Supplementary Material

Table 1 - Summary of the total electricity generation, electricity profile, and suppliers for each of Canada's provinces and territories.

Province/Territory	Total Generation (TWh)	Energy Profile	Energy Supplier
Alberta	81	In Alberta, about 91% of electricity comes from natural gas and coal, and about 8% is produced using renewable sources [55].	Alberta has a deregulated wholesale and retail electricity market as of 1996 and 2001, respectively [49].
British Columbia	74.2	In BC, 91% of electricity is from hydroelectric sources, with a small amount from biomass, solar, and wind power [56].	A majority is supplied by provincial crown corporation BC Hydro, a smaller portion of the power generation comes from independent producers [49].
Manitoba	36.9	97% of Manitoba's electricity generation comes from hydroelectricity, with the remaining, in order of magnitude, coming from wind, natural gas, coal, and biomass [49], [57].	The hydroelectric majority is owned and operated by the crown corporation Manitoba Hydro [49], [57]
New Brunswick	12.2	39% of electricity is generated from nuclear, 30% fossil fuels, and 21% hydroelectricity [49], [58].	A majority of capacity is owned by the vertically integrated crown corporation NB Power [49], [58].
Newfoundland and Labrador	42.8	Newfoundland and Labrador generates 95% of its electricity using hydroelectricity, with mostly oil and some natural gas and wind making up the remained of the generation [25].	Crown corporation Newfoundland and Labrador Hydro, with the investor-owned Newfoundland Power as the primary distributor [49], [50].
Nova Scotia	9.6	Coal accounts for over 60% of electricity generation in Nova Scotia, with oil, natural gas,	A majority is operated by the investor-owned Nova Scotia Power [49].

		hydro, wind, and biomass making up the rest [59].	
Ontario	151.1	In Ontario, 60% electricity generation is from nuclear, 26% from hydroelectricity, 7% from wind, 2% from solar, with the rest mainly being generated using fossil fuels and a small amount of biomass [51].	Electricity in Ontario is supplied by the publicly owned Ontario Power Generation and a mix of privately owned companies [49].
Prince Edward Island	0.7	In Prince Edward Island 98% of electricity generation comes from wind power, but a majority of the electricity consumed in PEI comes from New Brunswick [60].	PEI's electricity generation is owned and operated by Maritime Electric Company Ltd [49].
Quebec	213.7	95% of electricity generation in Quebec comes from hydroelectricity and 4% from wind [61].	Most is owned by Hydro-Québec [49].
Saskatchewan	24.3	Saskatchewan's electricity is generated by about 43% natural gas, 40% coal, and 17% from renewables (a majority of which is hydroelectric) [62].	Most capacity in Saskatchewan belongs to SaskPower [49].
Northwest Territories	0.4	For Northwest Territories, 75% of electricity comes from hydroelectric, 4% from wind, 1% from solar, and some natural gas. The rest is generated using diesel, which is also the primary source for remote communities not connected to the hydro-based grids [63].	The primary generator and distributor is the government-owned Northwest Territories Power Corporation [49].
Nunavut	0.2	Essentially 100% of the electricity generation in Nunavut comes from diesel and is community based, as there	N/A

		are no regional or territorial grids [64].	
Yukon	0.5	A majority of Yukon's grid connected electricity is generated from hydroelectricity. During times of peak demand, Yukon also uses diesel and natural gas [65].	Publicly owned Yukon Energy Corporation is the majority producer, with contributions from the privately owned ATCO Electric Yukon [49].

Table 2 - Emission Activity Ratios for electricity sources [99].

Technology	Emission Activity Ratio (Mto CO2eq/PJ)
Coal	0.092810282
Natural Gas	0.050342207
Oil	0.070889564
Cogeneration	0.050342207
Diesel	0.069788107
Gas	0.066795068
Biomass	0.063888889

Table 3 - Capital cost for land use intensities (M$/1000 km^2)

	Low Intensity	Intermediate Intensity	High Intensity
Rainfed	10	60	112
Irrigated	n/a	67	120

Table 4 - Number of cluster regions selected per province and territory.

Province/Territory	Number of Cluster Regions
Alberta	4
British Columbia	4
Manitoba	4
New Brunswick	2
Newfoundland	4

Nova Scotia	2
Northwest Territories	4
Nunavut	3
Ontario	4
Prince Edward Island	1
Quebec	4
Saskatchewan	4
Yukon Territories	4

Table 5 - Summary of input parameters and their corresponding data source. The vast majority of electricity system data comes from OSeMOSYS Global [11].

