Is the Pipeline Hydro-transport of Wheat Straw and Corn Stover to a Biorefinery Realistic?

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Abstract

Pipeline hydro-transport is an alternative to truck delivery of agricultural residue (lignocellulosic) biomass. Pipeline hydro-transport benefits from the economies of scale, reduces total delivery costs, and enables bio-based energy facilities to achieve higher capacities. In this study, the empirical correlation based on experimentally developed data for pipeline transport of agricultural residue-water mixtures (slurry) was used to develop a data-intensive techno-economic model to estimate the cost of pipeline hydro-transport of wheat straw and corn stover to a bio-ethanol refinery. The total cost of pipeline hydro-transport was found to be lowest at 8.8% dry matter slurry solid mass content and 2.5 m s^{-1} slurry velocity. At this biomass slurry solid mass content and velocity, the pipeline hydro-transport of biomass was found to be economically more viable than truck delivery at capacities of 0.45 M dry t yr^{-1} or more for a one-way pipeline and 1.4 M dry t yr^{-1} or more for a two-way pipeline (with the return of the carrier liquid . The ability to economically hydro-transport agricultural residue biomass in pipes offers the opportunity to develop large-scale bio-ethanol plants.

Keywords: Truck delivery, pipeline hydro-transport, agricultural residue biomass, bio-ethanol production, economies of scale

1. Introduction

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The United Nations[1] reports biomass as the most significant type of fuel in terms of the quantities used worldwide. Globally people depend on biomass more than any other fuel for energy production. While the residential sector is the largest consumer of biomass for small-scale applications, the industrial sector uses relatively small amount of biomass for electricity generation and fuel/chemical production globally. Trucks are used as the main mode of transporting biomass, and biomass materials come with low bulk density (kg m^{-3}) and low energy density (GJ m^{-3}) compared to fossil fuels. These factors result in high delivered cost of biomass, increasing frequency of delivery with increasing scale, and subsequent traffic congestion concerns. Consequently, the desire for short distance truck delivery with fewer congestion issues has favored small-scale biomass-based (bio-based) energy facilities. The challenge with small-scale development is that the capital cost per unit output of conversion facilities are high, resulting in high cost of product (i.e., heat, electricity or liquid fuels)[2, 3]. Earlier work has suggested that biomass conversion facilities have an economic optimum size at which the cost of production is minimum[4]. Such economic optimum size is a trade-off between the transportation cost of biomass (a function of yield of biomass, dry t ha^{-1}) and the capital cost per unit output of the plant. The studies have estimated the optimum sizes for a number of biomass-based products as well[5]. At economic optimum sizes the requirement of biomass is large but even these sizes of biomass-based facilities are very small compared to a fossil fuel based plants. For example, the production of ethanol from corn stover exemplifies the issues around large-scale industrial applications of biomass: a plant requires approximately 15 standard highway trucks per hour to receive 2 M dry t yr^{-1} of corn stover and produces only 960 Ml yr^{-1} of ethanol[6, 7];a very small production capacity compared to the 25 Gl yr^{-1} capacity of a typical oil refinery[8, 9].

Traffic congestion is not the only issue raised with increased scale. The transport and logistics arrangements of biomass from its point of availability, i.e., farm or forest, to its point of use, e.g., bio-based energy facility, contribute significantly to the total delivered cost of biomass. This cost is directly proportional to the number and frequency of trucks required and the distance over which the fuel has to be moved. These factors increase with increasing scale, i.e., economies of scale do not apply to truck delivery[5, 10, 11]. Allen and Browne[12] reported the cost of transporting biomass to be 29%, 22%, 17%, and 12% of the total delivered cost of straw, forest biomass, coppice, and miscanthus, respectively. Epplin[13] estimated the cost to transport switchgrass to a conversion facility to be 8.8 \$ dry t^{-1} or 24% of the total delivered cost. Morey et al.[14] found the truck transport of round bales of corn stover to contribute 24.9% to the total cost. Aden et al.[15] showed the contribution of corn stover delivery to the total delivered cost to be 24%. Kumar and Sokhansanj[16] also reported the cost of truck transport to contribute between 40 to 80% of total cost of transportation, including loading, unloading, stacking, and processing (size reduction) before or after transportation of biomass. Here there is an obvious need to develop an alternative biomass delivery system which is cost effective and can significantly reduce the delivered cost to a large-scale biomass-based facility, also reduce the traffic congestion issue.

Pipeline hydro-transport of biomass (i.e., transporting biomass solid particle-water mixtures in pipes) is an alternative mode of transport which can potentially reduce the cost of biomass transportation compared to trucks, benefit from economy of scale, and minimize the traffic congestion issues of overland transportation. Although such an approach comes with limitations for applications involving combustion[17], there is no penalty in pipeline hydro-transport of biomass in the form of a solid-liquid mixture (slurry) for conversion processes such as ethanol production via fermentation[8], hydrothermal hydrolysis[18], and hydrothermal liquefaction[19] since such conversion processes are all aqueous. In this case, most of the equipment at the pipeline inlet facility replaces those at the bio-refinery that would otherwise be required if biomass were directly delivered to the plant, e.g., washing, shredding, sizing, and slurrying machines[8]. Biomass slurry would contain almost the required amount of process water, and the slurry would enter the facility directly with or without adjustments in the biomass-water ratio, depending on the concentration at which the slurry is pipelined[20].

Kumar et al.[8, 17, 21] conducted a series of techno-economic analyses on pipeline hydro-transport of wood chips and corn stover. They investigated one-way and two-way pipeline scenarios wherein a one-way pipe would discharge/use the carrier liquid at the receiving facility and a two-way pipe would return all or a portion of the carrier liquid to the inlet facility. They found the cost of transport of wood chips by pipeline at a solid volume content of 30% to be less than the cost of truck delivery at capacities above 0.5 M dry t yr^{-1} for one-way pipeline and 1.25 M dry t yr^{-1} for two-way pipeline. They also studied the cost of pipeline hydro-transport of corn stover at a 20% solids volume content, compared it with the cost of truck delivery, and found that pipeline hydro-transport costs less than truck delivery at capacities above 1.4 M dry t yr^{-1} for one-way pipeline and 4.4 M dry t yr^{-1} for two-way pipeline. However, the pressure drop correlation used to obtain corn stover pipeline cost estimates had been originally proposed for transporting wood chips-water mixtures through a pipeline[22, 23]. Luk et al.[24] experimentally studied the technical feasibility of pipelining wheat straw slurries in order to understand the pressure drop behavior of corn stover and other agricultural residue (lignocellulosic) biomass slurries, and Vaezi et al.[20, 25] investigated the friction loss behavior of the slurries of knife-milled and size-classified wheat straw and corn stover particles in pipes as a function of biomass particle type and size, slurry solid mass content, and slurry velocity. They also proposed an empirical correlation to predict the pressure drop of the flow of agricultural residue biomass slurries in pipes which were significantly different than the correlations presented for wood chip-water mixtures.

In this work, the technical parameters and constraints as well as the empirical correlations obtained through the course of experimental study by Vaezi et al.[20, 25-27], together with the pipeline economic structure proposed by Kumar et al.[8, 17, 21], were used to develop a data-intensive techno-economic model to estimate the cost of pipeline hydro-transport of wheat straw and corn stover agricultural residue biomass to biorefinery. The specific objectives of the present study are:

- Estimating the cost of pipeline hydro-transport of agricultural feedstocks using the pressure drop correlations specifically proposed for agricultural residue biomass[25];
- Comparing the total cost of delivery with the total cost obtained using wood chip pressure drop correlations;
- Estimation of the optimum slurry solid mass content and velocity to obtain the highest throughput at the lowest transport cost;
- Investigating the effect of pipeline capacity and transport distance on the total cost of delivery.

2. Techno-economic Modeling

Techno-economic models are powerful tools that combine the technical and financial parameters of a system and help in decision making. In this study, a data-intensive techno-economic model for the transport of wheat straw and corn stover agricultural residue biomass via pipeline was developed. All the costs reported here, even those cited from literature, are based on the 2014 U.S. dollar.

2.1. Truck Delivery

The truck transportation cost of biomass consists of two components: distance variable cost (DVC) and distance fixed cost (DFC). The DVC includes equipment, labor, and fuel associated with delivery of biomass and DFC is comprised of equipment and labor associated with loading and unloading of biomass. Further details on this can be found in literature elsewhere[15, 28-32]. The techno-economic model developed in this study includes both DVC and DFC for truck delivery of biomass (Table 1). There is a significant variation in the DVC reported earlier, as it is dependent on the type of biomass feedstocks and the methodologies applied in estimation[8]. Figure 4 shows the total truck delivery costs (DVC plus DFC for known distance). This figure indicates the independency of truck delivery costs from capacity of transportation where no saving occurs with larger throughputs.

