fuel pathways considered in this assessment, together with major processing steps, platform molecules and other relevant intermediate products.

2.2 Method

2.2.1 Lifecycle energy use

EROI is defined as the useful energy (lower heating value) that is returned in the form of jet fuel to the energy required to obtain it. Different accounting techniques for conversion energy requirements can lead to variants in the EROI metric [11, 20–22]. Our lifecycle energy requirement calculations for alternative aviation fuels are carried out using the GREET model (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation model) [23]. The conventional jet, HEFA and FT pathways are analyzed in GREET version 2012 and the AF pathway is analyzed in GREET.net [24]. Assumptions used to build lifecycle energy use inventories for the AF-J pathways are sourced from Staples et al. [25], while others are sourced from Stratton et al. [26].

We adopt the net-energy balancing approach suggested by Shapouri et al. [27], and Wang [28] in the development of the GREET transportation fuel-cycle model. This approach has previously been used to develop EROI analysis frameworks [11, 29]. We account for direct and indirect energy usages at all stages of the fuel lifecycle. Direct energy inputs are calculated from the lower heating values (LHV) of process fuels and feedstocks. Indirect energy inputs occur during the production of process fuels and other resources used in the fuel production lifecycle, such as fertilizer and grid electricity.

The total energy input for converting a feedstock to a fuel can be traced back to the energy content (LHV basis) of feedstocks used to produce the process fuels in the lifecycle. As an example, consider diesel as a fuel input for transportation — we account for the energy content of the diesel used in addition to the process energy input for producing diesel, starting from crude oil recovery. Due to thermodynamic and process inefficiencies, some feedstock energy is wasted during conversion to fuel; we include this loss as a process energy input, derived as the reciprocal of the conversion efficiency minus one unit energy of fuel produced. While some studies suggest including the embodied energy in fuel production infrastructure [30], the contribution of such energy sources is small relative to primary energy inputs (such as process fuel combustion) [27]. Further, we neglect energy requirements for the construction of facilities, supporting infrastructure and machinery, which have been estimated at 1–4% of the total lifecycle energy requirements for liquid fuel production [13].

We address three key issues associated with the lifecycle analysis (LCA) approach:

1. **System boundaries**: The system boundaries for the LCA are drawn around the direct and indirect material and energy flows associated with the jet fuel lifecycle. The lifecycle steps include feedstock cultivation/extraction, transport, jet fuel production, and finally fuel distribution prior to combustion.

2. **Co-product allocation**: We follow recommendations set forth by Wang et al. [31] and allocate energy use among different fuel products on the basis of fuel energy content. Upstream energy usages are allocated on the basis of the relative market values of upstream co-products (such as soy meal), provided marketable goods exist.

3. **Data quality & uncertainty**: We study technologies that have either already been commercially deployed, or are soon to be commercialized. Low, baseline and high EROI scenarios (Table 2.1) capture data variability and uncertainty.

Table 2.1: Pathway-specific assumptions

		Key Assumption	Low	Baseline	High
	Conventional jet fuel	Refining Efficiency (LHV)	88%	91%	98%
FT-J	Natural gas FT-J	FT Process Efficiency (LHV)	60%	63%	65%
	Coal FT-J		47%	50%	53%
	Switchgrass FT-J		42%	45%	52%
	Coal & switchgrass FT-J		47%	50%	53%
		Biomass weight fraction	10%	25%	40%
HEFA-J	Soybean HEFA-J	Soybean yield (t/ha)	2.2	3.0	4.5
	Palm HEFA-J	Palm FFB yield (t/ha)	16.5	19.2	21.0
	Rapeseed HEFA-J	Rapeseed yield (t/ha)	2.8	3.4	3.9
		Seed oil fraction	41%	44%	45%
	Jatropha HEFA-J	Jatropha seed yield (t/ha)	1.0	2.5	5.0
		Seed oil fraction	34%	35%	37%
AF-J	Sugarcane AF-J	Pretreatment method (milling)	Conventional		State-of-the-art
		Metabolic efficiency	80%	85%	90%
	Switchgrass AF-J	Pretreatment method	Aq. ammonia	Dilute alkali	Dilute acid
		Metabolic efficiency	80% C6 sugars	85% C6 sugars	90% C6 sugars
			50% C5 sugars	60% C5 sugars	70% C5 sugars
	Corn grain AF-J	Pretreatment method	Dry milling		
		Metabolic efficiency	80%	85%	90%

2.2.2 EROI_1 definition and approximation approach

EROI_1 is defined as the ratio of fuel energy output, to **process fossil fuel** input and fossil-feedstock energy losses in fuel conversion.

$$\text{EROI}_1 = \frac{(\text{Energy Content of Jet Fuel})_{\text{out}}}{\sum(\text{Energy in Process Fossil Fuels \& Fossil Feedstock Loss})_{\text{in}}} \tag{2.1}$$

The definition represents the quantity of fuel energy out per unit of fossil energy in, or in other words, the ratio of fuel energy to the total process fossil energy used to obtain the fuel in its final form. All calculations assume energy content on an LHV basis. The loss of fossil feedstock is a result of the conversion efficiency between the feedstock and the fuel, and is therefore an unavoidable waste of energy to obtain the final fuel. An EROI_1 greater than one implies a net positive return on fossil energy investment, while an EROI_1 less than one implies that more fossil energy is used to produce the fuel than the energy contained within that fuel. Thus, renewable jet fuels reduce dependence on non-renewable fossil fuels if EROI_1 is greater than one.

Since energy consumption is accompanied by CO_2 emissions arising from fuel combustion, CO_2 emissions are an indicator of the amount of energy consumed during a process. Jet fuel combustion CO_2 emissions can be regarded as a proxy for the energy embedded in jet fuel, or in the context of EROI, as energy return. Non-biogenic well-to-tank (WTT) CO_2 emissions that occur during the different steps of the fuel production lifecycle, up to the aircraft tank, can serve as a proxy for energy use. We therefore define an approximation of EROI_1 (EROI'_1)

$$\text{EROI}'_1 = \frac{(\text{Jet fuel combustion emissions, gCO}_{2e}/\text{MJ})}{(\text{Total lifecycle WTT emissions gCO}_{2e}/\text{MJ})} \approx \text{EROI}_1 \tag{2.2}$$

This may be useful for feedstock-to-fuel pathways for which greenhouse gas (GHG) emissions LCA has already been conducted and emissions data is readily available. Note that the approximation assumes small relative differences in carbon intensity of fuels.

2.2.3 $EROI_2$ definition

$EROI_2$ is defined as the ratio of fuel energy output, to **total fossil energy input**, including the fossil energy comprising the fuel in addition to the process fossil energy inputs as previously defined

$$EROI_2 = \frac{(\text{Energy Content of Jet Fuel})_{\text{out}}}{\sum(\text{Energy in Process Fossil Fuels \& Fossil Feedstock})_{\text{in}}} \tag{2.3}$$

$EROI_2$ emphasizes the scarcity and non-renewable character of fossil resources by taking into account fossil energy contained in the feedstock that is converted into finished jet fuel. For example, although conventional jet fuel has a comparatively high $EROI_1$ due to low process fossil fuel use and minimal conversion losses, $EROI_1$ does not account for the fossil energy input of crude oil feedstock that is converted and embodied in the finished jet fuel. $EROI_2$ takes total fossil feedstock inputs into account, inclusive of feedstock losses, and therefore all fossil-based jet fuels will have an $EROI_2$ of less than one. Jet fuel produced from completely renewable feedstocks will have identical $EROI_1$ and $EROI_2$ values.

2.2.4 $EROI_3$ definition

$EROI_3$ is defined as the ratio of fuel energy output, to the energy content of **all process fuels** and feedstock loss, whether fossil or renewable

$$EROI_3 = \frac{(\text{Energy Content of Jet Fuel})_{\text{out}}}{\sum(\text{Energy in Process Fuels \& Feedstock Loss})_{\text{in}}} \tag{2.4}$$

$EROI_3$ places emphasis on the fact that while biofuels use renewable resources that replenish over time, there are opportunity costs associated not only with fossil, but also with biomass resources. Comparing $EROI_3$ against $EROI_1$ reveals the degree to which the total process energy use for jet fuel production is fossil based.

2.3 Results and discussion

2.3.1 Lifecycle energy use for alternative jet fuel production

Energy requirements in the baseline case (see Table 2.1), broken down by fossil and total energy requirements for each lifecycle step, are shown in Figure 2-2. The fuel energy return (1 MJ in this case), divided by the fossil and total energy inputs provides $EROI_1$ and $EROI_3$, respectively. We find that all biofuel pathways have higher total energy inputs than conventional jet fuel, as shown in Figure 2-2. There are several reasons for this: conventional crude oil requires relatively little energy to extract in liquid form, whereas biomass must be cultivated and harvested, requiring energy in the form of fertilizer production and application, for example. Also, in the case of HEFA jet and AF-J fuels, the feedstock must be extracted using energy-intensive technologies such as pressing of oily-feedstocks, or dilute acid pre-treatment of switchgrass [25]. Both HEFA-J and AF-J fuels have higher energy requirements for feedstock extraction and transportation. Using baseline values, soybean HEFA jet fuel, for example, requires ~100 kJ of energy input per MJ of finished jet fuel for feedstock extraction and transport, whereas conventional jet fuel requires ~44 kJ (see Figure 2-2).

Unlike crude oil and petroleum products, biomass feedstocks are essentially oxygenates. For instance, the oxygen-to-carbon ratio in soybean oil is 0.11 [32]. Before these oils can be used as jet fuel, their oxygen content must be removed. One way to do this is through hydroprocessing — a more energy-intensive process than its counterpart for conventional crude oil in petroleum refineries [33]. For conventional jet fuel, hydroprocessing is only applied to a portion of the fuel in order to remove sulfur content and/or to increase the jet fuel cut. As a result, the baseline fossil energy requirement for the fuel conversion step for soybean HEFA jet fuel, for instance, is ~422 kJ per MJ of jet fuel, whereas it is ~120 kJ/MJ for jet fuel from conventional crude. We note that alternative fossil-based fuels (FT-J from NG and coal) also have higher total production energy requirements than conventional jet fuel.

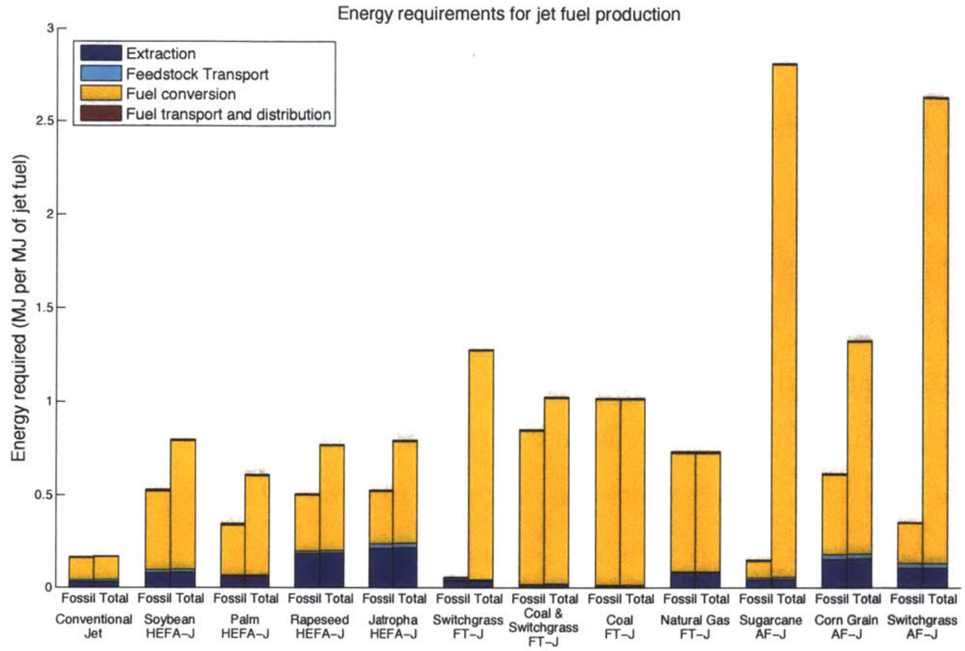

Figure 2-2: Baseline energy requirements, broken down into fossil and total energy requirements for each lifecycle step.

2.3.2 $\mathbf{EROI}_{1,2,3}$ results summary

$\mathrm{EROI}_{1,2,3}$ for the alternative jet fuels considered are presented in Figure 2-3 alongside the conventional jet fuel reference scenario. Depending on its definition, EROI in the baseline case for conventional jet varies from 0.9 (EROI_2) to 5.9 (EROI_1). Similarly, baseline EROI for other fossil-based jet fuels varies from 0.5 (EROI_2, coal FT-J) to 1.4 (EROI_1, NG FT-J). Accounting for fuel energy as a fossil input in the case of fossil-based jet fuels leads to the decrease from EROI_1 to EROI_2. Renewable jet fuels have a baseline EROI ranging from 0.4 (EROI_3, sugarcane AF-J) to 9.8 (EROI_1, switchgrass BTL). The decrease from EROI_1 to EROI_3 for renewable pathways scales with the feedstock energy wasted during fuel conversion and with the feedstock use for co-producing process utilities at the fuel production facilities. This is because EROI_3 is inclusive of renewable process energy inputs, together with the fossil energy inputs accounted for in EROI_1. Comparisons between EROI_1 and EROI_2 provide information on the degree to which fuel is sourced from fossil-based feedstocks, while comparisons between EROI_1 and EROI_3 provide information on the degree to which process energy inputs are renewable or fossil-based.

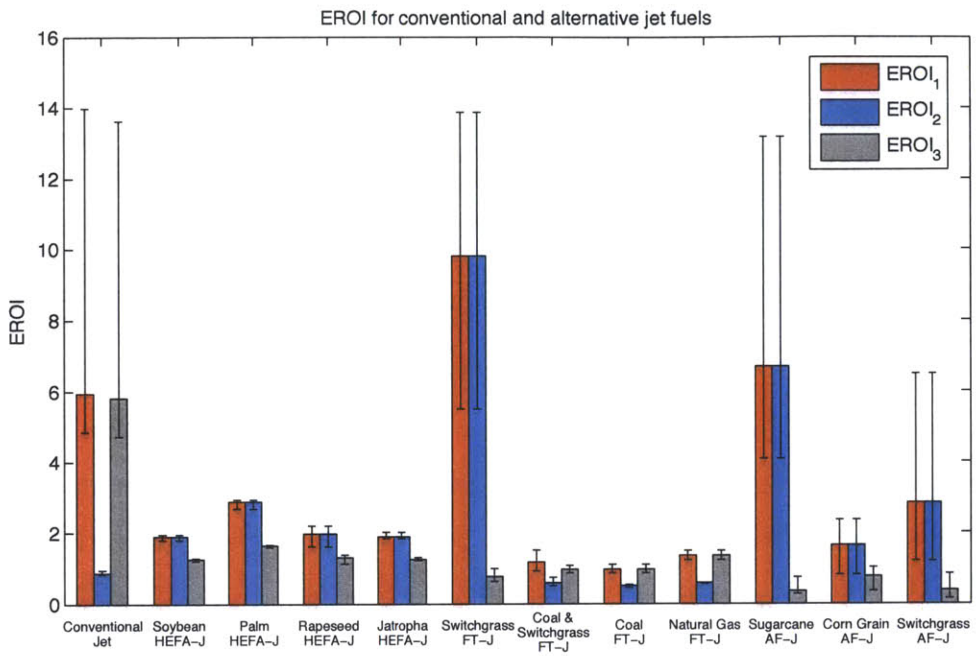

Figure 2-3: $\mathrm{EROI}_{1,2,3}$ for alternative jet fuels considered.