Model Parameter	Data Source
AccumulatedAnnualDemand (Annual crop demand)	[73]
AnnualEmissionLimit	[35], [49], [88]
AvailabilityFactor (Regional hydropower capacity)	[67], [68]
CapacityFactor	OSeMOSYS Global [11]
CapitalCost	OSeMOSYS Global [11] except Offshore Wind [100], Petroleum Products, Oil, Transmission, Biofuels from Switchgrass [86] and Biofuels with Carbon Capture and Storage [87]. Land use costs are based on reasonable estimates.
EmissionActivityRatio	[86], [101]
FixedCost	OSeMOSYS Global [11]
OperationalLife	OSeMOSYS Global [11], Land use values are based on reasonable estimates.
ResidualCapacity	Energy System: OSeMOSYS Global [11] Land and Water System: [73], [76], [77]
SpecifiedAnnualDemand. (Electricity demand projected to 2050.)	[68]
SpecifiedDemandProfile (The portion of annual demand required for each timeslice.)	OSeMOSYS Global [11]
TechnologyActivityByModeLowerLimit (Minimum area for land cover types other than for agriculture and	[13]

forest (built-up, barren, water bodies, grassland and woodland).)	
TotalAnnualMaxCapacity (Limit on nuclear and hydro capacity)	[102], [103]
TotalTechnologyAnnualActivityUpperLimit (Total land area of each region)	[13]
VariableCost	OSeMOSYS Global [11], Negative cost on forest land is based on reasonable estimates and are further explored in the Sensitivity Analysis.

Table 6 – Area (1000 km^2) per crop and land cover type for the net zero, biofuels, and water limit scenarios in 2050.

Crop	Base (No Biofuels)	Biofuels	Biofuels with Water Limit
Wheat	56.4	59.4	60.7
Switchgrass	n/a	643.4	72.3
Rapeseed	88.5	88.5	99.0
Maize	18.5	18.5	19.2
Other	82.7	82.7	89.1
Total Crop Area:	246.1	892.5	340.3
Forest	3414.7	2768.3	3320.5
Agriculture	246.31	892.5	340.4

Sensitivity Analysis

Nuclear and Hydropower Maximum Capacity Constraints

Figure 1 shows the electricity generation of the net zero biofuels scenario when there is no nuclear or hydro maximum capacity limit (a) and no nuclear maximum capacity limit (b). While it is difficult to say what the exact capacity limits of these technologies will be in Canada, some limitations due to possible physical capacity as well as political acceptability are appropriate. In addition, setting limits on nuclear and hydropower encourages uptake in biofuels, and so allows for deeper analysis of the impacts of the switchgrass biofuel pathway on electricity, land, and water systems in Canada.

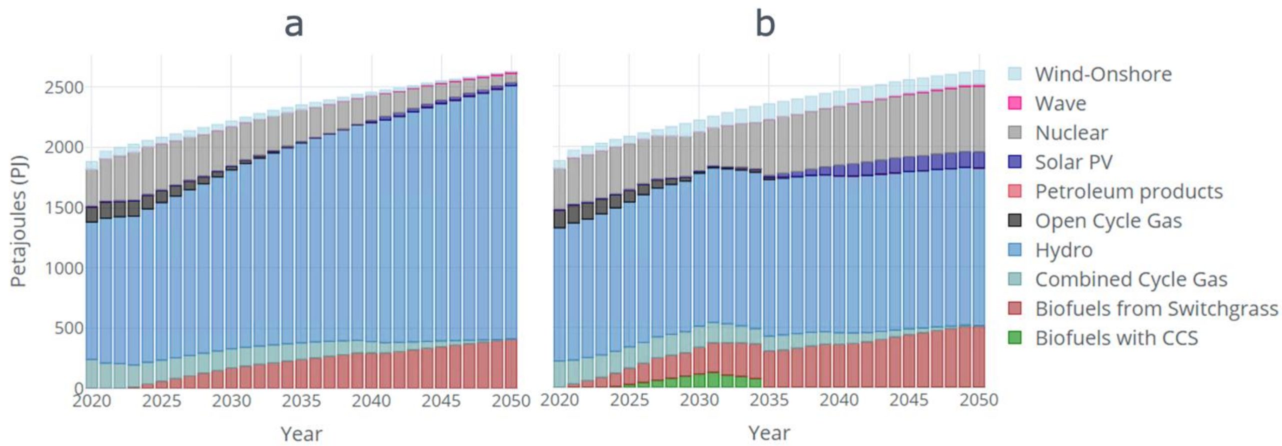

Figure 1 – Primary electricity consumption without exogenous hydro and nuclear maximum capacities (a) and no nuclear maximum capacity but with a hydro limit (b).

