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Applying the open-source climate, land, energy, and water systems (CLEWs) model to Canada

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A B S T R A C T

In this paper the Climate, Land, Energy, and Water system (CLEWs) interactions of biofuels production are addressed. We utilize an open-source modelling framework to assess direct and indirect impacts of biofuels on long-term electricity generation, land, and water use. We analyse a switchgrass biofuels pathway and find that while the land use implications are substantial, increasing by 646,190 km 2 in agricultural land area, the impacts on water systems, which increases by approximately 222 billion m 3 compared to the baseline, may be even more limiting for the Canadian context. While switchgrass biofuels can contribute low-carbon dispatchable electricity, the land and water use impacts suggest that any biofuels should be used for hard to decarbonize sectors prior to using them for electricity.

1. Introduction

This paper addresses the Climate, Land, Energy, and Water system (CLEWs) interactions of biofuels production and outlines the water and land system challenges that exist with biofuels, even in a large country such as Canada. In order to address this, we develop a CLEWs nexus model for Canada that includes the land and water requirements for a biofuels to electricity pathway, which are often not well represented in biofuels studies. In addition, though prior work has investigated either whole CLEWs model applications to a particular sub-region of Canada, or similar but distinct integrated assessment modelling frameworks to all of Canada, no prior work has developed a CLEWs model for all of Canada. This paper fills these gaps in the literature by developing a full country CLEWs model for Canada, and using it to assess water and land use for biofuels.

Due to the interdisciplinary nature of nexus challenges we apply the CLEWs modelling framework to understand the interlinkages and impact of policy interventions on managing interdependent resources [1,2]. The CLEWs modelling framework was developed by the Royal Institute of Technology in Sweden (KTH) in collaboration with the International Atomic Energy Agency (IAEA) [3] based on the OSeMOSYS Open-source Energy Modelling System [4–7]. The nexus concept is used to describe the interconnectedness of resources, and allows for a better understanding of the synergies and trade-offs between them [8]. Having modelling tools that incorporate these trade-offs increases analysts' and policymakers' ability to contribute to efficient and effective climate change mitigation strategies. Section 1.1 provides an overview to the CLEWs framework and its applications.

A choice example of the importance of incorporating the CLEWs nexus into energy system models is the use of biofuels, which is the focus of our analysis. Policy decisions targeting the growth of biofuel resources must consider the competition of energy resource with the agriculture sector on water and land. While Canada may have a high capacity for biofuels and interest as an alternative liquid fuel, the broader implications of increased uptake in biofuels particularly on land and water systems is crucial [9,10]. In section 1.2 the literature on trade-offs for biofuels is reviewed and in section 1.3 an overview of the energy and policy context to Canada is provided.

Section 2 describes our methods in developing the CLEWs Canada model. The CLEWs model of Canada uses OSeMOSYS and open data sets, making the model, data, and solver entirely open-source. As a representation of climate, land, energy, and water, CLEWs incorporates the most significant interactions between these systems. We model the electricity system, largely being sourced from OSeMOSYS Global [11,12], and its interactions with land and water use, as well as other land use impacts. Land and water is represented using the Global Agro-Ecological Zoning Database (GAEZ) [13]. This section concludes with a description of the scenarios that have been used for the analysis, which includes a baseline (no emission constraints, no biofuels), net zero without biofuels, net zero with biofuels, and a scenario with the

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agricultural water use limited.

The results of the analysis are in section 5. We find that the biofuels contribute to the net zero scenario with a lower overall cost compared to when biofuels are not available, and only a very small amount of biofuels are used once water use is limited. The emission limit is a binding constraint in all scenarios it is included in. The total crop area in the biofuels scenario is over 3.6 times more than the scenarios without biofuels, and the agricultural water demand is more than 200 billion m^3 by 2050, though agricultural water use was 2.95 billion m^3 in 2018 [14]. Both the increased land and water use due to biofuels lead to decreases in crop yields, particularly in the water limiting scenario.

