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Environmental and economic tradeoffs of using corn stover for liquid fuels and power production†

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Using agricultural residues, such as corn stover, as feedstocks for liquid fuel or electricity generation has the potential to offset anthropogenic climate impacts associated with conventional utilities and transportation fuels. In this paper, the environmental and economic costs and benefits associated with the usage of corn stover for different applications are calculated. Combined heat and power (CHP), ethanol, Fischer-Tropsch (FT) middle distillate (MD) fuels (i.e. diesel and jet), and advanced fermentation (AF) MD fuels are considered. The net societal costs or benefits of different corn stover usages are calculated as the difference between the sum of monetized greenhouse gas (GHG) 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. Uncertainty associated with the analysis is captured using a Monte Carlo approach. It is found that corn stover derived electricity and fuels, compared to their conventional counterparts, reduce GHG emissions by 21-92%. The mean reduction for electricity in a CHP plant is 89% compared to the US grid-average, 70% for corn stover ethanol compared to conventional US gasoline and 85% and 55% for FT MD and AF MD compared to conventional US MD, respectively. Mean supply costs for corn stover-derived utilities and liquid fuels are ∼9% and ∼1% lower than the conventional counterparts for electricity and FT MD, respectively, and ∼45% and ∼300% higher for ethanol and AF MD, respectively. Using corn stover for CHP yields a net mean societal benefit of \$131.23/t of corn stover, which decreases by two–thirds if only electricity is produced, while FT MD production presents a mean societal benefit of \$27.70/t of corn stover. Using corn stover for ethanol and AF MD results in a mean societal cost of \$24.86/t and \$121.81/t of corn stover use, respectively, driven by higher supply costs compared to their conventional counterparts.

1 Introduction

Bioenergy accounted for approximately 5% of primary energy consumption in the United States in 2013[1] and its share is expected to increase over time due to the implementation of bioenergy mandates or goals at the federal and state level. For example, the largest energy-consuming agency within the US government, the Department of Defense (DoD) has a goal of 25% renewable energy use by 2025[2] and most states in the US have implemented renewable portfolio standards (RPSs) for using renewable feedstocks to generate electricity[3]. For transportation fuels, the U.S. Environmental Protection Agency's Renewable Fuel Standard program mandates 0.14 trillion liters of renewable fuel use by 2022[4], which, according to the most recent EIA consumption forecast[5], might amount to approximately 13% of total transportation fuel consumption.

Bioenergy feedstocks may be used to produce liquid fuels and electricity. However, bioenergy crop cultivation competes for available land with food crops and industrial uses[6]. One strategy to mitigate such competition is to use agricultural residues – a by-product of agricultural production for food and feed purposes[7]. Agricultural residues available in the US include corn stover, rice straw and sugarcane bagasse, among others[8–10]. Corn stover is the most abundant of all such residues, amounting to 65 million t of dry corn stover in 2012 [10] or approximately three-quarters of available residues by mass[11], and has been studied previously as a feedstock for ethanol production in the US[8,12–14]. Globally, 27.2% of agricultural residues are estimated to come from corn, while rice and wheat straw account for 26.7% and 21.9%, respectively[15].

Approximately 5% of corn stover on the field is currently removed for use as a cattle feed and bedding[16]. The remainder is left on the field after harvesting corn grain, to preserve soil organic carbon levels and inhibit soil erosion[17]. Up to 30% of corn stover can be removed for alternative uses without affecting soil quality[18]. This presents an opportunity for additional bioenergy production such as ethanol[14], electricity, combined heat and electricity[19], or middle distillate (MD) (i.e.

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jet and diesel) fuel production[20], which is otherwise foregone if corn stover is left unutilized.

Given that corn stover biomass is a limited resource, a key question from a societal perspective is to determine the environmentally and economically optimal use of the resource. Answering this question first entails calculating the societal benefits or costs of producing a corn stover-derived transportation fuel or utility in terms of associated production costs and impact on the environment, and subtracting the costs of production and environmental impact of the conventional commodity that is being displaced by the corn-stover derived product. This yields the ”net benefit” of using corn stover for producing a specific transportation fuel or utility. Second, it entails comparing the net benefit among different usages of corn stover in order to determine the highest net benefit among the different competing usages. This second step deals with the “opportunity costs” of corn stover use, which arises from the fact that every unit of corn stover can only be used once.

