Feasibility Study of a Great Lakes Bioenergy System

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(**Supplementary Material**)

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The Supplementary Material contains 18 pages (3 Figures and 7 Tables)

1. Introduction

This document provides a more complete description of the systems model, assumptions, and methodologies used in the assessment of the bioenergy potential for the Canadian land adjacent to the Great Lakes St. Lawrence Seaway (GLSLS). Details are provided on the structure and boundaries of the modeled bioenergy system, as well as the calculation of land area and biomass production capacity.

2. Methodology

2.1. Systems model

Our study used a systems approach, where the entire supply chain was modeled by building relationships between the elements that make up the system. Our model tracked the flows of mass, energy, and greenhouse gas (GHG) emissions over the lifecycle of the process (Fig. S1). Processes and flows that were beyond the scope of our study are shown outside the system boundary. For example, carbon dioxide (CO_2) emissions as a result of biopower generation and green diesel use were outside the system boundary as well as CO_2 uptake during plant growth.

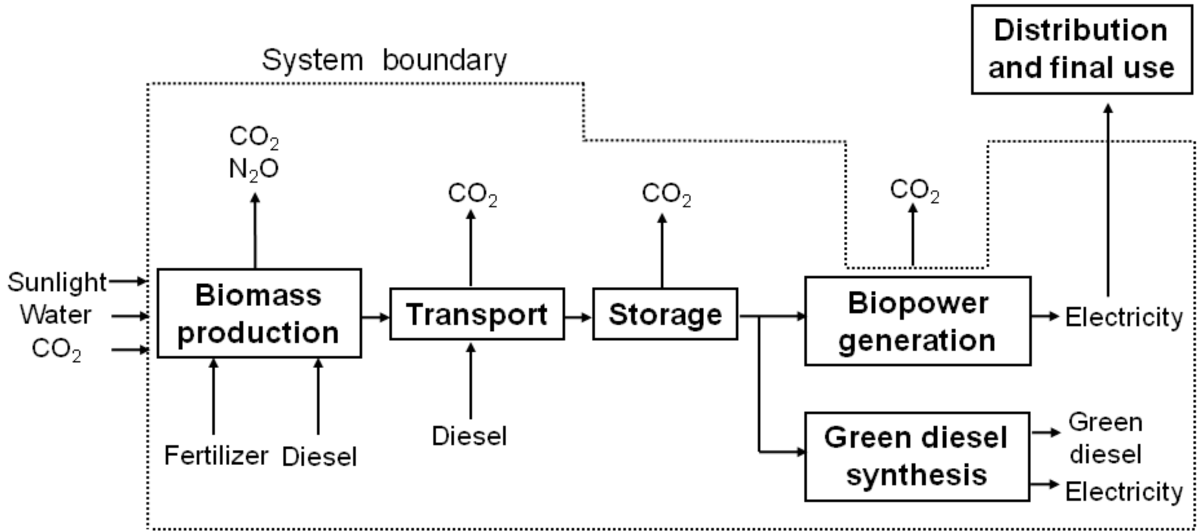

Figure S1. Systems model and boundary for the biopower and green diesel supply chains.

2.2. Layout of GLSLS system

The bioenergy system consisted of forest and agricultural biomass production sites, pellet mills, transportation corridors (truck, rail, and ship), and energy conversion facilities. A graphical illustration of the supply chain that connects areas of biomass production with conversion facilities via transportation corridors is presented in Fig. S2.

Pellet mills were modelled adjacent to the GLSLS or railway lines. Mills were supplied with biomass in the form of wood chips or straw bales from within a 100 km radius. Major unit operations such as drying, size reduction, and densification converted biomass into stable pellets of uniform size (Mani et al., 2006). Pellets were an ideal intermediate form of biomass for long-distance shipping due to low moisture content and physical properties that reduced handling and transportation costs (Zhang et al., 2010). Heat treating of pellets reduced the risk of disease transfer to other biological materials, although off-gassing of carbon monoxide in confined spaces was still a safety hazard (Svedberg et al., 2008).