Finally, in section 6, we conclude by considering the implications of our results, and how even in a country with plenty of land such as Canada, the land use demands for the energy system using biofuels can be significant and limiting. We analyze how national climate policy can best be leveraged to support a transition to renewable energy when it comes to biofuels, and how these policies affect land and water systems. While switchgrass biofuels can contribute low carbon dispatchable electricity to Canada there are significant impacts on land and water. For Canada specifically, the major limitation of biofuels will likely be water, not land. This in particular has major policy implications for countries that do not have the large water and land resources that Canada has. Given the limited availability of water for growing biofuels, it is likely that any biofuels should be used to decarbonize hard to decarbonize sectors prior to using them for electricity. CLEWs modelling can highlight interactions between land, water, and energy that are not included in typical energy modelling scenarios nor in energy-economy modelling, but are critically important for making effective policy decisions.

1.1. Review of the CLEWs framework

The Climate, Land, Energy, Water systems (CLEWs) framework has been applied internationally and demonstrated the importance of addressing inter-linkages in resource systems [3,15]. In this section, first an overview is given of the importance of this type of approach in addressing climate change and resource scarcity and provide some example applications of the framework. We finish the literature review with an overview of nexus modelling as applied to Canada.

1.1.1. CLEWs framework and applications

The term 'nexus' generally refers to the interactions between interdependent components, such as climate, land, energy, and water [16]. M. Howells et al. [17] outline the importance of integrated analysis in developing policy that is consistent and efficient, meaning that resource policy enacted for one system won't negatively affect another and undermine the efforts. Modelling the nexus interactions of a system, rather than analysing the systems in isolation, allows researchers to identify synergies in the systems to make strategies more efficient. The CLEWs framework has been applied in many places, including Mauritius [18], Sweden [19–22], Bolivia [23], Kenya [24], New York City [25], Eastern Africa [26], Uganda [2], and more. A review of CLEWs case studies is compiled by Ramos et al. [15]. Applications of the CLEWs framework have been used to demonstrate the unintended consequences of policies when not considered in conjunction with other resource systems.

Examples of previous CLEWs studies highlight the importance of analysing our resource systems as a whole to uncover the possibility of both synergies and unintended consequences for policy. A recent CLEWs case study of Uganda demonstrated how a policy intended to increase forest cover by reducing use of forest biomass will also have unintended consequences for energy, water, and land sectors [2]. The study found that while forest cover is increased, fossil fuel use increases as biomass use is decreased, which also increases the cost of electricity. This in turn causes a switch from irrigated to rainfed agriculture. The water-energy analysis of New York City examined the interlinkages between policies for water conservation, energy efficiency, and GHG reduction [25]. The results indicate that efforts to reduce water use tend to also reduce energy use and GHG emissions, and energy efficiency measures can lead to reduced water use. However, the actions that lead to the highest reduction in emissions and energy use were not necessarily the best for water conservation. Due to the dire nature of the climate emergency and with so many living without regular access to vital resources, the careful and efficient use of land and water, and the expansion of renewable energy sources is of the utmost importance.

1.1.2. CLEWs studies in Canada

Within the Canadian context, prior work has generally evaluated only specific climate impacts in specific provinces and/or has considered only pieces of the CLEWs nexus. Canada provides a novel application of the CLEWs framework because of its size, and the diversity of both its political and geographical regions, testing the framework given its multiple provinces and different grids.

There have been a number of studies that consider parts of the CLEWs nexus for specific regions of the country. A study of British Columbia by Parkinson and Djilala [27] considered the interaction of water and energy and found that expected climate impacts over the next 50 years would increase operating costs for the system by 7% due to changes in water available for hydroelectric generation. Agarwal et al. [28] develop a water-energy model for the province of Alberta and find that mitigation of emission will increase water use in the province. Ali [62] performs a similar analysis for Alberta and find that water use increases dramatically as energy development expand over to 2030. While both these studies of Alberta as well as the BC study uncovered interlinkages between energy system and water use changes, neither considered the impacts on land use.

Models have also been developed that consider the entire CLEWs nexus for specific regions in Canada. A CLEWs model of British Columbia was used to examine decarbonization strategies for the province and their impact on the CLEWs nexus, determining that deep decarbonization is not possible without reducing GHGs from industry by half [29]. Wu et al. [30,31] apply a water-energy-food model to Saskatchewan, examining interactions in the nexus. They find that irrigation expansion leads to increased food production and decreased hydropower production, wind power expansion leads to reduced GHG emissions and industrial water use, and increasing biofuel use in transportation reduces GHG emissions but also reduces food exports. Provincial CLEWs studies provide insights specific to that sub-region that a national model cannot, but do not provide the bigger picture aspects and implications developed in this work.