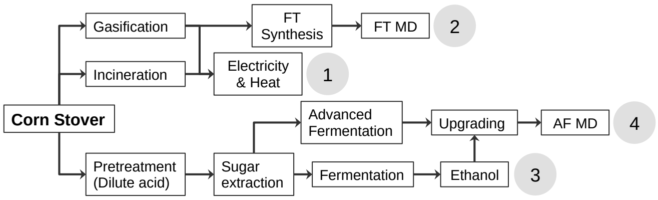

Fig. 1 Corn stover pathways for end uses considered

Figure 1 illustrates the different corn stover based products considered in this study and the key production steps involved. While prior studies have assessed lifecycle energy use and greenhouse gas (GHG) impacts of liquid fuel production from lignocellulosic biomass[21], this is the first assessment of both environmental and economic opportunity costs of using corn stover for liquid fuels and electricity generation. Previous analyses have assessed competing end uses of biomass from either an environmental perspective[12,22–26], or from a technoeconomic perspective[27–34]. To our knowledge, no study, to date, has integrated 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[35]. The latter is necessary for an analysis on the optimal use of resources from a societal perspective.

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 GHG emissions and the supply costs of a certain corn stover usage, and the sum of these metrics for the conventional commodity that is being displaced by the renewable alternative. Table 1 lists the conventional commodities that are assumed to be displaced for each scenario of corn stover usage. We note that our environmental analysis is limited to GHG emissions and associated climate impacts, and that other environmental impacts such as those on air quality and public health are not considered.

Table 1 Scenarios for corn stover end uses and conventional commodities displaced.

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

2 Materials and methods

A cost-benefit analysis framework for comparing alternative uses of corn stover is applied[36]. Costs and benefits to society from the use of corn stover are quantified relative to a conventional fuel or utility displaced.

2.1 Lifecycle GHG emissions

Three issues associated with lifecycle analyses (LCA) are addressed — system boundary definition, co-product allocation and data quality and uncertainty[37]. Feedstock recovery and transport, feedstock-to-fuel conversion, distribution and combustion of the finished fuel are included within the system boundary for the LCA. GHG emissions associated with direct farm operations such as swathing, baling and transport are included, 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. Potential emissions from land use change do not need to be considered in this study since no existing crops are being displaced. Emissions from the construction of facilities such as (bio)-refineries and machinery are not taken into account. Contribution of these steps have previously been estimated at approximately 1% of total lifecycle energy requirements for corn grain ethanol[38]. A full list of processes considered within the system boundary for each product is shown in the ESI. Following Wang et al.[39], GHG emissions are allocated among fuel co-products and utilities based on their energy content. Probability distributions (Table 2) capture uncertainty associated with parameters that affect the lifecycle GHG emissions for alternative corn stover uses. Fuel conversion parameters are used from industry data and archival literature on commercialized conversion technologies or those that are near commercial deployment.

2.2 Valuation of resource use and outputs

The production of corn stover derived products and their conventional counterparts requires the use of resources such as labor, capital, fuels and raw materials, and yields undesired co-products such as GHG emissions. For a societal analysis, resources and outputs should be valued according to their value to society, which is measured by the social opportunity costs, also known as shadow price[35]. If markets function well, market prices can be taken as a proxy for shadow prices. Where markets are significantly imperfect, market prices need to be corrected to obtain shadow prices by removing price distortions such as taxes, subsidies and profits[40]. Where market prices do not exist at all, as in the case of undesired environmental co-products such as GHG emissions, the physical impacts need to be monetized using appropriate monetization techniques[41].

2.3 Supply costs

Supply costs quantify the use of resources, including labor, capital, fuel and raw material. Supply cost calculations are devoid of monetary transactions that are not directly associated with any resource use, such as loan payments, taxes and subsidies. Supply costs calculations for the corn-stover derived products in this paper rely on technoeconomic (bottom up) approaches, which are corrected for monetary transactions without resource use. Capital costs in this approach are distributed over the lifetime total energy amount of fuel or utility produced. Since there are existing and mature markets for the conventional products being displaced by the corn stover derived products, a top-down approach is used for their supply costs in which existing market prices are corrected for taxes, subsidies and profits. Probability distributions (Table 2) capture uncertainty associated with parameters that affect the supply costs for alternative corn stover uses.

2.4 Societal costs and benefits

The societal costs comprise the supply cost and monetized climate impacts of GHG emissions. Doing so allows to consistently compare both economic and environmental impacts of corn stover use. To monetize lifecycle GHG emissions, we use estimates on the societal cost of CO_2 from the simplified climate and environmental impact model APMT[42]. APMT translates GHG emissions into temperature changes and quantifies the monetary costs of temperature change using damage functions. Uncertainty with regard to the societal costs of CO_2 are considered as shown in Table 2. The ESI contains additional detail about the APMT model.

In addition to the societal cost of alternative corn stover uses, the societal costs of conventional fuel counterparts are also assessed. The net societal cost is then calculated by subtracting the societal cost of the conventional commodity being displaced from the societal cost of alternative products from corn stover. In order to consistently compare the societal cost or benefit for each end use, the results are normalized on a per unit mass of corn stover basis.