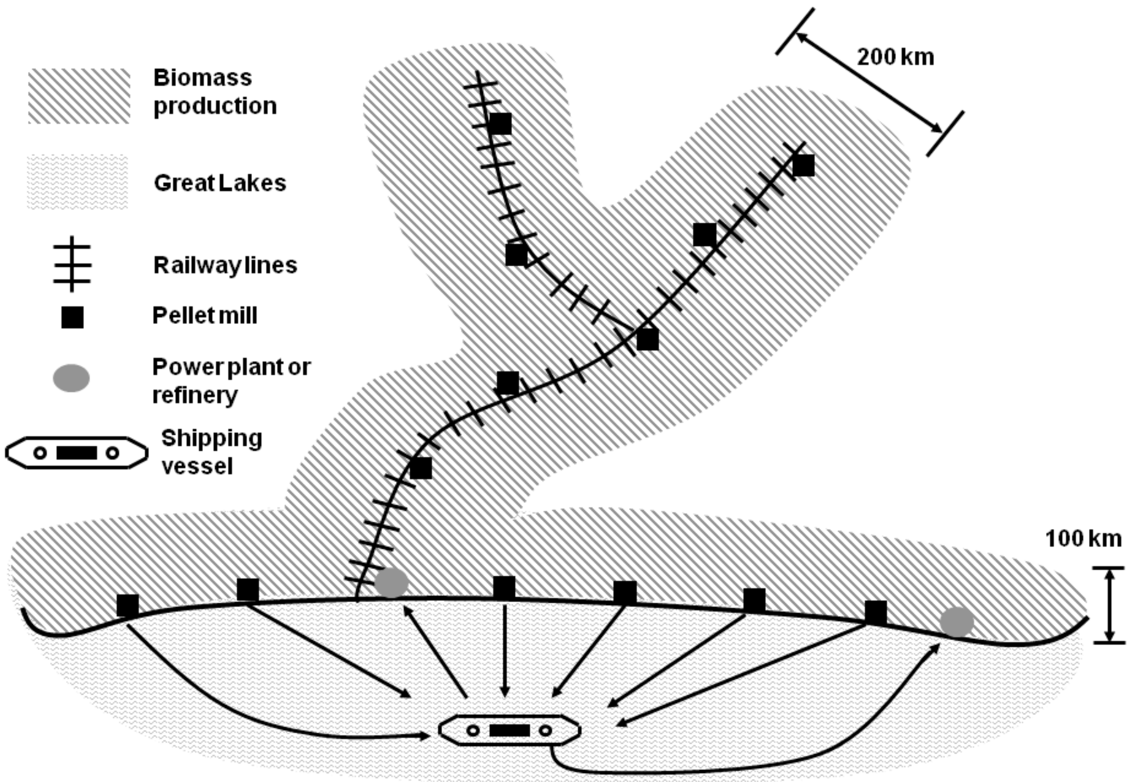

Figure S2. An illustration of the GLSLS bioenergy supply chain connecting areas of biomass production to pellet mills and energy conversion facilities via rail and water-borne transportation corridors.

Long-distance transport of pellets occurred by rail, ship, or a combination of both. Shipping in the GLSLS is often part of a greater intermodal network, where major ports on the system are linked to road and rail transportation offering shippers greater flexibility and cost savings (Transport Canada et al., 2007). Pellets transported by rail from several mills were concentrated at major ports and loaded on to lake freighters with a cargo capacity of 10,000 to 55,000 tonnes (Robertson, 2008). Conversely, individual mills adjacent to the

GLSLS employed smaller vessels such as barges pushed by tugboats that carried approximately 1500 tonnes of cargo.

Pellets were delivered to Ontario generating stations to replace coal with biomass. Nanticoke, Lambton, and Thunder Bay are current coal-fired power plants sited on the shores of the GLSLS (OPG, 2008) whereas Atikokan is a 215 MW station located further away and therefore more likely to be supplied with biomass by truck and/or rail. Co-firing biomass with coal in conventional boilers or modifying an existing power plant to accept 100% biomass was attractive because pellets could be handled and burned using similar equipment, which would result in lower investment costs and greater fuel flexibility (van Loo and Koppejan, 2003; Zhang et al., 2010). Pellet storage capacity would be required since the lower Great Lakes (Erie and Ontario) and the St. Lawrence Seaway are only available for commercial navigation about 280 days per year due to ice and weather conditions. On the other hand, the upper Great Lakes (Superior, Michigan, and Huron) usually operate at least a month longer (Robertson, 2008).