Table 1

2.2. Pipeline Hydro-transport

The techno-economic model of pipeline hydro-transport was based on economic principles also empirical correlations obtained through previous course of experimental measurements by the authors[20, 24, 27]. The technical model included parameters associated with all the unit operations at inlet, receiving, and booster station facilities involved in pipeline hydro-transport of wheat straw and corn stover. It also characterized operating conditions (e.g., density and viscosity of the biomass slurry, biomass slurry flow rate, etc.), process equipment (e.g., size of water/mixing tanks, diameter of the pipeline, power required for the main and booster pumps, etc.), and unit operations' inputs (water, electricity, biomass feedstock, etc.). The economic parameters in the model were comprised of capital, operating, and maintenance costs of unit operations. Similar to the model by Kumar et al.[8, 17, 21], one- and two-way pipeline scenarios were modeled here, where the two-way pipeline would be required in the case of the scarcity of water upstream or a downstream water discharge prohibition[8, 17]. The techno-economic model was capable of estimating the total cost of pipeline hydro-transport as well as the cost per unit input of feedstock as a function of biomass particle type and size, distance of transport, capacity of pipeline, slurry solid mass content, and pumping velocity.

Kumar et al.[8] reviewed several pressure drop correlations proposed for wood chip-water mixtures in pipes, including correlations by Hunt[22], Brebner[33], Elliot[34], and Faddick[35]. They used the correlation by Hunt[22] to predict the pressure drop of slurries of corn stover particles in pipes. Vaezi et al.[20] experimentally investigated the applicability of wood chip-water mixture correlations to estimate the pressure drop of slurries of knife-milled and size-classified wheat straw and corn stover particles through a 25 m long, 50 mm diameter closed-circuit pipeline . As observed in Fig. 1(a), while the woodchip correlations estimated friction factor values above those of pure water, the pressure drop of the slurries of both wheat straw and corn stover particles exhibited a unique trend and dropped below that of water at Reynolds numbers above 80,000 (equivalent to velocities above 2 m s^{-1}) due to the diverse nature and unusual characteristics of agricultural residue biomass particles, e.g., their relatively large mean particle size; wide size distribution; extreme shapes; fibrous, pliable, flexible, and asymmetric nature; and potential for forming networks (see Table 2)[26]. Also, unlike wood chip-water mixtures and all other traditional solid-liquid systems (e.g., sand, coal, clay, iron ore), the pressure drop of the slurry of agricultural residue biomass particles decreases with increasing solid mass content and proved the inapplicability of wood chip-water mixture correlations for the slurries of agricultural residue biomass particles. Figure 1(a) illustrates why applying appropriate pressure loss correlations is so critical. Calculating the pressure loss of slurries of agricultural residue biomass particles using correlations proposed for wood chip-water mixtures results in a noticeable overestimation of the pressure losses and, accordingly, the size of the pumps and the total power required. Based on experimental measurements, Vaezi and Kumar[25] later proposed an empirical correlation to predict the pressure drop of the slurries of agricultural residue biomass particles. The same correlation was then applied in this techno-economic model. The range of the variables were also adopted from the range tried while experimentally pipelining agricultural residue biomass particles[20]. For simplicity, minor losses due to bends, fittings, etc., as well as the change in elevation were ignored, since those are highly localized and specific to a given pipeline project. Table 3 shows the technical features of the model and Table 4 lists the general economic parameters of the pipeline.

Figure 1

Table 2

Table 3

Table 4

A contingency cost equal to 5% of the total capital and engineering cost of pipeline was calculated in the model, versus 20% contingency applied by Kumar et al.[17]. A sensitivity analysis on contingency cost revealed increasing the contingency from 5% to 20% will increase the cost of pipeline hydro-transport of biomass (\$ dry $t^{-1}km^{-1}$) between 7 to 11%.

Table 5 summarizes the major unit operations at inlet, booster stations, and receiving facilities together with the capital and operating/maintenance costs of the units. The unit operations' capital cost estimates were made according to correlations proposed in earlier studies[17, 40-42]. The capital, operating, and maintenance costs were calculated in Table 5 for a sample case of pipeline hydro-transport of biomass: a 1.16 m diameter one-way pipeline transporting 2,000,000 dry t yr^{-1} slurry of <3.2 mm (d_{50} = 2.42 mm) wheat straw particles at 8.8% dry matter solid mass content and 2.5 m s^{-1} velocity over a distance of 200 km. All the initial and operating variables were chosen from corresponding ranges presented on Tables 2 and 3. The pipeline diameter was calculated based on the pipeline transport capacity and slurry velocity, and the number of booster stations was obtained by dividing the total pressure drop throughout the pipeline by the total head produced by the main and booster pumps.

Pipeline hydro-transport has a cost structure similar to that of truck delivery with costs either fixed or variable with distance. The fixed (distance-independent) cost is associated with the equipment at inlet and receiving facilities, and variable (distance-dependent) costs come from operating and maintenance costs, recovery of the capital investment in the pipeline and booster stations, and associated infrastructures such as road access. Fixed capital costs at inlet and receiving facilities are typically lower than the total capital costs of the pipeline system. It can be observed on the same example as of Table 5 that, in a pipeline with a capacity of 2 M dry t yr^{-1} that hydraulically transports an 8.8% slurry of <3.2 mm wheat straw particles at a velocity of 2.5 m s^{-1} over a distance of 200 km, the investment in inlet and receiving facilities comprises only

5.6% of the pipeline costs (material, construction, etc.) and 5.2% of the total capital cost of the one-way pipeline system.

Table 5

3. Results and Discussion

3.1. Sensitivity Analysis

Every single parameter studied here, if changed, could change the total cost of pipeline hydro-transport independently of the other parameters. Of all the variables (biomass particle type and size, pipeline capacity, pipeline length, and slurry solid mass content and velocity), the slurry solid mass content and slurry velocity were optimized first, as the former defines the material/water ratio at the inlet facility and the latter determines the diameter of the pipe. In addition, the two variables impact the pressure drop throughout the pipeline and contribute to the total power required. Therefore, the effect of these parameters on the cost of pipeline hydro-transport was investigated first to obtain the optimum (with respect to the cost) velocity and solid mass content.

Vaezi et al.[20] found that the slurry pressure drop decreased with increasing velocity and solid mass content (Fig. 1(a)). In another study[27], it was observed that the pump input power increased with an increase in slurry velocity and solid mass content (Fig. 1(b)). Therefore, although increasing the slurry velocity and solid mass content decreased the pressure drop, it increased the power required to run the centrifugal pumps. The authors first tried to find an optimum slurry velocity and solid mass content where the cost of pipeline hydro-transport was the lowest. Figure 2 presents the cost of hydro-transport of <3.2 mm wheat straw particles using a commercial scale pipeline with a capacity of 2 M dry t yr^{-1} over a long distance of 200 km as a function of slurry velocity and solid mass content. Considering the variation of the cost of pipeline hydro-transport with respect to the slurry solid mass content only, it was noted that the cost continuously decreased with increasing solid mass content. This was because an increase in slurry solid mass content decreased the slurry volumetric flow rate, which subsequently, at fixed slurry velocity, decreased the pipe diameter and hence the corresponding capital costs. However, at fixed slurry solid mass content, fluctuations in the cost were observed with continuous increase in slurry velocity. The total cost first decreased with an increasing velocity from 1.5 to

2.5 m s^{-1} and then increased with increasing velocity from 2.5 to 4.5 m s^{-1}. The reason is that although the diameter of the pipe and the total capital cost continuously decreased with increasing velocity, the pressure drop and, consequently, the number of booster stations and total operating cost increased with increasing velocity more noticeably at elevated velocities.

Consequently, at a velocity of 2.5 m s^{-1} and a solid mass content of 8.8%, the variable cost of pipeline hydro-transport was found to be at its lowest in both one-way and two-way pipeline systems. This was true for all the pipeline lengths, capacities, biomass particles types and sizes. The optimum velocity was, in fact, within the range of velocity of commercial pipelines, 1.5 to 3 m s^{-1} [43].