2.5 Monte Carlo analysis

Uncertainty associated with the analysis is quantified using a Monte Carlo approach. Probability distributions are defined and referenced in Table 2. Section 2.7 discusses key parameters and pathway-specific assumptions.

Table 2 Input values for Monte Carlo analysis (Triangular: [Low (a), Mode (b), High (c)])

Parameter	Nominal range [Low, Mode, High]	Units	Distribution
Feedstock			
Corn stover yield[10]	[1.5,2.4,4.5]	t/ha	Triangular
Moisture content (at field)[17,18,43]	[0.15,0.25,0.35]	%	Triangular
Moisture content (at facility)[44,45]	[10,15,20]	%	Triangular
Nitrogen fertilizer application[12,25,46,47]	[0,7.4,8.8]	(kg/t stover)	Triangular
Phosphorus fertilizer application[12,25,46,47]	[0,2.9,4.1]	(kg/t stover)	Triangular
Potassium fertilizer application[12,25,46,47]	[0,12.5,16.5]	(kg/t stover)	Triangular
Tractor hauling distance[19,48]	[10,15,20]	km	Triangular
Truck transport distance[19,48]	[40,60,80]	km	Triangular
GHG footprint, farming hay[49]	$\mu = 94.5$, $\sigma = 10.1$	gCO_{2e}/kg	Normal
Swathing cost[50]	[25.20,31.88,39.54]	\$/t	Triangular
Baling cost[50]	[51.50,43.69,36.48]	\$/ha	Triangular
Transport cost[50]	[4,5,6]	\$/ha	Triangular
Nitrogen fertilizer cost[51]	[551,863,992]	\$/bale (700 kg)	Triangular
Phosphorus fertilizer cost[51]	[551,800,992]	\$/t	Triangular
Potassium fertilizer cost[51]	[551,863,882]	\$/t	Triangular
Price of hay[10]	[159.13,211.37, 261.17]	\$/t	Triangular
US grid electricity price[52]	[6.40,9.84,12.30]	cents/kWh	Triangular
US NG extraction cost[53]	[4.27,5.83,8.91]	\$/MMBtu	Triangular
Brent crude oil price[54]	[79.61,111.63,143.65]	\$/bbl	Triangular
Crude transport cost[55]	[2,3,5]	\$/bbl	Triangular
Fuel conversion			
CHP rating[56–58]	[10000,25000,40000]	kW	Triangular
Overall CHP efficiency[57,58]	[70,75,80]	%	Triangular
GHG footprint, US grid[52,59]	[170.7,186.2,190.7]	gCO_{2e}/MJ	Triangular
GHG footprint, N.G. heat[59]	[59.2,66.2,75]	gCO_{2e}/MJ	Triangular
CHP O&M cost[57]	[0.42,0.49,0.50]	cents/kWh	Triangular
Ethanol yield[13,14,29–32,60]	[42,79,90]	gal/ton	Triangular
GHG footprint, ethanol refinery[59]	[9.7,12.0,19.7]	gCO_{2e}/MJ	Triangular
GHG footprint, US gasoline[59,61]	[90.0,92.0,95.2]	gCO_{2e}/MJ	Triangular
Cost of raw materials (EtOH production)[13,14]	[36.3,48.4,60.5]	cents/gal EtOH	Triangular
Fixed cost for EtOH production[13,14]	[14.5,19.4,24.2]	cents/gal EtOH	Triangular
Capital cost for EtOH production[13,14]	[351.2,468.3,585.3]	\$MM	Triangular
Advanced fermentation MD yield[62]	[8.19,5.19,2.34]	MJ/kg stover	Triangular
GHG footprint, US conventional MD[59,61]	[82.7,90.5,97.5]	gCO_{2e}/MJ	Triangular
Capital cost for AF MD production[62]	[0.38,0.53,2.93]	\$/gal MD	Triangular
Fixed cost for AF MD production[62]	[1.20,1.90,4.36]	\$/gal MD	Triangular
FT synthesis efficiency[63]	[42,45,52]	%	Triangular
Capital cost for FT MD production[64,65]	[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

2.6 Discount rates for climate costs

Discounting addresses the time value of environmental costs, 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[66]. The damages are assessed over a 30 year accrual period, which is considered to be appropriate for policy analyses[42]. The choice of discount rate is debated in published literature[67]. Reported choices for the appropriate discount rate for climate change impacts range between 1–7%. The US Office of Management and Budget (OMB) suggests using a discount rate of 2–7%[68], while widely cited studies by Stern (2007) [69] and Nordhaus (1992)[70] discount climate damages at 1.4% and 5.5%, respectively. A discount rate of 2% in the baseline case is applied, and sensitivity of societal costs to discount rates of 1% and 7% as done by Withers et al. (2014) is assessed [71].

