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Biomass Feedstock Transport Using Fuel Cell and Battery Electric Trucks Improves Lifecycle Metrics of Biofuel Sustainability and Economy

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Abstract

The use of new vehicle technologies such as fuel cell hybrid electric and fully electric powertrains for biomass feedstock supply is an unexplored solution to reducing biofuel production cost, greenhouse gas emissions, and health impacts. These technologies have found success in light-duty vehicle applications and are in development for heavy-duty trucks. This study presents the first detailed stochastic techno-economic analysis and life-cycle assessment of biomass feedstock supply systems with diesel, fuel cell hybrid electric, and fully electric trucks and determines their impacts on biofuel production considering butanol as a representative biofuel. This study finds that fuel cell hybrid electric and fully electric trucks consume less energy relative to the diesel-powered truck regardless of the evaluated circumstances, including payloads of truck (loaded and empty), pavement types (gravel and paved), road conditions (normal and damaged), and road networks (local and highways). The use of fuel cell hybrid and fully electric trucks powered by H_2-fuel and renewable sources of electricity, respectively, results in a large reduction in cost and carbon footprint, specifically for a long-distance hauling, and minimize other economic and environmental impacts. While the economic advantage of fuel cell hybrid electric vehicle is dependent on the price of H_2-fuel and road conditions, use reduces the GHG emissions of biobutanol per 100 km-trucking-distance by 0.98 to 10.9 gCO_{2e}/MJ. Results show that converting to fully electric truck transport decreases the biobutanol production cost and GHG emissions per 100 km-trucking-distance by 0.4 to 7.3 cents/L and 0.78 to 9.1 gCO_{2e}/MJ, respectively. This study establishes the foundation for future investigations that will guide the development of economically, socially, and environmentally sustainable biomass feedstock supply system for cellulosic biorefineries or other goods transportation systems.

Keywords: Biomass feedstock supply; hydrogen fuel; butanol fermentation; technoeconomic analysis; lifecycle assessment

Abbreviations

CV	Conventional vehicle (Class-8-Truck)
FCHEV	Fuel cell hybrid electric vehicle (Class-8-Truck)
EV	Fully electric vehicle (Class-8-Truck)
GHG	Greenhouse gas
U.S.	United States
HEVs	Hybrid electric vehicles
LCFS	Low carbon fuel standard
RFS	Renewable fuel standard
HHDDT	Heavy Heavy-Duty Diesel Truck
t	bone-dry metric ton
gal	gallon
gge	gasoline gallon equivalent
SAE	Society of Automotive Engineers
H_2	Hydrogen

Word count: 8063

1. Introduction

Among the several promising biomass feedstocks (including corn stover, miscanthus, switchgrass, biomass sorghum, and poplar) current cellulosic biorefineries in the United States (U.S.) utilize corn stover as a primary feedstock due to its immediate availability (DOE, 2016). While cellulosic biorefineries are at an early stage of commercial production of ethanol, it is well recognized that the feedstock supply is a major contributor to production costs (Humbird et al., 2011). Current cellulosic biorefineries, in general, collect the required corn stover feedstock directly from corn fields located in close proximity to the biorefinery through diesel powered 5 or 6-axle tractor semi-trailers (class 8 trucks) in the form of bales. Feedstock transportation is responsible for 11-58 % of the overall feedstock supply cost (Ebadian et al., 2011; Hess et al., 2009; Humbird et al., 2011; INL, 2014; Roni et al., 2018.) and 14-35% of the overall greenhouse gas (GHG) emissions (Baral et al., 2017; INL, 2014; Morey et al., 2010), although the transportation cost and emissions are dependent on the required amount of biomass and the feedstock supply radius. Additionally, biomass feedstock transportation cost and GHG emissions are associated with a high degree of uncertainty (Baral et al., 2017; Hess et al., 2009) when compared to other components of the feedstock supply system, such as replenishing nutrient, harvesting, collection, and storage. Therefore, there is a keen interest to implement a reliable and sustainable means of biomass feedstock transportation to reduce the overall biomass feedstock supply cost while concurrently reducing GHG emissions.

New vehicle technologies, such as fuel cell hybrid electric vehicles (FCHEVs) and fully electric vehicles (EVs), have the potential to serve as a more sustainable means of commercial transportation. Additionally, adoption of hybrid electric vehicles (HEVs) (Schaltz et al., 2009), EVs (Davis et al., 2016), and FCHEVs (Schaltz et al., 2009) can significantly reduce the health (IEA, 2016; WHO, 2016), environment (IEA, 2017; NRC, 2015), and economic (EIA, 2018; Greene and Ahmad, 2005; Olson and Lenzmann, 2016) issues associated with conventional diesel-based vehicles (CVs). These new heavy-duty truck types have been announced for near-term commercial release from automotive companies including Volvo, Daimler, Tesla, and Toyota and Nikola. Examples include the class 8 HEV from Volvo (Edelstein, 2019), a class 6 EV from Daimler (White, 2017), a class 8 EV from Tesla (Tesla, 2019), and class 8 FCHEVs from Toyota and Nikola (NMC, 2019; Toyota, 2019) which are all planned for release between the years 2019 to 2021. Collectively, these announcements demonstrate a potential solution to heavy-duty truck transportation sustainability. In the U.S., class 8 long-haul trucks compose just 2.5% of the total truck fleet but are responsible for 20.7% of fuel use due to their low fuel economy and large distances travelled (Davis et al., 2016). Due to their high fuel consumption and regular maintenance requirements, costs can be as high as 85 cents per mile (Barnes and Langworthy, 2003). These new class 8 truck architectures could significantly reduce costs and environmental impacts associated with transportation.

Due to the recent surge in the development and deployment of electrified heavy-duty trucks, researchers have begun investigating their potential impact on transport economics and the environment. In an initial study, researchers found that the Tesla class 8 trucks would require multiple charges to complete more than 65% of current class 8 truck trips and for trips that can be achieved without multiple charges it would require 3.5% of the national electricity production (EPRI, 2019). In another study, electric class 8 trucks are dominated by battery replacement and electricity costs (Sripad and Viswanathan, 2018). Other studies have demonstrated the potential of electrified heavy-duty trucks in other applications (Çabukoglu et al., 2018; Moultak et al., 2017; Talebian et al., 2018). Of the existing preliminary studies most consider impacts from a national and general implementation. This study is unique in that it determines the impact of these vehicles for a specific transportation need, biomass delivery to biorefineries. This application is interesting in that GHG emissions reduction of biofuel can be readily monetized through the low carbon fuel standard (LCFS) and renewable fuel standard (RFS) credits.

This study presents the first evidence of the economic and environmental impacts of advanced vehicle technologies on biomass supply logistics and quantifies their contributions in biofuel production cost and GHG emissions considering butanol as a representative biofuel. While this work is focused on biomass feedstock transportation with advanced truck types, challenges associated with butanol production, specifically the downstream recovery and separation processes, are not fully addressed. This study considers vacuum fermentation and recovery of butanol and other coproducts-acetone and ethanol (Baral et al., 2018). A recent review (Pugazhendhi et al., 2019) summarizes challenges associated with butanol production, including fermentation and separation, and provides future research directions. Another recent study (Shibata et al., 2020) investigated microwave-induced butanol recovery and found a higher evaporation rate of butanol relative to water, which has potential to reduce the energy required for the recovery process. These recent developments require further evaluation to determine their impacts on the butanol production cost and GHG emissions. In this study, costs and GHG emissions of biomass feedstock supply and butanol through the vacuum fermentation and recovery-based butanol production system are determined as this pathway represents the current state of technology.

1.1. Summary of prior studies and contributions of this study

Prior studies on biomass feedstock supply systems, a few examples are summarized in Table 1, have determined the biomass feedstock supply cost and GHG emissions of the supply chain considering woody biomass, energy crops, and agricultural residues, Table 1,. These studies are primarily developed by using two notable commercial-scale cellulosic biomass feedstock supply models, 1) the Integrated Biomass Supply Analysis and Logistics (IBSAL) model (Sokhansanj et al., 2008) developed by Oak Ridge National Laboratory (ORNL) and 2) the Uniform-Format Solid Feedstock Supply System (Hess et al., 2009) developed by Idaho National Laboratory (INL). Later studies on biomass feedstock supply systems are focused on optimizing feedstock supply cost: (i) by reducing preprocessing, handling, and storage costs at the biorefinery (Hess et al., 2009; Ebadian et al., 2011; INL, 2014), (ii) by supplying densified feedstock thereby reducing transportation cost (Morey et al., 2010; Sokhansanj et al., 2010; Lin et al., 2016; Mamun et al., 2020), and (iii) by supplying blended biomass feedstock to the biorefinery (INL, 2014, Roni et al., 2018; Baral et al., 2019a). Recent studies (Baral et al., 2017; Mamun et al., 2020) have focused on determining uncertainty associated with feedstock supply chain and identifying risk mitigation measures. Two other studies (Sahoo et al., 2016; Wang et al., 2017) focused on evaluating the impacts of the scale of a biorefinery on the resource requirements and biomass feedstock supply cost. A few prior studies have done integrated analysis of combining biomass feedstock supply and the downstream conversion processes (Sheehan et al., 2003; Spatari et al., 2005; Baral et al., 2018, 2019; Mamun et al., 2020).