After substitution of coal-fired power, surplus pellets were delivered to biomass-to-liquid (BTL) plants that produced alternative transportation fuels. Biomass gasification followed by gas cleaning and conditioning produced a clean syngas rich in carbon monoxide and hydrogen (Tijmensen et al., 2002). Syngas was then catalytically reformed to synthetic green diesel via high-pressure Fischer-Tropsch synthesis. Fischer-Tropsch liquids are clean-burning fuels free of sulphur and nitrogen that can be blended with petroleum diesel (Klass, 1998). Implementation of a biomass-based liquid transportation fuel strategy was enabled by integrating biomass conversion and fuel distribution operations with the existing fossil energy infrastructure. Co-locating BTL plants adjacent to petroleum refineries would allow green and fossil diesel to share product distribution systems, steam production, utilities, and local expertise.

2.3. Lifecycle emission factor for power generation in the GLSLS region

The overall lifecycle emission factor for electricity use in the GLSLS region was calculated from provincial emission factors. In 2006, the GHG intensities of the electric power sectors in Ontario, Quebec, New Brunswick, and Nova Scotia were 180, 6, 366, and 549 $gCO_2e\ kWh^{-1}$, respectively (Environment Canada, 2008). Moreover, the provincial distribution of biomass adjacent to railway lines and the GLSLS was estimated as 50%, 40%, 5%, and 5%, respectively. The weighted average lifecycle emission factor for the region was calculated as 138 $gCO_2e\ kWh^{-1}$, which was significantly less than the overall emission factor for Canada (205 $gCO_2e\ kWh^{-1}$).

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Table S1. Assumed parameters and results for the base case or optimistic estimate of land area and biomass production within 100 km of railway lines or the Great Lakes St. Lawrence Seaway for forest (FOR), good agriculture (GA), and marginal (MAR) land.

Land type	Land area (Mha)[a]	Biomass type	Accessible land area (% yr^{-1})	Yield (t(dry) ha^{-1})	Available land area (Mha yr^{-1})[m]	Biomass (Mt(dry) yr^{-1})[n]
			Base Case			
FOR	105	Residues	0.42[b]	17[c]	0.44	7.4
		Whole trees	0.093[d]	73[e]	0.098	7.1
GA	10	Residues	55[f]	0.23[g]	5.5	1.3
		Biomass crops	2.3[h]	8.0[i]	0.23	1.8
MAR	10	Biomass crops	20[j]	6.4[k]	2.0	13
Total	**125**				**8.3**	**30**
			Optimistic			
FOR	105	Residues	0.34[b]	22[c]	0.35	7.6
		Whole trees	0.35[d]	85[e]	0.37	31
GA	10	Residues	52[f]	0.35[g]	5.2	1.8
		Biomass crops	6.1[h]	12[i]	0.61	7.3
MAR	10	Biomass crops	25[j]	8.5[k]	2.5	21
Total	**125**				**9.1**	**69**

Note: Values in footnotes refer to base case {optimistic} assumptions.

[a] Estimated land area within 100 km of GLSLS and railway lines.

[b] Calculated as 70% {70%} of land area as forest management × 0.60% {0.48%} of area harvested per year for traditional forest products (CFS, 2006).

[c] Calculated as 80 {90} t(dry) ha^{-1} × 30% {30%} forest biomass residue fraction × 70% {80%} removal of forest residues (CFS, 2006).

[d] Calculated as 0.42% {0.34%} traditional forest harvest rate × 18% {47%} additional land area available (based on 15% unused annual allowable cut and 0% {20%} diverted from pulp and paper production systems) + 100,000 {150,000} ha yr^{-1} of forests disturbed by fire, pests, and disease × 20% {25%} accessible ÷ 105,000,000 ha yr^{-1} + 0.11% {0.19%}

additional forest harvest × 0% {100%} increase in forest productivity from silvicultural practices.