Figure 2

Other variables whose impacts on the cost of pipeline hydro-transport were investigated were biomass particle type and size. As observed on Table 2, two types of agricultural residue biomass of wheat straw and corn stover were chosen for this study. In an earlier study, Vaezi et al.[26] investigated the particle size, particle size distribution, and morphological features of wheat straw and corn stover and found that the knife-milled pre-classified wheat straw and corn stover particles had nominal sizes of <3.2, 3.2, 6.4, and 19.2 mm with corresponding median lengths (d_{50}) between 1.9 mm and 8.29 mm (Table 2).The nominal sizes were chosen in this work as the common dimensions of significance to refer to the biomass particles throughout the paper. It was found that, although slurry pressure drop throughout the pipe is a function of biomass particle type and size, or more specifically biomass shape factor (see Table 3), the effect of biomass shape on the cost of pipeline hydro-transport was negligible. Figure 3 compares various particle types and sizes, where for a certain type a change in the size of the particles resulted in an average change of only1.4% in the pipeline hydro-transport cost. However, the authors are not able to validate the same effect on the particles that are out of the range of the dimensions studied here. For simplicity, <3.2 mm wheat straw particles were chosen for which, together with a slurry velocity of 2.5 m s^{-1} and solid mass content of 8.8% (fixed when needed), all the costs of pipeline hydro-transport were calculated and reported. However, practically considering, the size of the particles chopped by a large-scale mill to use on a commercial scale pipeline would be most probably closer to the largest size of the particles studied here, i.e., 19.2 mm.

Figure 3

3.2. Truck Delivery vs. Pipeline Hydro-transport of Biomass

In light of the sensitivity analyses conducted on biomass particle type and size, as well as slurry velocity and solid mass content, results were calculated for slurries of <3.2 mm wheat straw particles at a velocity of 2.5 m s^{-1}. When needed, the solid mass content was fixed at the optimum value of 8.8% dry matter, and the cost of pipeline hydro-transport was compared with the total cost of truck delivery from four sources (Kumar et al.[28], Aden et al.[15], and Duffy[29], and personal communication with a local transport company[32]) and is shown in Table 1.

Figure 4 shows the cost of one-way and two-way pipeline hydro-transport of <3.2 mm wheat straw particles at 2.5 m s^{-1} over 150 km as a function of pipeline capacity and slurry solid mass content. As observed, unlike with truck delivery, there are strong economies of scale in pipeline hydro-transport of agricultural residue biomass. The economies of scale benefits are associated with the cost of pipeline and its construction, also the cost of equipment at inlet and receiving facilities. Increasing the pipe diameter also decreases the slurry pressure drop[17] which cause saving in the total pumping power required. For instance, on a 200 km one-way pipeline transporting 8.8% solid mass content slurry of <3.2 mm wheat straw particles at 2.5 m s^{-1}, doubling the pipeline capacity from 2 M dry t yr^{-1} to 4 M dry t yr^{-1}, increased the capital cost, operating cost, and total cost by 49%, 27%, and 44%, respectively. This resulted in a decrease in the total cost per unit mass delivered (\$ dry t^{-1}) by 28%. Liu et al.[40] suggested a capital cost scale factor of 0.59-0.62 for a pipeline systems. However, a more conservative scale factor of 0.75 was applied here to inlet, receiving, and booster station facilities, excluding pumps and pipes. Figure 4 also reveals the significant cost of a two-way pipeline with the return of the carrier liquid, as compared with a one-way pipeline.

For a given distance, pipeline hydro-transport costs decreased with increasing solid mass content (as discussed in section 3.1) and pipeline capacity. The point at which pipeline hydro-transport costs drop below truck delivery costs depends strongly on the total truck delivery cost for a given distance. Based on an 8.8% slurry solid mass content, 2.5 m s^{-1} slurry velocity, and the lowest estimate of the total truck delivery costs reported[29] (i.e., 0.22 \$ dry $t^{-1}km^{-1}$), pipeline hydro-transport becomes economically more viable than truck delivery at capacities of 0.45 M dry t yr^{-1}

or more for a one-way pipeline and 1.4 M dry t yr^{-1} or more for a two-way pipeline. However, the highest estimate of truck delivery costs (i.e., 0.46 \$ dry t^{-1})[32] would always cost more than pipeline hydro-transport for one-way pipelines. It would also cost more for two-way pipelines with capacities above 0.35 M dry t yr^{-1}.

For this specific case of study (<3.2 mm wheat straw particles at 2.5 m s^{-1} over 150 km), at a typical pipeline capacity of 2 M dry t yr^{-1} and slurry solid mass content of 8.8%, 76% of the total costs of a one-way pipeline system is due to its capital cost (22.6 M \$ yr^{-1}) and 24% are operating costs (7.3 M \$ yr^{-1}). Among the operating costs, the largest component, 56%, is electrical power for pumping (4.1 M \$ yr^{-1}). Corresponding numbers for two-way pipelines are 80%, 20%, and 64%, respectively.

Figure 4

Figure 5 compares the DFC and DVC of pipeline hydro-transport and truck delivery of biomass. The costs for pipeline hydro-transport of biomass are calculated for a slurry of <3.2 mm wheat straw particles at the optimum slurry and operating conditions of 8.8% solid mass content and 2.5 m s^{-1} velocity (section 3.1). The distance fixed and variable costs for truck delivery are taken from Table 1. As observed in Fig. 4(a), all one-way pipelines with transport capacities of 1 M dry t yr^{-1} and higher, always have DFC and DVC lower than those for hauling by truck. For a one-way pipeline with a capacity of 0.5 M dry t yr^{-1}, pipeline hydro-transport of biomass can compete with truck delivery only up to a distance of 228 km, based on the lowest estimate of reported truck delivery costs[29]. For a one-way pipeline with a capacity of 0.25 M dry t yr^{-1}, the viability of the pipeline hydro-transport of biomass depends strongly on DVC and DFC of truck delivery, as considering the reported lowest estimate of the cost of truck delivery[29] makes the pipeline competitive only up to a distance of 30 km, and choosing the highest cost estimate of truck delivery[32] makes the pipeline hydro-transport cost always less than truck delivery.

Figure 5(b) compares the costs of two-way pipeline hydro-transport of biomass and truck delivery for similar slurry and operating conditions. For two-way pipelines with capacities of 2 M dry t yr^{-1} and more, pipeline hydro-transport would always cost less than truck transport.

Technically, every extra booster station required for extra distances would slightly increase the total cost and would shape the pipeline hydro-transport cost curve like a sawtooth. However, in practice, the cost of an incremental booster station is negligible compared to the total cost of the pipeline system, and so the sawtooth effect can be ignored[17]. For instance, for a pipeline system with a capacity of 2 M dry t yr^{-1} pumping 8.8% solid mass content slurry of <3.2 mm wheat straw particles at 2.5 m s^{-1}, every extra booster stations adds only 1.8% to the total cost of pipeline system.

Figure 5

3.3. Integrated Truck/Pipeline ransport of Biomass

Kumar et al.[17] pointed out that pipeline hydro-transport of biomass normally requires an initial truck delivery of biomass to the pipeline inlet, where the fixed costs of both truck delivery and hydro-transport are incurred. In this study, considering an average yield of 0.39 dry t ha^{-1} for straw[28], the initial distance of truck delivery to collect and transport 0.5 M dry t yr^{-1} (minimum economic capacity for one-way pipeline as per Fig. 4(a)) and 1.4 M dry t yr^{-1} (minimum economic capacity for two-way pipeline as per Fig. 4(b)) of wheat straw was calculated[44] to be 59 and 96 km, respectively. The corresponding costs of truck delivery to a pipeline inlet facility were afterwards included into the model, with further transport of wheat straw by one- and two-way pipeline in the form of 8.8% solid mass content slurry at 2.5 m s^{-1} velocity. Figure 6 shows the cost curves of integrated truck/pipeline systems together with truck-only transport. As it is observed, pipeline transport always cost more than truck delivery at capacities of 0.5 M dry t yr^{-1} for one-way and 1.4 M dry t yr^{-1} for two-way pipelines thus cannot compete with truck delivery over the extra distance. This occurs because DVC of truck delivery is smaller than DVC of truck plus either one- or two-way pipeline at these minimum economic capacities. However, there will be intersection between truck and integrated truck/pipeline DVC lines at higher capacities, where integrating will cost less than truck-only delivery. For instance, at a capacity of 2 M dry t yr^{-1}, the minimum pipeline distance to recover the fixed costs of the pipeline and the initial 115 km truck delivery to the pipeline inlet is 141 km for a one-way pipeline. Pipelines shorter than 141 km are less economical than truck-only delivery.