2.7 Assumptions for corn stover sourcing and conversion

The bottom-up method for calculating lifecycle GHG emissions and supply costs for the considered corn stover uses is specified in the following sections.

2.7.1 Feedstock. Corn stover is assumed to be sourced from a 40–80 km radius around the fuel production or electricity generation facility. A removal sjare of 30% of corn stover by mass from the field post corn harvest is applied, referring to previous estimates for sustainable residue removal rates[11,17,19,72–74]. Further, the ratio of corn stover yield to corn yield is assumed to be 1.0 on a mass basis[18]. Higher removal rates (double that of the assumed rate) have been shown to deplete soil organic carbon levels[75]. 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. GHG emissions from swathing, baling and transporting corn stover from the field to the farm gate[48] are included. Additional fertilizer required to replace lost nutrients during corn stover remova is accounted for, as well 1[12,25,46,47]. Corn stover bales are assumed to be 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[50] and fertilizer price indices[51]. Variability and uncertainty in collection and transport costs are captured using probability distributions based on reported cost data (summarized in Table 2).

2.7.2 Electricity and heat. Chopped corn stover can be incinerated or gasified to produce electricity through a steam or gas turbine. In the analysis, combined heat and power (CHP) plants are modelled with an electrical generation capacity of 10-40 MW, based on a survey of existing plants[58]. The reported electrical efficiency of steam turbine CHP systems varies between 15-38%, with a US industry average of 18%, while gas turbine-based systems have a typical electrical efficiency of 35%[57,76], reaching 40% as a maximum. 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%[57]. The quantity of heat generated for each scenario is determined from:

$$\text{Efficiency} = \frac{\text{Elec. output (MJ) + Heat output (MJ)}}{\text{LHV of fuel input (MJ)}} \qquad (1)$$

The GHG emissions for the CHP facility are estimated using the ecoinvent LCA database[49]. Electric power transmission and distribution line losses are assumed to amount to 6.5%[77]. Combined heat and power systems are installed onsite to meet local power or thermal requirements[57]. Emissions are allocated among electricity and heat outputs in CHP system scenario 1a, and only to electricity in scenario 1b. The cost of CHP generation is based on statistics of installed capital costs together with operating and maintenance costs[57]. Costs for steam and gas turbine technology-based CHP plants are calculated with respect to their rated capacity, with a capacity factor of 82%[57,78]. The cost of fuel is assessed as the cost of delivered dry corn stover.

2.7.3 Fischer-Tropsch MD. Fischer-Tropsch MD is produced through catalytic synthesis of gasified biomass to paraffinic hydrocarbons. The production of FT MD is modeled for a biorefinery with a capacity of 5000 fuel barrels per day[63]. Following Baitz et al. (2004) [79] and Stratton et. al. (2011)[63], the facility is assumed to produce utilities internally using biomass. We assume an FT synthesis efficiency of 45% in the baseline case[63]. Lifecycle GHG emissions for FT MD from corn stover are calculated using a greenhouse gas accounting model for transportation fuels called GREET ("The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model") developed and maintained by Argonne National Laboratory[80]. The supply costs of MD from the FT facility are calculated using capital and operating expenditure data from Pearlson et al. (2012)[64], corrected for financing costs, profit margins and taxes as in all supply costs calculations.

2.7.4 Ethanol. Assumptions are based on a literature review of 7 studies that assess the production of ethanol from corn stover[13,14,29–32,60].

Ethanol is produced from corn stover using enzymatic sugar extraction and conversion in a biorefinery. Steps include dilute-acid pretreatment of corn stover, saccharification, fermentation, separation and distillation[14]. 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[13,14,29–32,60]. Waste residue and biogas are combusted to produce steam, which is run through a steam turbine for fulfilling plant utility requirements. Lifecycle GHG emissions of corn stover ethanol are modeled in GREET, using the existing pathway in this model for the US. Supply cost calculations are based on a process simulation from the National Energy Technology Laboratory for an ethanol production facility[14,81]. The costs of ethanol production comprise the cost of installed capital, as well as fixed and variable operating costs. Variable operating costs include the feedstock costs and the cost of raw materials, while the fixed operating costs include labor and maintenance. The ethanol plant is assumed to operate at a 96% capacity factor[82].

2.7.5 Advanced fermentation MD.

Corn stover delivered to an AF middle distillate production facility is pretreated and hydrolyzed 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 are taken from Staples et al.[20]. Lifecycle GHG emissions for AF MD are calculated in GREET. 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[83].

2.8 Assumptions for conventional transportation fuels and utilities displaced by corn-stover products

Below the top-down approach is described for calculating the supply costs and lifecycle GHG emissions of conventional fuels or utilities that can be displaced by corn stover derived fuels and utilities.