[e] Calculated as 80 {90} t(dry) ha^{-1} × 91% {94%} fraction removed (CFS, 2006).

[f] Assumed 55% {55%} of good agricultural land was initially reserved for food and forage crop production each year × 100% {95%} of land was not diverted to biomass crops.

[g] Calculated as 1.0 {1.5} t(dry) ha^{-1} (Statistics Canada, 2007a; Statistics Canada, 2007b) × 23% {23%} removal of food crop residues for bioenergy production (Layzell et al., 2006; Wood and Layzell, 2003).

[h] Calculated as 55% {55%} of cropland per year × 0% {5%} of cropland (previously used to grow feed crops) diverted to biomass + 11% {11%} of total good agricultural land reserved for natural and tame pasture × 20% {30%} of pasture land diverted to biomass crops.

[i] Calculated as 10 {14} t(dry) ha^{-1} × 80% {85%} fraction removed (Khanna et al., 2008).

[j] Assumed 20% {25%} of marginal land could support biomass crop production each year.

[k] Calculated as 8.0 {10} t(dry) ha^{-1} × 80% {85%} fraction removed (Klass, 1998).

[m] Obtained by multiplying "Land area" and "Accessible land area".

[n] Obtained by multiplying "Available land area" and "Yield".

Table S2. Parameters for diesel fuel, natural gas, and electricity including supporting references.

Parameter	Base case	Optimistic	Units	Reference
Diesel fuel				
Lower heating value	42.8	-	MJ kg^{-1}	GHGenius
Density	843	-	g L^{-1}	GHGenius
Lifecycle GHG emissions	95.4	-	$kgCO_2e$ GJ^{-1}	GHGenius
Natural gas				
Lower heating value	47.0	-	MJ kg^{-1}	GHGenius
Density	0.716	-	g L^{-1}	GHGenius
Lifecycle GHG emissions	63.5	-	$kgCO_2e$ GJ^{-1}	GHGenius
Electricity				
Lifecycle GHG emissions (GLSLS region)	138	-	gCO_2e kWh^{-1}	Environment Canada, 2008
Lifecycle GHG emissions (Canada)	205	-	gCO_2e kWh^{-1}	Environment Canada, 2008
Lifecycle GHG emissions (coal)	1026	-	gCO2e kWh^{-1}	GHGenius

Table S3. Biomass production parameters and supporting references.

Parameter	Base case	Optimistic	Units	Reference
Higher heating value (forest biomass)	20.0	-	GJ t(dry)$^{-1}$	Klass, 1998
Higher heating value (agricultural biomass)	18.5	-	GJ t(dry)$^{-1}$	Klass, 1998
Weight % of hydrogen (forest biomass)	6.0%	-	%	van Loo and Koppejan, 2003
Weight % of hydrogen (agricultural biomass)	5.5%	-	%	van Loo and Koppejan, 2003
Moisture content (wood chips)	45%	-	%	
Moisture content (straw bales)	25%	-	%	
Energy input in growing woody biomass (diesel)	0.72	0.61	GJ t(dry)$^{-1}$	Turhollow and Perlack, 1991
Energy input in harvesting forest residues (diesel)	0.65	0.55	GJ t(dry)$^{-1}$	Turhollow and Perlack, 1991
Energy input in growing woody biomass (natural gas)	0.26	0.22	GJ t(dry)$^{-1}$	Turhollow and Perlack, 1991
Energy input in growing woody biomass (electricity)	0.0099	0.0084	GJ t(dry)$^{-1}$	Turhollow and Perlack, 1991
Energy input in growing herbaceous biomass (diesel)	0.70	0.60	GJ t(dry)$^{-1}$	Turhollow and Perlack, 1991
Energy input in harvesting crop residues (diesel)	0.61	0.52	GJ t(dry)$^{-1}$	Turhollow and Perlack, 1991
Energy input in growing herbaceous biomass (natural gas)	0.44	0.37	GJ t(dry)$^{-1}$	Turhollow and Perlack, 1991
Energy input in growing herbaceous biomass (electricity)	0.030	0.025	GJ t(dry)$^{-1}$	Turhollow and Perlack, 1991
Cost of chipped forest residues at roadside	$41	-	$ t(dry)$^{-1}$	Kumar et al., 2008
Cost of chipped whole trees at roadside	$49	-	$ t(dry)$^{-1}$	Kumar et al., 2008
Farm gate cost of wheat straw	$62	-	$ t(dry)$^{-1}$	Samson et al., 2008
Farm gate cost of baled switchgrass	$70	-	$ t(dry)$^{-1}$	Samson et al., 2008
Fertilizer inputs (switchgrass)	5	-	kg N t(dry)$^{-1}$	Samson et al., 2008
Reference fertilizer rate	60	-	kg N ha^{-1}	Samson et al., 2008
Reference N_2O emissions (at a fertilizer rate of 60 kg N ha^{-1})	0.5	-	kg N_2O-N ha^{-1}	Samson et al., 2008