All prior studies (Table 1) have used diesel-powered trucks as the default for biomass transportation and have reported it as a major contributor to the feedstock supply cost and associated GHG emissions. This highlights the importance of determining the impacts of new vehicle technologies such as FCHEV and EV architectures for biomass feedstock supply, which have had success in light duty vehicles and are in development for heavy-duty trucks. Both electricity and H_2-fuel are clean energy sources and do not emit GHG emissions during utilization phase. This study considers three different trucks, including conventional diesel-fueled truck, FCHEV, and EV, determines energy efficiency under various road and payload conditions (Table 2), develops a robust model and quantifies the cost and GHG emissions impacts of the selected vehicle technologies on biomass feedstock supply and biofuel (butanol) production. To fully demonstrate the impacts of new vehicle technologies, this study considers four different sizes of the biorefinery and two different locations of the biorefinery including in resource-rich area (farm-to-biorefinery supply radius of 63.6 km or about 40 miles) and outside the resource-rich area (farm-to-biorefinery supply radius of 1287.5 km or 800 miles (a typical distance from the U.S. state of Iowa to the state of Colorado) (Figure 1). These scenarios allows us to accurately assess the impacts of the advanced trucks for the short- and long-haul feedstock supply systems at different quantities of biomass feedstock levels. While the FCHEV and EV are still in the early-stages of their commercial deployment, the results of this study allow researchers and policymakers to understand their long-term economic and environmental impacts, possible bottlenecks, and specific use-case scenarios. To provide robust results, this study estimates uncertainties in feedstock supply and butanol production costs and GHG emissions. Additionally, other environmental and health impacts of the selected vehicles are assessed to understand their overall sustainability and future research needs. The implementation of the advanced technologies considered requires the development of the infrastructure along the highways for refueling or charging which is not considered within this work.

2. Methods

2.1 Scope and system boundary

The main goal of this study is to quantify and compare the corn stover feedstock supply cost and GHG emissions considering three different truck types, including diesel-fueled truck, FCHEV, and EV, and determine their impacts on the downstream butanol production cost and GHG emissions. For the comparison, the entire supply chain of the two most common corn stover feedstock supply systems are considered: (i) direct transportation of corn stover bales from the field to the biorefinery; and (ii) corn stover bales transported from the field to the nearby storage depot (preprocessing depot), transformed into denser feedstock, pellets, and then pellets are transported to the biorefinery via truck. Figure 1 depicts the overview of biomass feedstock supply system considered in this study with different lifecycle stages. All the required operations are modelled for biomass procurement and delivering, including nutrient application, biomass harvesting (windrowing, baling, and stacking at the field edge), outdoor storage of bales at the biorefinery or storage depot, optional pellet production or preprocessing, and transportation. The bale form of the feedstock is transported directly to the biorefinery when it is produced in the resource-rich area. If the biorefinery is located outside the resource-rich area, then the pellet form of the feedstock is more common. Biomass pellets can be directly fed to the pretreatment reactor, while bale form of feedstock requires preprocessing before the downstream operations at the biorefinery. Therefore, for a consistent comparison, a preprocessing step at the biorefinery is added if bales are delivered to the biorefinery. These lifecycle stages of the biomass feedstock supply system are well defined and discussed in the previous studies and so are leveraged in this study (Baral et al., 2017; Hess et al., 2009; Roni et al., 2018). The butanol production model is directly adopted from our recent study (Baral et al., 2018), which includes the detailed discussion of the process model and modelling assumptions. Figure 2 presents the overview of the methods implemented in this study. Prior studies are referenced for the detailed descriptions and mathematical equations leveraged where appropriate. The following sections describe the vehicle model development process (a major contribution of this study), the overview of changes made in each lifecycle stage, and the current as well as future scenarios considered for analysis in this study.

2.2 Process model development

2.2.1 Vehicle model development. Modeling of FCHEV is performed using Autonomie, which was developed at Argonne National Laboratory (ANL) and has shown strong correlation with real world measured data (Kim et al., 2012, 2013; Rousseau et al., 2006). This software has also been used to develop class 8 truck models with a high level of accuracy (Karbowski et al., 2010; Rousseau and Vijayagopal, 2011). In order to model advanced and recently announced vehicles in Autonomie, preloaded vehicle models are modified and scaled to represent state-of-the-art performance. This same process has been used by other researchers to model state-of-the-art class 8 trucks (Kast et al., 2017; Marcinkoski et al., 2016).

Autonomie was the modeling platform used to determine fuel economy (for conventional truck), hydrogen consumption (for FCHEV), and electricity consumption (for EV) under different payloads (empty or fully loaded), road types (gravel or paved), and road conditions (normal/new or damaged). All the required input data for vehicle model development of each of the selected truck types are summarized in the Supporting Information (SI)-Tables S1 and S2. Class 8 truck models were developed from a conventional vehicle configuration to represent the Freightliner Cascadia class 8 truck (FTC, 2019), an FCHEV configuration to represent the recently announced Toyota (Toyota, 2019) and Nikola(NMC, 2019) class 8 trucks, and an EV configuration to represent the recently announced Tesla class 8 truck (Tesla, 2019). Few technical details have been publicly released, but the details that are available were used to inform the Autonomie models.

Currently, most of the road infrastructure around US cornfields are gravel and not expected to change in the near future. This study assumes that 50 % of the total road length (feedstock supply radius) is gravel (because most of the roads around the agricultural field in the U.S. are graveled) and the remaining is paved roads if the biorefinery is located in the resource-rich area (Figure 1). If the biorefinery is located outside the resource-rich area, the same road types are assumed for the field to storage depot section and all the roads from storage depot to biorefinery are assumed to be paved (Figure 1). Physical vehicle parameters were adjusted to reflect the near-term and the future state-of-the-art, and the model inputs were adjusted to reflect road conditions as well as empty and full load weights. The coefficient of drag was set at 0.45 for all class 8 trucks to reflect the Tesla focus of lowering this coefficient (Tesla, 2019). The coefficient of rolling resistance was modified for gravel roads by adding 0.08, and for damaged roads by adding 0.02 (Ebbott et al., 1999; Grappe et al., 1999). Vehicle empty and full weights are chosen based on the definitions of class 8 truck, (DOE, 2018) which are summarized in the SI-Table S1. The assumptions in this work are intended to be a conservative estimate of the expected performance.

The drive cycles used for analysis are chosen to specifically apply to class 8 trucks. To accurately represent the feedstock vehicle operations, two drive cycles were chosen from the Heavy Heavy-Duty Diesel Truck (HHDDT) drive cycles, the HHDDT transient cycle and HHDDT Cruise cycle which were developed by West Virginia University and the California Air Resources Board (Clark et al., 2004; M Gautam et al., 2002; Mridul Gautam et al., 2002). The HHDDT transient cycle is used to model transportation from the field to biorefinery (if located within the resource-rich area) or storage depot. The HHDDT Cruise cycle is used to model transportation from storage depot to biorefinery (located outside the resource-rich area. The velocity traces of these drive cycles are shown in the SI-Figure S1).

2.2.2 Techno-economic model development. The baseline biorefinery was sized to process 2000 bone-dry metric ton (t) of corn stover per day. The macro-enabled Microsoft Excel and the process modeling software, SuperPro Designer (SPD)-V10.2, were used to develop the techno-economic analysis (TEA) model for feedstock supply and butanol production. The TEA model developed in this study incorporated all the required capital and operating costs including depreciation, repair and maintenance, labor and fuel costs, property taxes, and insurance (Figure 2). Unless otherwise noted, the detailed methods and mathematical equations for each stage of biomass feedstock supply system (Figure 1) are documented in prior studies (Hess et al., 2009; ORNL, 2009). Modeling details for butanol production and recovery are available in our previous work (Baral et al., 2018) and for other butanol production stages, including biomass deconstruction, neutralization, wastewater treatment, and onsite energy generation are available in the published reports on corn stover-based ethanol production (Aden et al., 2002; Humbrid et al., 2011). These prior ethanol studies also provide process flow sheet for ethanol production. The same system can be used for butanol production; however, butanol fermentation and recovery systems require a rigorous process that is different from ethanol. The modeled butanol production system included the detailed process requirements and the built-in mathematical equations and scaling factors (Humbird et al., 2011). These built-in equations capture the changes in material and energy requirements as well as capital and operating costs when the size of biorefinery is altered. The following paragraphs provide some main points and modifications made in this study for each of the stages shown in Figure 1.

The nutrient replacement stage includes replenishment of N, P, and K, which are removed from the field as they are entrained in the corn stover. The removal of corn stover does reduce N_2O emission from the field (0.69 % of N per unit mass and 1.25 % of N_2O per unit of nitrogen in corn stover)(Kaliyan et al., 2014). In addition to this N_2O emission reduction benefit, the N_2O emission from the application of additional nitrogen fertilizer (1.325 % of nitrogen (Kaliyan et al., 2014)) was considered. Field operations include windrowing, baling, and stacking operations. All the required resources for field operations including quantity of field equipment/machinery, fuel, and labor were calculated (Figure 2). The data inputs used to determine capital and operating resources required for nutrient replacement and field operation stages are summarized in the SI-Tables S3-S5.

The feedstock transportation section was modified for all the selected advanced class-8 trucks. The feedstock transportation includes loading, transport, and unloading operations (Figure 2). The results obtained from vehicle modeling software were used for the analysis of the feedstock transportation model. The required battery size and energy efficiency as a function of different truck loads, road types, and road conditions were used to model each class-8 truck's transport energy and costs. These results are summarized in Table 2 and the SI-Tables S1 and S8. Additional input parameters for biomass transportation are documented in the SI-Tables S7 and S8. This study considered outdoor storage of bales with the storage unit co-located with the biorefinery or storage depot depending on the location of the biorefinery (Figure 1). Bales are stored over gravel and under tarp to ensure protection from moisture and precipitation (Baral et al., 2017). The required input data for storage operation is summarized in the SI-Table S6 and the methods are summarized in Figure 2.