2.8.1 Electricity and heat from conventional sources.

The GREET model is employed for calculating average GHG emissions of the US grid electricity mix[84], and to calculate the GHG emissions for heat from natural gas. Supply costs for the US grid average are assessed via a revenue analysis of existing electric utilities, estimated at 70% of the electricity price[85]. The retail price of electricity is assumed to vary between 6-12 cents/kWh, with a mean of 9.84 cents/kWh[52]. The ESI contains additional data on grid electricity assumptions.

The US Department of Energy estimates the US average exploration and recovery cost of natural gas at \$6.24/MMBtu (0.59 cents/MJ)[53]. 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)[71]. The delivered supply cost of natural gas is estimated at \$6.52/MMBtu (0.62 cents/MJ). An annual fuel utilization efficiency of between 75-95%[86] is taken and capital and operating costs for natural gas fired heating units are assumed to be 4% of the overall heating cost[87].

2.8.2 US conventional MD.

Lifecycle GHG emissions for conventional MD are calculated in GREET using the US averaged conventional crude oil mix and refining assumptions from Stratton et al. (2011)[63]. The Energy Information Administration reports the 2012 US Brent crude price at \$111.63/bbl (94 cents/l)[54]. 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[71,88]. 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 US refiners, along with a 40% corporate income tax[88], an MD refining cost of \$14.87/bbl (12 cents/l) is obtained. Transport and distribution costs are estimated at \$3/bbl (2.5 cents/l)[55].

2.8.3 US conventional gasoline.

Lifecycle GHG emissions for US gasoline from the US average crude oil mix are calculated using the existing pathway in the GREET model. For the supply costs, the difference between the gasoline spot price and the Brent crude price is taken as the cost to refine crude oil to gasoline, after removing profit margins and taxes. Assuming a 2012 gasoline spot price of \$118.23/bbl (99 cents/l) in the baseline case, and removing profit margin and taxes, gasoline refining costs of \$5.87/bbl (5 cents/l) are calculated. Transport and distribution costs are estimated at \$3/bbl (2.5 cents/l)[55].

3 Results and discussion

3.1 High-level results for GHG emissions and supply costs

The results for each corn stover use are compared against the results for conventional fuels or utilities that are displaced.

Lifecycle GHG emissions for the US grid average are estimated at 182.6 gCO_{2e}/MJ of electricity in the baseline case. The supply cost for US grid in the baseline case is found to be 6.65 cents/kWh, compared to the US average retail price of 9.84 cents/kWh in 2012[52]. Mean lifecycle GHG emissions for electricity from a corn stover fueled CHP plant are found to be 20.5 gCO_{2e}/MJ in a scenario where no heat is displaced, resulting in a potential GHG emissions reduction of $\sim$89% relative to the US grid average. The supply cost of electricity from corn stover is approximately 12% less than that of the US 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 costs for US gasoline are estimated at 1.89 \$/gal (1.54 cents/MJ) in the baseline case, while lifecycle GHG emissions for US gasoline are estimated at 92.4 gCO$_{2e}$/MJ. Lifecycle GHG emissions for corn stover ethanol are computed at 27.8 gCO$_{2e}$/MJ, resulting in a ∼70% reduction relative to US gasoline. The supply cost for corn stover ethanol is found to be ∼45% higher than US gasoline in the baseline case. Compared to the baseline lifecycle GHG emissions of 90.3 gCO$_{2e}$/MJ for conventional US MD, those of FT MD and AF MD fuel are 87% lower (12.0 gCO$_{2e}$/MJ) and 55% lower (40.3 gCO$_{2e}$/MJ), respectively. The supply costs for FT MD fuel in the baseline case at \$1.99/gal (1.57 cents/MJ) are 6% less than those of conventional MD (\$2.11/gal or 1.60 cents/MJ). The supply cost of AF MD fuel is \$5.99/gal (4.74 cents/MJ) in the baseline case, which is 183% higher than the cost of conventional MD.

3.2 Discussion of lifecycle GHG emissions of corn-stover derived products

GHG emissions from corn stover sourcing are 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. GHG emissions for transporting corn stover to the facility contribute 15% of sourcing GHG emissions, and chopping corn stover in preparation for fuel conversion contributes 18% of sourcing 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 US grid average. Feedstock sourcing, transport and preparation collectively comprise 83% of lifecycle GHG emissions for electricity generation in a CHP plant in the baseline case.

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[62].