Only limited studies have considered aspects of the nexus for all of Canada. A case study for all of Canada used an integrated assessment model with a focus on decarbonizing electricity generation and the associated water consumption [32]. The study modelled current policy trajectories and compared it with a deep electricity decarbonization scenario, finding that the latter reduced water use while greatly reducing GHG emissions. Akhtar et al. [33,34] uses a system dynamics simulation model that includes the full country and shows connections between energy, economy, climate, land, and water systems. This study uses a different model approach and includes more socioeconomic considerations, meaning that it can show different impacts than an optimization style CLEWs framework. Both these studies model Canada as a whole, with the former focusing on the water-electricity nexus, and the latter providing economic and social systems in addition to CLEWs, but with a different model framework than the present study. These Canadian energy system models provide insights complimentary, but not equivalent, to the CLEWs model developed in this work.

A full CLEWs nexus, capacity expansion type model of Canada was not developed previous to this study. The type of CLEWs modelling utilized in this project builds on and improves energy system modelling by using the existing approach developed for capacity expansion modelling. With a CLEWs model we can help to recognize and reduce the potential trade-offs among interdependent components when it comes to policy-decisions and investment.

1.2. Biofuels trade-off

While biofuels have been proposed as a key technology for decarbonization, the trade-offs must also be considered. Biofuels are proposed to play an important role in decarbonization in reports such as Canada's climate plan [35] and in the Paris Agreement to help reach countries' Nationally Determined Contributions [36]. While there is some biofuel production in Canada, the potential far exceeds the current use [10]. Biofuels offer an alternative to fossil fuels and a way to diversify the energy system. To assess the effectiveness of biofuel as a sustainable energy source, the impact on the natural resources should also be assessed. This impact includes those resources being no longer available for alternative uses, such as land and water being used for food or other forms of renewable energy.

Many studies have assessed the different aspects of biofuel trade-offs. A global study assessing the biofuels water-land-food trade-offs found that about 280 million people could be fed with the current crops put towards biofuels, and that between bioethanol and biodiesel, Canada uses 1,445,800 ha of land and 7,969, 800, 000 cubic meters of water to produce 80 PJ of energy annually [37]. Another global study uses a demand trajectory for biofuels to limit GHGs to 1100 Gtonnes CO_2eq by 2095, finding that to produce 300 EJ/yr from biofuel crops agricultural water use is doubled and land use increases 41% [38]. Another land-water nexus study for Brazil uses an input-output model to examine the current direct and indirect land and water footprint of biofuels, determining a clear trade-off for irrigated and rainfed ethanol production [36]. Watkins Jr. et al. review the impact of biofuels on water availability and quality, and provide a discussion on the many intersections of water use and biofuels, such as crop type, environmental conditions, and how the water is being managed [39]. The authors recommend that studies consider the socio-economic impacts, as well as the direct and indirect impacts on water use.

For the Canadian context, using the Canadian Economic and Emission Model for Agriculture (CEEMA), Liu et al. [40] looked at the potential impacts of converting forested land to land for biofuel production. CEEMA is a partial equilibrium type model used to assess the economic and resource impacts of market and policy changes to the agricultural sector, not considering the growth of the sector. In this study, the majority of biofuels were produced using crop residues, and found that 33.4 TW h of energy were produced, requiring 0.32 million hectares of land be converted to cropland. Advanced, or second generation, biofuels can have less trade-offs with water and land than conventional biofuels. To date, virtually all the biofuels in Canada have been from conventional biofuels and, though advanced biofuels have higher public acceptability [41], more research and policy support is needed to reach market favourability of advanced biofuels [42]. Another study in Ontario, Canada, assessed the trade-off between using land for solar or biofuels, highlighting the importance of considerate land use allocation for sustainable energy [43].