Table S4. Biomass transportation parameters and supporting references.

Parameter	Base case	Optimistic	Units	Reference
Forest road tortuosity	2.0	-	unitless	
Agricultural road tortuosity	1.5	-	unitless	
Truck fuel economy	0.85	-	MJ t^{-1} km^{-1}	Statistics Canada, 2006
Distance fixed cost (truck; wood chips)	3.1	-	\$ t^{-1}	Searcy et al., 2007
Distance variable cost (truck; wood chips)	0.072	-	\$ t^{-1} km^{-1}	Searcy et al., 2007
Distance fixed cost (truck; straw bales)	4.5	-	\$ t^{-1}	Searcy et al., 2007
Distance variable cost (truck; straw bales)	0.12	-	\$ t^{-1} km^{-1}	Searcy et al., 2007
Rail fuel economy	0.70	-	MJ t^{-1} km^{-1}	Börjesson, 1996
Rail transportation distance	500	-	km	
Distance fixed cost (rail; pellets)	5.6	-	\$ t^{-1}	Searcy et al., 2007
Distance variable cost (rail; pellets)	0.018	-	\$ t^{-1} km^{-1}	Searcy et al., 2007
Ship fuel economy	0.23	-	MJ t^{-1} km^{-1}	Börjesson, 1996
Ship transportation distance	1000	-	km	
Distance fixed cost (ship; pellets)	11.5	-	\$ t^{-1}	Searcy et al., 2007
Distance variable cost (ship; pellets)	0.01	-	\$ t^{-1} km^{-1}	Searcy et al., 2007
Dry matter losses prior to energy conversion	14%	-	%	Hamelinck et al., 2005

Table S5. Pellet production parameters and supporting references.

Parameter	Base case	Optimistic	Units	Reference
Moisture content of pellets	8%	-	%	
Lower heating value of wood pellets	17.0	-	GJ t^{-1}	van Loo and Koppejan, 2003
Lower heating value of switchgrass pellets	15.7	-	GJ t^{-1}	van Loo and Koppejan, 2003
Pellet mill power use	113	-	kWh $t(pellet)^{-1}$	Raymer, 2006
Investment cost of a 6 tonne per hour pellet mill	$2.3	-	Million $	Mani et al., 2006
Capital cost scale factor	0.75	0.60	N/A	Mani et al., 2006
Project lifetime	20%	-	%	
Interest rate	10%	-	%	
Market power price	$54	-	$ MWh^{-1}	Samson et al., 2008

Table S6. Biopower generation parameters and supporting references.

Parameter	Base case	Optimistic	Units	Reference
Electric conversion efficiency	39%	-	%	Kumar et al., 2008
Internal power use	10%	-	%	Kumar et al., 2008
Capital cost to retrofit a coal plant to accept 100% biomass	10	-	$ MWh^{-1}	Layzell et al., 2006
Operating costs	16	-	$ MWh^{-1}	Layzell et al., 2006

Table S7. Green diesel synthesis parameters and supporting references.