Switchgrass Biofuels Energy Efficiency

To find the sensitivity of the switchgrass biofuels' efficiency, we tested a scenario where the efficiency of converting the switchgrass to biofuels changed from 17.45 GJ/tonne (as in the modelled scenarios) to 15 GJ/tonne (Figure 2a) and to 18 GJ/tonne (Figure 2b). In Figure 3 the changes in crop land area based on this parameter is shown. We find that electricity generation from biofuels will increase or decrease proportionally with the value of the efficiency and that there is some sensitivity to this parameter.

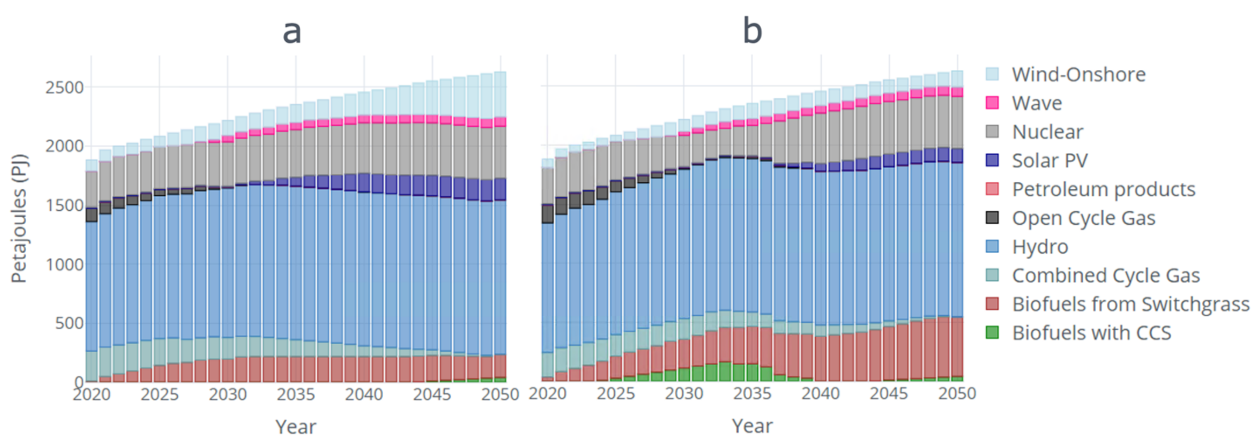

Figure 2 – Electricity generation for all net zero, including biofuels scenarios when the efficiency of the switchgrass biofuels is 15 GJ/tonne (a) and 18 GJ/tonne (b).

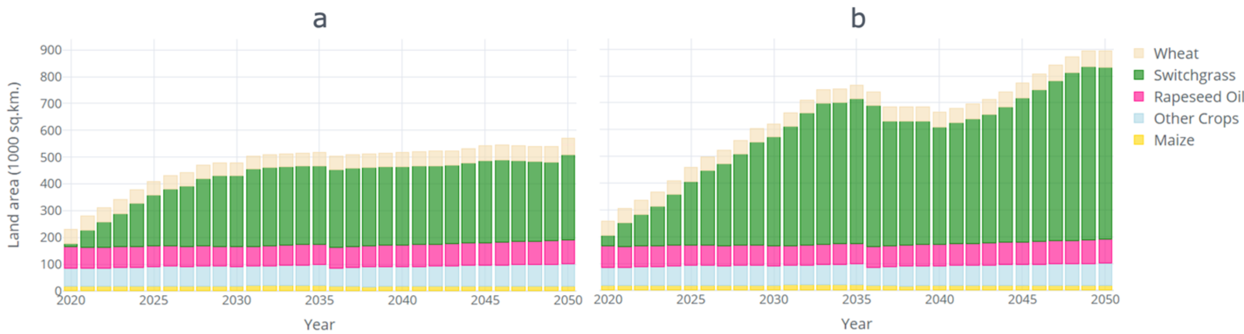

Figure 3 – Area by crop for all net zero, including biofuels scenarios when the efficiency of the switchgrass biofuels is 15 GJ/tonne (a) and 18 GJ/tonne (b)

Cost on Forest Land

The CLEWs Canada model includes a negative cost on forest land, which acts to represent the value of maintaining forest land in Canada. To test the sensitivity of this parameter, we run the net zero with biofuels scenario with this parameter halved (-$5 USD/1000 km) and doubled (-$20 USD/1000 km). The results are shown for the area by land cover type (Figure 4) and the land area by crop type (Figure 5). The model is clearly sensitive to this parameter. Putting a dollar amount to parameters such as forest land cover is challenging as forest have economic value, intangible value, and more and little research has been done to quantify these. The value of forests also varies with location and geography. Recent work is beginning to examine the importance of considering factors such as ecological diversity and natural capital in energy models, but it is not well established [104]. In our model we choose a value of $10 USD/1000 km^2 (-$10 USD/1000km^2 variable cost) as this provides a balance between enabling agricultural expansion for biofuels and crop demand while ensuring that forests are not undervalued. A full analysis of this parameter, and its impact on OSeMOSYS based CLEWs models, is beyond the scope of this paper but is an area for future research.