1.3. Canada's energy landscape and policy context

Canada is one of the largest countries in the world by land area but has a relatively low population density. Its per capita greenhouse gas (GHG) emissions are relatively high at 4.1 tonnes per person in 2018 [44], making it seventh highest in the world and third highest of the OECD countries [45,46]. Canada also has the third highest per capita water consumption of the OECD countries [47]. Due to its high per-capita resource use and GHG emissions, there is a need to plan for efficient GHG emission reduction while safeguarding Canada's resource systems. Canada is fortunate to have relatively abundant energy, water, and land resources, but the use of these systems still requires careful planning and forethought.

Overall, Canada's electricity is generated from 61% hydroelectricity, 15% nuclear, 18% fossil fuels, and only about 7% from non-hydro renewables [48]. A majority of electricity generation in Canada comes from hydroelectricity produced mainly in British Columbia, Manitoba, Quebec, Newfoundland and Labrador, and Yukon. Alberta, Saskatchewan, Nunavut, and Nova Scotia use mostly fossil fuels in their electricity generation. Ontario produces 23% of Canada's electricity, making it the second largest electricity producer in Canada after Quebec [51]. In Canada's northern region, where communities are smaller and farther

Table 1
Overview of the scenarios used in the analysis.

	Baseline	Net Zero	Net Zero with Biofuels	Water Limit
Emission Limit	No emission limit	Increasing annual emission limit to net zero in 2050	Increasing annual emission limit to net zero in 2050	Increasing annual emission limit to net zero in 2050
Switchgrass Biofuels	No switchgrass biofuels or BECCS	No switchgrass biofuels or BECCS	Switchgrass biofuel and BECCS pathway	Switchgrass biofuel and BECCS pathway
Water Limit	No water limit	No water limit	No water limit	Water limit of 6 billion m^3

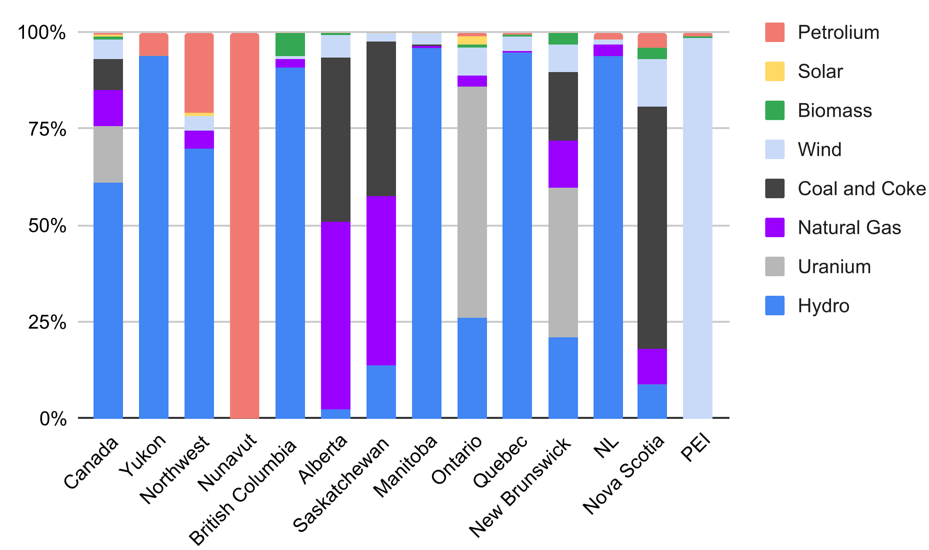

Fig. 1. Electricity generation by fuel type for each province and territory, as well as Canada as a whole [50,51,55–65].

apart, there is less incentive to develop electricity grids to all areas and diesel is used most often in these remote areas [49]. A summary of each region's electricity profile is shown in Fig. 1, and the electricity profile, supplier, and total electricity generation for each region can be found in the Supplementary Materials in Table 1.

There are several hydroelectric power plants currently under construction in Canada, but hydro potential is not unlimited [52]. The future for nuclear is uncertain, with a powerplant supplying 15% of Ontario's electricity planned for closure by 2025, and the possibility of a shift towards small modular reactors (SMR) deployment in the future [53]. To reach net zero by 2050 the country will need to move away from fossil fuels, but if hydroelectric and nuclear capacity limits are reached, renewable sources such as wind and solar pose different challenges, namely being non-dispatchable and variable. The Canadian energy plan focuses on biofuels for transportation and using biofuels to replace fossil fuels in sectors other than electricity may be more efficient, especially with the uptake of electric vehicles [35], but this requires land area for crops dedicated to biofuel production.