Figure 6

4. Conclusions

Pipeline hydro-transport can economically compete with truck delivery of agricultural residue biomass at medium to large capacities over long distances. Based on 8.8% slurry solid mass content, 2.5 m s^{-1} slurry velocity, 150 km medium-range distance, and the lowest estimate of the total cost of truck delivery reported (0.22 \$ dry $t^{-1}km^{-1}$), pipeline hydro-transport is economically more viable than truck delivery at capacities of 0.5 M dry t yr^{-1} or more for one-way pipelines and 1.4 M dry t yr^{-1} or more for two-way pipelines. Considering the highest estimate of the total cost of truck delivery reported (\$0.46 dry t^{-1}), pipeline hydro-transport of the same slurry would always cost less than truck delivery for one-way pipeline, also it would cost less than truck delivery at capacities above 0.35 M dry t yr^{-1} for two-way pipelines. Integrated truck/pipeline transport of agricultural residue biomass at minimum economic capacities of 0.5 and 1.4 M dry t yr^{-1} for one- and two-way pipeline with initial truck delivery of 59 and 96 km was also studied. For these scenarios, pipeline transport was found economically not capable of competing with truck delivery over the extra distance. However, benefits were found at higher capacities to integrate truck and pipeline, where truck plus pipeline transport of biomass would cost less than truck-only delivery. Understanding the structure of the cost of the pipelines transporting agricultural residue biomass helps to identify and optimize critical variables to reduce the total cost of delivery and enable bio-based energy facilities to achieve higher capacities.

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Table 1. Distance variable and fixed cost of biomass transportation by truck in North America

Biomass[1]	Distance Fixed Cost ($ dry t^{-1})	Distance Variable Cost[2] ($ dry $t^{-1}km^{-1}$)	Total Cost Over A Distance of 150 km ($ dry t^{-1})
Wheat straw[28]	6.66	0.27	47.16
Corn stover[15] (NREL[3])	9.45	0.24	45.45
Switchgrass[29]	10.77	0.15	33.27
Hay and forage[30]	9.20	0.16	33.2
Hay (less than 100 km)[Personal Communication, 32]	9.02[4]	0.40	69.02
Wheat straw[31] (less than 100 km)	-	0.37	-
Wheat straw[31] (more than 200 km)	-	0.25	-

[1] All the costs in the tables are for transportation of biomass in the form of large round bales
[2] The distance accounts for the one-way trip, but the cost includes the return trip
[3] U.S. National Renewable Energy Laboratory
[4] Not available - average of all the distance fixed costs

Table 2. Physical properties and shape specifications of wheat straw and corn stover knife-milled and size-classified particles

Solid Particle	Nominal Particle Size (mm)	Median Length (mm)	Particle Aspect Ratio	Particle Specific Gravity	Particle Shape Factor	Slurry Solid Mass Content
	X_n	d_{50}		$\rho_p \rho_f^{-1}$	S	C_d
Wheat Straw	19.2	8.29	6.28	1.026	0.133	1-5.4
	6.4	5.00	4.47		0.196	1-6.5
	3.2	3.92	3.53		0.298	1-7.6
	<3.2	2.42	3.47		0.908	1-8.8
Corn Stover	19.2	7.58	5.93	1.169	0.113	-
	6.4	4.72	4.08		0.169	1-6.5
	3.2	3.32	2.88		0.351	1-7.6

	<3.2	1.90	2.89	0.610	1-8.8

Table 3. Input parameters for the present techno-economic model

Item	Description/Value
Pipeline capacity*	250,000 to 4,000,000 M dry t yr^{-1}
Average transportation distance*	50 to 300 km
Slurry and water pipe material	commercial steel pipe
Slurry and water pipe roughness[36]	0.06096 mm
Biomass particle type*	wheat straw and corn stover
Biomass particle size [26*]	Nominal: <3.2, 3.2, 6.4, and 19.2 mm d_{50}: 1.9 to 8.29 mm
Particle shape factor correlation[25, 27]	$\square = \frac{\square_{\square}}{\square_{\square} \times \sum_{\square=1}^{\square} (\square_{\square\square,\square} \times \square_{\square,\square}}$ $\square\square\square\square\square\ \square\square\square\square\square\square = \square \times \sqrt{\frac{\square_{\square\square}}{\square_{\square\square}}}$

Item	Description
λ	Parameter dependent of th flakiness of the particle; dimensionless
M_s	Mass of solid particle sample, kg
ρ_p	Density of solid particle, kg m^{-3}
X_{gw}	Geometric mean width, mm
X_{gl}	Geometric mean length, mm
A_s	Solid particle area, mm^2

Item	Description/Value
Particle saturated moisture content[20]	82%
Saturated biomass particle density[20]	1050 kg m^{-3}
Dry matter solid mass content*	2 to 8.8%
Slurry velocity*	1.5 to 4.5 m s^{-1}
Velocity of water in water return pipeline	2 m s^{-1}
Slurry pressure drop correlation[25] **Note***: The model is not limited to the agricultural residue biomass studied here. Common agricultural residue biomass or, generally, non-wood fibers and energy crops, if ground, would be fibrous in nature[37-39] and are expected to come with similar mechanical behavior when mixed with water and pumped into pipeline.*	$\frac{\Delta \square}{\square} = [\sum_{\square=1}^{3} (\square_{\square}\square^{\square} + \square_{\square}\square^{\square} + \square_{\square}\square_{\square}^{\square} + \square_{\square}\square^{\square}\square_{\square}^{\square})](\frac{\square}{\square_{0}})^{-1.2}$

Item	Description
$\Delta H\ L^{-1}$	Longitudinal pressure gradient in the pipe, kPa m^{-1}
S	Solid particle shape factor; dimensionless

	n = 1	n = 2	n = 3
α	1.2246	-1.9709	0.6485
β	0.0000	0.16389	0.000(
γ	0.0000	0.00000	0.0006
δ	0.0000	-0.0010	0.000(
D	0.0508 m		

	V	slurry bulk velocity, m s^{-1}	θ	
	C_d	Dry solid mass content, %		
	D	Pipe internal diameter, m		
	$\alpha, \beta, \gamma, \delta$	Constants		
Slurry and water pump efficiency[40]	80%			
Maximum pressure of the pump	3100 kPa			

* Model initial and operating variables

Table 4. General economic parameters of the present techno-economic model

Item	**Values**
Inflation rate	2.1%
Discount rate	10%
Life of pipeline	30 yr
Life of pump	20 yr
Capacity factor of pipeline	0.85
Maintenance cost of	
- equipment	3% of capital cost
- pipeline	0.5% of capital cost
Power cost	50 $ MWh^{-1}
Engineering cost	10% of total capital cost
Contingency cost	5% of total cost
Scale factor	0.75

Table 5. Capital, operating, and maintenance costs of inlet, booster stations, and receiving facilities

Item	**Cost**	**Description***
Note: *The results are for a 1.16 m diameter one-way pipeline transporting 2 M dry t yr^{-1} slurry of <3.2 mm (d_{50} = 2.42 mm) wheat straw particles at an 8.8% dry matter solid mass content and 2.5 m s^{-1} velocity over a distance of 200 km with one booster station in the middle*		
Inlet Facility		
Capital Costs		
Land, $	51,513	- 30 hectare - Includes truck unloading area, weight scale, dead storage area, tank space, and pump space - Estimated by Kumar et al.[17] based on 2000 USD

		and inflated to 2014 USD with a rate of 7.1%
Intake piping for water, $	708,316	- 100 m long and 0.6 m diameter pipeline to transport 0.6 m^3 s^{-1} of water - Includes piping from mixing tank to the water storage tank - Calculated using the formula by Liu et al.[40]
Mixing tank, $	80,949	- 27 m^3 with a slurry residence time of 45 s - Calculated using the formula by Peter et al.[42]
Storage tank for water, $	1,015,535	- 790 m^3 - 30 min storage - Calculated using the formula by Peter et al.[42]
Power supply lines, $	528,000	- 4.5 MW - Estimated by Epcor Utilities Inc.[8, 17]
Building, $	312,631	- 300 m^2 - Includes control room for pump, site monitoring, maintenance area, warehouse, communication and pipeline control room - Estimated by Kumar et al.[17]
Slurry pipeline, $	225,777,903	- Calculated using the formula by Liu et al.[40] as a function of pipe diameter
Main pump (with one redundant pump), $	5,538,211	- Calculated using formula by Liu et al.[40] as a function of total pump power required - Total power required is the product of flow rate (m^3 s^{-1}), head loss (m), and efficiency of the pump
Total capital cost at inlet facility, $	235,325,298	
Amortized capital cost at inlet facility, $ yr^{-1}	25,034,571	
O/M Costs		
Main pump power, $ yr^{-1}	2,737,079	- Based on 60 $ MWh^{-1} electricity cost and 0.85 pipeline capacity factor
Salary and wages, $ yr^{-1}	1,080,000	- Based on 4 staffs, 2000 hr yr^{-1}, 27 $ hr^{-1}
Maintenance cost, $ yr^{-1}	1,359,657	- Based on 3 and 0.5% of capital costs for equipment and pipeline, respectively
Total operating cost at inlet facility, $ yr^{-1}	5,493,731	
Booster Station Facility		
Capital Costs		
Booster pump, $	2,783,718	- Calculated using formula by Liu et al.[40] as a function of extra pump power required in addition to the initial power provided by the main pump
Substation, $	528,000	- 4MW - Estimated by Epcor Utilities Inc.[8, 17]
Total capital cost at booster station, $	3,476,760	
Amortized capital cost at booster station, $ yr^{-1}	525,691	
O/M Costs		
Booster pump, $ yr^{-1}	2,755,020	- Based on 60 $ MWh^{-1} electricity cost and 0.85 pipeline capacity factor
Maintenance cost, $ yr^{-1}	83,511	- Based on 3% of capital cost for equipment
Total operating cost at booster station, $ yr^{-1}	2,866,081	
Receiving Facility		
Capital Costs		
Buildings, $	312,631	- 300 m^2 - It includes control room for pump and pipeline, site monitoring, and communication - Estimated by Kumar et al.[17]
Water intake tank, $	1,015,535	- 790 m^3 - Heated and insulated - Calculated using the formula by Peter et al.[42]