2.3.3 EROI_1 results

Conventional jet fuel from conventional crude oil has an EROI_1 of 5.9 in baseline scenario (U.S. refinery average). Straight run jet fuel (high EROI scenario) and hydroprocessed jet fuel (low EROI scenario) have an EROI_1 of 14.0 and 4.9, respectively. Additional energy requirements for the latter (resulting in a lower $\mathrm{EROI}_{1,2,3}$) arise from processes including vacuum distillation, hydrotreating, and hydrocracking [34]. EROI_1 results lie between 1.6–2.9 for HEFA jet, between 0.9–13.9 for FT-J and between 0.8–13.2 for AF jet fuel. All renewable pathways considered have a baseline EROI_1 of greater than unity. Of the pathways considered, FT-J fuel from switchgrass has the highest EROI_1 due to onsite utility co-generation minimizing the need for fossil energy inputs at the facility. The lowest EROI_1 is calculated for coal FT-J, since relatively more fossil energy is required for the F-T production process, including the coal combusted onsite for utility generation and feedstock loss during FT synthesis.

Gasification efficiency, on an LHV of feedstock basis, is 50% in the baseline case for coal FT-J, compared to 63% for NG FT-J. Therefore, more feedstock energy in the form of coal is required to produce the same amount of jet fuel – resulting in a lower $\mathrm{EROI}_{1,2,3}$.

2.3.4 $\mathbf{EROI_1}$ approximation ($\mathbf{EROI'_1}$) results

Figure 2-4 shows the results for the EROI'_1 approximation alongside EROI_1. Detailed results of EROI'_1 and well-to-tank CO_2 emissions are available in Appendix A. Since we require a proxy for the energy used, we use the WTT CO_2 emissions without any biomass credit apportioned to the jet fuel. Lifecycle emissions are calculated for each pathway using the GREET model. As can be seen from Figure 2-4, EROI'_1 agrees to within 20% of EROI_1 on average. We note that EROI'_1 is subject to having knowledge of lifecycle CO_2 emissions of the pathways.

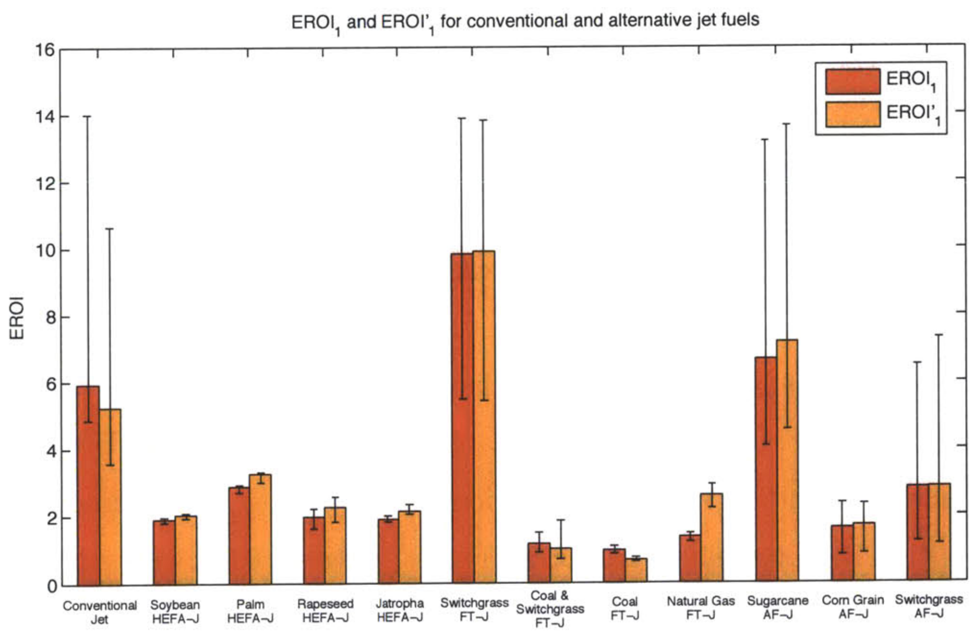

Figure 2-4: EROI_1 and EROI'_1 estimation for the alternative jet fuels considered

EROI'_1 is exactly equal to EROI_1 only when the average CO_2 intensity of process fossil fuels is equal to the CO_2 intensity of jet fuel combustion. Therefore, EROI_1 is overestimated when low-carbon process fuels (relative to conventional jet fuel on a lifecycle basis) are predominant, and it is underestimated when carbon-intensive process fuels are used. Since most alternative fuel pathways rely on high shares of natural gas among the process fuels used, EROI_1' is higher than the actual EROI_1 in 75% of cases examined.

2.3.5 $\mathbf{EROI_2}$ results

EROI_2 differs from EROI_1 for only those pathways where the feedstock is at least partially fossil-based. Of the non-renewable feedstock options studied herein, conventional jet from crude oil has the highest baseline EROI_2 of 0.9, followed by NG FT-J with an EROI_2 of 0.6 and coal FT-J at 0.5. For coal and switchgrass FT-J, EROI_2 values increase with increasing biomass blend share from 0.5 for a 25% mass-based switchgrass blend to 0.7 for a 40% switchgrass blend.

We can use the results for EROI_2 and EROI_1 to calculate the amount of fossil energy displaced by the production and combustion of a renewable alternative jet fuel

$$\frac{\mathrm{MJ}_{\text{fossil displaced}}}{\mathrm{MJ}_{\text{renewable}}} = \frac{1}{\mathrm{EROI}_{2,\text{ conv. jet}}} - \frac{1}{\mathrm{EROI}_{1,\text{ ren. jet}}} \tag{2.5}$$

The first term on the right side of the equation gives the total lifecycle fossil energy input of using one MJ of conventional jet fuel, which amounts to 1.2 MJ, since an additional 0.2 MJ of fossil fuels are required throughout the jet fuel production lifecycle. The second term on the right side of the equation gives the fossil energy investment for producing one unit of renewable jet fuel, which varies depending on the feedstock and pathway considered. We find that the HEFA based jet fuels considered here displace approximately 0.7 MJ of fossil fuels for every 1 MJ of HEFA jet fuel produced and combusted. AF-J pathways displace between 0.6 MJ (corn grain AF-J) and 1.02 MJ (sugarcane AF-J) of fossil energy per MJ of jet, while FT-J from switchgrass displaces 1.1 MJ per MJ produced and combusted.

2.3.6 $EROI_3$ results

The difference between $EROI_1$ and $EROI_3$ scales with decreasing fossil energy share of the total energy inputs for fuel production. $EROI_3$ is approximately 30–43.5% lower than $EROI_1$ for the HEFA pathways considered in this analysis. Fossil pathways (conventional jet fuel, coal FT-J, NG FT-J) rely on conventional fuel inputs and grid electricity as well. Although unlike the HEFA pathways, where the conversion losses are renewable in nature, fossil-based feedstock losses are accounted for in both $EROI_1$ and $EROI_3$, and consequently the difference between them is also small (<3% for fossil-based feedstocks).

In the switchgrass FT-J pathway, biomass is gasified to satisfy the utility requirements of the process. Since there are no other significant external process energy inputs, the lifecycle fossil energy input share is ~6% of the total energy required during lifecycle. Consequently, while switchgrass FT-J has a baseline $EROI_1$ of 9.8, which is 66% higher than the $EROI_1$ for conventional jet fuel, its baseline $EROI_3$ is 0.75, which is 87% lower than the baseline $EROI_3$ for conventional jet fuel. The same trends occur for the sugarcane and switchgrass AF-J fuels, for which the utility requirements of the biorefinery are satisfied by combustion of biomass or biomass residue that remains after sugars have been extracted.

2.4 Conclusion

Energy return on investment is the ratio of useful fuel energy return to the conversion process energy required. $EROI_1$ can be used to compare the fossil-fuel intensity of alternative fuel pathways. Along with lifecycle GHG emissions and other metrics, $EROI_2$ can be used to compare environmental performance of alternative fuels, while $EROI_3$ can be used to compare conversion efficiencies. For all of the renewable jet fuel pathways studied in this analysis, the fossil energy inputs required to extract and process feedstock into jet fuel are smaller than the total amount of energy in the final fuel. Consequently, the renewable fuels considered have the potential to decrease reliance on fossil energy resources for fuel production and use. The ability to produce renewable jet fuels without any use of non-renewable resources depends on the rate of adoption of renewables in sectors providing inputs to the fuel pathway under consideration, such as electricity and hydrogen production.

The definition of EROI can significantly change the results, as observed in the case of $EROI_1$, $EROI_2$ and $EROI_3$. We have discussed the reasons for differences between variants of the EROI metric as doing so provides information on how different energy input accounting techniques affect EROI. We close by noting that EROI is an instructive metric to quantify the viability of alternative jet fuels from the standpoint of the energy investment. For a holistic picture of the sustainability of a certain alternative jet fuel, the results from EROI calculations need to be complemented by calculations for other metrics such as lifecycle greenhouse gas emissions, costs of production, water footprint and land requirements.

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3. Environmental and economic trade-offs of agricultural residue use as transportation fuel

3.1 Introduction

Agricultural residues available in the United States include corn stover, rice straw and sugarcane bagasse, among others. Corn stover is the most abundant of all such residues, amounting to approximately three-fourths of available residues by mass [35]. Approximately 5% of corn stover on the field is currently removed for use as a cattle feed and bedding [36]. The remainder is left on the field after harvesting corn grain, to preserve soil organic carbon levels and inhibit soil erosion [37]. Up to 30% of corn stover can be removed for alternative uses without affecting soil quality [1]. This presents an opportunity for corn stover use for ethanol [38], combined heat and power [39] or middle distillate (MD) fuels production [2], which is otherwise foregone if corn stover is left unutilized.

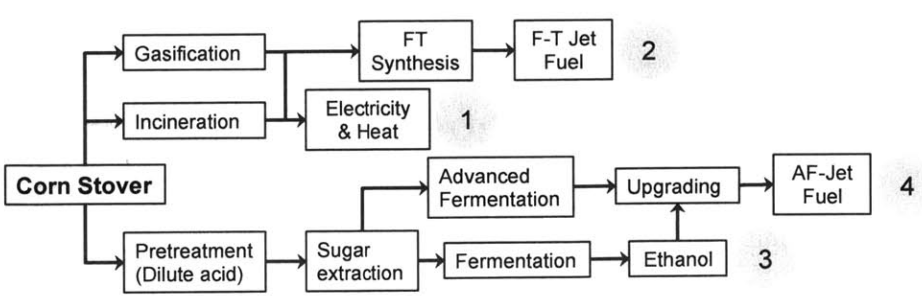

Figure 3-1: Corn stover pathways for end uses considered

This is the first assessment of the environmental and economic opportunity costs of using agricultural residues for liquid fuels and power production. Figure 3-1 illustrates the pathways for corn stover uses considered. Previous analyses have assessed competing end uses of biomass from either an environmental perspective [40–45], or from a technoeconomic perspective [46–53]. To our knowledge, no study integrates these metrics in a societal cost-benefit framework. Moreover, available technoeconomic studies usually calculate minimum selling prices, rather than supply costs valued at the shadow price of resources. The latter is necessary for a societal cost-benefit analysis.

In this study, the societal cost or benefit of using corn stover for production of liquid fuels and power is calculated as the difference between the sum of monetized greenhouse gas emissions and the supply costs of a certain corn-stover usage, and the sum of these metrics for the conventional commodity, that is assumed to be displaced by the renewable alternative. Table 3.1 lists the conventional commodities that are assumed to be displaced with respect to each scenario of corn stover usage.

Table 3.1: Scenarios for corn stover end uses and conventional commodities displaced

Scenario	End use of corn stover	Conventional commodity displaced
1a	Electricity production	U.S. grid average electricity
	Heat production	Natural gas heat
1b	Electricity production	U.S. grid average electricity
2	Fischer-Tropsch (FT) MD production	U.S. conventional MD
3	Ethanol production	U.S. conventional gasoline
4	Advanced fermentation (AF) MD production	U.S. conventional MD

3.2 Materials and methods

We use a cost-benefit analysis framework for comparing alternative uses of corn stover [10]. Costs and benefits to society from the use of corn stover are quantified relative to a conventional fuel or utility displaced.

3.2.1 Lifecycle GHG emissions impact

We address three issues associated with lifecycle analyses (LCA) — system boundary definition, co-product allocation and data quality and uncertainty. Feedstock recovery and transport, feedstock-to-fuel conversion, distribution and combustion of the finished fuel are included within the system boundary for the LCA. We include the GHG emissions associated with direct farm operations such as swathing, baling and transport, in addition to indirect GHG emissions arising from the production and use of replaced fertilizer after corn stover removal. Upstream direct and indirect emissions arising from feedstock transport to facility, pretreatment and conversion to fuel are taken into account. Land use change emissions are not accounted for in this study. Following Wang et al. [31], we allocate GHG emissions among fuel products and utilities on an energy allocation basis. Probability distributions (Table 3.2) capture variability associated with parameters that affect the lifecycle GHG emissions and the supply costs for alternative corn stover uses. We use fuel conversion parameters from industry data and archival literature on commercialized conversion technologies or those that are pending near-term deployment.

3.2.2 Supply costs

Supply cost includes costs associated with the use of resources, including labor, capital, fuel and raw material. Supply cost calculations in this context are therefore devoid of monetary transactions that are not directly associated with any resource use, such as loan payments, taxes and subsidies. Capital costs for facilities are distributed over the lifetime total energy amount of fuel or utility produced, and are thus captured in the supply costs. Resources used are valued at their 'shadow' or 'accounting' price, reflecting the associated societal opportunity costs. The shadow price of outputs is measured by the utility derived from their consumption. In the case where the shadow price of a resource is unavailable, market price is used as a proxy after removing taxes and profit margins.

3.2.3 Societal costs and benefits

The societal cost comprises of the cost of resource use (supply cost) and the cost of externalities determined by monetizing environmental impacts. Doing so allows us to consistently compare both economic and environmental impacts of corn stover use. To calculate the societal cost of lifecycle greenhouse gas (GHG) emissions, we use estimates on the societal cost of CO_2 from the simplified climate and environmental impact model of the Aviation Portfolio Management Tool (APMT) [54]. APMT calculates the net present value (NPV) of climate damages, using damage functions to translate environmental impacts into societal costs. We do not consider environmental externalities other than monetized lifecycle GHG emissions, such as air quality impacts from particulate matter.

In addition to the societal cost of alternative uses, we also assess the societal costs of conventional fuel counterparts. The net societal cost is calculated by subtracting the societal cost of the conventional commodity being displaced from the societal cost of alternative fuels from corn stover. We normalize the results on a per unit mass of corn stover basis, to emphasize and homogeneously compare the societal cost or benefit for each end use. Finally, we assess the GHG abatement cost, or the break-even cost of CO_2 for each end use to have zero societal cost.

3.2.4 Monte-carlo analysis

Uncertainty associated with the analysis is quantified using a Monte-Carlo simulation. Probability distributions are defined and referenced in Table 3.2. Section 3.2.6 discusses key parameters and pathway-specific assumptions.