Federally, Canada has a nationally determined contribution to the Paris Agreement to reach or exceed 30% reduction in emissions below 2005 levels by 2030 and achieve net-zero emissions by 2050 [54]. The 2020 climate plan from the Canadian government emphasises leveraging those areas of Canada with more existing clean energy infrastructure, such as hydropower, to those that do not [35].

2. Methods

In Section 2 we provide the methods used to build the CLEWs Canada model, including tools and data sources. In 2.1 we discuss the OSeMOSYS modelling tool with which the CLEWs Canada model is built. In section 2.2 OSeMOSYS Global [12] is introduced, which provides the bases for the electricity system representation. While a CLEWs model requires additional data for the climate, land, and water systems, having the energy system model base has the potential to make generating CLEWs models much more accessible. In section 2.3 we discuss the land and water use representation from the Global Agro-Ecological Zoning Database (GAEZ) [13]. In section 4.4 the switchgrass biofuels pathway for our model scenario are explained, including the motivation for using switchgrass as a biofuel crop. Finally, section 2.5 outlines the scenarios to be examined in the results. All data used for the model is openly available, and the modelling tools used are open-source ensuring the model and tools are reusable and available for reanalysis. The model is used to look at scenarios using biofuels and bioenergy with carbon capture and storage (BECCS) from Switchgrass, with and without emission and water limits.

2.1. OSeMOSYS

The modelling system used to build the CLEWs model of Canada is the Open-Source Energy Modelling System (OSeMOSYS) [4–7]. OSeMOSYS is an open-source linear optimization modelling system widely used in academia and for long-term energy planning that assumes a rational decision maker with perfect foresight. The model minimizes total discounted cost to meet the energy demand from a mix of technologies and resources defined by the user. Optimization models that utilize linear programming, such as OSeMOSYS, are powerful tools capable of finding an optimal equilibrium over an entire, complex system. Though primarily used for energy system modelling, land and water use can be included in the system by creating additional technologies and commodities for land and water use.

The objective of the OSeMOSYS used in this application of the modelling tool is to find the minimal cost of the system while meeting the electricity demand, defined in the specified annual demand, and the crop demand, defined in the accumulated annual demand [4]. To find the cost, the capital and operational (fixed and variable) costs of each technology is calculated for each region and time slice, in this case provinces and seasons, respectively. A technology will have an input of resources and output of energy – this may include an input of land and water. In the case of biofuels, it requires a crop input, which in turn required an input of agricultural land and water to be produced. A full explanation of OSeMOSYS would make this paper overly lengthy, but we refer the reader to Ref. [4] for a more detailed model description. The process for including land and water in the model will be explained in more detail in section 4.2.

OSeMOSYS is an appropriate modelling tool for this analysis because of its use for CLEWs modelling and capacity, and is also selected for being openly available, with transparent documentation and an active community of practice [7]. Given the complexity of Canada's different energy markets, in our model we assume rational, cost optimizing decision makers across Canada to find the least-cost options to meet energy demand would be, though this would likely be unrealistic with the current market structures.

2.2. Modelling Canada's electricity systems: OSeMOSYS global

A vast majority of the energy system data for the CLEWs Canada model comes from OSeMOSYS Global [11], a global power system model generator based off of the PLEXOS-World dataset [12]. Both PLEXOS-World and OSeMOSYS Global are based on open data sources and the software is freely available. OSeMOSYS Global has an optional geo-filter, which was used to generate an electricity system model of Canada. To simplify the modelling, we model only Canada and not the interconnections Canada has with other jurisdictions. Although this is a simplification, it is a reasonable simplification given the focus of this work on biofuels production within Canada. For a more detailed breakdown of what model parameters come from OSeMOSYS Global, see Table 7 in the supplementary materials.