SPD was used to develop a process model for the preprocessing and the downstream butanol production stages at the biorefinery as well as pellet production process at the storage depot (Figure 2). The input data and assumptions for the preprocessing stage are consistent with feedstock handling systems developed by National Renewable Energy Laboratory (NREL) (Aden et al., 2002). This process model includes weighing, dust collection, shredding and storage (Aden et al., 2002; Humbird et al., 2011). Butanol production stage includes dilute sulfuric acids pretreatment and neutralization, fermentation, recovery and separation, wastewater treatment, and onsite energy generation (Baral et al., 2018). Instead of baseline butanol yield from fermentable sugars of 23.9 g/100 g of sugar used in our previous study, this study assumes an optimistic butanol yield of 90% of the theoretical yield of 41 g/100 g of sugar (Baral et al., 2018). All other operating parameters and modeling assumptions for butanol fermentation and recovery are consistent with previous studies (Baral et al., 2018) and for other stages are consistent with other prior studies (Aden et al., 2002; Humbrid et al., 2011). Similarly, the pellet production process includes all the required operations (primary milling, drying, secondary milling, feedstock conditioning, and pellet production) is consistent with recent works (Baral et al., 2019a; Roni et al., 2018). The methods used for developing pellet production, preprocessing, and butanol production models are summarized in Figure 2.

2.2.3 Lifecycle assessment model development. A macro-enabled Microsoft Excel-based lifecycle assessment (LCA) model including all the unit operations from corn stover production at the field-to-butanol production at the biorefinery was developed (Figure 2). The LCA model encompasses all the required materials, fuel, and electricity, which were obtained from the TEA model developed in this study. These results are summarized in the SI-Tables S4, S9 and S10. Lifecycle energy and emissions associated with the production of process equipment, farm machinery and trucks are excluded in this study as all the scenarios considered in this study require similar quantities of these equipment and facilities. However, GHG emissions associated with the production of the truck battery is included. This study does not include the impacts from direct and indirect land use changes assuming that corn stover residue is widely available in the U.S. for biorefineries' uses (DOE, 2016) without any changes in the current corn production practices. The impacts from the direct and indirect land use changes could alter the GHG emissions footprint of butanol estimated in this study and are important to consider if biomass feedstock production displaces crop land or natural habitats (Yang, 2017). The environmental sustainability of the feedstock supply systems considered in this study was measured using Global Warming Potential (GWP). The GWP was evaluated considering the emissions contributed by the common GHGs including CO_2, CH_4, and N_2O using the 100-year horizon GWP factors of 1, 25 and 298 for CO_2, CH_4, and N_2O, respectively (Yang et al., 2011). Lifecycle energy use and GHG emissions factors for the required materials, fuel and electricity were gathered from widely used LCA databases (Ecoinvent, 2017; GREET, 2017; USLCI, 2018) and previous studies (Baral et al., 2017; Neupane et al., 2017), which are summarized in the SI-Table S11.

In addition to GHG emissions, the life cycle inventory data for diesel production (Wernet et al., 2016) and combustion (USLCI, 2018), hydrogen production (USLCI, 2018), and electricity production (Wernet et al., 2016), was further analyzed for potential environmental differences among the conventional, advanced FCHEV and EV configurations. These additional impacts include ecotoxicity, eutrophication, carcinogenic and non-carcinogenic to human health, stratospheric ozone and fossil fuel resources depletions, acidification and photochemical ozone formation potentials, and respiratory effects all based on the ReCiPe methods (Huijbregts et al., 2017). The impact vectors used for analysis in this study are summarized in SI-Table S12.

2.3 Scenario analysis

In order to understand the economic feasibility, environmental impacts, and applicability of the advanced vehicle technologies for feedstock supply system, different scenarios are evaluated in this study as described in the following sections. These scenarios are considered under the two different locations of biorefineries, including resource-rich area (a baseline supply radius of 63.64 km or 40 miles) and outside the resource-rich area (a baseline supply radius of 1287.5 km or 800 miles), and three different vehicle types, including conventional diesel-fueled truck, FCHEV, and EV. The methods used for the scenario analysis are summarized in Figure 2.

2.3.1 Biorefinery size. Four different sets of biorefinery capacity including near term (94.6 million liters/year or 25 million gal/year), small-scale (50 million liters/year or 189.2 million gal/year), medium-scale (75 million liters/year or 283.9 million gal/year), and large-scale (100 million liters/year or 378.5 million gal/year) are considered for analysis in this study.

While the different locations of biorefineries allow us to assess the impacts of feedstock supply radius to feedstock cost and GHG emissions, the different sizes of the biorefinery reflect the impact of the different level of logistical resources to feedstock supply and butanol production costs, and associated GHG emissions. These near-term, small, medium, and large scale biorefineries require at least 1000, 2000, 3000, and 4000 bone-dry metric ton (t) of corn stover, respectively, resulting in the different annual truck trips and the quantity of trucks.

2.3.2 Road conditions. The large traffic volumes of fully loaded heavy-duty trucks which are required to meet the scale of the biorefinery cause wear and tear on the road surface resulting in additional maintenance costs when compared to the normal maintenance schedule (Bai et al., 2010). The impact of continued travel over damaged roads is considered in this study by including two different road conditions: (i) normal and (ii) damaged.

2.4 Sensitivity and uncertainty analyses

The input parameters were gathered from literature have associated variabilities. The average value of each input parameters (SI-S1-S2) was used to determine the baseline corn stover feedstock supply cost and GHG emissions, and determine their resulting uncertainties in butanol production cost and associated GHG emissions. The single point sensitivity analysis was performed considering minimum and maximum values of each input parameter (SI-Tables S3 to S8). This study further determined a combined impact of a set of two most influential input parameters on the overall feedstock supply cost and GHG emissions (two-point sensitivity analysis) where the values of each parameters were varied from their minimum to maximum values. For the uncertainty analysis, the minimum and maximum values, and standard deviation of input parameters were considered to model them with different probability distributions including uniform, triangular, normal, and lognormal. Based on the probability distribution of the input parameters, the uncertainty associated with the feedstock cost and emissions is determined with 10,000 Monte Carlo trials. This study developed Visual Basic (VB) Programming code to perform sensitivity and risk analyses and to support integration with the process modeling software-SuperPro Designer. The methods used for the sensitivity and risk analyses are summarized in Figure 2.

3. Results and discussion

3.1 Fuel economy of conventional and advanced trucks

Table 2 summarizes equivalent fuel economy (fuel and energy consumption) results of the selected trucks obtained from vehicle models developed in Autonomie under different drive cycles, road conditions, and payload scenarios. Since these vehicles are still in development, most vehicle parameters are currently unknown and an iterative vehicle parameter design process was required to ensure the drive cycles were driven with a low deviation in achieved velocity from the drive cycle velocity. The results obtained in this study reflect the information provided in public announcements of vehicles in development (SI-Table S1). To compare all fuel economy results, the gasoline equivalent fuel economy is reported for all FCHEV and EV configurations. For the hybrid electric vehicle configurations, Autonomie provides the gasoline equivalent fuel economy according to the recommended standards (SAE, 2014, 2010). For the EV, gasoline equivalent fuel economy (MPGe) is calculated from the modeled energy consumption result according to the U.S. EPA standard (EPA, 2011).

Comparing the fuel economy across the various vehicle architectures and driving scenarios yielded interesting results. First, it can be stated that the fully electric class 8 truck provided the best overall fuel economy, followed by the fuel cell hybrid electric class 8 truck, and finally by the conventional class 8 truck which achieved the worst fuel economy. Additionally, in general, the conventional class 8 truck and the fuel cell class 8 truck have higher fuel economy on the HHDDT Cruise drive cycle compared to the HHDDT Transient drive cycle while the fully electric class 8 truck is more efficient over the HHDDT Transient drive cycle. As expected, in all cases the fuel economy decreases when the truck is carrying a load or when road conditions degrade.

3.2 Baseline cost and GHG emissions

The contribution from each stage of the feedstock supply chain to the overall feedstock supply cost and GHG emissions and their resulting impacts on the butanol production cost and GHG emissions for the baseline scenario are presented in Figure 3. The baseline scenario includes the biorefinery size of 2000 t of bone-dry biomass per day and the normal road condition. Regardless of the location of the biorefinery, biomass transportation stage is a key contributor to the overall biomass supply cost and GHG emissions. For the resource-rich area, biomass transportation is responsible for 32% of the overall supply cost and 29% of the GHG emissions from biomass supply chain. Transportation cost and associated GHG emissions are responsible for 11% and 9% of the gross selling price and GHG emissions of butanol, respectively, and increases with increase in the field-to-biorefinery distance. For instance, if the biorefinery is located outside the resource-rich area (20-fold km away), transportation cost and GHG emissions contributions are increased to 56% and 49%, respectively, and their contributions to butanol production cost and GHG emissions, respectively, reach to 30% and 27%. These results suggest that the contribution from transportation stage to the overall feedstock supply cost and associated GHG emissions will go up with an increase in the feedstock supply radius, which warrants cost and energy-efficient biomass transporters.

Although EVs require a higher capital investment relative to the conventional truck (Table S8), their improved equivalent fuel economy results in 2.3% and 6.9% lower overall feedstock supply cost and GHG emissions, respectively, for the resource-rich area. The differences in supply cost and GHG emissions will increase with increasing supply distance (Figure 3). The FCHEV architecture could provide similar economic benefits as the EV (Figure 3) if H_2-fuel price(NREL, 2016) at the fueling station is reduced from the baseline price of \$5.3/kg to \$3.2/kg. Additionally, resources utilized for H_2-fuel and electricity productions have a dramatic impact on the total GHG emissions. For instance, if solar energy-based hydrogen(GREET, 2017) or electricity (NREL, 2012) is utilized, the overall GHG emissions for supplying corn stover in the resource-rich area will reduce by 9.8% with FCHEV and 14.5% with EV, relative to their baseline results. The GHG emissions reduction is increased to 23.7 % with FCHEV and 32.4% with EV if biomass feedstock is transported to the biorefinery with a longer supply radius of 1287 km. These variations in the overall feedstock supply costs and GHG emissions are due to the variabilities present in the fuel prices and their production methods, and thus are represented by the uncertainty bars in the figure (Figure 3). These results suggest that an efficient advanced truck could economically deliver biomass feedstock to a longer supply radius relative to the conventional truck and could provide substantial carbon reduction benefits for biofuel production.