Table 3.2: Input values for Monte-Carlo analysis (Triangular: [Low (a), Mode (b), High (c)])

Parameter	Nominal range	Units	Distribution
Feedstock			
Corn stover yield [55]	[1.5,2.4,4.5]	t/ha	Triangular
Moisture content (at field) [1, 37, 56]	[0.15,0.25,0.35]	%	Triangular
Moisture content (at facility) [57, 58]	[10,15,20]	%	Triangular
Nitrogen fertilizer application [43, 44, 59, 60]	[0,7.4,8.8]	(kg/t stover)	Triangular
Phosphorus fertilizer application [43, 44, 59, 60]	[0,2.9,4.1]	(kg/t stover)	Triangular
Potassium fertilizer application [43, 44, 59, 60]	[0,12.5,16.5]	(kg/t stover)	Triangular
Tractor hauling distance [39, 61]	[10,15,20]	km	Triangular
Truck transport distance [39, 61]	[40,60,80]	km	Triangular
GHG footprint, farming hay [62]	$\mu = 94.5$, $\sigma = 10.1$	gCO_{2e}/kg	Normal
Swathing cost [63]	[25.20,31.88,39.54]	$/t	Triangular
Baling cost [63]	[51.50,43.69,36.48]	$/ha	Triangular
Transport cost [63]	[4,5,6]	$/ha	Triangular
Nitrogen fertilizer cost [64]	[551,863,992]	$/bale (700 kg)	Triangular
Phosphorus fertilizer cost [64]	[551,800,992]	$/t	Triangular
Potassium fertilizer cost [64]	[551,863,882]	$/t	Triangular
Price of hay [55]	[159.13,211.37, 261.17]	$/t	Triangular
U.S. grid electricity price [65]	[6.40,9.84,12.30]	cents/kWh	Triangular
U.S. NG extraction cost [66]	[4.27,5.83,8.91]	$/MMBtu	Triangular
Brent crude oil price [67]	[79.61,111.63,143.65]	$/bbl	Triangular
Crude transport cost [68]	[2,3,5]	$/bbl	Triangular
Fuel conversion			
CHP rating [69 71]	[10000,25000,40000]	kW	Triangular
Overall CHP efficiency [70, 71]	[70,75,80]	%	Triangular
GHG footprint, U.S. grid [65, 72]	[170.7,186.2,190.7]	gCO_{2e}/MJ	Triangular
GHG footprint, N.G. heat [72]	[59.2,66.2,75]	gCO_{2e}/MJ	Triangular
CHP O&M cost [70]	[0.42,0.49,0.50]	cents/kWh	Triangular
Ethanol yield [38, 48–51, 73, 74]	[42,79,90]	gal/ton	Triangular
GHG footprint, ethanol refinery [72]	[9.7,12.0,19.7]	gCO_{2e}/MJ	Triangular
GHG footprint, U.S. gasoline [34, 72]	[90.0,92.0,95.2]	gCO_{2e}/MJ	Triangular
Cost of raw materials (EtOH production) [38, 73]	[36.3,48.4,60.5]	cents/gal EtOH	Triangular
Fixed cost for EtOH production [38, 73]	[14.5,19.4,24.2]	cents/gal EtOH	Triangular
Capital cost for EtOH production [38, 73]	[351.2,468.3,585.3]	$MM	Triangular
Advanced fermentation MD yield [25]	[8.19,5.19,2.34]	MJ/kg stover	Triangular
GHG footprint, U.S. conventional MD [34, 72]	[82.7,90.5,97.5]	gCO_{2e}/MJ	Triangular
Capital cost for AF MD production [25]	[0.38,0.53,2.93]	$/gal MD	Triangular
Fixed cost for AF MD production [25]	[1.20,1.90,4.36]	$/gal MD	Triangular
FT synthesis efficiency [26]	[42,45,52]	%	Triangular
Capital cost for FT MD production [8, 75]	[68,213.5,408]	thousand $/bpd	Triangular
Societal cost of CO_2			
Societal cost of CO_2, 2% discount rate	$\mu = 41.5$, $\sigma = 22.3$ 95% C.I. range [2.3,89.2]	$/$tCO_2$	Normal
Societal cost of CO_2, 1% discount rate	$\mu = 149.7$, $\sigma = 80.9$ 95% C.I. range [8.1,326.5]	$/$tCO_2$	Normal
Societal cost of CO_2, 7% discount rate	$\mu = 4.9$, $\sigma = 2.6$ 95% C.I. range [0.3,10.3]	$/$tCO_2$	Normal

3.2.5 Discount rates for climate costs

Discounting addresses the time value of societal externalities, and is used to assess the present value of future climate damages. APMT uses a constant discount rate to calculate the monetized net present value of CO_2 emissions induced climate damages [76]. The damages are assessed over a 30 year accrual period, which is considered to be appropriate for policy analyses [54]. The choice of discount rate is debated in published literature [77]. Reported choices for the appropriate discount rate for climate change range between 1–7%, based on the intergenerational, irreversible damages of long lived atmospheric greenhouse gases. The U.S. Office of Management and Budget (OMB) suggests using a discount rate of 2–7% [78], while notable studies by Nicholas Stern and William Nordhaus discount climate damages at 1.4% and 5.5%, respectively [77]. We apply a discount rate of 2% in the baseline case [79], and assess the sensitivity of societal costs using discount rates of 1% and 7%.

3.2.6 Corn stover feedstock and end uses

The method for calculating lifecycle GHG emissions and supply costs for each alternative use is specified in the following sections.

Feedstock

Corn stover is assumed to be sourced from a 40–80 km radius around the fuel or power production facility. We assume removal of 30% of corn stover by mass from the field post corn harvest, referring to previous estimates for sustainable residue removal rates [35, 37, 39, 80–82]. Further, the ratio of corn yield to corn stover yield is assumed to be 1.0 on a mass basis [1]. The system boundary for corn stover collection includes farm operations required to gather and remove corn stover from the field in a second swathing pass, after corn harvest. We determine the GHG emissions from swathing, baling and transporting corn stover from the field to the farm gate [61]. We account for additional fertilizer required to replace lost nutrients during corn stover removal [43, 44, 59, 60] (see Table 3.2). The low GHG emissions scenario assumes no impact on nutrient loss from stover removal. Corn stover bales are delivered to the facility via truck, prior to being chopped in preparation for conversion or combustion. The cost of delivered corn stover is computed using survey data on farm operation costs [63] and fertilizer price indices [64]. Variability and uncertainty in collection and transport costs are captured using probability distributions based on reported cost data (summarized in Table 3.2).

Electricity and heat

Chopped corn stover may either be incinerated or gasified to produce electricity through a steam or gas turbine, respectively. We model combined heat and power, or CHP plants with an electrical generation capacity of between 10-40 MW, based on a survey of existing plants [71]. The electrical efficiency of steam turbine CHP systems reportedly varies between 15-38%, with a U.S. industry average of 18%, while that of gas turbine-based systems reportedly approaches 40%, with a typical electrical efficiency of 35% [70, 83]. The range of CHP configurations and efficiencies is correlated against rated capacity to establish bounds for fuel requirements. The overall efficiency of the CHP system is estimated to vary between 70-80% [70]. We determine the quantity of heat generated for each scenario from:

$$\text{Efficiency} = \frac{\text{Elec. output (MJ)} + \text{Heat output (MJ)}}{\text{LHV of fuel input (MJ)}} \tag{3.1}$$

The GHG emissions for the CHP facility were estimated based on the ecoinvent LCA database [62]. We assume 6.5% electric power transmission and distribution line losses [84]. Combined heat and power systems are installed onsite to meet local power or thermal requirements [70]. Emissions are allocated among electricity and heat outputs in CHP system scenario 1a, and to electricity in scenario 1b. The cost of CHP generation is based on statistics of installed capital costs together with operating and maintenance costs [70]. Costs for steam and gas turbine technology-based CHP plants are calculated with respect to their rated capacity, with a capacity factor of 82% [70, 85]. The cost of fuel is assessed as the cost of delivered dry corn stover.

Fischer-Tropsch MD

Fischer-Tropsch or FT MD is produced through catalytic synthesis of gasified biomass to paraffinic hydrocarbons. We model the production of FT MD in a biomass-to-liquid (BTL) facility with a capacity of 5000 fuel barrels per day [26]. The facility is assumed to be self-sufficient with respect to energy requirements. We assume an FT synthesis efficiency of 45% in the baseline case [26]. Lifecycle GHG emissions for FT MD from corn stover are calculated using GREET, accounting for fuel transport and distribution to pumps. The supply cost of MD from the FT facility is calculated using capital and operating expenditure data from Pearlson et al. (2012) [75], along with the supply cost of delivered corn stover as the feedstock cost. Financing, profit margins and taxes are removed from all supply cost calculations.

Ethanol

Ethanol is produced from corn stover using enzymatic sugar extraction and conversion in a biorefinery. The steps include dilute-acid pretreatment of corn stover, prior to saccharification, fermentation, separation and distillation [38]. Ethanol yields are assumed to vary between 42–90 gal/ton (175–376 l/t) of corn stover, with a baseline value of 79 gal/ton (330 l/t) in a 61 MMgal/year (230.9 million l/year) facility [38, 48–51, 73, 74]. Waste residue and biogas are combusted to produce steam, which is run through a steam turbine for fulfilling plant utility requirements. The ethanol production pathway is modeled in GREET for calculating lifecycle GHG emissions. We account for GHG emissions of U.S. domestic transport and distribution of ethanol. Both the GREET model calculations, as well as supply cost calculations are based on an NREL model (Aspen plus) ethanol production facility [38, 86]. The cost of ethanol production is based on the cost of installed capital, as well as fixed and variable operating costs. Variable operating costs include the feedstock cost and the cost of raw materials, while the fixed operating cost includes labor and maintenance. The ethanol plant is assumed to operate at a 96% capacity factor.

Advanced fermentation MD

Corn stover delivered to an AF middle distillate production facility is pretreated and hydrolysed to extract monomer sugars. Engineered microorganisms metabolize sugars into intermediate platform molecules, which are subsequently upgraded to produce the final fuel. Data on feedstock-to-fuel conversion efficiency, utility requirements and other process parameters is taken from Staples et al. [2]. Lifecycle GHG emissions for AF MD are calculated in GREET, using the energy allocation method to allocate emissions among fuel co-products at the fuel production facility. Inputs for calculating lifecycle GHG emissions and supply costs are based on probability distributions corresponding to a range of possible intermediate platform molecules: fatty acids, ethanol and triglycerides. Supply cost for AF MD is calculated using industry and literature estimates for capital and operating costs for a 4000 bpd facility [87].

3.2.7 Conventional commodities displaced

We describe the top-down approach used to calculate the supply costs and lifecycle GHG emissions for conventional fuels or utilities (commodities) that can be displaced by the use of corn stover derived fuels/utilities.

Electricity and heat from conventional sources

We use the GREET model to calculate U.S. grid average GHG emissions, based on the U.S. grid generation mix [88], and for calculating the GHG emissions for heat from natural gas. Supply costs for the U.S. grid average are assessed via a top-down revenue analysis of existing electric utilities, estimated at 70% of the electricity price [89]. The retail price of electricity is assumed to vary between 6-12 cents/kWh, with a mean of ~9.84 cents/kWh [65].

The U.S. Department of Energy estimates the U.S. average exploration and recovery cost of natural gas at $6.24/MMBtu (0.59 cents/MJ) [66]. The Henry Hub spot price of natural gas has been lower than its extraction cost over the past five years, indicating a cross-subsidy from the co-production of crude oil. The natural gas pipeline transport cost is estimated at \$0.28/MMBtu (0.03 cents/MJ) [79]. The delivered supply cost of natural gas is estimated at \$6.52/MMBtu (0.62 cents/MJ). We take an annual fuel utilization efficiency of between 75-95% [90], and add capital and operating costs for natural gas fired heating units, assumed to be 4% of the overall heating cost [91].

U.S. conventional MD

We calculate lifecycle GHG emissions for conventional MD from the U.S. averaged conventional crude oil mix, based on refining assumptions from Stratton et al. (2011) [26]. The Energy Information Administration reports the 2012 U.S. Brent crude price at \$111.63/bbl (94 cents/l) [67]. The supply cost of crude oil is calculated by factoring oil producers' profit margins and corporate income taxes, estimated at 26.4% and 40%, respectively [79, 92]. This results in a crude supply cost of \$70.37/bbl (59 cents/l). The difference between the MD spot price and the brent crude price is taken as the cost to refine crude oil to MD fuels, after accounting for profit margins and taxes. Using a 2012 MD spot price of \$128.35/bbl (\$1.08/l), and removing a profit margin of 7.9% for U.S. refiners, along with a 40% corporate income tax [92], we arrive at a MD refining cost of \$14.87/bbl (12 cents/l). Transport and distribution costs are estimated at \$3/bbl (2.5 cents/l) [68].

U.S. conventional gasoline

Lifecycle GHG emissions for U.S. gasoline from the U.S. average crude oil mix are calculated using GREET. We take the difference between the gasoline spot price and the Brent crude price as the cost to refine crude oil to gasoline, after accounting for profit margins and taxes. Taking a 2012 gasoline spot price of \$118.23/bbl (99 cents/l), and removing profit margin and taxes, we arrive at a gasoline refining cost of \$5.87/bbl (5 cents/l). Transport and distribution costs are estimated at \$3/bbl (2.5 cents/l) [68].

3.3 Results and discussion

The results of the bottom-up analysis for each alternative use is compared against the top-down analysis for conventional fuels or utilities that are displaced. Lifecycle GHG emissions for the U.S. grid average is estimated at 182.6 gCO_{2e}/MJ of electricity in the baseline case. The supply cost for U.S. grid in the baseline case is found to be 6.65 cents/kWh, compared to the U.S. average retail price of 9.84 cents/kWh in 2012 [65]. Lifecycle GHG emissions for electricity from a corn stover fueled CHP plant is found to be 20.5 gCO_{2e}/MJ (mean), in a scenario where no heat is displaced, resulting in a potential GHG emissions reduction of ~89% relative to the U.S. grid average. The supply cost of electricity from corn stover is approximately 12% less than that of the U.S. grid average at 5.95 cents/kWh in the baseline case. The mean supply cost of natural gas heat is estimated at 0.82 cents/MJ, compared to a mean supply cost of $0.70 cents/MJ for heat from corn stover.

Average supply cost for U.S. gasoline is estimated at 1.89 $/gal (1.54 cents/MJ) in the baseline case, while lifecycle GHG emissions for U.S. gasoline is estimated at 92.4 gCO_{2e}/MJ. Lifecycle GHG emissions for corn stover ethanol is computed at 27.8 gCO_{2e}/MJ, resulting in a ~70% reduction relative to U.S. gasoline. The supply cost for corn stover ethanol is found to be ~45% higher than U.S. gasoline in the baseline case. We find that compared to the baseline lifecycle GHG emissions of 90.3 gCO_{2e}/MJ for conventional U.S. MD, that of FT MD and AF MD fuel is 87% lower (12.0 gCO_{2e}/MJ) and 55% lower (40.3 gCO_{2e}/MJ), respectively. The supply cost for FT MD fuel in the baseline case is 6% less than that of conventional MD ($2.11/gal or 1.60 cents/MJ), at $1.99/gal (1.57 cents/MJ). That of AF MD fuel, however, is $5.99/gal (4.74 cents/MJ) in the baseline case, within a range of $3.98-8.34/gal in the 95% confidence interval. Variability in the AF MD pathway is driven primarily by the conversion efficiency of the platform molecule, while that of FT MD is driven by the FT synthesis efficiency.

3.3.1 Lifecycle GHG emissions

Greenhouse gas emissions for corn stover is primarily driven by nutrient or fertilizer replacement rates — accounting for 56% of the GHG emissions in the baseline case. Of the nutrients reapplied, nitrogen (N) fertilizer has the highest GHG emissions footprint, accounting for up to 40% of the total GHG emissions for baled corn stover. We account for the GHG emissions for transporting corn stover to the facility (15% of total GHG emissions) and for chopping corn stover in preparation for fuel conversion (18% of total GHG emissions).

The GHG footprint for combined heat and power for corn stover is driven by the conversion efficiency of the CHP plant. Using gas turbine technologies with an electrical efficiency as high as 38% can result in the lifecycle GHG emissions for electricity from corn stover being a factor of 20 less than the U.S. grid average. Feedstock recovery, transport and preparation collectively comprises 83% of lifecycle GHG emissions for electricity generation in a CHP plant. Approximately 47% of the GHG emissions for corn stover ethanol are attributable to the feedstock-to-fuel conversion process, driven by cellulase and yeast requirements at the facility for metabolic conversion (comprising 57% of lifecycle GHG emissions attributable to the conversion process). Reported ethanol yields are highly variable (42–90 gal/ton of corn stover), resulting in a lifecycle GHG footprint of 22.2–35.4 gCO_{2e}/MJ of ethanol.