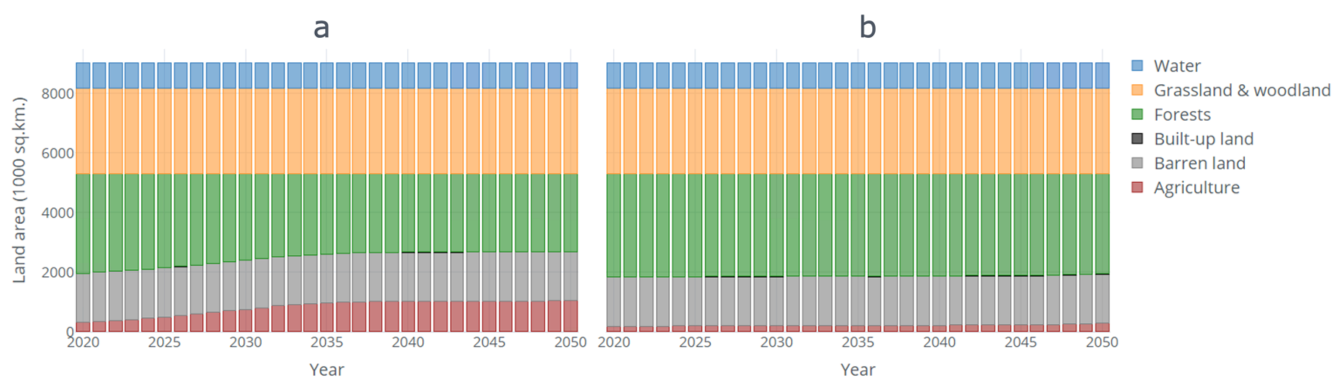

Figure 4 - Land area by cover type with a variable cost on forest land of -$5 (a) and -$20 (b).

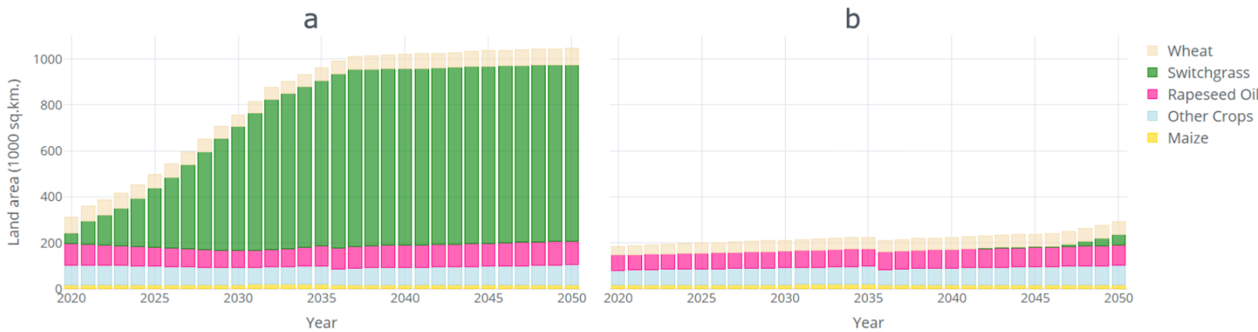

Figure 5 - Land area by crop type with a variable cost on forest land of -$5 (a) and -$20 (b).