Total capital cost at receiving facility, $	2,337,895	
Amortized capital cost at receiving facility, $ yr^{-1}	279,877	
O/M Costs		
Salary and wages, $ yr^{-1}	540,000	- Based on 2 staffs, 2000 hr yr^{-1}, 27 $ hr^{-1}
Maintenance cost, $ yr^{-1}	70,897	- Based on 3, 0.5, and 5% of capital costs for equipment, pipeline, and conveyer belts, respectively
Total operating cost at receiving facility, $ yr^{-1}	678,087	
Total capital cost of pipeline hydro-transport system, $	241,139,955	
Total operating cost of pipeline hydro-transport system, $ yr^{-1}	9,037,901	
Fixed cost of pipeline hydro-transport, $ dry t^{-1}	1.23	
Variable cost of pipeline hydro-transport, $ dry $t^{-1}km^{-1}$	0.10	

* The unit operations capital cost estimates were made according to correlations proposed by Liu et al.[40], Chandler et al.[41], Peters and Timmerhaus[42], and Kumar et al.[17]

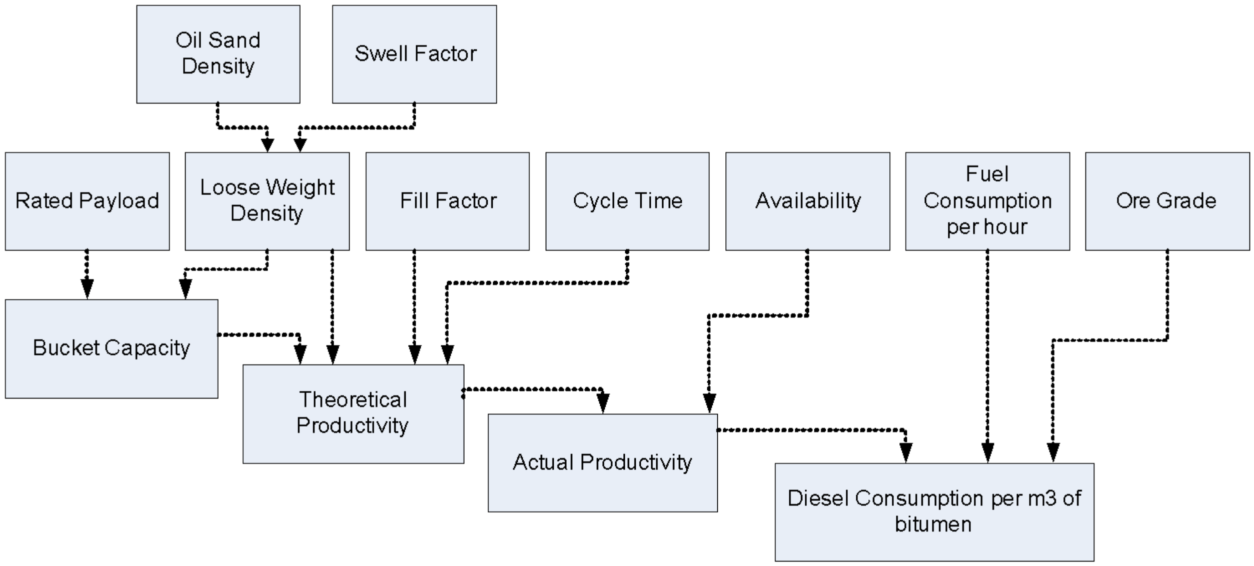

Figure 1. Methodology for calculating diesel consumption in shovels and trucks

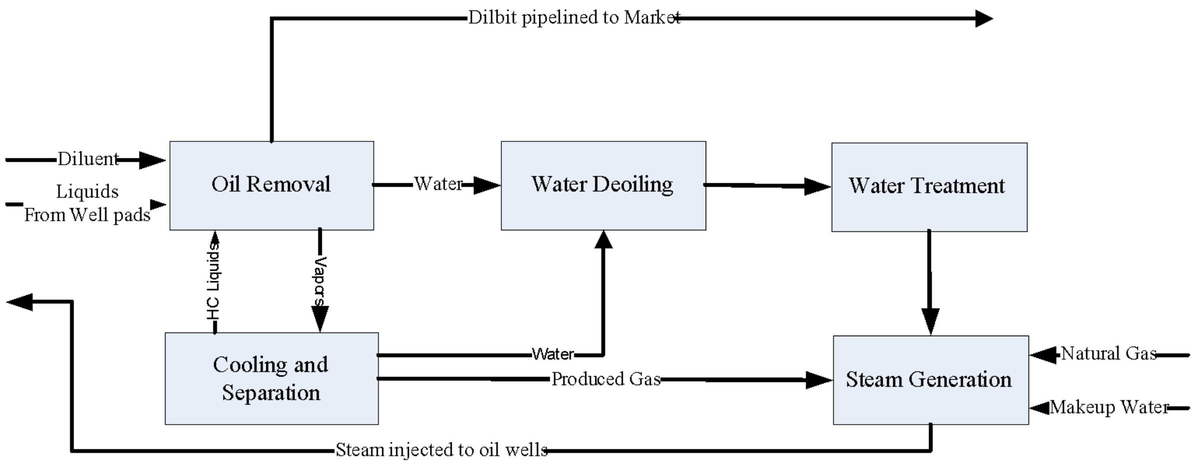

Figure 2. Subunit operations in SAGD

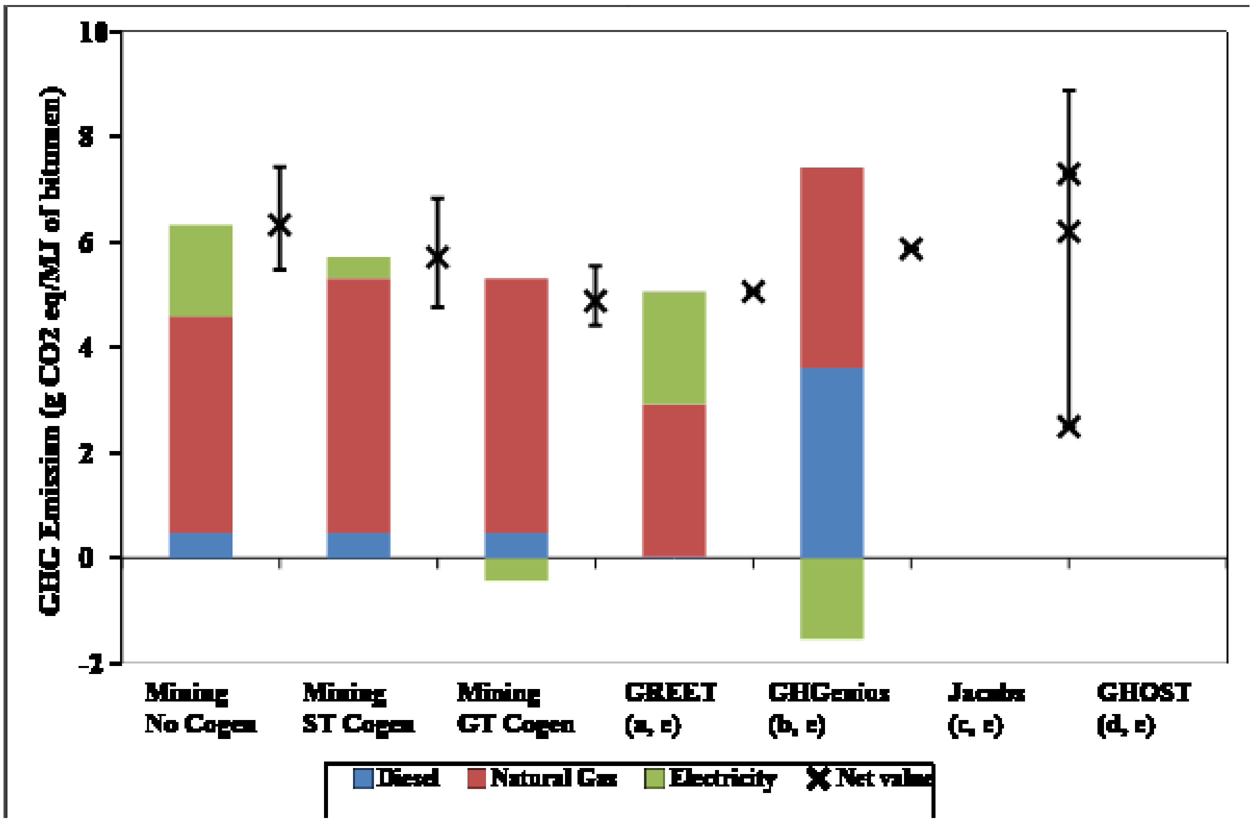

Figure 3. Estimated GHG emissions in surface mining in comparison to existing literature and models

(a) [21] Emissions are calculated based on default values of fuel consumption specified in the model; (b) [20] Emissions are calculated based on default values of fuel consumption specified in the model; (c) [10] The lower value is with cogeneration and the higher value corresponds to the “no cogeneration” case. The emissions reported are based on the assumption