A majority of the GHG footprint of FT MD production comprises feedstock recovery, transport and chopping in preparation for gasification (95% in the baseline case). Energy requirements at the FT facility are fulfilled by cogeneration of heat and power, therefore leading to a relatively low GHG footprint for feedstock conversion as compared to ethanol or AF MD production from corn stover. Feedstock extraction, transportation and processing accounts for 61% of the lifecycle GHG emissions for AF MD production in the baseline case. The remainder is driven by utility requirements for fuel conversion [25].

3.3.2 Supply costs

Supply costs for baled corn stover at the farm gate are primarily driven by the cost of farm operations (~60%), including diesel and labor costs for swathing, baling and transport. Fertilizer costs account for ~40% of corn stover supply costs, primarily driven by the cost of potassium. Transporting corn stover to a fuel conversion or CHP facility accounts for roughly 21% of the supply costs in the baseline case. In the baseline case, capital costs, fuel and operating costs account for 12%, 80% and 8% of supply costs for combined heat and power generation systems, respectively. Variability in the supply cost of electricity ranges within ±20–28% of the mean supply cost, within the 95% confidence interval (CI), primarily due to variable feedstock costs. Feedstock costs vary between \$55.98–88.07/t of corn stover (95% CI), with a mean of \$71.68/t.

Corn stover ethanol supply costs comprise primarily of variable operating costs (75% of total in the baseline case). Variable operating costs are driven by feedstock costs and the cost of enzyme production for fermentation, comprising 68% and 19% of total variable operating costs, respectively. Unlike other fuel pathways, where the capital costs comrpise less than 15% of total supply costs, FT MD production has high capital requirements, leading to 33% capital costs as a percentage of supply costs. Feedstock costs primarily drive supply costs for both FT and AF MD production, comprising 65% and 45% of supply costs in the baseline case, respectively. Other operating costs at the AF facility, such as utility requirements, account for 43% of AF MD supply costs in the baseline case.

3.3.3 Societal costs and benefits

We normalize the results with respect to corn stover unit mass. We then monetize lifecycle greenhouse gases using estimates for the societal cost of CO_2, with a mean value of \$149.70/tCO_2 and a range of \$2.30–89.20/tCO_2 (95% confidence interval). The resulting societal cost of corn stover use (sum of monetized GHG and supply cost) is compared against that of displaced conventional fuels to result in a net societal cost (or benefit), per unit mass of corn stover usage. Figure 3-2 illustrates the net GHG emissions and societal cost for each end use of corn stover considered. A negative value indicates a net GHG or societal benefit, while a positive value indicates a net societal cost.

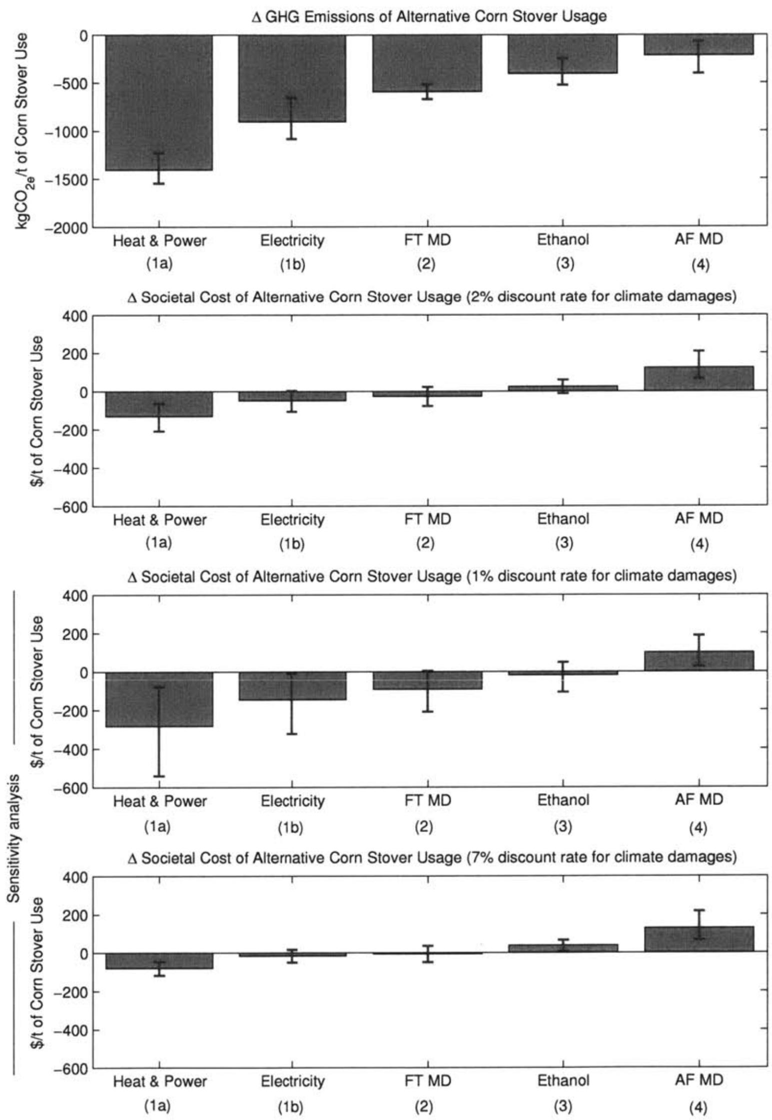

Figure 3-2: Overview of societal costs/benefits from alternative corn stover use

From a societal standpoint, displacing the U.S. grid average in addition to heat from natural gas with combined heat and power from corn stover results in the highest mean societal benefit ($131.23/t corn stover). The mean societal benefit decreases by

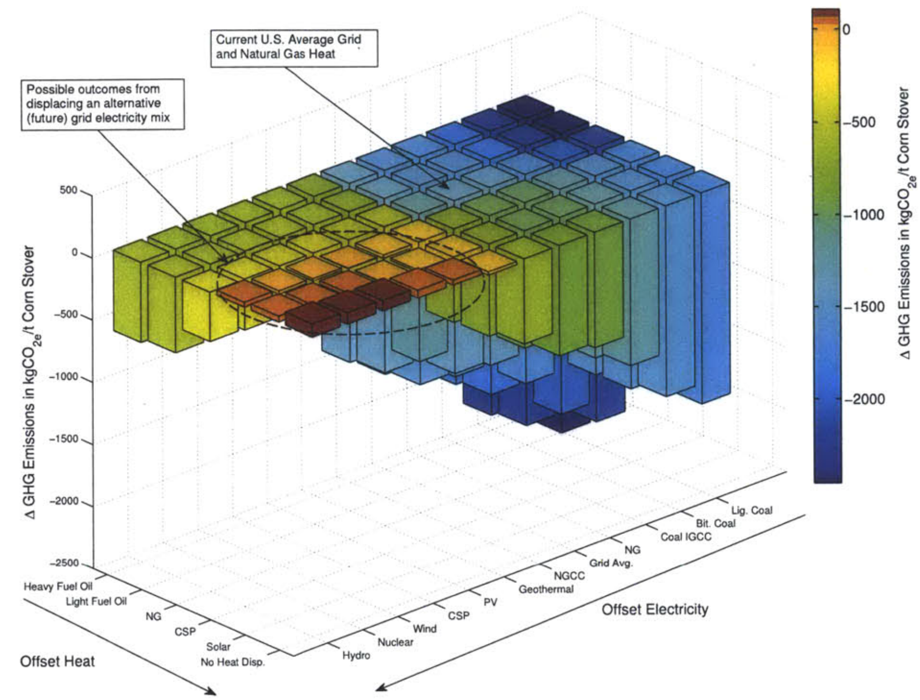

Figure 3-3: Alternative displacement scenarios for electricity and heat from corn stover

approximately two-thirds for a scenario where electricity alone from the CHP plant displaces the U.S. grid average electricity (\$48.79/t corn stover). The use of FT MD fuel may result in a mean societal benefit of approximately \$27.70/t of corn stover in the baseline case. Ethanol and AF MD fuels incur a net mean societal cost of \$24.86/t and \$121.81/t of corn stover in the baseline case, respectively.

The net delta in societal cost of alternative corn stover uses is driven by the difference between the supply cost of conventional and corn stover based fuels/utilities. The cost of feedstock comprises ~80% of the total supply cost for combined heat and power from corn stover, ~52% of the supply cost for ethanol production, and ~65% of the supply cost of FT MD production from corn stover. For AF MD production, the cost of feedstock comprises ~45% of the supply cost, while the remainder consists of other operating costs, such as enzyme costs, and the cost of capital equipment. The overall feedstock-to-fuel conversion efficiency for AF MD ranges between 14-50%, with a baseline of 32%, driven by the choice of corn stover pretreatment technology, target platform molecule and the metabolic efficiency.

The net lifecycle GHG emissions for power and heat is driven by the difference between the lifecycle GHG emissions footprint of the current U.S. grid and natural gas derived heat, and that of combined heat and power from corn stover. We assess cases where electricity and heat from corn stover displace other non-renewable and renewable sources of electricity and heat. The net lifecycle GHG emissions from displacing various combinations of electricity and heat from corn stover are presented in Figure 3-3. The EIA projects that renewables in the electricity mix will increase from the current value of 10% of electricity generation to 16% of total generation by 2040 [93]. Natural gas is predicted to supply ~80% of heat from combined heat and power facilities in 2040. Of the renewables, wind and conventional hydropower generation is forecast to comprise ~80% of total renewable electricity generation in 2040. In such a scenario, displacing a hydroelectric source of power can result in a net increase in lifecycle GHG emissions of ~100 $kgCO_{2e}/t$ of corn stover used for electricity generation, against a lifecycle GHG emissions benefit of ~900 $kgCO_{2e}/t$ for displacing the current U.S. grid average electricity mix. Outcomes of displacing potential alternative sources of electricity and heat are illustrated in Figure 3-3.

The result of our Monte Carlo analysis indicates that in all cases analyzed, the net GHG emissions impact for alternative corn stover usage as a fuel was negative — indicating an emissions saving. Although the net environmental benefit (as measured by the GHG emissions impact) of corn stover usage for combined heat and power is the greatest in the reference scenario of natural gas and current U.S. grid average displacement, there are other technologies such as hydro-electric power sources which result in a lower GHG footprint. Monetized GHG emissions account for 3–7% of net societal costs for CHP generation and ethanol production from corn stover, 2–4% for FT MD production and 1–6% for AF MD production from corn stover. For conventional fuels displaced, monetized GHG emissions account for 19–40% of U.S. grid average societal costs, and 17–34% of societal costs for heat from U.S. natural gas. That for conventional MD and conventional gasoline accounts for 12–27% and 12–28% of societal costs, respectively.

Supply costs for power generation from corn stover are lower (by ~9%) than that of the conventional U.S. grid in 73% of cases analyzed, while supply costs for heating from a corn stover CHP facility are lower (by ~13%) than that of natural gas heating in 80% of cases analyzed. Net societal costs for combined heat and power are less than zero (lower than that of conventional generation) in all cases analyzed, while that of power generation is lower than the societal cost of the U.S. average grid in 99% of cases analyzed. The supply cost for corn stover derived ethanol is higher (by ~47%) than U.S. gasoline supply costs in 99% of cases analyzed, whereas the net societal cost of ethanol is higher than that of U.S. gasoline in 91% of cases analyzed due to the inclusion of monetized GHG benefits. The net societal cost for FT MD production is negative (less than conventional MD) in 85% of cases, while that for AF MD is greater than zero (higher than conventional MD) in all cases. The supply cost of conventional MD is higher than FT MD in 55% of cases (with a mean value of ~1% higher across all cases), and lower (by approximately a factor of 3) than AF MD in all cases.

We assess the societal cost of CO_2 that is required for net societal cost neutral usage of alternative fuels from corn stover. Combined heat and power and FT MD have at least a 50% probability of a societal benefit (negative societal cost) with a zero societal cost of CO_2. Producing ethanol and AF MD incur mean societal costs of \$24.86/t and \$121.81/t of corn stover in the case of zero cost of CO_2, respectively. We find that the societal cost of CO_2 required to achieve a 50% probability of net zero societal cost of corn stover usage is ~\$100/tCO_2 for ethanol production and ~\$600/tCO_2 for AF MD production, respectively.

3.3.4 Sensitivity to choice of discount rate

The results of our sensitivity analysis indicate that producing electricity, heat and FT MD from corn stover leads to a societal benefit in almost all cases (97 100%) for a 1% discount rate. The societal costs of ethanol and FT MD production from corn stover are found to be most sensitive to the societal cost of CO_2. Ethanol production from corn stover incurs a societal cost in 99% of cases, and a societal benefit in 66% of cases analyzed, using a societal cost of CO_2 that corresponds to a 7% and 1% climate cost discount rate, respectively. FT MD from corn stover results in a mean societal benefit of \$6.20/t and \$91.97/t using discount rates of 7% and 1%, respectively. AF MD from corn stover results in a societal cost in 99% of cases assessed using a 1% discount rate, and in all cases for higher discount rates.

Table 3.3: Societal cost sensitivity analysis

	Mean societal cost (\$/t)			**Probability of societal benefit**		
	Discount rate for climate cost			Discount rate for climate cost		
	1%	2%	7%	1%	2%	7%
CHP	-\$282.89	-\$131.23	-\$80.06	100%	100%	100%
Electricity	-\$146.25	-\$48.79	-\$15.82	99%	97%	80%
FT MD	-\$91.97	-\$27.70	-\$6.20	97%	85%	61%
Ethanol	-\$18.87	\$24.86	\$39.77	66%	9%	1%
AF MD	\$98.71	\$121.81	\$129.58	1%	0%	0%

3.4 Conclusion

We find that CHP, ethanol and MD produced from corn stover results in a 21-92% reduction in GHG footprint compared to conventional fuels. The net benefit in the environmental case is greatest for combined heat and power, and electricity in the reference scenario of displacing the U.S. average grid and natural gas (1.4 tCO_{2e}/t corn stover). We demonstrate that there is significant variability in the results (net GHG emissions increase of 0.1 tCO_{2e}/t to a net benefit of 2.5 tCO_{2e}/t of corn stover), associated with offsetting sources of electricity and heat beyond the current U.S. grid and natural gas, respectively. With a mean societal cost of CO_2 of \$41.50/tCO_2 (2% discount rate for NPV of climate costs), power and CHP generation from corn stover present a mean societal benefit of \$48.79/t and \$131.23/t of corn stover, respectively, while FT MD production presents a mean societal benefit of \$27.70/t of corn stover. From a societal cost standpoint, AF MD and ethanol production from corn stover incur higher supply costs than their conventional fuel counterparts, resulting in a mean societal cost of \$121.81/t and \$24.86/t of corn stover use, respectively. Finally, we note that the societal cost of CO_2 required to achieve a 50% likelihood of net zero societal cost of corn stover usage is approximately $\sim\$100/tCO_2$ for ethanol production and $\sim\$600/tCO_2$ for AF MD production.