The spatial disaggregation of the electricity system from OSeMOSYS Global has each province represented separately except for New Brunswick, Nova Scotia, and Prince Edward Island which are grouped together as the 'Atlantic Region,' and the Northwest Territories, Yukon, and Nunavut are represented together as the 'Northern Region.' Each region has representative electricity technologies representing the capacity of that technology in the region.

To make the model computationally tractable it is not possible to model all 8760 h in the year for all years of the model period. We therefore reduce the temporal resolution of the model with a focus on ensuring that the resolution is sufficient to address any temporal aspects of biofuel production and consumption. Specifically, we have eight time slices total, where a time slice is defined as a representative time split of the year. The year is subdivided into four seasons: winter (December, January, February), spring (March, April, May), summer (June, July, August), and fall (September, October, November), and each day is divided into day and night.

To complete the energy system section of the model, a few changes and additions were made to the OSeMOSYS Global base model. The electricity demand from OSeMOSYS Global was replaced with annual demand from Canada Energy Regulator (CER), using 'Canada's Energy Future 2020′ electricity 'End-Use Demand' appendices, using the reference case for each region [66]. Emissions data used for each technology and fuel source can be found in the supplementary materials Table 4. While OSeMOSYS Global provided the capacity factor for all other renewables, a yearly availability factor was added for hydropower for each region, calculated from historical capacity and generation data [67,68].

A default reserve margin of 15% is included that can be met by biofuels, gas, coal, oil, geothermal, hydroelectric, diesel, and nuclear. NERC recommends a reserve margin of 15% for majority thermal systems and 10% for majority hydro [69]. While Canada's electricity system is 61% hydro, this is very geographically specific with some provinces having a high hydro resource while others are more thermal based so we therefore adopt a 15% reserve margin across the country for consistency. This higher reserve margin than required by NERC also partly accounts for the time slicing not fully representing the peak demand.

Maximum annual capacities were added for nuclear, which was kept at the current capacity for the model period, and hydropower, which was given a maximum capacity equal to the current capacity plus all planned hydro plants for Canada. Without these limits, nuclear and hydropower become the vast majority source for electricity in all scenarios, as seen in the Sensitivity Analysis details in the supplementary materials. The limits are imposed to better reflect geographic and political constraints. This comes both from physical constraints, of which there are varying estimates [70,71], as well as political acceptability given that the currently under development site C dam has faced many issues and backlash in its construction [72]. For nuclear, the limit is imposed due to the perceived risk and political acceptability of nuclear energy in Canada. Nuclear capacity in Canada may very well increase in the future [53]. As hydro, and then nuclear, will dominate the energy mix in our model results, the limits are imposed both to reflect the political acceptability, as well as to allow us to explore biofuels as an alternative option to these power sources as a future electricity resource for Canada.

2.3. Modelling land and water interconnections

To model the land use in Canada we use data from the Global Agro-Ecological Zoning Database (GAEZ), a spatial analysis that provides an assessment of agricultural potential for each 30 arc-second (0.9 × 0.9 km) globally [13]. To connect water, land, energy, and climate, the GAEZ provides information on the agro-climatically attainable crop yield for every given location in Canada. The land area is divided into cells, and the achievable yield for a cell is determined for a set of potential input combinations. The inputs for each combination are crop, water usage (irrigated and non-irrigated), and agricultural intensity input. For each cell, and each combination of crop, water usage and agricultural intensity, the GAEZ provides an attainable yield and a crop water deficit. Both these values are used in the model, the yield to determine the required land area for a given crop, and the crop water deficit to determine the quantity of water required when irrigated agriculture is chosen. The crops chosen for the analysis are based on the primary crops with the highest area, yield, and production in Canada [73]. The crops are wheat, rapeseed, switchgrass, and other crops (combined values for other principal crops). The demand for each principal crop is exogenous and was projected to 2050 using the years 2015–2021 as a trend and projecting based on population data [73–75]. To represent land use in the model, each province and territory is represented as its own region.

The water use can be either rain-fed or irrigated, and the agricultural intensity is classified as low (such as small community agriculture), intermediate, or high (such as factory farming). As the combination of low intensity and irrigated water use is not possible, this results in five combinations per crop per cell determining the potential achievable yield. The combinations are also given a capital cost (for an operational life of 15 years) to differentiate the higher cost for higher intensity agriculture and irrigation, and lower cost for simpler agricultural practices, as found in the supplementary materials Table 5. The capital cost essentially represents the investment in agricultural machines, with a 15-year lifetime as a reasonable estimate of how long agricultural machinery lasts.