that energy in surface mining is about one half of the energy consumed in SAGD operation with SOR of three; (d) [24] The “no cogeneration” and “with cogeneration” ranges overlap; the range shown is a combined range; (e) Values reported in the literature have been converted using 8 API gravity and LHV of bitumen from the GHGenius, for comparison purposes.

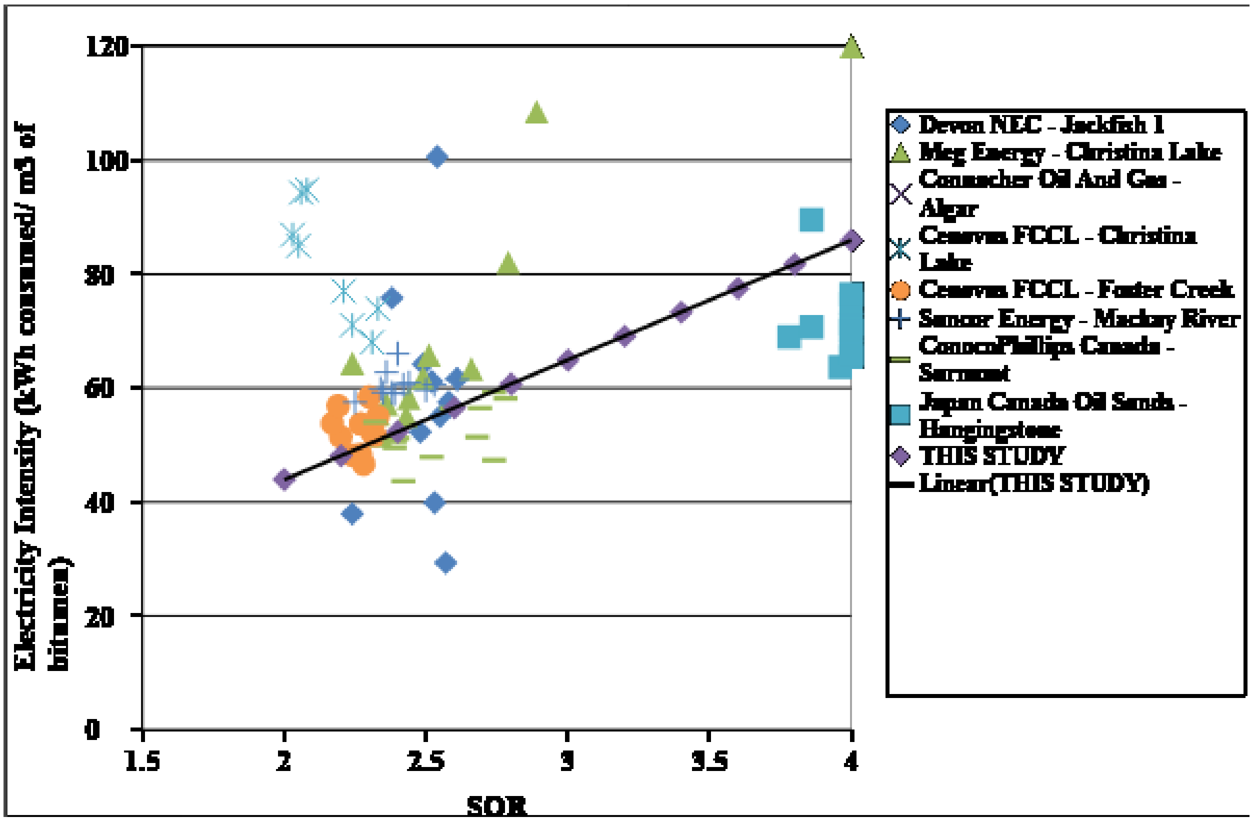

Figure 4. Correlation between electricity consumption and instantaneous SOR in SAGD

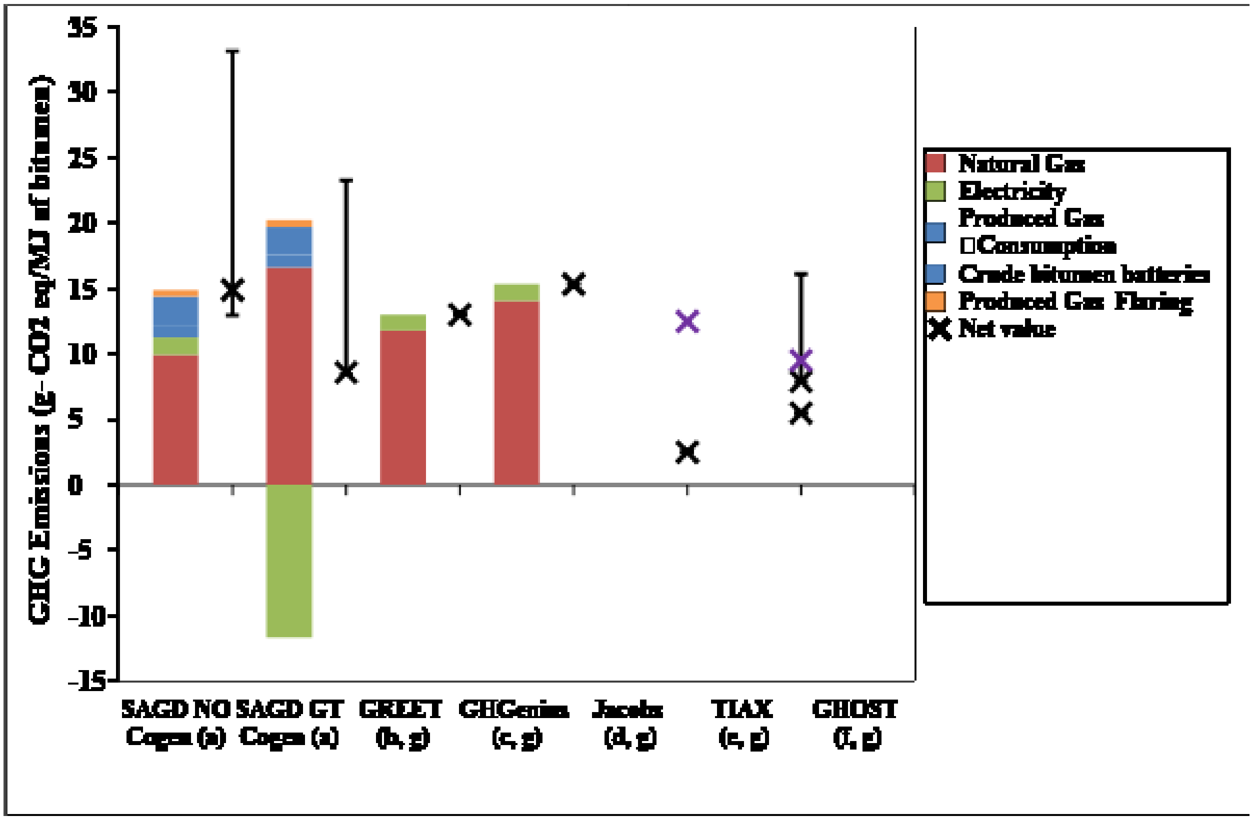

Figure 5. Estimated GHG emissions in SAGD in comparison to existing models and literature

(a) The wide range of values is due to the exclusive range of SOR considered – 2.1 to 6.54 [56], with a default value of 2.89; (b) [21]. Emissions are calculated based on default values of energy consumption specified in the model; (c) [20]. Emissions are calculated based on default values of energy consumption specified in the model; (d) [10]. The lower value is associated with cogeneration and the higher value corresponds to the "no cogeneration" case. A SOR of 3 is considered. The credits for electricity export are given based on 80% coal based grid electricity; (e) [9]. A SOR of 2.5 is considered. The higher value is for bitumen production in SAGD with electricity export; (f) The SOR considered is in the range of 2.2-3.3; (g) Values reported in the literature were converted for comparison purposes using 8 API gravity and LHV of bitumen from the GHGenius model. The GHG emissions from crude bitumen batteries are not accounted for in these studies.