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4. Conclusion

In this thesis, two metrics for the environmental and economic sustainability of alternative fuel production and use have been quantified. The first metric, the Energy Return on Investment (EROI), deals with the sustainability of alternative fuels from an energy return standpoint, while the second addresses the opportunity costs of bioenergy feedstock use for liquid fuels and power production. Since energy investment can be defined in different ways, we consider three variants that include both fossil and total energy inputs to calculate EROI. The energy in a unit quantity of renewable jet fuel is greater than the sum of fossil energy inputs required to produce the fuel from a renewable feedstock. Conventional jet fuel from conventional crude oil (U.S. refinery crude average) has an $EROI_1$ of 5.9 in the baseline scenario. This amounts to 1.2 MJ of fossil energy use for every 1 MJ of conventional U.S. jet fuel produced and combusted. FT-J from switchgrass and AF-J from sugarcane have the potential for a higher $EROI_1$ than conventional jet fuel, with a baseline $EROI_1$ of 9.8 and 6.7, respectively. From a lifecycle perspective, the use of renewable jet fuel displaces fossil energy by up to 1.1 MJ, per MJ produced and combusted (range of 0.6–1.1 MJ/MJ).

As a second metric, we have quantified the net societal costs and benefits of using agricultural residues for the production of liquid fuels and power. The societal cost or benefit is calculated as the difference between the sum of monetized greenhouse gas emissions and the supply costs of a certain corn stover usage, and the sum of these metrics for the conventional commodity, that is assumed to be displaced by the renewable alternative. The net environmental benefit (as defined by net GHG emissions) is greatest for combined heat and power in the reference scenario of displacing the U.S. average grid and natural gas (1.4 tCO_{2e}/t corn stover). CHP, ethanol and MD produced from corn stover presents a 21–92% reduction in GHG footprint compared to conventional fuels. With climate costs discounted at a rate of 2%, CHP and power generation from corn stover result in a mean societal benefit of \$131.23/t and \$48.79/t of corn stover use, respectively. At a 1% discount rate for climate costs, ethanol production from corn stover results in a net societal benefit (mean of \$18.87/t) in 66% of cases analyzed, while FT MD results in a net societal benefit in almost all cases analyzed (mean of \$91.97/t). At a 2% discount rate, FT MD from corn stover results in a net mean societal benefit of \$27.70, in 85% of cases. AF MD production from corn stover results in a net societal cost of between \$98.71–129.58/t of corn stover in >99% of cases analyzed for discount rates of 1–7%. We note that for ethanol production, the societal cost of CO_2 that would need to be assumed to achieve a 50% likelihood of net zero societal cost of corn stover usage amounts to approximately ~\$100/tCO_2, and for AF MD production to ~\$600/tCO_2.

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A. Energy return on investment – supplemental information

A.1 Pathway-specific assumptions

A.1.1 EROI for conventional jet fuel from conventional crude oil

Table A.1: EROI 1, 2 and 3 for Conventional Jet (GREET 2012)

	Low	Baseline	High
Key Assumptions			
Process Efficiency (LHV)	88%	91.10%	98%
Life cycle Fossil Energy Input by Stage			
Fossil Energy Inputs			
Feedstock Extraction & Transportation (J input / MJ fuel)	42,516	42,516	42,516
Fuel Conversion & Distribution (J input / MJ fuel)	163,673	126,080	29,002
$EROI_1$	4.85	5.93	13.98
$EROI_2$	0.83	0.86	0.93
Total Energy Inputs			
Feedstock Extraction & Transportation (J input / MJ fuel)	44,126	44,126	44,126
Fuel Conversion & Distribution (J input / MJ fuel)	167,418	127,884	29,295
$EROI_3$	4.73	5.81	13.62

Table A.2: U.S. Crude Import Fractions by Source (2003)

U.S. Crude Oil Sources	Production/Import as % of Refinery Crude Input Assumed values, based on EIA [94]
Saudi Arabia Crude Oil	9.70%
Kuwait Crude Oil	1.60%
Iraq Crude Oil	3.50%
Venezuela Crude Oil	8.40%
Venezuela Heavy Oil	0.00%
U.S. Crude Oil	35.00%
Ecuador Crude Oil	1.90%
Algeria Crude Oil	1.60%
Canada Crude Oil	7.50%
Mexico Crude Oil	10.60%
Other	9.80%
Angola Crude Oil	3.10%
Canada Oil Sands	0.00%
Nigeria Crude Oil	7.40%

Note: Canadian oil sands and Venezuelan heavy oil, are not included in this analysis.

Table A.3: Source-specific US Crude Oil extraction properties

U.S. Crude Oil Sources [95]	Mass Fraction of Crude	Crude Density (lb/gal)	Extraction energy (Electrical) (Btu/lb of HC)	Extraction Energy (Mechanical) (Btu/lb of HC)	Transport to US Port by ocean tanker (nm)
Saudi Arabia Crude Oil	81.99%	7.26	24.51	219.25	12018
Kuwait Crude Oil	89.86%	7.25	24.5	219.25	12526
Iraq Crude Oil	96.18%	7.28	24.5	219.25	12370
Venezuela Crude Oil	86.55%	7.26	22.79	206.36	1789
U.S. Crude Oil	34.80%	7.25	26.23	236.45	-
Ecuador Crude Oil	99.59%	7.31	22.79	206.36	5653
Algeria Crude Oil	32.77%	7.01	34.39	309.54	4452
Canada Crude Oil	36.05%	7.3	85.98	412.71	675
Mexico Crude Oil	80.12%	6.88	22.78	202.06	1061
Other	-	7.16	-	-	-
Angola Crude Oil	98.89%	7.15	34.39	309.54	6736
Nigeria Crude Oil	85.95%	7.12	34.39	309.54	5672

HC Hydrocarbon. Includes crude oil, natural gas (NG), and natural gas liquids (NGL)

Table A.4: $EROI_1$ Sensitivity for Conventional Jet Fuel from Conventional Crude

	Low	Baseline		High
		NETL	GREET 2012	
Key Assumptions				
Crude oil source	Canada	U.S. weighted average		Mexico
Refining process	Hydroprocessed	U.S. refinery average efficiency		Straight run
Life cycle Fossil Energy Input by Stage				
Feedstock Extraction & Transportation (J input / MJ fuel)	84,395	33,145	44,126	20,165
Fuel Conversion & Distribution (J input / MJ fuel)	158,745	121,154	126,080	24,080
$EROI_1$	4.11	6.48	5.93	22.6

A.1.2 EROI for FT jet fuel

Table A.5: EROI 1, 2 and 3 for Natural Gas (GTL) FT Jet (GREET 2012)

	Low	Baseline	High
Key Assumptions			
Process Efficiency (LHV)	60%	63%	65%
Life cycle Fossil Energy Input by Stage			
Fossil Energy Inputs			
Feedstock Extraction & Transportation (J input / MJ fuel)	86,376	86,376	86,376
Fuel Conversion & Distribution (J input / MJ fuel)	733,640	647,453	594,354
$EROI_1$	1.22	1.36	1.47
$EROI_2$	0.55	0.58	0.59
Total Energy Inputs			
Feedstock Extraction & Transportation (J input / MJ fuel)	86,783	86,783	86,783
Fuel Conversion & Distribution (J input / MJ fuel)	734,029	647,810	594,691
$EROI_3$	1.22	1.36	1.47

Table A.6: EROI 1, 2 and 3 for Coal (CTL) FT Jet (GREET 2012)

	Low	Baseline	High
Key Assumptions			
Process Efficiency (LHV)	47%	50%	53%
Lifecycle Fossil Energy Input by Stage			
Fossil Energy Inputs			
Feedstock Extraction & Transportation (J input / MJ fuel)	10,844	10,844	10,844
Fuel Conversion & Distribution (J input / MJ fuel)	1,148,313	1,019,201	904,705
$EROI_1$	0.86	0.97	1.09
$EROI_2$	0.46	0.49	0.52
Total Energy Inputs			
Feedstock Extraction & Transportation (J input / MJ fuel)	11,443	11,443	11,443
Fuel Conversion & Distribution (J input / MJ fuel)	1,149,059	1,019,898	905,359
$EROI_3$	0.86	0.97	1.09

Table A.7: EROI 1, 2 and 3 for Coal & Biomass (CBTL) FT Jet (GREET 2012)

	Low	Baseline	High
Key Assumptions			
Biomass Weight Fraction	10%	25%	40%
Biomass Input	Switchgrass	Switchgrass	Switchgrass
Process Efficiency (LHV)	47%	50%	53%
Lifecycle Fossil Energy Input by Stage			
Fossil Energy Inputs			
Feedstock Extraction & Transportation (J input / MJ fuel)	14,982	16,352	17,549
Fuel Conversion & Distribution (J input / MJ fuel)	1,077,972	848,590	645,063
$EROI_1$	0.91	1.16	1.51
$EROI_2$	0.49	0.59	0.73
Total Energy Inputs			
Feedstock Extraction & Transportation (J input / MJ fuel)	15,684	16,936	18,086
Fuel Conversion & Distribution	1,153,841	1,025,390	911,250

Table A.8: EROI 1, 2 and 3 for Biomass (BTL) FT Jet (GREET 2012)

	Low	**Baseline**	**High**
Key Assumptions			
Biomass Input	Switchgrass	Switchgrass	Switchgrass
Process Efficiency (LHV)	42%	45%	52%
Lifecycle Fossil Energy Input by Stage			
Fossil Energy Inputs			
Feedstock Extraction & Transportation (J input / MJ fuel)	73,053	42,117	33,232
Fuel Conversion & Distribution (J input / MJ fuel)	109,215	59,745	38,887
EROI 1, 2	5.49	9.82	13.87
Total Energy Inputs			
Feedstock Extraction & Transportation (J input / MJ fuel)	75,195	42,631	33,624
Fuel Conversion (J input / MJ fuel)	1,493,304	1,282,793	962,535
$EROI_3$	0.64	0.75	1

A.1.3 EROI for Renewable Jet Fuel from Hydroprocessed Esters and Fatty Acids (HEFA)

Table A.9: EROI 1, 2 and 3 for Soybean HEFA Jet (GREET 2012)

	Low	Baseline	High
Key Assumptions			
Soybean Yield (bu/ha)	79.5	110	129
Lifecycle Fossil Energy Input by Stage			
Fossil Energy Inputs			
Feedstock Extraction & Transportation (J input / MJ fuel)	124,503	97,853	83,667
Fuel Conversion & Distribution (J input / MJ fuel)	429,688	429,688	429,688
EROI 1, 2	1.8	1.9	1.95
Total Energy Inputs			
Feedstock Extraction & Transportation (J input / MJ fuel)	126,570	99,641	85,294
Fuel Conversion & Distribution (J input / MJ fuel)	698,012	698,012	698,012
EROI$_3$	1.21	1.25	1.28

Table A.10: EROI 1, 2 and 3 for Palm HEFA Jet (GREET 2012)

	Low	Baseline	High
Key Assumptions			
Palm FFB Yield (ton/ha)	18.2	21.2	23.1
Lifecycle Fossil Energy Input by Stage			
Fossil Energy Inputs			
Feedstock Extraction & Transportation (J input / MJ fuel)	94,866	68,490	63,413
Fuel Conversion & Distribution (J input / MJ fuel)	276,990	276,990	276,990
EROI 1, 2	2.69	2.89	2.94
Total Energy Inputs			
Feedstock Extraction & Transportation (J input / MJ fuel)	95,582	69,070	63,947
Fuel Conversion & Distribution (J input / MJ fuel)	539,015	539,015	539,015
$EROI_3$	1.58	1.64	1.66

Table A.11: EROI 1, 2 and 3 for Rapeseed HEFA Jet (GREET 2012)

	Low	Baseline	High
Key Assumptions			
Rapeseed Yield (t/ha)	2.79	3.35	3.89
Seed Oil Fraction	41%	44%	45%
Lifecycle Fossil Energy Input by Stage			
Fossil Energy Inputs			
Feedstock Extraction & Transportation (J input / MJ fuel)	306,551	196,206	144,368
Fuel Conversion & Distribution (J input / MJ fuel)	312,181	309,048	308,068
EROI 1, 2	1.62	1.98	2.21
Total Energy Inputs			
Feedstock Extraction & Transportation (J input / MJ fuel)	310,983	199,004	146,325
Fuel Conversion & Distribution (J input / MJ fuel)	576,459	573,209	572,193
$EROI_3$	1.13	1.29	1.39

Table A.12: EROI 1, 2 and 3 for Jatropha HEFA Jet (GREET 2012)

	Low	Baseline	High
Key Assumptions			
Jatropha Seed Yield (t/ha)	1	2.5	5
Seed Oil Fraction	34%	35%	37%
Lifecycle Fossil Energy Input by Stage			
Fossil Energy Inputs			
Feedstock Extraction & Transportation (J input / MJ fuel)	253,329	237,244	211,141
Fuel Conversion & Distribution (J input / MJ fuel)	289,205	288,088	284,159
EROI 1, 2	1.84	1.9	2.02
Total Energy Inputs			
Feedstock Extraction & Transportation (J input / MJ fuel)	256,880	240,644	214,127
Fuel Conversion & Distribution (J input / MJ fuel)	554,058	552,867	546,472
$EROI_3$	1.23	1.26	1.31

A.1.4 EROI for AF jet fuel pathways

Table A.13: AF pathway-dependent assumptions, technology characteristics

Pathway	Case	Pretreatment	Saccharification efficiency (% of theoretical max. from polymer to monomer sugar)	Target platform molecule, theoretical max. mass conversion efficiency of sugars to platform molecules	Metabolic efficiency (% of theoretical max.)	Extraction /purification technology	Upgrading to drop-in fuel	Excess biomass co-generation technology
Sugarcane AF	High	State-of-the-art milling	100%	EtOH, 51% (from stoichiometry)	90% C6 sugars	Distillation	Dehydration, oligomerization and hydroprocessing	n/a
	Base	Conventional milling	97.50%	Fatty acids, 34%	85% C6 sugars	Centrifugation	66% of hydroprocessing requirements	
	Low	Conventional milling	95%	iBuOH, 41% (from stoichiometry)	80% C6 sugars	Distillation.	Dehydration, oligomerization and hydroprocessing	
Corn Grain AF	High	Dry milling	100%	Alkanes, 34%	90% C6 sugars	KOH steam extraction and centrifugation	33% of hydroprocessing requirements	Gasification
	Base	Dry milling,	97.50%	Fatty acids, 34%	85% C6 sugars	Centrifugation	66% of hydroprocessing requirements	Incineration
	Low	Dry milling, .	95%	iBuOH, 41% (from stoichiometry)	80% C6 sugars	Distillation,	Dehydration, oligomerization and hydroprocessing	Incineration
Switchgrass AF	High	Dilute acid	n/a	Alkanes, 34%	90% C6 sugars 70% C5 sugars	KOH steam extraction and centrifugation	33% of hydroprocessing requirements	Gasification
	Base	Dilute alkali	(Saccharification efficiency is included in pretreatment references, in the form of raw feedstock to sugar monomers)	Fatty acids, 34%	85% C6 sugars 60% C5 sugars	Centrifugation	66% of hydroprocessing requirements	Incineration
	Low	Aq. ammonia		iBuOH, 41% (from stoichiometry)	80% C6 sugars 50% C5 sugars	Distillation,	Dehydration, oligomerization and hydroprocessing	Incineration

Table A.14: EROI 1, 2 and 3 for Sugarcane AFJ

	Low	**Baseline**	**High**
Key Assumptions			
Pretreatment Method	Conventional Milling	Conventional Milling	State-of-the-art milling
Metabolic Efficiency	80%	85%	90%
Lifecycle Fossil Energy Input by Stage			
Fossil Energy Inputs			
Feedstock Extraction & Transportation (J input / MJ fuel)	63,799	53,762	33,767
Fuel Conversion & Distribution (J input / MJ fuel)	181,335	96,037	42,084
EROI 1, 2	4.08	6.68	13.18
Total Energy Inputs			
Feedstock Extraction & Transportation (J input / MJ fuel)	67,588	56,955	35,772
Fuel Conversion & Distribution (J input / MJ fuel)	3,525,076	2,758,056	1,336,680
$EROI_3$	0.28	0.36	0.73

Table A.15: EROI 1, 2 and 3 for Switchgrass AFJ

	Low	**Baseline**	**High**
Key Assumptions			
Pretreatment Method	Aq. Ammonia	Dilute Alkali	Dilute acid
Metabolic Efficiency	80% C6 sugars 50% C5 sugars	85% C6 sugars 60% C5 sugars	90% C6 sugars 70% C5 sugars
Lifecycle Fossil Energy Input by Stage			
Fossil Energy Inputs			
Feedstock Extraction & Transportation (J input / MJ fuel)	302,560	133,977	84,395
Fuel Conversion & Distribution (J input / MJ fuel)	524,238	218,666	69,814
EROI 1, 2	1.21	2.84	6.48
Total Energy Inputs			
Feedstock Extraction & Transportation (J input / MJ fuel)	306,776	135,843	85,570
Fuel Conversion & Distribution (J input / MJ fuel)	6,959,410	2,499,519	1,121,332

Table A.16: EROI 1, 2 and 3 for Corn Grain AFJ

	Low	**Baseline**	**High**
Key Assumptions			
Pretreatment Method	Dry Milling	Dry Milling	Dry Milling
Metabolic Efficiency	80%	85%	90%
Lifecycle Fossil Energy Input by Stage			
Fossil Energy Inputs			
Feedstock Extraction & Transportation (J input / MJ fuel)	282,759	181,459	164,552
Fuel Conversion & Distribution (J input / MJ fuel)	951,991	431,819	258,789
EROI 1, 2	0.81	1.63	2.36
Total Energy Inputs			
Feedstock Extraction & Transportation (J input / MJ fuel)	287,583	184,555	167,360
Fuel Conversion & Distribution (J input / MJ fuel)	2,636,608	1,145,564	811,766
$EROI_3$	0.34	0.75	1.02

A.2 Well-to-wake CO_2 emissions and $EROI_1$ approximation

We report the calculated lifecycle (well to wake, WTW) total greenhouse gas and CO_2 emissions using GREET 2012 (for conventional jet fuel, HEFA jet, FT jet) and GREET.net beta (for AFJ sugarcane, switchgrass and corn). The WTW CO_2 results are used in an approximation of $EROI_1$, which we also report in the following tables.