Compared to a mean value of 70% in this paper, prior studies estimate a 70–89% reduction in GHG emissions for corn-stover ethanol relative to conventional gasoline [25,75,89,90]. Differences in results are primarily attributable to differences in assumed rates of corn stover removal, rates of nutrient replacement and assumed yields of ethanol. Compared to a mean of 20.5 gCO$_{2e}$/MJ of electricity corn stover CHP, reported lifecycle GHG emissions for biomass CHP systems lie between -175–21 gCO$_{2e}$/MJ[91]. Differences to prior estimates are a function of the LCA method used, the biomass assumed to be used as fuel, and the assumed CHP technology. Finally, compared to a mean value of 12.0 gCO$_{2e}$/MJ of FT MD in our analysis, Stratton et al. report a baseline value of 18.2 gCO$_{2e}$/MJ for FT MD from switchgrass, Wu et al (2006)[92] calculate approximately 5.5 gCO$_{2e}$/MJ, and Xie et al. (2011)[93] report a value of approximately 20.5 gCO$_{2e}$/M for FT diesel from forest residues.

3.3 Discussion of supply costs of corn-stover derived products

Supply costs for baled corn stover at the farm gate are primarily driven by the costs 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 costs 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 comprise 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.

3.4 Results for societal costs and benefits

3.4.1 High-level results. We normalize the results with respect to corn stover unit mass. We then monetize lifecycle GHGs using estimates for the societal cost of CO_2, with a mean value of \$41.50/tCO_2 and a range of \$2.30–89.20/tCO_2 (95% CI). The resulting societal costs of corn stover use (sum of monetized GHG emissions and supply costs) are compared against those of displaced conventional products to calculate a net societal cost (or benefit), per unit mass of corn stover usage. Figure 2 illustrates the net GHG emissions and net societal costs for each end use of corn stover considered. A negative value indicates savings in net GHG emissions or a net societal benefit, while a positive value indicates increases in net GHG emissions or a net societal cost.

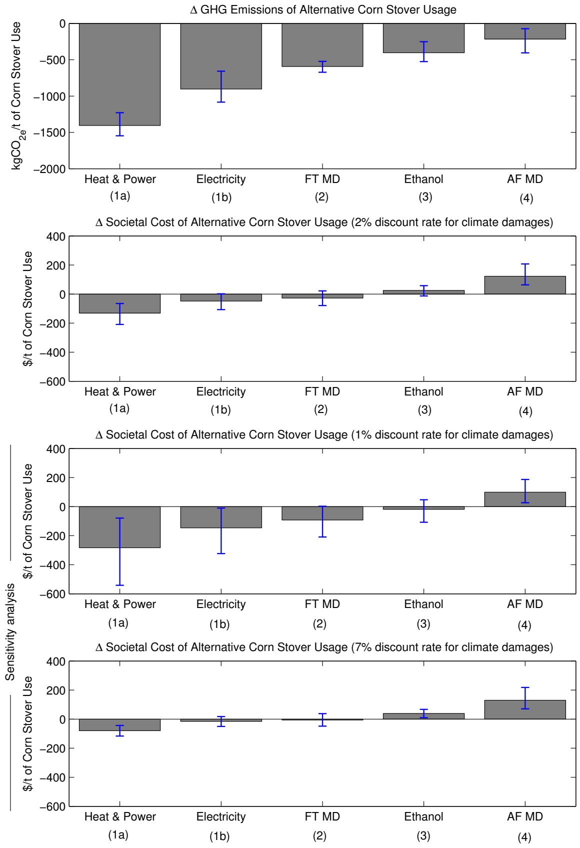

Fig. 2 Overview of societal costs/benefits from alternative corn stover use

From a societal standpoint, displacing the average US electricity grid and heat from natural gas with combined heat and power from corn stover results in a mean societal benefit of \$131.23/t corn stover. The mean societal benefit decreases by approximately two-thirds for a scenario where electricity alone from the CHP plant displaces the US grid average electricity (\$48.79/t corn stover). The use of FT MD fuel results 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.

3.4.2 Variability in results. In all simulations of the Monte Carlo analysis, the net GHG emissions impact for alternative corn stover usage as a transportation fuel or utility is negative — indicating a net emissions saving.

Supply costs for power generation from corn stover are lower (by ∼9%) than that of the conventional US grid in 73% of simulation runs, while supply costs for heating from a corn stover CHP facility are lower (by ∼13%) than that of natural gas heating in 80% of simulations. As shown on the left side of Table 3, net societal costs for combined heat and power are less than zero (lower than that of conventional generation) in all simulations at the baseline discount rate of 2%, while that of power generation is lower than the societal cost of the US average grid in 99% of simulations analyzed. The supply costs for corn stover derived ethanol are higher (by ∼45%) than US gasoline supply costs in 99% of simulations, whereas the net societal cost of ethanol is higher than that of US gasoline in 91% of simulations. The net societal cost for FT MD production is negative (less than conventional MD) in 85% of simulations, while that for AF MD is greater than zero (higher than conventional MD) in all simulations. The supply costs of conventional MD are higher than FT MD in 55% of simulations and lower than AF MD in all simulations.