Biomass preprocessing cost and associated GHG emissions at the biorefinery is approximately 3 and 11 times lower relative to the preprocessing cost and associated GHG emissions at the storage depot, respectively. This is mainly due to different forms of the preprocessed biomass requiring different levels of capital and operating costs, and process energy. The preprocessing at the biorefinery includes milling, handling, and short-term storage unit operations, while preprocessing at the storage depot includes milling, drying, pellet production, handling, and short-term storage unit operations. Pellets can be directly fed to the pretreatment reactor without further preprocessing and reduces transportation cost relative to bale or milled biomass transportation due to full utilization of the truck carrying capacity. On average, the pellet production is responsible for 8.8% and 13.5% of the overall biomass supply cost and 6.9% and 28.5% of the associated GHG emissions, respectively, when pellets are delivered to the biorefinery located in the resource-rich and outside the resource-rich areas.

While transportation has a dramatic impact on the overall economics and GHG emissions the other stages of the supply chain cannot be ignored. Among the other stages of biomass supply chain, nutrient replacement is the major contributor followed by the baling, windrowing, storage, and stacking at the field-edge. Results from the resource-rich area scenario have a nutrient replacement cost of 25.7% with GHG emissions accounting for 42.4% of the total. The next largest contribution is from baling (15.2 and 9.6%) followed by windrowing (10.2 and 8.3%), storage (8.8 and 2%), and stacking at the field-edge (3.2 and 2%). Sustainable agricultural practices with a low nutrient application and a sustainable biomass harvesting are required to reduce the cost and GHG emissions of nutrient replenishment. Nutrient (fertilizer) is required to achieve a good biomass yield. The biomass yield not only determines the required biomass collection area, but also the performances of the balers and windrowers are dependent on it. Overall, biomass supply is responsible for at least 36% of the overall butanol production cost and 37% of the overall GHG emissions, and the GHG emissions reduction benefits increases with the use of EVs and FCHEVs, specifically for long distance hauling (Figure 3).

3.3 Impacts of road conditions and biorefinery sizes

As expected, transportation cost and GHG emissions are amplified with increasing biorefinery size and when trucks travel over the damaged roads for a long period (Figure 4). Regardless of truck types, the damaged road alters the tire-pavement contact area and increases accelerating and deaccelerating events resulting in a lower fuel economy (Table 2). Results show that biomass transportation costs for delivering biomass within the resource-rich areas and outside the resource-rich areas increase between 4.2%-24.4% and 17.1%-52.3%, respectively, relative to the normal road condition. For these selected locations of the biorefinery, GHG emissions from biomass transportation through the damaged road networks, relative to the normal road condition, increase between 25.4%-94.7%, and 91.1%-133.3%, respectively. Regardless of biomass supply routes, the largest increments in cost and GHG emissions are found with the conventional class-8 truck. The FCHEV and EV offer the smallest increments. Each cent increase in transportation cost per kg of biomass increases the butanol production cost by 4 cents per liter. The carbon footprint of butanol, per km increase in the feedstock supply distance, is increased by at least 0.02 gCO_{2e}/MJ with conventional truck and by 0.01 gCO_{2e}/MJ with the EV and FCHEV.

An increase in the size of a biorefinery reduces biomass preprocessing and downstream conversion costs due to better utilization of capital and operating resources (referred to as economy of scale). However, biomass transportation costs, associated GHG emissions, and their contribution to butanol production cost and carbon footprint are increased with increasing the size of the biorefinery (Figure 4). This is mainly because the size of biorefinery changes the feedstock collection areas, feedstock handling, and transportation equipment due to a shorter time window, and associated material/energy inputs. For instance, if the size of biorefinery is increased from 2000 to 4000 metric ton/day, the feedstock supply radius is increased by 1.4 times. Feedstock transportation costs for delivering biomass in the resource-rich and outside the resource-rich areas increase by 37.2% and 2.0% and their corresponding GHG emissions increase by 40.8% and 2.1%, respectively, when the size of biorefinery is increased by 2 times. These increments are about 1% more with the damaged road relative to the normal road. Results show similar increments in their contributions to butanol production cost (Figure 4-c) and associated GHG emissions (Figure 4-d). The large increment in cost and GHG emissions even with short hauling distance (resource-rich area) is due to about 15% underutilization of the allowable truck carrying capacity (Hess et al., 2009) of 22.5 metric ton. This underutilization is mainly because the volume of bales limits the truck carrying capacity instead of their weights. The results highlight the importance of densified biomass, such as pellet, for long distance hauling that helps utilizing the allowable the truck carrying capacity (Federal weight limit) and reducing both transportation cost and associated GHG emissions. However, supplying densified biomass for short distance hauling (<112 km) is not economic (Baral et al., 2019a) due to additional cost and GHG emissions associated with pelletizing process (Figure 3). Results suggest that the biomass supply system follows the reverse economy of scale, in contrast to bioconversion process at the biorefinery, therefore location of the biorefinery and choice of feedstock form are important to reduce biofuel production cost and to meet the RFS target.

These results not only reinforce benefits of having EV and FCHEV for biomass feedstock transportation but also warrant a regular repair and maintenance of the road surface. Another aspect of the damaged road is that it could increase transportation time, and maintenance of the vehicles, which could add indirect cost to biomass feedstock. Therefore, additional repair and maintenance of road networks, choice of the appropriate location of biorefineries, and using a combination of road and rail networks to transport the required feedstock for longer distance could enhance the sustainable operation of cellulosic biorefineries in the future and longevity of the available road networks.

3.4 Most influential input parameters to cost and GHG emissions

Outside of the selected truck types, feedstock supply radius and biomass harvest rate (corn stover yield) are the most influential parameters to the overall feedstock supply cost and GHG emissions (SI-S3.5), and are thereby influential to butanol production cost and GHG emissions. These parameters determine the required resources and energy for field operations (including windrowing, baling, and stacking) and biomass transportation. In addition to these parameters, the relative impact of several other input parameters to the overall feedstock supply cost and associated GHG emissions with each truck type are presented in the SI-S3.5. Some of the other influential parameters include dry matter loss, corn stover removal rate, fuel economy of a truck, replenishing nutrients, productivity and efficiency of the field machinery, bulk density of a bale, moisture content, biorefinery size, and preprocessing energy. These parameters either impact the delivered biomass to the reactor throat (such as dry matter loss) or alter the required material, energy/fuel, and capital that impact supply cost and GHG emissions. If biomass is transported with FCHEVs or

EVs, energy sources used for the production of electricity and H_2-fuel (their production costs and specifically the GHG emissions associated with their production processes) are influential to the overall biomass feedstock supply cost and GHG emissions (SI-Figures S12-S15). Sensitivity analysis shows emissions from hydrogen is the fourth most influential parameter for the FCHEV (SI-Figure S13). Likewise, emissions from electricity generated from different energy sources (such as coal and solar) is the fifth most influential parameter for the EV (SI-Figure S15). However, both hydrogen and electricity are efficient clean energy sources relative to diesel.

3.5 Roles of EVs and FCHEVs in the future supply chain

The EV and FCHEV have shown potential to reduce the overall feedstock supply cost and associated GHG emissions for short hauling distance and could be even more useful for long distance hauling relative to the conventional truck (Figure 3). Therefore, potential benefits these advanced trucks are further determined and highlight the challenges associated with them expecting future growth in this field.

The current estimated price of H_2-fuel is \$13-16/kg (CEC, 2015)and GHG emissions of H_2-fuel production through the conventional centralized natural gas steam methane reforming pathway is 14 $kgCO_{2e}$/kg-H_2 fuel (well to wheel) (Lee et al., 2018) result in no economic and environmental benefits relative to the conventional truck. These extreme fuel price and carbon footprint increase the overall feedstock supply cost and GHG emissions for the resource-rich area by 1.9% and 25.4%, respectively, relative to conventional class-8 truck. While the supply cost goes up with an increase in the feedstock supply radius, the difference in GHG emissions between conventional diesel-powered truck and FCHEV is decreased with an increase in the supply radius, as FCHEVs are more energy efficient. Further, there are continuous efforts to reduce H_2-fuel cost, and alternative pathways are available to reduce GHG emissions associated with hydrogen production by 20-90% relative to the conventional process, including chlor-alkali processes and utilization of solar energy (Lee et al., 2018; NREL, 2016). The impacts of these future improvements on the overall feedstock supply cost and GHG emissions with fuel cell hybrid electric class-8 truck are presented in Figure 5 (a1 and b1).

At the baseline fuel economy of FCHEV (Table 2), the threshold values of H_2-fuel price of \$3.7/kg and GHG emissions of 13.7 $kgCO_{2e}$/kg-H_2 fuel are required for reducing the overall feedstock supply cost and associated GHG emissions below the conventional diesel-based truck (Figure 5-a1, b1). These margins could change by increasing fuel economy through technology advancement. Results show that H_2-fuel consumption above 0.18 kg/km can substantially increase feedstock supply cost and GHG emissions. The vehicle modeling results (Table 2) suggest that this required fuel economy can be achieved with normal road and highway driving, but may be challenging for local paved and gravel roads.

Distance driven after fully charged (equivalent to fuel economy) and charging time are the most critical parameter for the EVs. The distance driven after fully charged and charging time alter both the required capital resources (number of trucks, labor, and maintenance and insurance costs) and energy, thereby key to both cost and GHG emissions (Figure 5-a2 and b2). Results highlight that the EV must be driven at least 470 km (292 miles) after fully charged and charging time should be less than 48 minutes in order to reduce cost and GHG emissions below the conventional truck. Interestingly, if electric truck can drive more than 470 km after charging, increasing the charging time does not increase the supply cost and GHG emissions for a typical biomass feedstock supply radius of 63.6 km (40 miles) or for delivering biomass in the resource-rich area. This is mainly because the truck can be charged during the lead-time (overnight) when truck is not used. These cut-off driving distances and charging times could be challenging although manufacturers of the class-8 EVs (Tesla, 2019) claim the driving distance is in the range of 482-805 km (300-500 miles) on a single charge, and charging time is as low as 30 minutes, both of which are yet to be validated. If these expectations are achieved, the EVs could be used for long distance hauling at a reasonable price with a large reduction in GHG emissions relative to the conventional diesel-based truck.