Table A.17: Lifecycle WTW GHG, WTT CO_2 emissions, and $EROI'_1$ for Jet from Conventional Crude (GREET 2012)

	Low	Baseline	High
Key Assumptions			
Refining Efficiency	98%	93.50%	88%
Lifecycle GHG Emissions			
Feedstock Extraction & Transportation (gCO_2e/MJ)	6.5	6.5	6.5
Fuel Conversion & Distribution (gCO_2e/MJ)	3	10.8	17.8
Combustion (gCO_2e/MJ)	73.2	73.2	73.2
Total WTT CO_2 Emissions (gCO_2/MJ)	6.9	14	20.5
Total WTW GHG Emissions (gCO_2e/MJ)	82.7	90.5	97.5
$EROI'_1$	3.6	5.2	10.6

Table A.18: Lifecycle WTW GHG, WTT CO_2 emissions, and $EROI'_1$ for Natural Gas (GTL) FT Jet (GREET 2012)

	Low	Baseline	High
Key Assumptions			
Process Efficiency (LHV)	65%	63%	60%
Lifecycle GHG Emissions			
Feedstock Extraction & Transportation (gCO_2e/MJ)	14.9	14.9	14.9
Fuel Conversion & Distribution (gCO_2e/MJ)	24.9	28.4	34
Combustion (gCO_2e/MJ)	70.4	70.4	70.4
Total WTT CO_2 Emissions (gCO_2/MJ)	24.1	27.1	31.9
Total WTW GHG Emissions (gCO_2e/MJ)	110.3	113.7	119.4
$EROI'_1$	2.2	2.7	2.9

Table A.19: Lifecycle WTW GHG, WTT CO_2 emissions, and $EROI'_1$ for Coal (CTL) FT Jet (GREET 2012)

	Low	Baseline	High
Key Assumptions			
Process Efficiency (LHV)	53%	50%	47%
Lifecycle GHG Emissions			
Feedstock Extraction & Transportation (gCO_2e/MJ)	4.4	4.4	4.4
Fuel Conversion & Distribution (gCO_2e/MJ)	116.5	105.1	94.9
Combustion (gCO_2e/MJ)	70.4	70.4	70.4
Total WTT CO_2 Emissions (gCO_2/MJ)	92.6	102.4	113.4
Total WTW GHG Emissions (gCO_2e/MJ)	191.3	179.9	169.7
$EROI'_1$	0.6	0.7	0.8

Table A.20: Lifecycle WTW GHG, WTT CO_2 emissions, and $EROI'_1$ for Coal & Biomass (CBTL) FT Jet (GREET 2012)

	Low	Baseline	High
Key Assumptions			
Biomass Weight Fraction	40%	25%	10%
Biomass Input	Switchgrass	Switchgrass	Switchgrass
Process Efficiency (LHV)	53%	50%	47%
Lifecycle GHG Emissions			
Feedstock Extraction & Transportation (gCO_2e/MJ)	5	5	4.9
Fuel Conversion & Distribution (gCO_2e/MJ)	68.4	88.1	109.7
Combustion (gCO_2e/MJ)	70.4	70.4	70.4
Biomass credit (gCO_2e/MJ)	-55.5	-32.6	-13.6
Total WTT CO_2 Emissions (gCO_2/MJ)	10.9	52.9	93
Total WTW GHG Emissions (gCO_2e/MJ)	88.3	130.9	171.4
$EROI'_1$	0.7	1	1.9

Table A.21: Lifecycle WTW GHG, WTT CO_2 emissions, and $EROI'_1$ for Switchgrass (BTL) FT Jet (GREET 2012)

	Low	Baseline	High
Key Assumptions			
Biomass Input	Switchgrass	Switchgrass	Switchgrass
Process Efficiency (LHV)	52%	45%	42%
Lifecycle GHG Emissions			
Feedstock Extraction & Transportation (gCO_2e/MJ)	6.3	7.9	11.8
Fuel Conversion & Distribution (gCO_2e/MJ)	6.6	10.5	17
Combustion (gCO_2e/MJ)	70.4	70.4	70.4
Biomass credit (gCO_2e/MJ)	-70.4	-70.4	-70.4
Total WTT CO_2 Emissions (gCO_2/MJ)	5.1	7.1	12.9
Total WTW GHG Emissions (gCO_2e/MJ)	12.9	18.4	28.8
$EROI'_1$	5.4	9.9	13.8

Table A.22: Lifecycle WTW GHG, WTT CO_2 emissions, and $EROI'_1$ for Soybean HEFA Jet

	Low	**Baseline**	**High**
Key Assumptions			
Soybean Yield (bu/ha)	129	110	79.5
Lifecycle GHG Emissions			
Feedstock Extraction & Transportation (gCO_2e/MJ)	9.5	11.3	13.4
Fuel Conversion & Distribution (gCO_2e/MJ)	32	32	32
Combustion (gCO_2e/MJ)	70.4	70.4	70.4
Biomass Credit (gCO_2e/MJ)	-70.4	-70.4	-70.4
Total WTT CO_2 Emissions (gCO_2/MJ)	33.6	34.6	36.5
Total WTW GHG Emissions (gCO_2e/MJ)	41.6	43.4	45.5
$EROI'_1$	1.9	2	2.1

Table A.23: Lifecycle WTW GHG, WTT CO_2 emissions, and $EROI'_1$ for Palm HEFA Jet (GREET 2012)

	Low	Baseline	High
Key Assumptions			
Palm FFB Yield (bu/ha)	23.1	21.2	18.2
Lifecycle GHG Emissions			
Feedstock Extraction & Transportation (gCO_2e/MJ)	9.7	10.5	13.4
Fuel Conversion & Distribution (gCO_2e/MJ)	19.9	19.9	19.9
Combustion (gCO_2e/MJ)	70.4	70.4	70.4
Biomass Credit (gCO_2e/MJ)	-70.4	-70.4	-70.4
Total WTT CO_2 Emissions (gCO_2/MJ)	21.2	21.5	23.3
Total WTW GHG Emissions (gCO_2e/MJ)	29.6	30.4	33.3
$EROI'_1$	3	3.3	3.3

Table A.24: Lifecycle WTW GHG, WTT CO_2 emissions, and $EROI'_1$ for Rapeseed HEFA Jet (GREET 2012)

	Low	Baseline	High
Key Assumptions			
Rapeseed Yield (t/ha)	2.79	3.35	3.89
Seed Oil Fraction	41%	44%	45%
Lifecycle GHG Emissions			
Feedstock Extraction & Transportation (gCO_2e/MJ)	23.6	31.7	45.8
Fuel Conversion & Distribution (gCO_2e/MJ)	21.8	21.9	22.1
Combustion (gCO_2e/MJ)	70.4	70.4	70.4
Biomass Credit (gCO_2e/MJ)	-70.4	-70.4	-70.4
Total WTT CO_2 Emissions (gCO_2/MJ)	27.5	30.9	38.6
Total WTW GHG Emissions (gCO_2e/MJ)	45.4	53.5	67.9
$EROI'_1$	1.6	2.3	2.9

Table A.25: Lifecycle WTW GHG, WTT CO_2 emissions, and $EROI'_1$ for Jatropha HEFA Jet (GREET 2012)

	Low	Baseline	High
Key Assumptions			
Jatropha Seed Yield (t/ha)	5	2.5	1
Seed Oil Fraction	37%	35%	34%
Lifecycle GHG Emissions			
Feedstock Extraction & Transportation (gCO_2e/MJ)	26	28.9	30.8
Fuel Conversion & Distribution (gCO_2e/MJ)	21.9	22.6	22.8
Combustion (gCO_2e/MJ)	70.4	70.4	70.4
Biomass Credit (gCO_2e/MJ)	-70.4	-70.4	-70.4
Total WTT CO_2 Emissions (gCO_2/MJ)	30	32.8	34
Total WTW GHG Emissions (gCO_2e/MJ)	47.9	51.5	53.6
$EROI'_1$	2.1	2.1	2.3

Table A.26: Lifecycle WTW GHG, WTT CO_2 emissions, and $EROI'_1$ for Sugarcane AFJ (GREET.net Beta)

	Low	Baseline	High
Key Assumptions			
Pretreatment Method	Conventional Milling	Conventional Milling	State-of-the-art milling
Metabolic Efficiency	90%	85%	80%
Lifecycle GHG Emissions			
Feedstock Extraction & Transportation (gCO_2e/MJ)	3.7	5.9	7
Fuel Conversion & Distribution (gCO_2e/MJ)	3	6.7	12.6
Combustion (gCO_2e/MJ)	70.4	70.4	70.4
Biomass Credit (gCO_2e/MJ)	-70.4	-70.4	-70.4
Total WTT CO_2 Emissions (gCO_2/MJ)	5.2	9.8	15.4
Total WTW GHG Emissions (gCO_2e/MJ)	6.8	12.7	19.7
$EROI'_1$	4.6	7.2	13.6

Table A.27: Lifecycle WTW GHG, WTT CO_2 emissions, and $EROI'_1$ Switchgrass AFJ (GREET.net Beta)

	Low	Baseline	High
Key Assumptions			
Pretreatment Method	Aq. Ammonia	Dilute Alkali	Dilute acid
Metabolic Efficiency	80% C6 sugars 50% C5 sugars	85% C6 sugars 60% C5 sugars	90% C6 sugars 70% C5 sugars
Lifecycle GHG Emissions			
Feedstock Extraction & Transportation (gCO_2e/MJ)	12.3	19.6	44.4
Fuel Conversion & Distribution (gCO_2e/MJ)	4.9	17.7	45.3
Combustion (gCO_2e/MJ)	70.4	70.4	70.4
Biomass Credit (gCO_2e/MJ)	-70.4	-70.4	-70.4
Total WTT CO_2 Emissions (gCO_2/MJ)	9.6	24.8	62.3
Total WTW GHG Emissions (gCO_2e/MJ)	17.3	37.4	89.8
$EROI'_1$	1.1	2.8	7.3

Table A.28: Lifecycle WTW GHG, WTT CO_2 emissions, and $EROI'_1$ for Corn AFJ (GREET.net Beta)

	Low	Baseline	High
Key Assumptions			
Pretreatment Method	Dry Milling	Dry Milling	Dry Milling
Metabolic Efficiency	90%	85%	80%
Lifecycle GHG Emissions			
Feedstock Extraction & Transportation (gCO_2e/MJ)	28.1	31	48.3
Fuel Conversion & Distribution (gCO_2e/MJ)	19.3	31.5	69.1
Combustion (gCO_2e/MJ)	70.4	70.4	70.4
Biomass Credit (gCO_2e/MJ)	-70.4	-70.4	-70.4
Total WTT CO_2 Emissions (gCO_2/MJ)	29.9	41.5	82.2
Total WTW GHG Emissions (gCO_2e/MJ)	47.5	62.6	117.5
$EROI'_1$	0.9	1.7	2.4

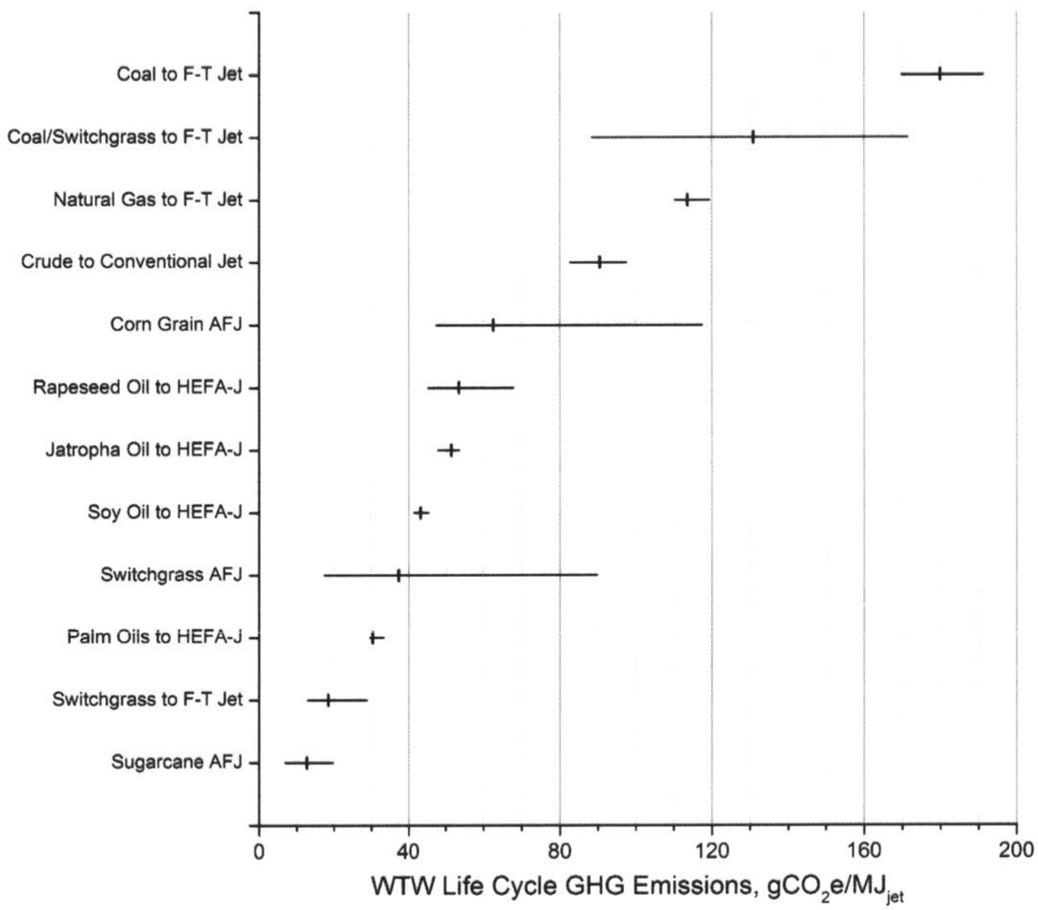


Figure A-1: WTW life cycle GHG emissions for alternative aviation fuels under an assumption of no land-use change induced by fuel production

B. Corn stover usage – supplemental information

B.1 Pathway-specific results and assumptions

B.1.1 Livestock feed

Corn stover at the farm gate is assumed to offset hay as a livestock roughage supplement. Studies indicate that replacing up to half of the roughage feed with corn stover did not affect weight gain rates in steers [96]. Life cycle GHG emissions for hay are derived from the ecoinvent LCA database [62]. The cost of hay production is assessed by taking historical price statistics for alfalfa hay from the USDA [55]. The cost of hay production is estimated at 30% less than the indicated selling price [97].