Switchgrass Crop Yield

In the CLEWs Canada model, the attainable yield of each crop is based on the GAEZ, and is dependent on the location, water use, and agricultural intensity used to produce the crop. As there is significant uncertainty in the yield of switchgrass, we have tested the sensitivity of model results to this parameter by comparing the baseline (GAEZ switchgrass yield) to a scenario with twice and three times the yield of the baseline, the results of which are shown in Figure 6. The new crop yields are shown in Figure 18a and b, and can be compared to the baseline (**Error! Reference source not found.**b). As the biofuels are now a lower cost, they play a more significant role in the energy system and more switchgrass is produced overall. Figure 6c-f show the impacts on land and water of a higher yield switchgrass, with the demand for each predictably lower with a higher yield. Despite the higher yield of switchgrass in these scenarios, the land and water impact is still considerable to produce the biofuels from switchgrass, reaching 752 000 km^2 and 257 billion m^3 when the yield is doubled and 533 000 km^2 and 225 billion m^3 when the yield is tripled, compared to the GAEZ estimated 646 000 km^2 and 238 billion m^3

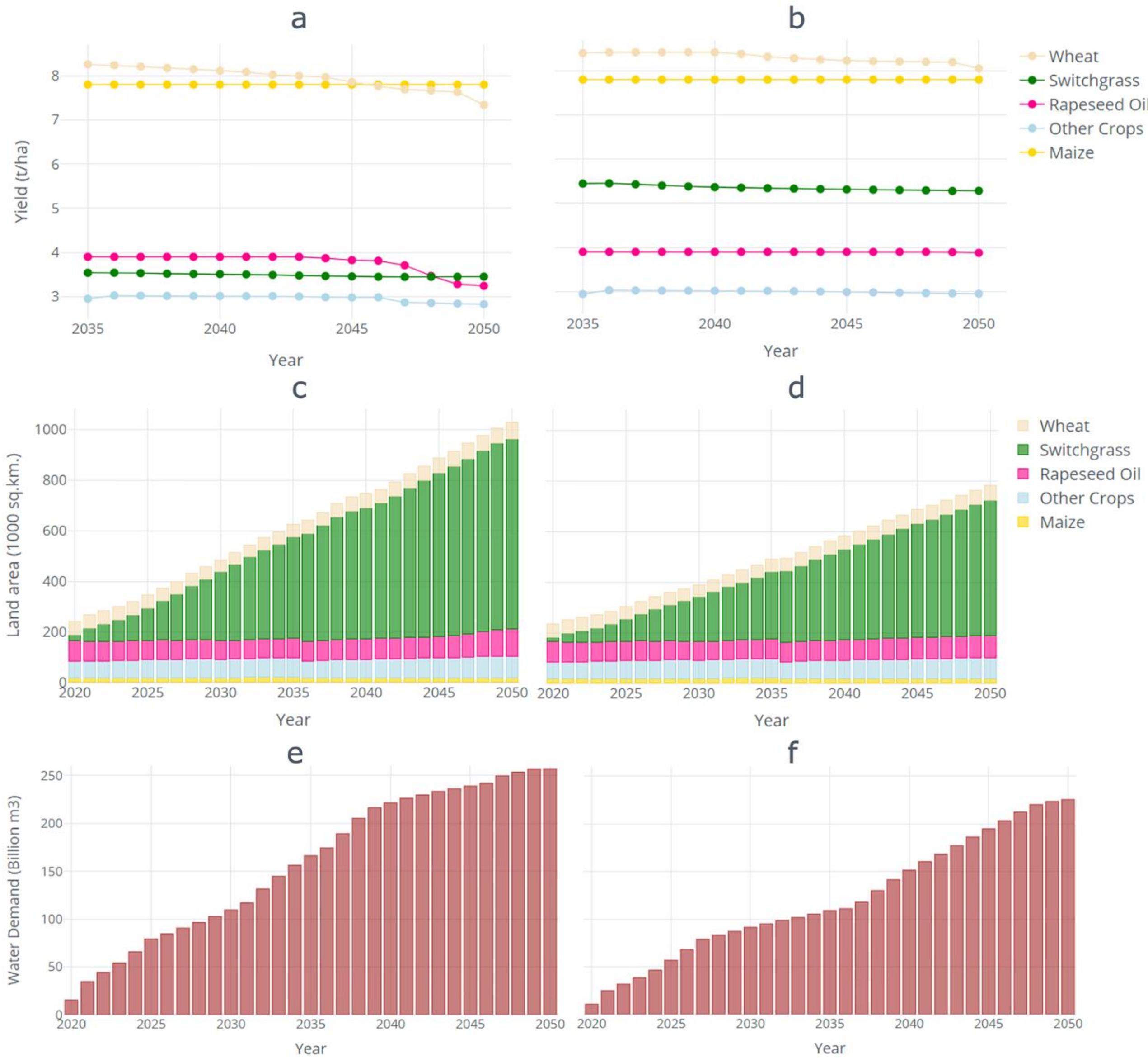

Figure 6 - Crop yield, crop area, and agricultural water demand when the attainable yield of switchgrass is twice (respectively: a, c, e) and three times (respectively: b, d, f) that of the baseline.