Parameter	Base case	Optimistic	Units	Reference
Fischer-Tropsch energy conversion efficiency	46%	55%	%	Tijmensen et al., 2002; Boerrigter, 2006
Net power generation	4%	0%	%	Tijmensen et al., 2002; Boerrigter, 2006
Overall investment cost of a 400 MW_{th} plant	$400	-	Million $	Tijmensen et al., 2002
Overall scale factor < 400 MW_{th}	0.74	-	unitless	Tijmensen et al., 2002
Overall scale factor > 400 MW_{th}	0.91	-	unitless	Tijmensen et al., 2002
Project lifetime	20%	-	%	
Interest rate	10%	-	%	
Operating and maintenance costs (% of total investment)	4%	-	%	Tijmensen et al., 2002
Market power price	$54	-	$ MWh^{-1}	Samson et al., 2008

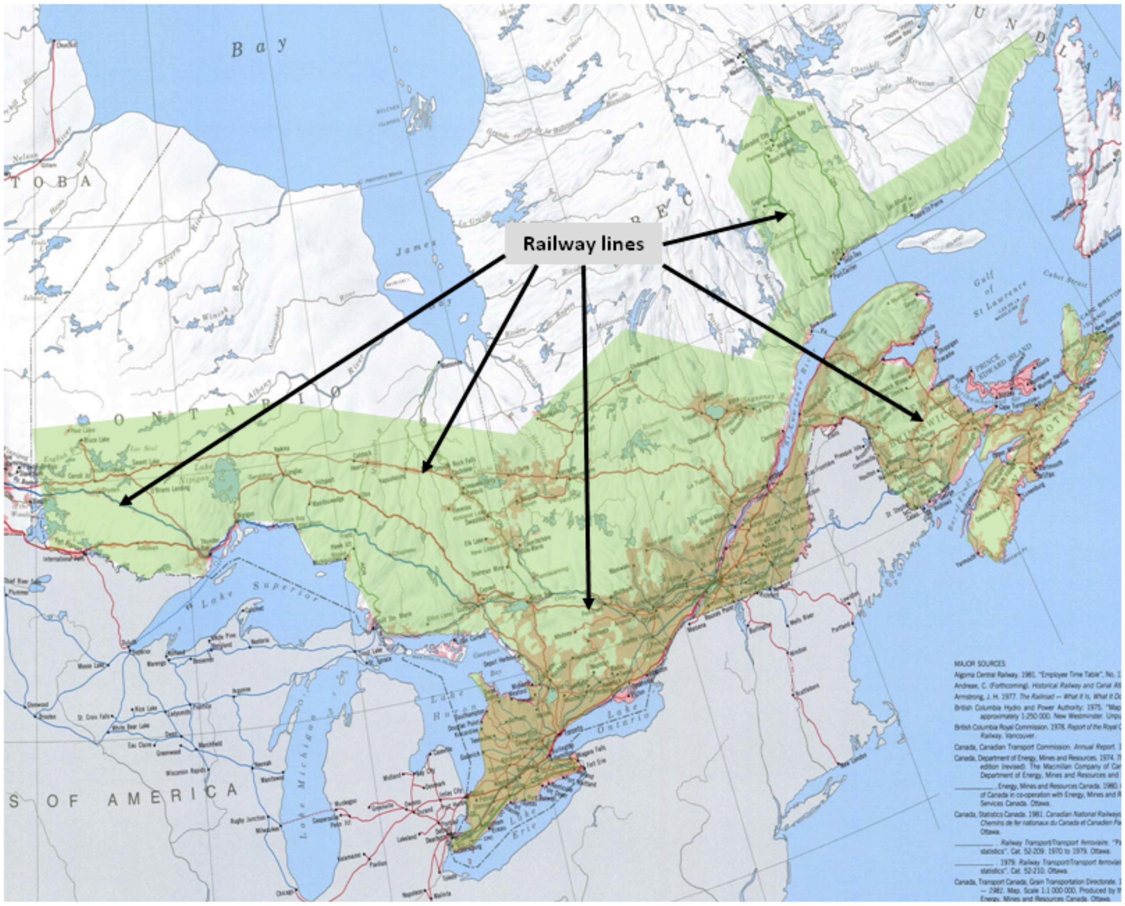

Figure S3. Map of railways in the Great Lakes St. Lawrence Seaway region (in red) with green shading of the land area within 100 km of a railway line or the Great Lakes or St. Lawrence River. Source: Natural Resources Canada, 1981.