3.4.3 Sensitivity to electricity and heat displacement scenarios. The net lifecycle GHG emissions for power and heat is driven by the difference between the lifecycle GHG emissions footprint of the current US grid and natural gas derived heat, and that of combined heat and power from corn stover. Cases are assessed 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. For example, if cornstover based electricity were to displace a hydroelectric source of power, this would yield a net increase in lifecycle GHG emissions of ∼100 kgCO_{2e}/t of corn stover used for electricity generation, compared to a lifecycle GHG emissions benefit of ∼900 kgCO_{2e}/t for displacing the current US grid average electricity mix.

3.4.4 Sensitivity to choice of discount rate. The results of the sensitivity analysis as shown in Table 3 indicate that higher discount rates are associated with decreases in the net benefit of corn-stover utilization. That is because GHG emissions savings attributable to the use of corn-stover derived

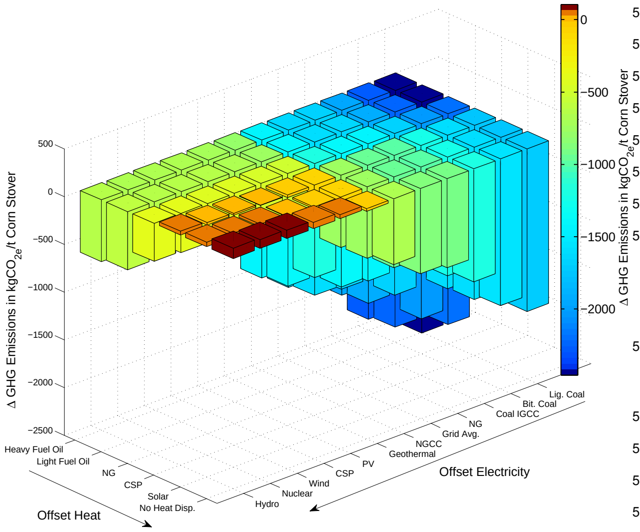

Fig. 3 Alternative displacement scenarios for electricity and heat from corn stover

products occurring in the future are valued less at higher discount rates. However, in case of corn stover based CHP, while the mean benefit decreases by 39%, using it still leads to a net societal benefit with 100% probability even when a high-bound discount rate of 7% is chosen. For corn-stover derived ethanol the choice of discount rate determines the sign of the mean societal costs, which becomes negative for a low discount rate of 1%. AF MD from corn stover results in a societal cost with 99% probability for a 1% discount rate, and with 100% probability for higher discount rates. Compared to the results for a 2% discount rate, AF MD mean societal costs decrease by 19% if a discount rate of 1% is chosen, and increase by 6% for a discount rate of 7%.

Table 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%

3.4.5 Break-even societal costs of CO_2.

As shown in Table 2, there is significant uncertainty associated with the choice of an appropriate value for the monetary costs of CO_2. Therefore, the break-even societal costs of CO_2 are calculated, at which the net societal costs of using corn-stover for the different bioenergy products would be less than zero with at least 50% probability. Combined heat and power and FT MD have at least a 50% probability of a societal benefit with a zero societal cost of CO_2. For ethanol and AF MD, one would need to choose a value in excess of ∼$100/$tCO_2$ and ∼$600/$tCO_2$, respectively, in order for the Monte Carlo simulations to yield at least a 50% probability of a net societal benefit for these usages.

4 Conclusion

It is found that CHP, ethanol and MD produced from corn stover results in a 21-92% reduction in GHG emissions compared to their conventional counterparts. The environmental benefit is greatest for combined heat and power in the reference scenario of displacing the US average grid and natural gas (1.4 tCO_{2e}/t corn stover). 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 other than the current US grid and natural gas, respectively. After accounting for differences in supply costs between corn stover-derived products and their conventional counterparts, power and CHP generation from corn stover present a mean societal benefit of $48.79 and $131.23 per t of corn stover (at a 2% discount rate), respectively, while FT MD production presents a mean societal benefit of $27.70/t of corn stover. If 30% of the ∼65 million t of dry corn stover available in the U.S. in 2012[10] were removed from the field and used for bioenergy production, the total mean societal benefit at a 2% discount rate for FT MD or CHP production would amount to $1.8 billion or $8.5 billion, respectively. From a societal cost standpoint, AF MD and ethanol production from corn stover incur higher supply costs than their conventional fuel counterparts that more than offset monetized GHG emissions savings, resulting in a mean societal cost of $121.81/t and $24.86/t of corn stover use, respectively.