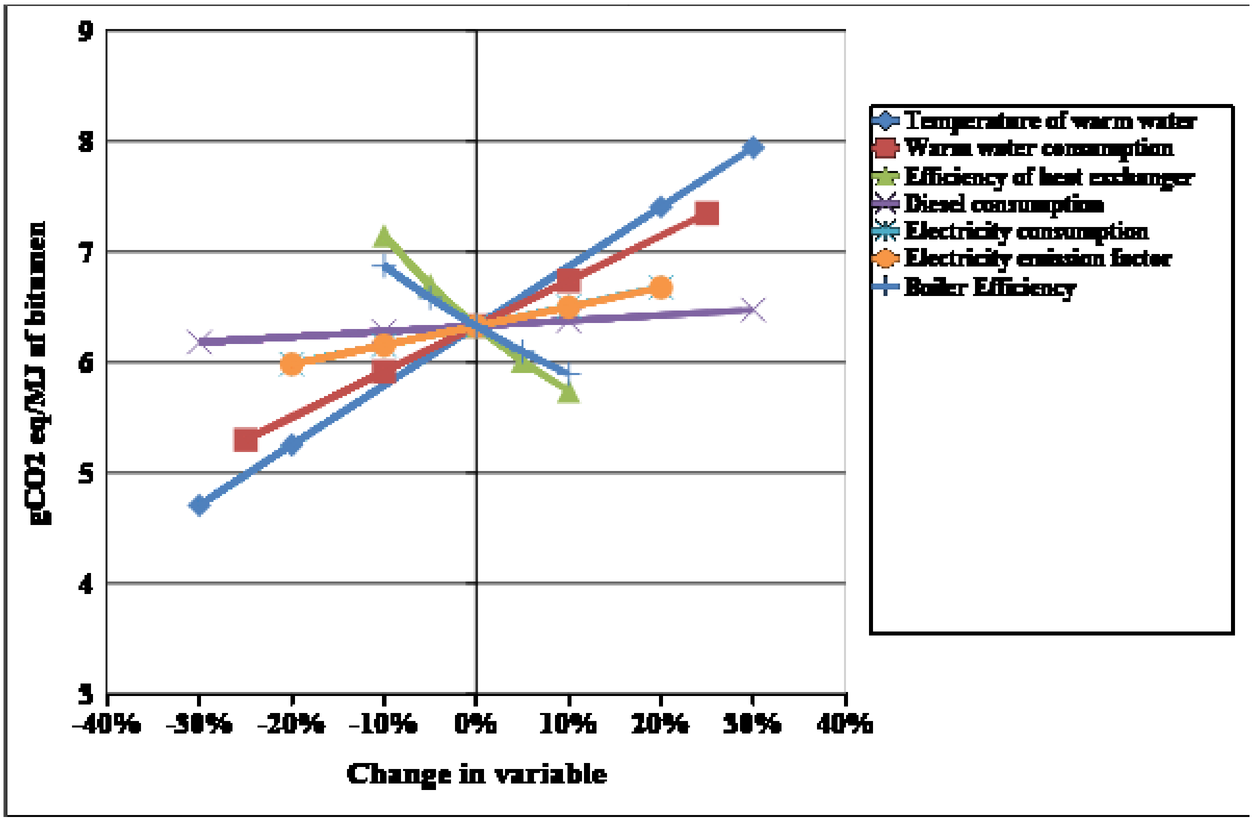

Figure 6. Sensitivity analysis of GHG emissions on key parameters in surface mining (Mining NO Cogen)

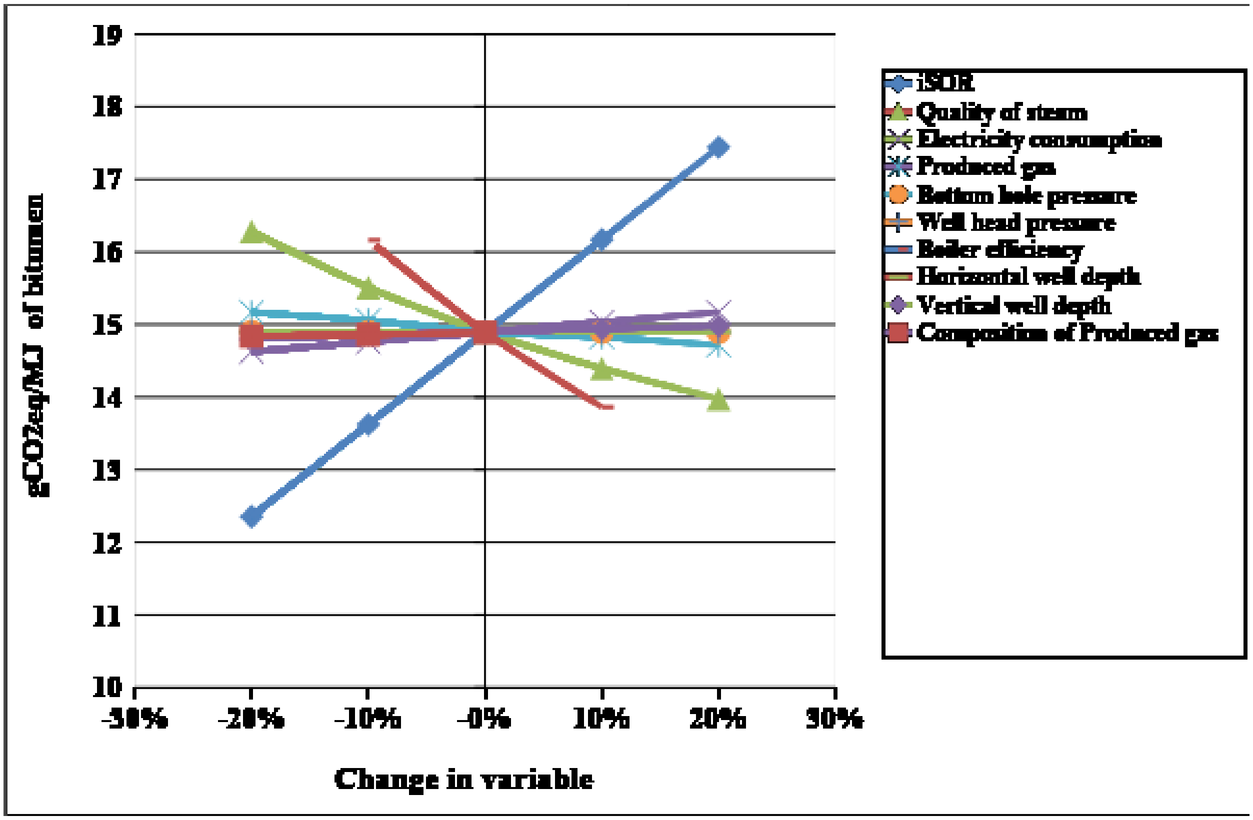

Figure 7. Sensitivity analysis of GHG emissions on key parameters in SAGD (SAGD NO Cogen)