3.6 Uncertainty associated with cost and GHG emissions

Uncertainty associated with the overall feedstock supply cost and GHG emissions and their contributions to butanol production cost and GHG emissions are shown in Figure 6. The detailed uncertainty associated with each stage of the overall feedstock supply chain are documented in the SI-S3.6. Regardless of the biorefinery locations and truck types, biomass transportation is responsible for the large uncertainties to both cost and GHG emissions. Direct transportation of bale from the field to the biorefinery results in large variations in transportation cost and associated GHG emissions. These variations still exist when the bales are transported from the field to the storage or preprocessing depot. This is mainly because the feedstock supply distance from the field to the biorefinery or preprocessing depot located in the resource-rich area is dependent on several parameters, including corn stover harvest rate, dry matter loss, available corn field, farmers interest to supply corn stover, and available road network (road winding factor). These input parameters have large variabilities, which are summarized in the SI-Table S3 and S7.

Underutilization of truck carrying capacity and the variability present in the bale density further enhanced uncertainty in transportation cost and associated GHG emissions. When these variabilities are reduced by fully utilizing truck carrying capacity with pellets and supplying biomass at a set distance from the storage or preprocessing depot to the biorefinery located outside the resource-rich area, the resulting uncertainty in transportation or biofuel production costs and GHG emissions are reduced. However, variabilities present in the purchasing price of truck (SI-Table S8) and uncertainty in the field to preprocessing depot transportation cost and associated GHG emissions results in a large variation in the overall biomass supply and butanol production costs relative to GHG emissions (Figure 6).

3.7 Benefits of the advanced trucks beyond the feedstock supply chain

The results presented demonstrate that the FCHEV and EV have potential to be improved transportation carriers for the feedstock supply system due to their economic and environmental benefits relative to the conventional truck. These advanced trucks could help to reduce the minimum selling price of biofuels as the biomass feedstock accounts for at least 36% of the butanol production cost and 37% of the overall GHG emissions (Figure 3). FCHEV and EV reduce GHG emissions contribution by 17% and 11%, respectively, and the reduction percentage increases with supply radius. These advanced trucks have the potential to displace 12.3 billion liters of diesel fuel and could reduce 14-19 million metric tons of GHG emissions when 76 billion liters of cellulosic ethanol is produced in the U.S. (SI-Figure S24). This highlights the importance of utilizing these advanced trucks to achieve the Renewable Fuel Standard target of 60% GHG emissions reduction relative to petroleum baseline (NRC, 2012). The importance of these advanced trucks is further increased if the conversion rates of biomass to biofuels/bioproducts are low. A recent work (Baral et al., 2019) determined that a large GHG emissions contribution from feedstock supply system (in the range of 19 to 65%) to the overall GHG emissions from renewable jet and missile fuels, which have a low biomass to fuel conversion rate relative to butanol considered in this study. For instance, the GHG emissions from tetrahydromethylcyclopentadiene dimer (RJ-4), a missile fuel, at the current yield easily overshoot the petroleum baseline of 89 gCO_{2e}/MJ with the conventional truck (Baral et al., 2019), while the advanced vehicles could help to reduce the resulting GHG emissions of the overall production chain.

Saving in GHG emissions using FCHEVs and EVs could help to achieve a targeted butanol selling price of 0.79/L-gasoline-equivalent ($3/gge) by providing the LCFS credits. For a conventional truck, a carbon reduction credits of $106 and $168 per tonne of CO_{2e}-avoided are required to reach the targeted selling price of butanol when the biorefinery is located in the resource-rich and outside the resource-rich areas, respectively. Using EV and FCHEV technologies, the required carbon reduction credits could be reduced by $2/tonne-$CO_{2e}$-avoided for resource-rich area and $27/tonne-$CO_{2e}$-avoided for outside the resource-rich area. These carbon credits are lower than the California's LCFS credit in 2019 of $192/tonne-$CO_{2e}$-avoided (CARB, 2020). Therefore, EV and FCHEV trucking can improve the value of corn stover butanol in LCFS markets.

In addition to reducing cost and GHG emissions, the FCHEVs and EVs have the potential to minimize other global and local environmental impacts (Figure 7). Two environmental impacts that are reduced as a result of using FCHEVs or EVs are the depletion of fossil fuel resources and stratospheric ozone. These results show that sourcing electricity from a low emissions technology such as solar largely reduces the respiratory impact. The absence of tailpipe emissions from both FCHEVs and EVs means that all emissions associated with combustion will be avoided. Therefore, the sustainable operation of the FCHEV is largely dependent on the selection and availability of renewable resources to generate H_2-fuel and electricity, respectively.

4. Conclusions and future perspectives

There is a need for the transportation sector to satisfy the national and international targets of GHG emissions reduction, reduce dependency on fossil fuel, decrease air pollution impacts on human health, and enhance the economy by transitioning away from internal combustion engine vehicles. By using fully electric and fuel cell hybrid electric trucks for biomass feedstock transportation, GHG emissions of biobutanol can be reduced by 11 to 25%, respectively, relative to conventional trucks. Therefore, switching to these promising advanced transport trucks, a typical biorefinery utilizing 2000 bone-dry-metric ton of biomass feedstock per day could reduce 4 to 55 thousand metric tons of CO_2 per year depending on the location of the biorefinery. While electric truck can reduce the butanol production cost by 1 to 4%, the economic benefits of fuel cell hybrid electric truck is dependent on the H_2-fuel price. However, both trucks can provide economic and environmental benefits when road is damaged or graveled and have the potential to provide a large RFS and LCFS credits available from biobutanol. If several cellulosic biorefinery are established in the future to meet the renewable fuels mandate of the United States, transporting biomass feedstock through EVs and FCHEVs displace a billion liters of diesel and saves a million metric tons of GHG emissions relative to the convention diesel-based truck. The economic and environmental benefits of EVs and FCHEVs over the range of feedstock supply radius, sizes of the biorefinery, and road conditions determined in this study supports future adoption. Future developments, such as cheap and renewable H_2-fuel production, establishing H_2-fuel distribution network and storage across the highways; wireless battery charging system on road or stationery fast charging system and durable, reliable, and recyclable batteries will support the commercialization of these advanced trucks. While this study demonstrates the potential impact of advanced trucking on the biomass feedstock supply network and biorefineries, it is noted that the impact of advanced trucking will include other sectors including the transportation of goods further supporting the development of the industry.

Conflicts of interest

There are no conflicts to declare.

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Figure Captions

Figure 1. An overview of the corn stover supply and butanol production system considered for analysis in this study

Figure 2. A summary of the methods used for analysis in this study

Figure 3. Baseline costs and greenhouse gas (GHG) emissions under several scenarios. CV = Conventional class 8 truck; FCHEV = Fuel cell hybrid electric class 8 truck; and EV = Fully electric class 8 truck. The horizontal dashed lines represent (c) last 10-year (2010-2019) average price of gasoline at the refinery gate of \$0.6/L (EIA, 2020); and (d) GHG emissions of isobutanol (ANL, 2019) produced from fossil energy of 71.52 gCO_{2e}/MJ. The uncertainty bars represent variations in costs and GHG emissions due to the variabilities present in the fuel prices (a and c) and carbon footprints due to different production methods of electricity and hydrogen fuel (b and d).

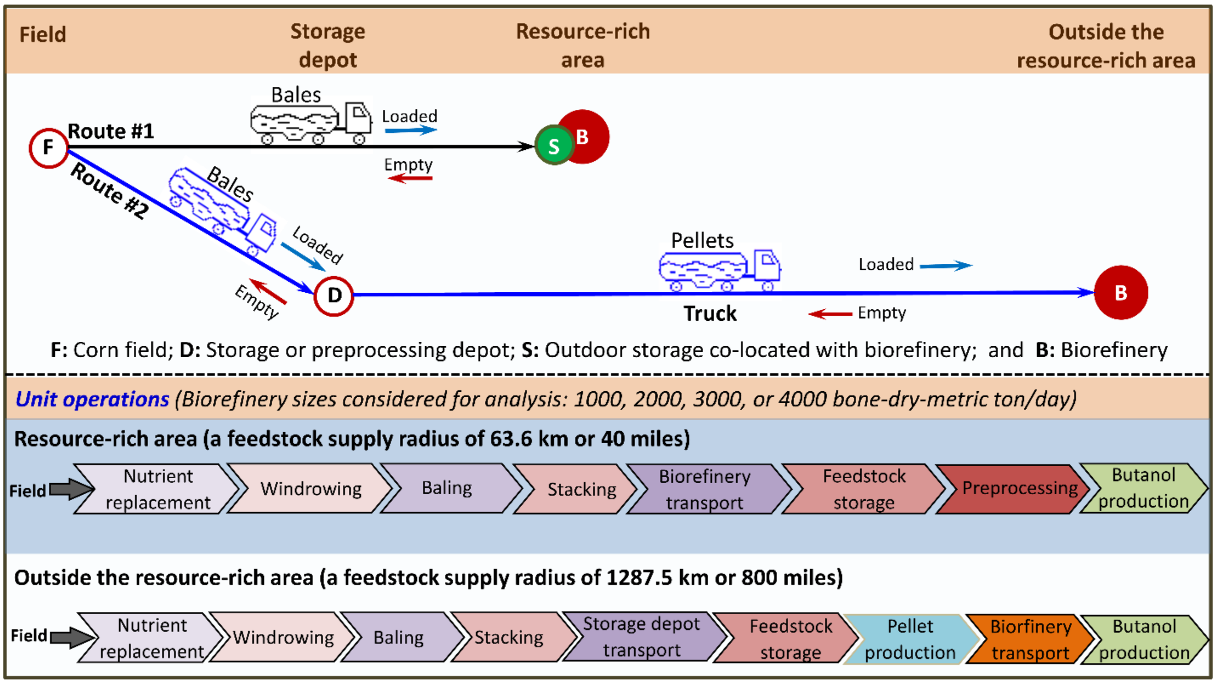
Figure 4. Biomass feedstock transportation cost and associated greenhouse gas emissions at different biorefinery sizes, and their contributions to the butanol production cost and carbon footprint. This is a representative case considering the location of biorefinery in the resource-rich area.