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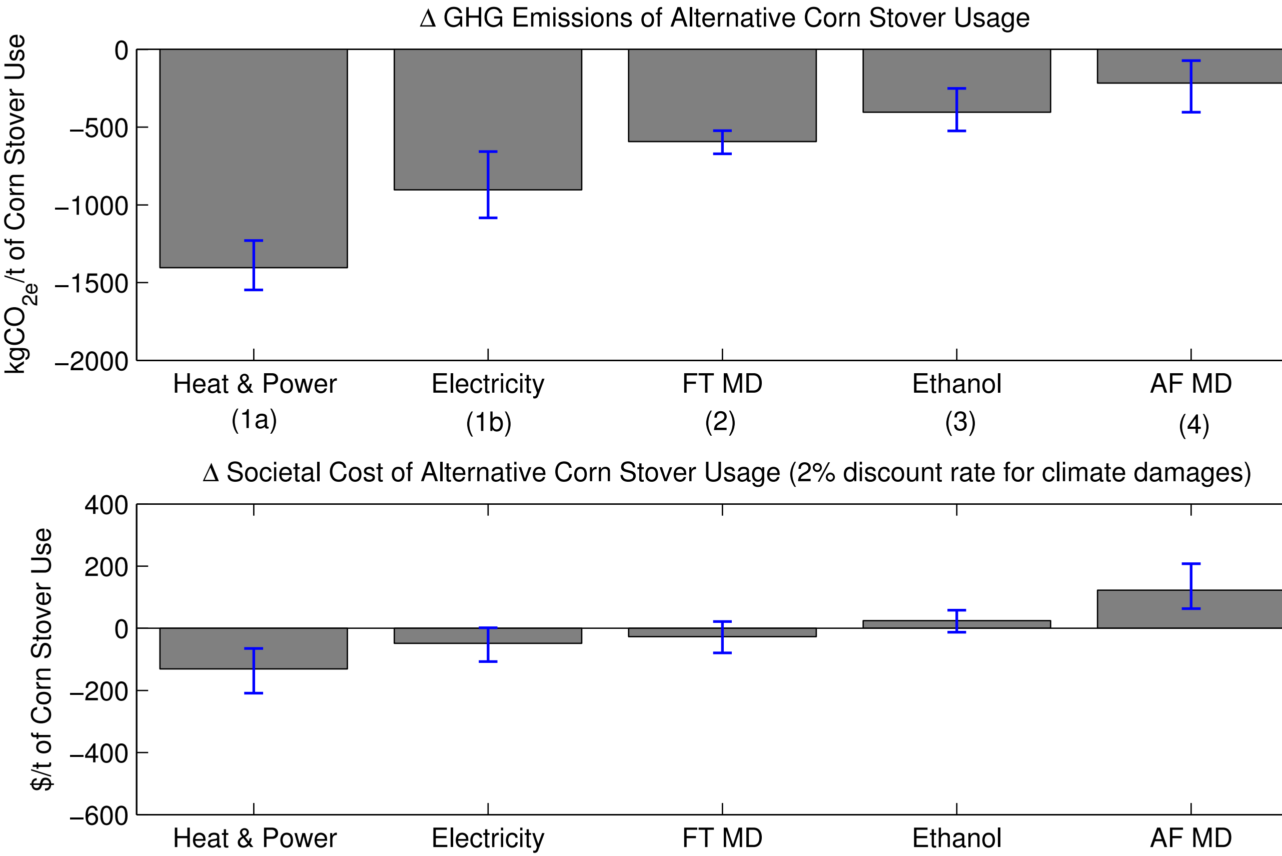
Δ GHG Emissions of Alternative Corn Stover Usage
$kgCO_{2e}$/t of Corn Stover Use
0
−500
−1000
−1500
−2000
Heat & Power
(1a)
Electricity
(1b)
FT MD
(2)
Ethanol
(3)
AF MD
(4)
Δ Societal Cost of Alternative Corn Stover Usage (2% discount rate for climate damages)
$/t of Corn Stover Use
400
200
0
−200
−400
−600
Heat & Power
Electricity
FT MD
Ethanol
AF MD

Broader context

Biomass can be used for different purposes such as the production of transportation fuels or electricity and heat. Given this choice, a key question from a societal perspective is to determine the environmentally and economically optimal use of the resource. Our analysis quantifies the societal benefit of different possible bioenergy-related uses of corn stover, which is the largest source of agricultural residue in the United States and one that is currently largely left unutilized. We find a net greenhouse gas (GHG) emissions benefit from using corn stover derived transportation fuels compared to fossil transportation fuels. We also find that the GHG emissions benefit of corn stover derived electricity and heat is significantly larger than that of corn stover transportation fuels. This is because of the relative ease of corn stover conversion into electricity and heat, and relatively high GHG emissions of current grid electricity in the US. When factoring in differences in production costs, we find that for some corn stover derived transportation fuels the higher production costs compared to their conventional counterparts more than offset monetized savings in GHG emissions, whereas corn stover derived electricity and heat remain societally beneficial even after production costs are factored in.

TOC entry

Using agricultural residue biomass for electricity and heat production results in greater carbon dioxide emissions reductions than creating transportation biofuel.