The existing agricultural intensity and irrigation profile of crop land in Canada was set based on data from the Food and Agriculture Organization of the United Nations (FAO) Aquastat and Statistics Canada Databases [76,77]. However, the available data did not provide all necessary details and many of the values provided were indicated to be estimated. To address this all crops in Canada were assumed to be high intensity farming as most farming in Canada is heavily mechanized on commercial farming operations. Based on the data from the GAEZ, each crop requires a certain water input. The water source for irrigated crops can be ground water or surface water, and precipitation is the source for rainfed crops. To approximate the irrigated crop area in each region, we scaled the available data on irrigated crops in Canada with the ratio of crop produced in each province.

In this model we are only tracking water used for agriculture. In 2018, agricultural water use was 2.95 billion cubic meters for crop irrigation [14]. More than two-thirds of the water use in Canada is used in Alberta, and was primarily used for field and forage crops. Off-farm water accounts for approximately two-thirds of the agricultural water use, and one-third from on-farm sources. In the model, we account only for the difference in ground or surface water. Based off of the reported use of ground water vs surface water for irrigation, we assume that 10% of the water use is from surface water and 90% is from ground water.

The land area in the model is represented by cover type including agricultural lands (as discussed below), barren lands, built-up lands, forest lands, grassland and woodlands, and water bodies. Water bodies, barren land, built-up land, and grassland and woodland are not available for agricultural use and minimum areas for each are defined based on data from the GAEZ. Though it is a simplification to say that grassland and woodland cannot be converted to agricultural land, it is a reasonable simplification for the present study as it is the scale of land use impacts that is being assessed. To account for population growth and increased urbanization, built-up land minimum areas are increased proportional to projected population and urbanization over the model period [74,75,78,79]. Finally, forest lands are given a negative variable cost of −10 (Million \$ USD/1000 km^2) to represent the intangible value of forest lands. Our sensitivity analysis indicates that this is a reasonable value to ensure that biofuels do not take over all forest areas while still allowing for reasonable agricultural expansion. See the supplementary material for the results of our sensitivity analysis on the value of forests.

To model land use in a computationally efficient manner we use a method described by Shivakumar et al. [80]. In this approach, agglomerative hierarchical clustering is utilized to group cells together based on their agro-climatically attainable crop yield. The clustering process works by grouping cells based on their similarities across each combination of crop, water input, and agricultural intensity input. To begin, each cell is a cluster of one on its own, then pairs of clusters are successively merged until there is only one cluster. This creates a tree of different cluster formulations with different spatial resolutions, from which the number of clusters is selected based on the threshold after which the advantage of having more clusters (and therefore better resolution of what land is optimal for which crops) is small compared to the increased computational complexity to reach this resolution. This approach will optimize between the computational efficiency and error due to clustering. The land use data from GAEZ and clustering process allows us to model land use and its interactions with climate, land, energy, and water. Fig. 2 shows the clustered regions for BC as an example, and the number of clusters used for each region can be found in Table 6 in the supplementary material.

2.4. Biofuels

The biofuels pathway implemented in the model uses switchgrass as a fuel source. The yield for biofuel from switchgrass was estimated to be 17.45 GJ per dry tonne [81]. Switchgrass was chosen as the biofuel crop due to its relatively high conversion rate and economic viability as a biofuel [82–84]. It is known to have relatively high productivity and adaptability, with the ability to grow in lower quality soil [85]. Switchgrass is not currently a major crop in Canada, and no exogenous demand for switchgrass is included in the model. Therefore, all switchgrass produced will be used for biofuels.