Figure 5. Impacts of a set of two different influential input parameters on biomass feedstock supply cost (a) and GHG emissions (b). This is a representative case considering the location of the biorefinery in resource-rich area. The dashed lines represent cost and GHG emissions resulted from the conventional truck for the baseline scenario. FCHEV = Fuel cell hybrid electric vehicle; and EV = Fully electric vehicle.

Figure 6. Uncertainties in costs and GHG emissions of feedstock supply chain and butanol. The horizontal dashed lines represent (c) last 10-year (2010-2019) average price of gasoline at the refinery gate of \$0.6/L (EIA, 2020); and (d) GHG emissions of isobutanol (ANL, 2019) produced from fossil energy of 71.52 gCO_{2e}/MJ.

Figure 7. Health and environmental impacts of biomass transportation with conventional, and advanced fuel cell hybrid electric, and fully electric class-8 trucks when delivering biomass feedstock outside the resource-rich area (1287 km away from the field). CV = conventional vehicle; EV-M = electric vehicle charging with mixed grid electricity (US average); EV-R = electric vehicle charging with renewable electricity (solar); and FCHEV = fuel cell hybrid electric vehicle.

The environmental impacts of hydrogen fuel are determined considering natural gas-based liquid hydrogen production system as a representative case (USLCI, 2018).



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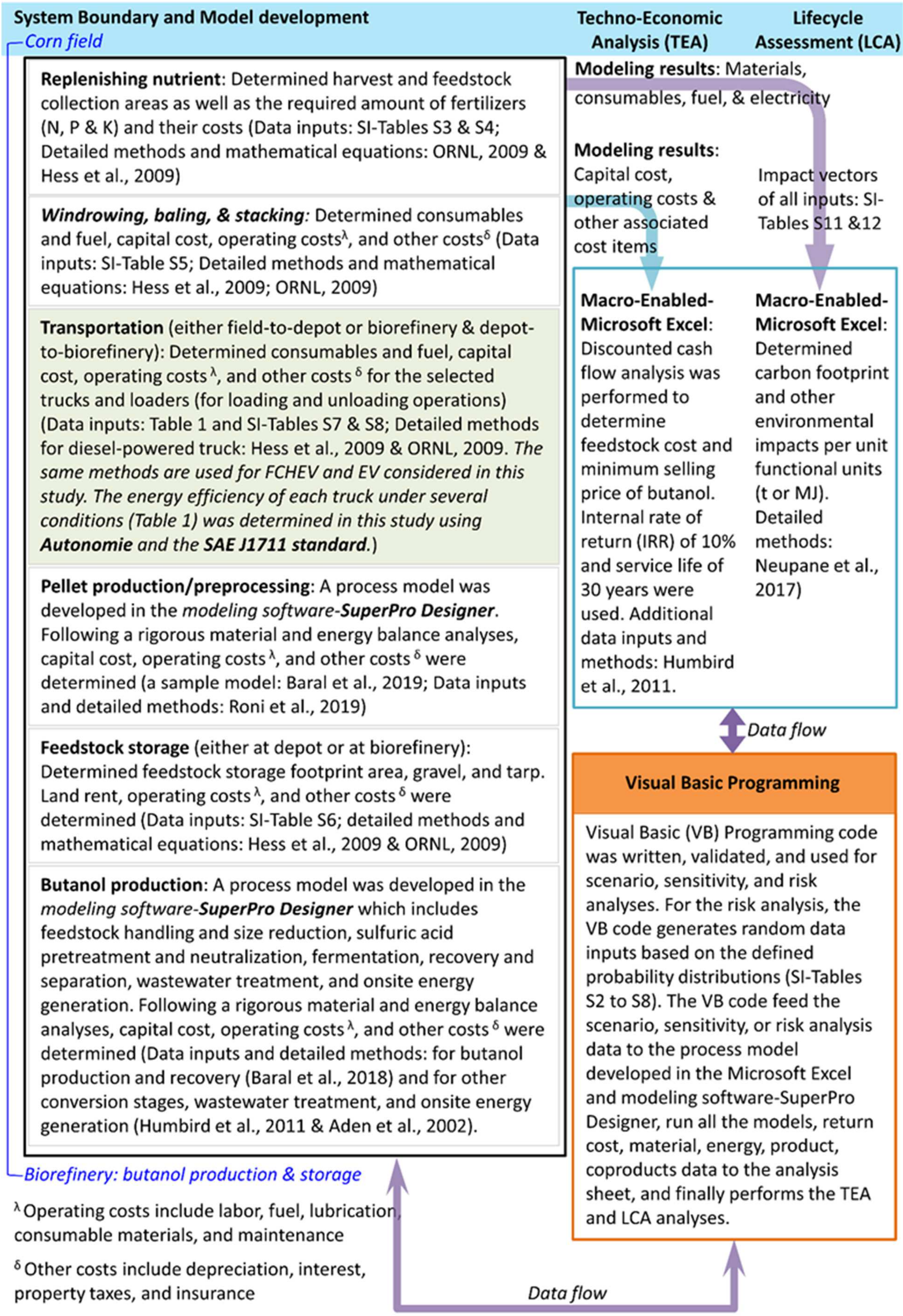

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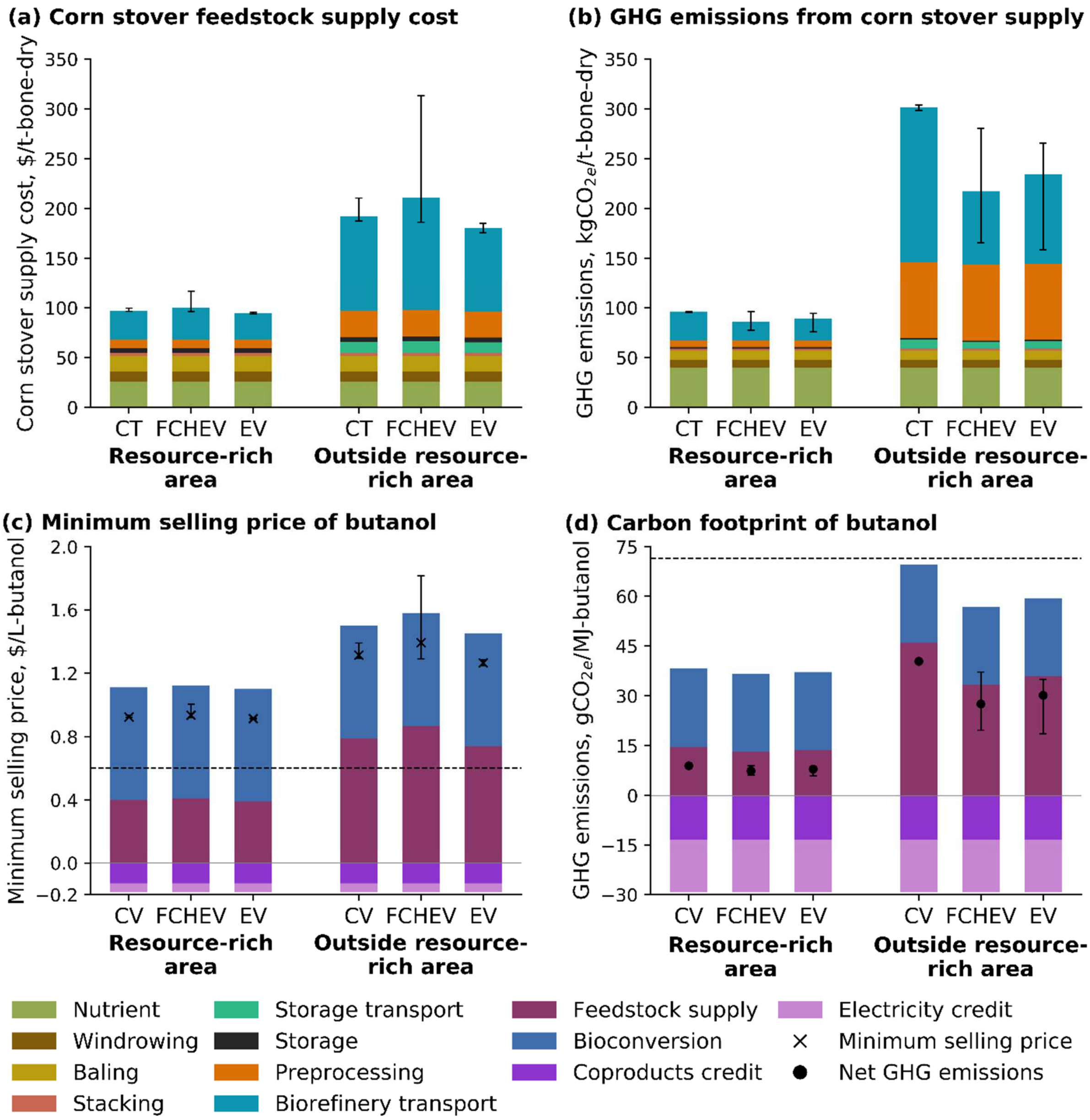