For the reference scenario of current corn stover use as cattle feed, the GHG emissions for corn stover at the farm gate is estimated at 53.9 gCO_{2e}/kg, with a supply cost of 62.15 \$/t in the baseline case. The life cycle GHG emissions of hay varies between 52.6-133.1 gCO_{2e}/kg, with a supply cost of between 112.20-182.38 \$/t. We find that the reference scenario for corn stover use as a feed supplement (offsetting hay) results in a mean societal benefit of \$86.88/t of corn stover.

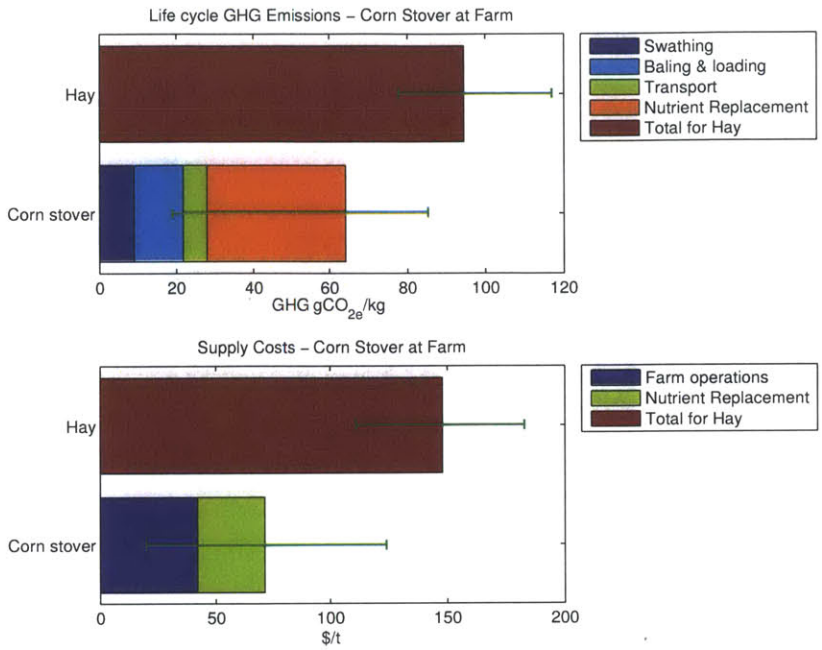


Figure B-1: Lifecycle GHG emissions and supply costs for feed production

B.1.2 Electricity and Heat

CHP from corn stover

Assumptions for heat and power production in CHP systems is tabulated below:

Table B.1: Cost and performance of CHP systems

Parameter	Low	Base	High
CHP rating (MW)	10	25	40
Overall efficiency (%)	70	75	80
Capital cost (M$)	7.5	28.8	50.0
Operating cost (cents/kWh)	0.5	0.49	0.42

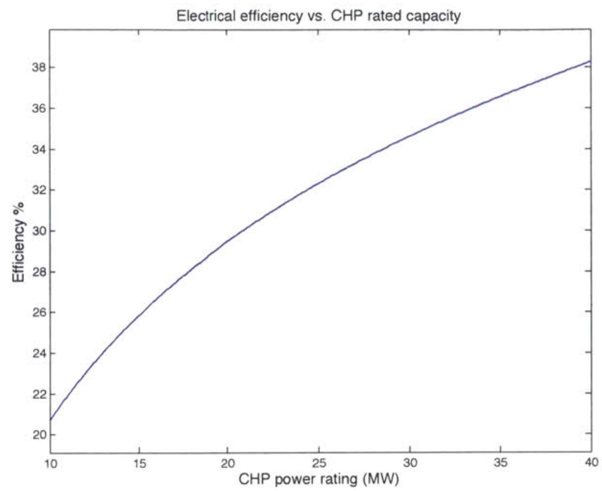


Figure B-2: Efficiency against capacity of CHP systems

Delivered dry corn stover is chopped, prior to being transported on a conveyor belt and stored. The feedstock is then loaded into the incineration or gasification facility. We assume the biomass credit from corn stover to offset combustion CO_2 emissions. The GHG emissions from waste disposal at the facility are accounted for. Capital costs for CHP generation are scaled linearly (coupled uncertainty) based on rated plant capacity in the Monte-Carlo framework.

U.S. grid average electricity

United States grid average emissions are calculated based on the electricity fuel mix [88]. The low, baseline, and high GHG profiles calculated using GREET are tabulated below.

Table B.2: GHG emissions and profile: U.S. electric grid

Feedstock share (%)	Low	Base	High
Coal	37	46	49
Natural gas	30	22.7	20
Nuclear (M$)	19	20.3	20.3
Fuel oil	0.9	0.9	0.9
Biomass	0.5	0.3	–
Other (renewable)	12.6	9.8	9.8
GHG emissions (gCO_{2e}/MJ)	170.7	186.2	190.7

Results – CHP from corn stover

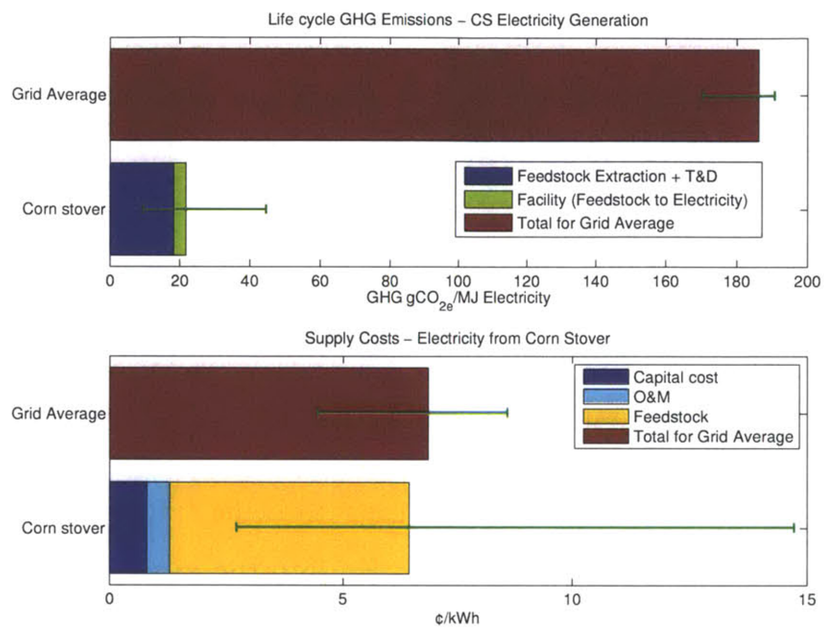


Figure B-3: Lifecycle GHG emissions and supply costs for electricity generation

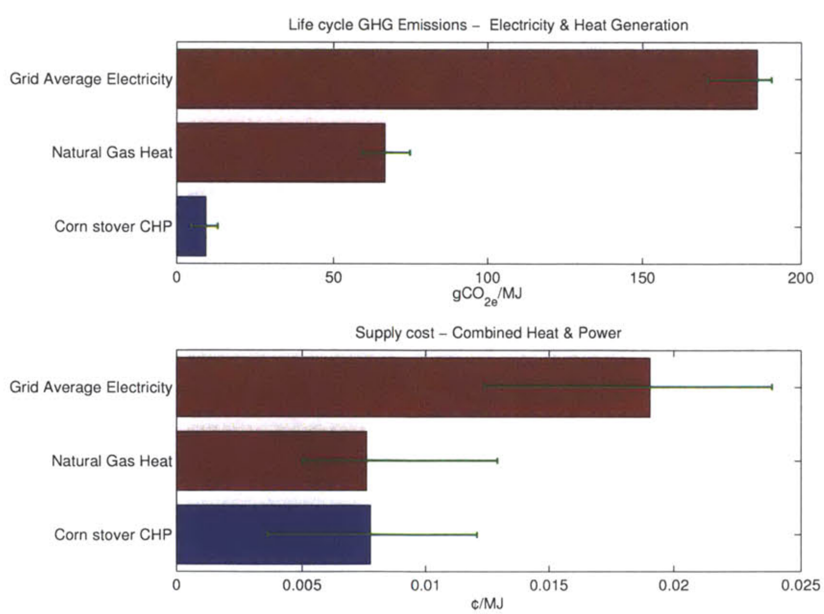


Figure B-4: Lifecycle GHG emissions and supply costs for combined heat and power generation

B.1.3 Ethanol and U.S. gasoline

Ethanol from corn stover

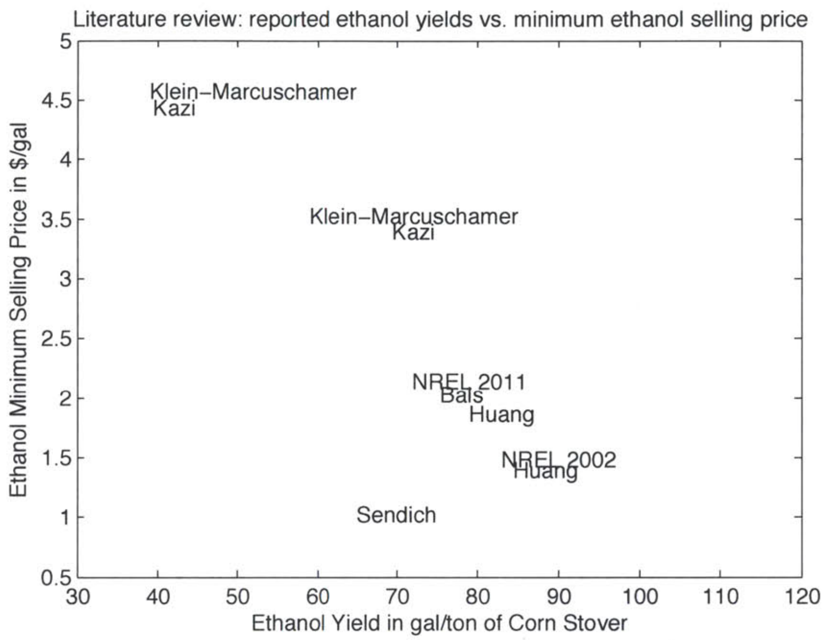


Figure B-5: Review of ethanol yields reported in literature

Table B.3: Cost and performance of Ethanol Production

Parameter	Low	Mean	High
Ethanol yield (gal/ton)	42	79	90
Capital cost (M$)	351.2	468.3	585.3
Operating cost ($/gal)	0.70	1.53	3.73

Ethanol is assumed to be transported within the U.S. using barge (40% by mass, 520 mi), rail (40%, 800 mi), and truck (20%, 80 mi) to bulk terminals, prior to being distributed to pumps via truck (30 mi).

U.S. conventional gasoline

Table B.4: Cost and performance of U.S. gasoline production

Parameter	Low	Mean	High
Refining efficiency (%)	85.1%	90.6%	96.1%
Brent crude price ($/bbl)	79.61	111.63	143.65
Crude transport cost ($/bbl)	2.00	3.00	4.00
Gasoline spot price ($/bbl)	86.23	118.23	150.23

Results – ethanol from corn stover

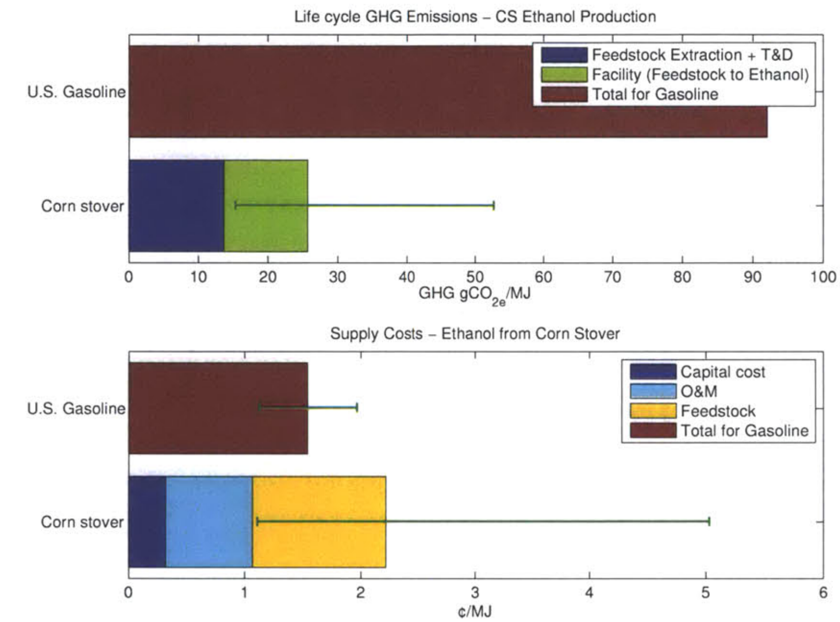


Figure B-6: Lifecycle GHG emissions and supply costs for ethanol production

B.1.4 Fischer-Tropsch MD and U.S. conventional MD

FT MD from corn stover

We assess FT MD production in a 5000 barrel per day facility, with a 20 year lifetime. Key parameters are tabulated in Table B.5. Operating costs are assumed to be 5% of plant capital costs [75].

FT MD is assumed to be transported within the U.S. using barge (33% by mass, 520 mi), rail (7%, 800 mi), and pipeline (60%, 400 mi) to bulk terminals, prior to being distributed to pumps via truck (30 mi).

Table B.5: Cost and performance of Fischer-Tropsch MD production

Parameter	Low	Mean	High
FT synthesis efficiency (%)	42	45	52
Capital cost (thousand \$/bpd)	68	213.5	408

U.S. conventional MD

Table B.6: Cost and performance of U.S. MD production

Parameter	Low	Mean	High
Refining efficiency (%)	88%	91%	98%
Brent crude price (\$/bbl)	79.61	111.63	143.65
Crude transport cost (\$/bbl)	2.00	3.00	4.00
MD spot price (\$/bbl)	90.26	128.35	166.45

Results – FT MD from corn stover

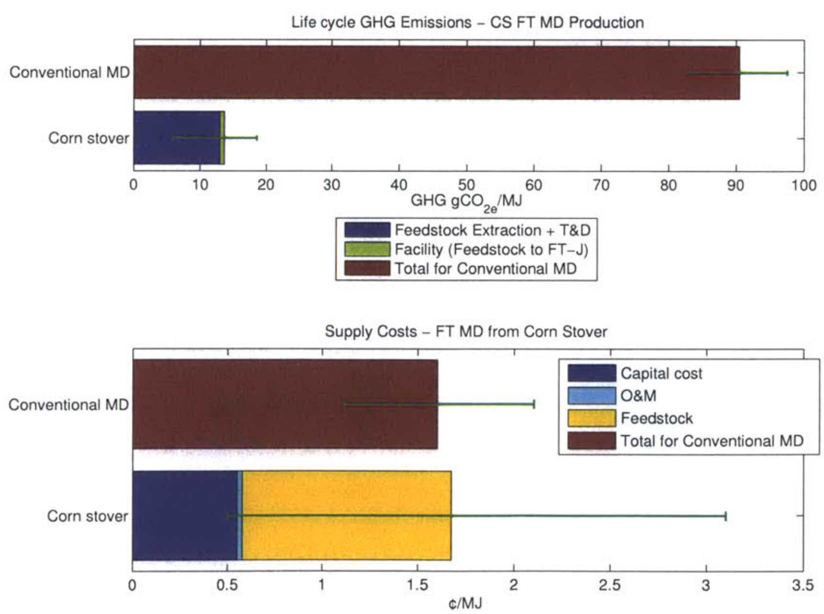


Figure B-7: Lifecycle GHG emissions and supply costs for FT MD production

B.1.5 Advanced Fermentation MD

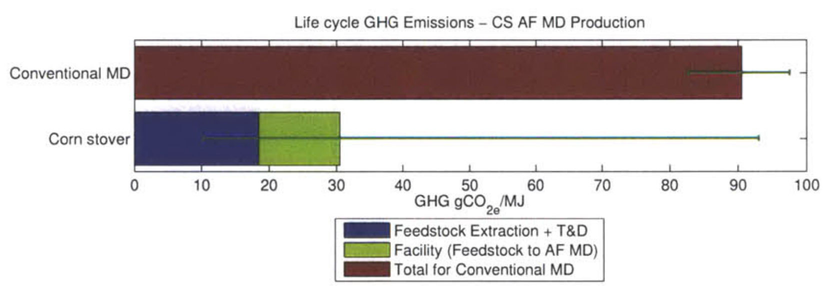
AF MD from corn stover

Advanced fermentation MD production is modeled in a 4000 barrel per day facility, based on Staples et al. (2014) [25]. Key process assumptions and costs are outlined in Table B.7.