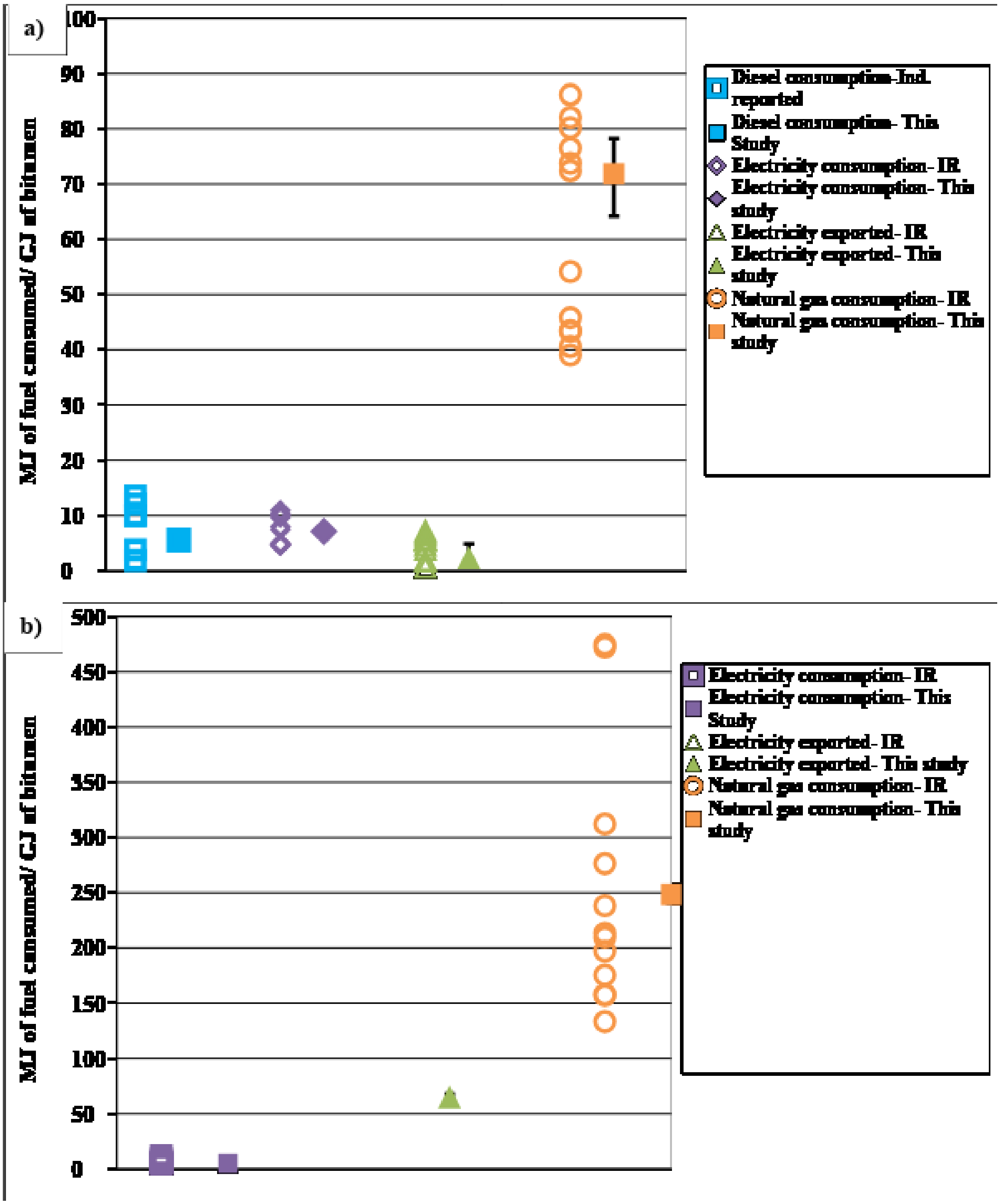

Figure 8. Comparison of energy values estimated by this research to those reported by the industry for a) surface mining, b) SAGD operation.

Note: IR refers to average annual fuel consumption values reported by the industry [45, 49].

Table 1. Distance variable and fixed cost of biomass transportation by truck in North America

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	3.2	3.32	2.88		0.351	1-7.6
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Table 3. Input parameters for techno-economic model

Item	Description/Value
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Average transportation distance*	50 to 300 km
Slurry and water pipe material	commercial steel pipe
Slurry and water pipe roughness[37]	0.06096 mm
Biomass particle type*	wheat straw and corn stover
Biomass particle size [26*]	Nominal: <3.2, 3.2, 6.4, and 19.2 mm d_{50}: 1.9 to 8.29 mm
Particle shape factor correlation[25, 27]	$\lambda = \frac{M_s}{\rho_p \times \sum_{i=1}^{n} (X_{gw,i} \times A_{s,i}}$ $Shape\ factor = \lambda \times \sqrt{\frac{X_{gw}}{X_{gl}}}$
Particle saturated moisture content[20]	82%
Saturated biomass particle density[20]	1050 kg m^{-3}
Dry matter solid mass content*	2 to 8.8%
Slurry velocity*	1.5 to 4.5 m s^{-1}
Velocity of water in water return pipeline	2 m s^{-1}
Slurry pressure drop correlation[25] **Note:** *The model is not limited to the agricultural residue biomass studied here. Common agricultural residue biomass or, generally, non-wood fibers and energy crops, if ground, would be fibrous in nature*[38-40] *and are expected to come with similar mechanical behavior when mixed with water and pumped into pipeline.*	$\frac{\Delta H}{L} = [\sum_{n=1}^{3} (\alpha_n V^n + \beta_n S^n + \gamma_n C_d^n + \delta_n V^n C_d^n)](\frac{D}{D_0})^{-1.2}$

Particle shape factor correlation — symbols:

Item	Description
λ	Parameter dependent of the flakiness of the particle; dimensionless
M_s	Mass of solid particle sample, kg
ρ_p	Density of solid particle, kg m^{-3}
X_{gw}	Geometric mean width, mm
X_{gl}	Geometric mean length, mm
A_s	Solid particle area, mm^2

Slurry pressure drop correlation — symbols:

Item	Description
$\Delta H\ L^{-1}$	Longitudinal pressure gradient in the pipe, kPa m^{-1}
S	Solid particle shape factor; dimensionless
V	slurry bulk velocity, m s^{-1}
C_d	Dry solid mass content, %
D	Pipe internal diameter, m
α, β, γ, δ	Constants

	n = 1	*n* = 2	*n* = 3
α	1.2246	-1.9709	0.6485
β	0.0000	0.16389	0.0000
γ	0.0000	0.00000	0.0006
δ	0.0000	-0.0010	0.0000
D_0	0.0508 m		

Slurry and water pump efficiency[41]	80%
Maximum pressure of the pump	3100 kPa

* Model initial and operating variables

Table 4. General economic parameters of the techno-economic model

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Inflation rate	2.1%
Discount rate	10%
Life of pipeline	30 yr
Life of pump	20 yr
Capacity factor of pipeline	0.85
Maintenance cost of	
- equipment	3% of capital cost
- pipeline	0.5% of capital cost
Power cost	50 \$ MWh^{-1}
Engineering cost	10% of total capital cost
Contingency cost	5% of total cost
Scale factor	0.75

Table 5. Capital, operating, and maintenance costs of inlet, booster stations, and receiving facilities

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Note: *The results are for a 1.16 m diameter one-way pipeline transporting 2 M dry t yr^{-1} slurry of <3.2 mm (d_{50} = 2.42 mm) wheat straw particles at an 8.8% dry matter solid mass content and 2.5 m s^{-1} velocity over a distance of 200 km with one booster station in the middle*		
Inlet Facility		
Capital Costs		
Land, $	51,513	- 30 hectare - Includes truck unloading area, weight scale, dead storage area, tank space, and pump space - Estimated by Kumar et al.[17] at 2000 and inflated to 2014 USD with a rate of 7.1%
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Main pump power, $ yr^{-1}	2,737,079	- Based on 60 $ MWh^{-1} electricity cost and 0.85 pipeline capacity factor
Salary and wages, $ yr^{-1}	1,080,000	- Based on 4 staffs, 2000 hr yr^{-1}, 27 $ hr^{-1}
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Buildings, $	312,631	- 300 m^2 - It includes control room for pump and pipeline, site monitoring, and communication - Estimated by Kumar et al.[17]
Water intake tank, $	1,015,535	- 790 m^3 - Heated and insulated - Calculated using the formula by Peter et al.[43]
Total capital cost at receiving facility, $	2,337,895	
Amortized capital cost at receiving facility, $ yr^{-1}	279,877	
O/M Costs		
Salary and wages, $ yr^{-1}	540,000	- Based on 2 staffs, 2000 hr yr^{-1}, 27 $ hr^{-1}
Maintenance cost, $ yr^{-1}	70,897	- Based on 3, 0.5, and 5% of capital costs for equipment, pipeline, and conveyer belts, respectively
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Total operating cost of pipeline hydro-transport system, $ yr^{-1}	9,037,901	
Fixed cost of pipeline hydro-transport, $ dry t^{-1}	1.23	
Variable cost of pipeline hydro-transport, $ dry t^{-1}km^{-1}	0.10	

[*] The unit operations capital cost estimates were made according to correlations proposed by Liu et al.[41], Chandler et al.[42], Peters and Timmerhaus[43], and Kumar et al.[17]