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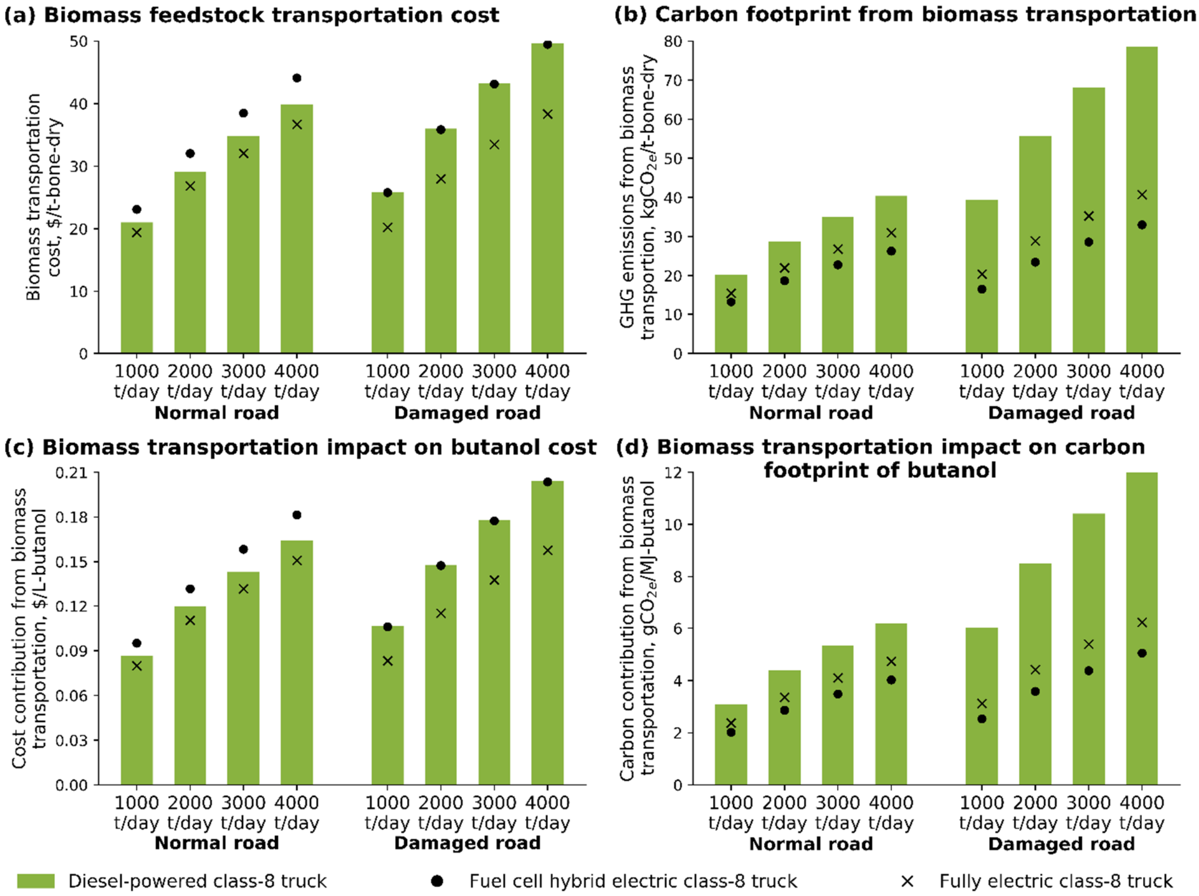

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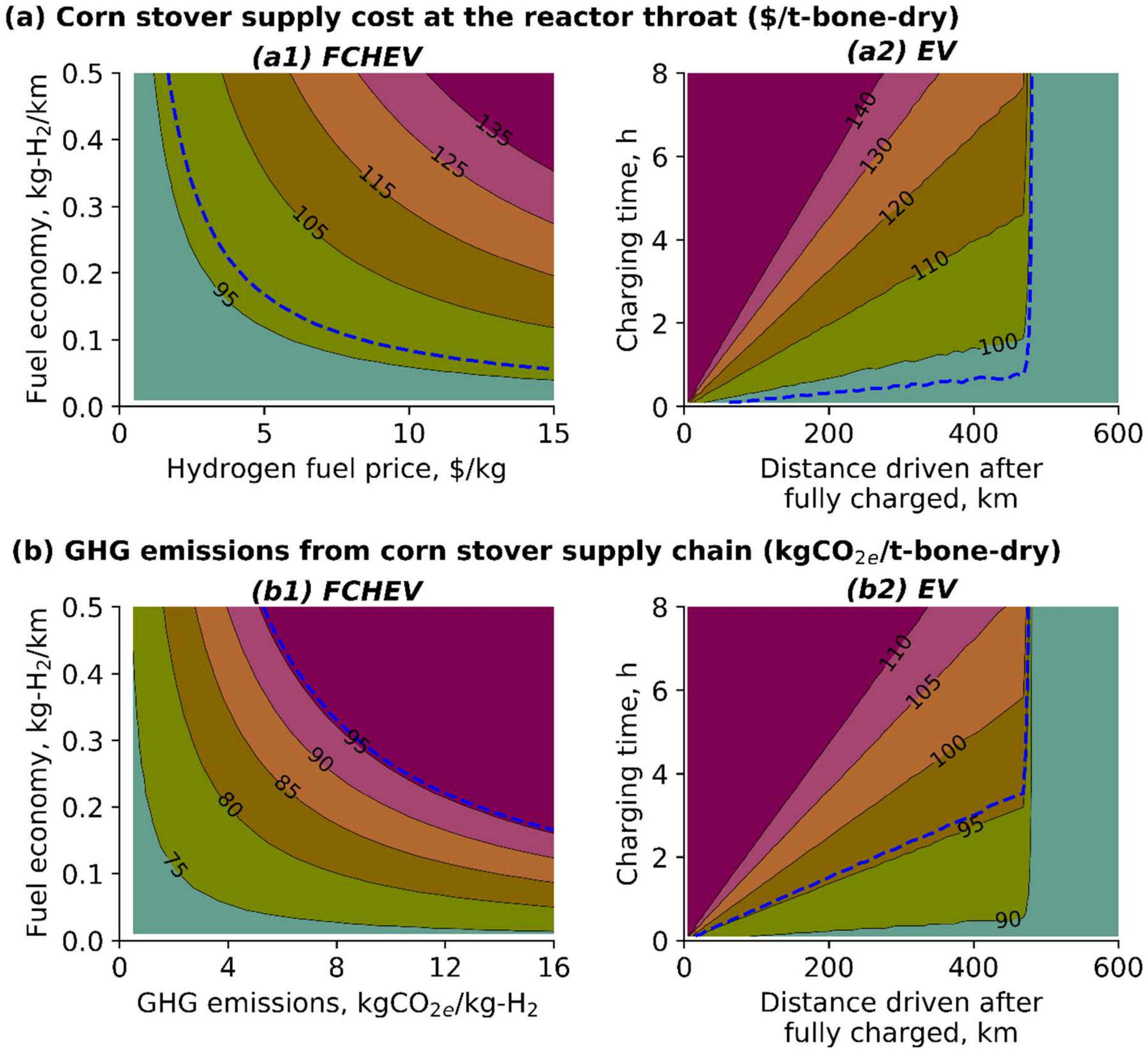

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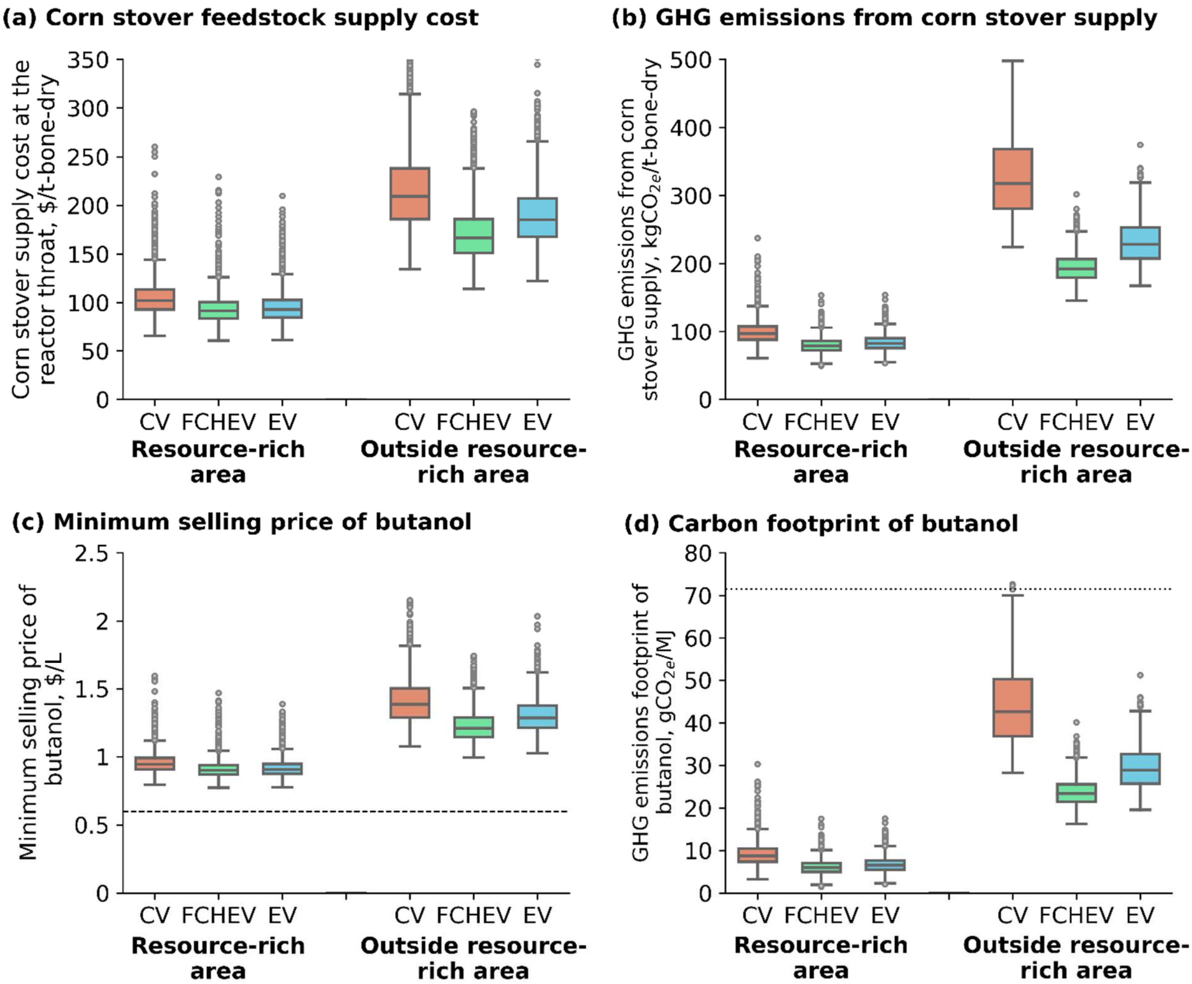