Table B.7: Cost and performance of Advanced Fermentation MD production

Parameter	Low	Mean	High
Pretreatment method	Aq. ammonia	Dilute alkali	Dilute acid
Metabolic efficiency (C6 sugars)	80% C6 sugars	85% C6 sugars	90% C6 sugars
Metabolic efficiency (C5 sugars)	50% C5 sugars	60% C5 sugars	70% C5 sugars
Capital cost (M$)	487.5	629.9	1,356.3
Operating cost ($/gal)	1.20	1.90	4.36

Results – AF MD from corn stover



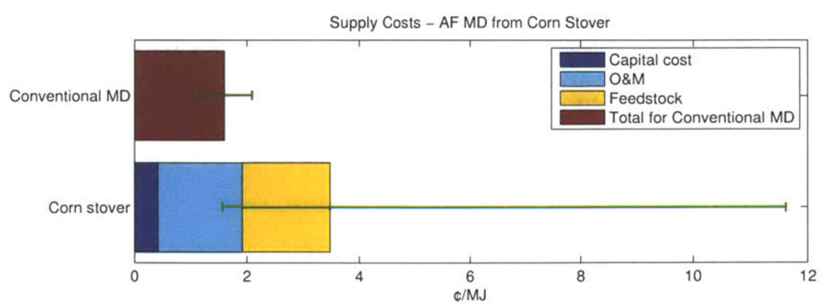


Figure B-8: Lifecycle GHG emissions and supply costs for AF MD production

B.1.6 Summary of results

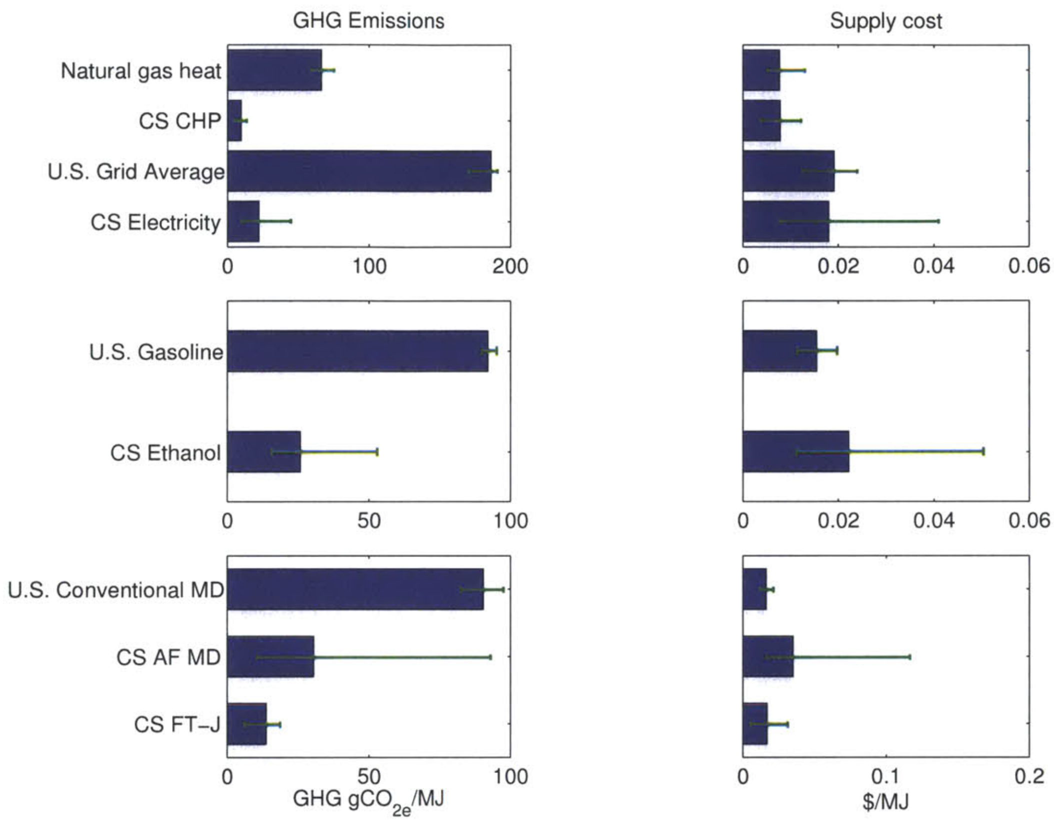


Figure B-9: Summary of lifecycle GHG emissions and supply costs

B.2 Monte-Carlo analysis

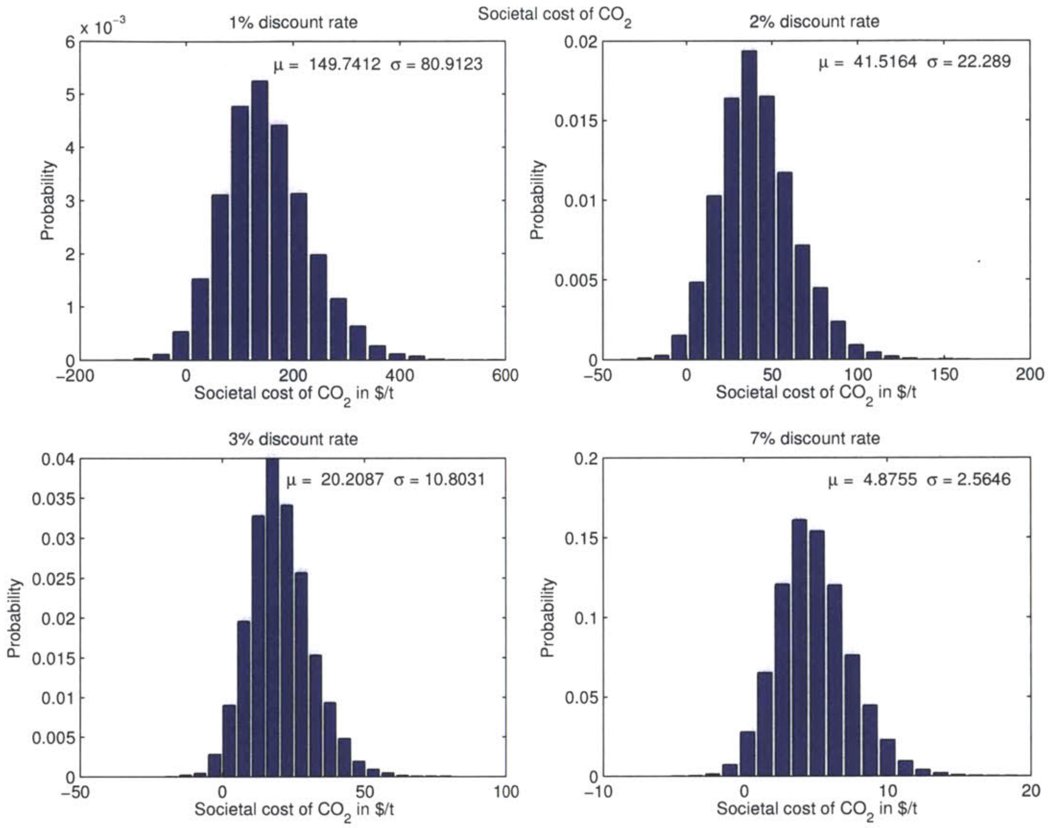


Figure B-10: Probability distributions - societal cost of CO_2 for discount rates of 1–7%

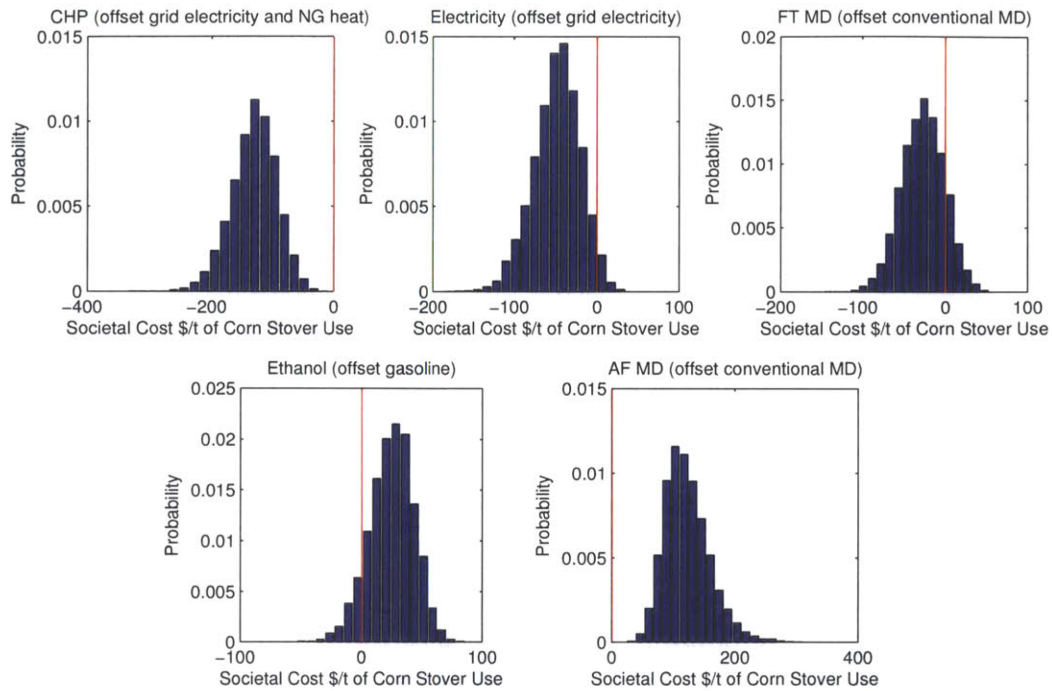


Figure B-11: Probability distributions of societal cost results (2% discount rate for climate cost)

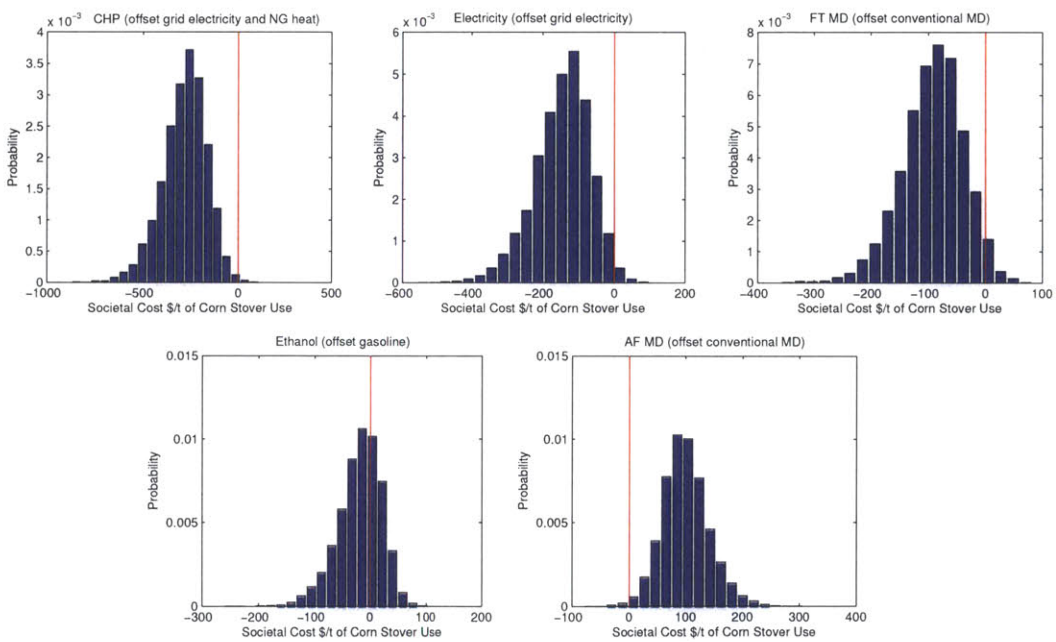


Figure B-12: Probability distributions of societal cost results (1% discount rate for climate cost)

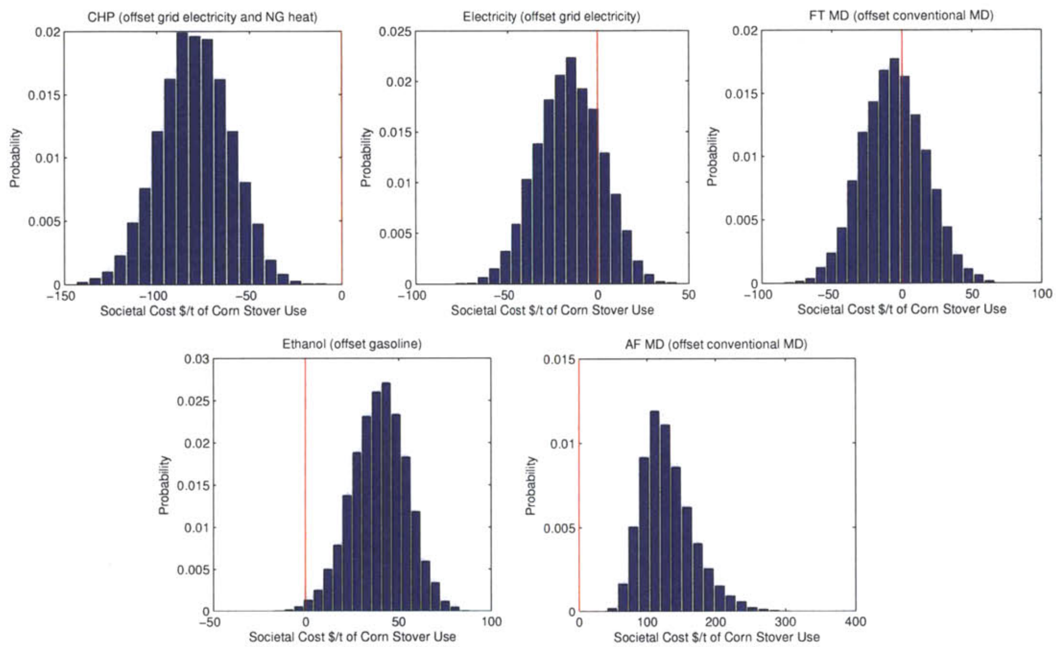


Figure B-13: Probability distributions of societal cost results (7% discount rate for climate cost)