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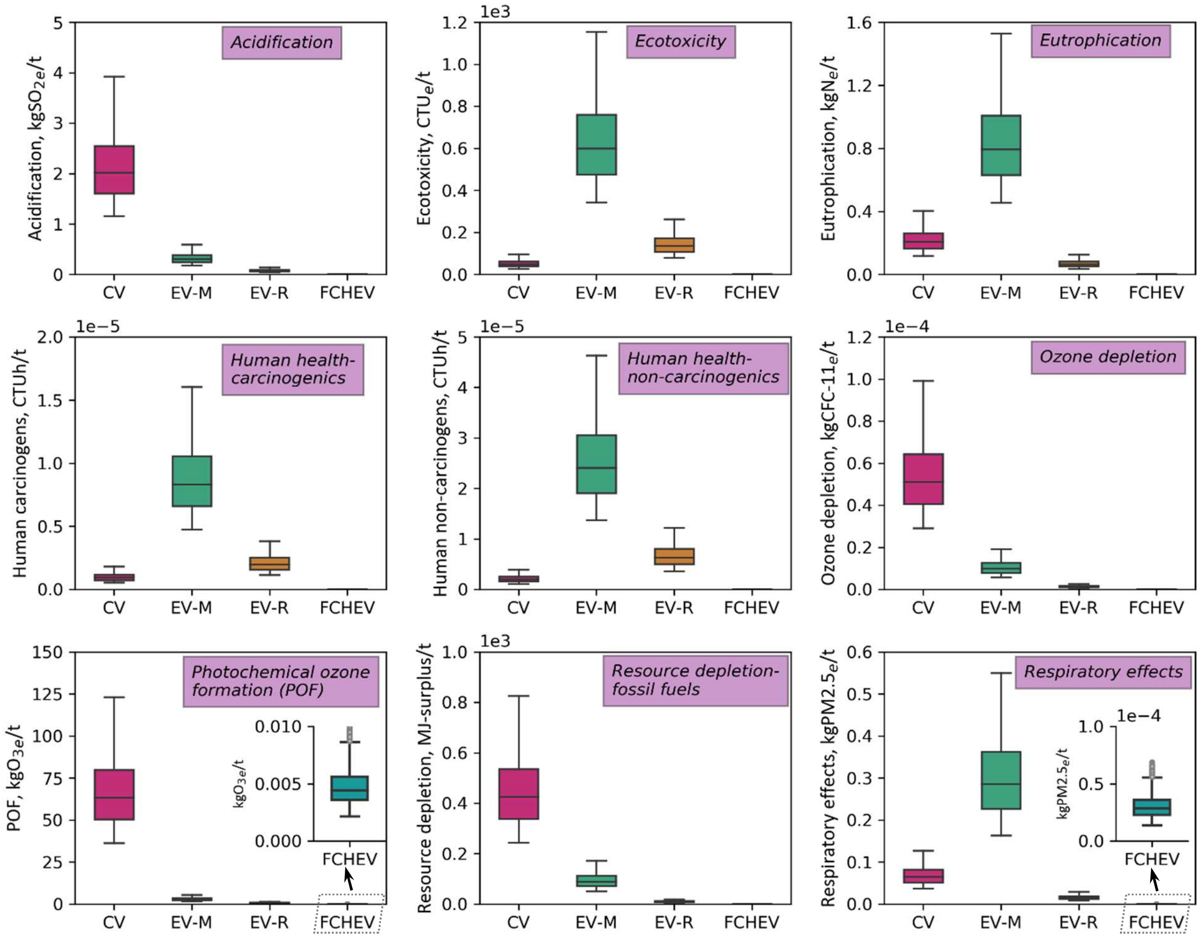

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List of Tables

Table 1. Summary of prior studies on biomass feedstock supply and contributions of this study

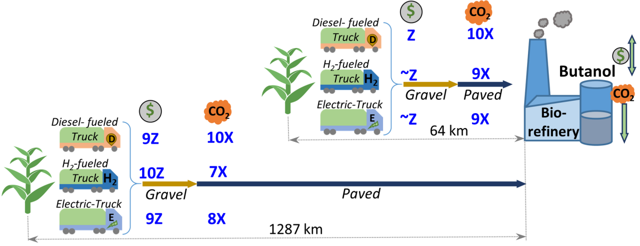
Description	Hess et al., 2009	INL, 2014	Roni et al., 2018	Ebadian et al., 2011	Morey et al., 2010	Ni et al., 2019	Sokhansanj et al., 2010	Sahoo et al., 2016	Lin et al., 2016	Wang et al., 2017	Mamun et al., 2020	Baral et al., 2017	Baral et al., 2018	Baral et. al., 2019	Baral et al., 2019a	This study
Biomass feedstock	CS, SWG	Woody & other*	Mixed[δ]	WS	CS	WS, MCT	CS	CTS	MCT	CS	CS	CS	CS	BS	CS, MCT, SWG	CS
Feedstock form	Bale, uniform format[Φ]	Uniform format[Φ]	Pellet	Uniform format[Φ]	Bulk material	Bale	Bale, chopped, pellet	Bale	Pellet, briquette, milled	Bale	Pellet	Bale	Bale	Bale	Bale, Pellet	Bale, Pellet
Biorefinery location	RR	RR	RR & ORR	RR	RR	RR	RR	RR	RR & ORR	RR	RR & ORR	RR	RR	RR	RR	RR & ORR
Farm-to-biorefinery trucking distance (km)	74 & 105	<74	64-355	5-160	37.6	100	70	<100	100-200	53-98	80-523	55.3	57-88	64.4	112	63.6 & 1287.5
Consideration of different scales of biorefinery								√		√						√
Use of drive cycle determining fuel economy/energy efficiency of truck																√
Use of diesel-powered truck	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Use of fuel-cell hybrid electric truck and fully electric trucks																√
Determined the impacts of gravel and paved roads																√
Determined the impacts of normal and damaged roads																√
Determined the impacts on human health and environment (except GWP)																√
Determined the impact of biomass transportation on fuel production cost														√		√
Determined the impact of biomass transportation on the carbon footprint of fuel													√			√
Uncertainty analysis of each stage of the supply chain	√											√	√	√	√	√
Integrated analysis including biomass cultivation to fuel production											√		√	√		√

Note: CS = Corn stover; WS = Wheat straw; BS = Biomass sorghum; MCT = Miscanthus; CTS = Cotton stalk; SWG = Switchgrass; RR = Resource-rich area or feedstock growing region; ORR = Outside the resource-rich area; GWP = Global Warming Potential. *Pulpwood, Wood Residues, Switchgrass, Construction and Demolition Waste, and their Blend; [δ]Corn stover, Switchgrass, Miscanthus, grass clippings, and their blend; [Φ]Uniform format feedstock, which can be directly fed to the reactor at the biorefinery without any preprocessing.

Table 2. Fuel economy (diesel for conventional truck, hydrogen for FCHEV, and electricity for EV) of the different truck types considered in this study

Truck type	**Unit**	**Fuel/energy consumption**							
		Paved road				Gravel road			
		Empty truck		Loaded truck		Empty truck		Loaded truck	
		Normal road	Damaged road	Normal road	Damaged road	Normal road	Damaged road	Normal road	Damaged road
Drive Cycle: HHDDT Transient (Represents City and Rural Driving)									
Conventional Class 8	MPG (L/100km)	5.84 (40.3)	3.99 (59.0)	2.47 (95.2)	1.36 (173)	2.27 (104)	1.87 (126)	1.99 (118)	0.55 (428)
Fuel Cell Hybrid Electric Class 8	MPGe (eqv L/100km)	7.87 (29.8)	5.74 (41.0)	3.71 (63.4)	2.23 (105)	3.67 (64.1)	3.05 (77.1)	1.27 (185)	0.95 (248)
Fully Electric Class 8	MPGe (kWh/100 km)	30.0 (69.8)	16.1 (131)	10.3 (203)	4.84 (432)	8.30 (252)	6.67 (314)	2.24 (933)	1.72 (1,218)
Drive Cycle: HHDDT Cruise (Represents Highway Driving)									
Conventional Class 8	MPG (L/100 km)	8.60 (27.4)	4.10 (57.4)	4.23 (55.6)	1.70 (138)	-	-	-	-
Fuel Cell Hybrid Electric Class 8	MPGe (eqv L/100 km)	10.1 (23.3)	6.80 (34.6)	5.29 (44.5)	2.35 (100)	-	-	-	-
Fully Electric Class 8	MPGe (kWh/100 km)	22.9 (91.3)	13.9 (151)	11.0 (190)	4.85 (432)	-	-	-	-

Note: Major input parameters for vehicle model development are summarized in the SI-Tables S1 and S2. For the fully electric truck: MPGe = ((kWh/100 mi))⁄3370 (EPA, 2011). 1 mile = 1.60934 km and 1 gallon = 3.78541 L.



$
CO_2
Diesel- fueled
Truck
D
Z
10X
H2-fueled
Truck
H2
~Z
9X
Butanol
Gravel
Paved
Electric-Truck
E
~Z
9X
Bio-
refinery
64 km
$
CO_2
Diesel- fueled
Truck
D
9Z
10X
H2-fueled
Truck
H2
10Z
7X
Gravel
Paved
Electric-Truck
E
9Z
8X
1287 km