We model both a biomass only and a bioenergy with carbon capture and storage (BECCS) pathway from switchgrass with the same yield and efficiency, but different cost and emissions. The capital cost and emissions for biomass from switchgrass are 3600 \$/kW and 0 $MtCO_2eq/PJ$ (while zero emission from biofuels is a simplification, it allows for

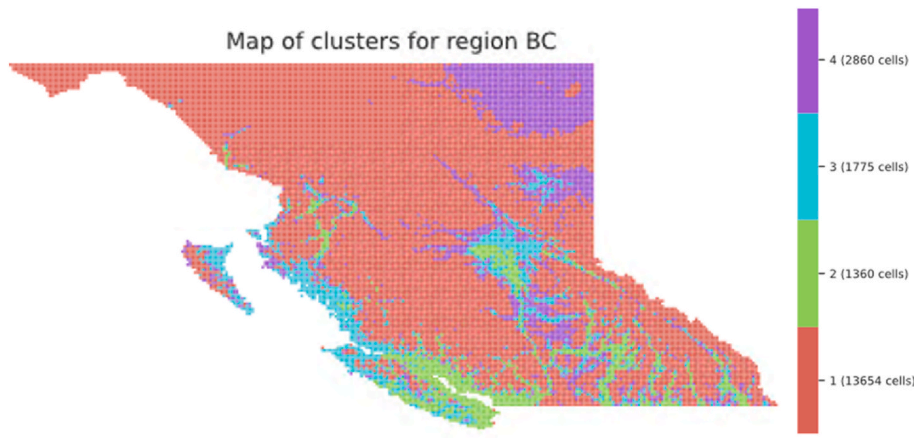

Fig. 2. Clustering map of B.C. showing the distribution of the four regions and how many cells are in each of the four regions.

greater uptake and examination as a renewable fuel source in the model), and for BECCS from switchgrass are 8867 \$/kW and −0.024975 $MtCO_2eq/PJ$ [86,87]. As the model would already include costs from agriculture, we did not add a fixed cost for simplicity. The BECCS technology is the only one in the model that uses CCS and as our focus is on biofuel implementation, as a simplification, this has not been provided as an option for fossil fuel technologies. The OSeMOSYS Global base model already had a biofuel technology representing the small existing biofuel capacity in Canada, primarily from woodchips and forest waste [52]. This results in three biofuel technologies in the model, biofuels from switchgrass with and without CCS, and biofuels (from woodchips and forest waste) not linked to a crop, without land and water interlinkages. It should be noted that there are exports of woody biomass from Canada, but since this is mostly from wood waste this does not impact our results in this work. As such, and since the biofuels not from switchgrass are not a focus of the scenarios, for the remainder of the paper, unless otherwise specified, when discussing biofuels, we are only referring to the switchgrass-based biofuels.

2.5. Scenario description

We analyze a mix of scenarios with and without an annual emission limit, switchgrass biofuel pathways, and agricultural water use limits. A summary of all scenarios can be found in Table 1, along with the scenario names that will be used in the remainder of the paper.

As discussed in section 2, Canada has committed to reaching net zero by 2050 [35]. As an intermediary step, the electricity sector is expected to decrease by 47 $MtCO_2eq$ by 2030 [88]. For our emission limit cases we used the current federal government goals to dictate our model emission limit for the net zero scenario. Using the starting point that electricity generation emitted 78.7 Mt CO_2 eq in 2015 [89], the annual emission limit was decreased linearly to 31.7 Mt CO_2 eq by 2030, and then linearly from that point to reach 0 by 2050.

To account for the impacts of increased biofuels use on agricultural demands, in addition to examining water demand for the baseline, net zero, and net zero with biofuels scenarios, we also include a scenario that applies a maximum of 6 billion m^3 of agricultural water annually. Annual water use for irrigation in Canada was 2.95 billion m^3 in 2018 [14,90], and to keep water levels to a similar but increasing value to 2050 we set the maximum water use of just over double this value. As water use is limited based on source (ground water vs surface water) and at the regional level, we use the following values to breakdown the 6 billion m^3 limit: Ground water accounts for about 10% of the agricultural water use, while surface water accounts for 90% [14]. By region, Alberta uses 67% of the agricultural water, British Columbia uses 15%, Saskatchewan 8%, Manitoba and Quebec use 3%, Ontario uses 4%, and the Atlantic provinces use 0.4% [91].

Table 1 provides a summary of these scenarios and the label with which they will most often be referred. By examining the baseline, net zero, biofuels, and water limit scenarios, we are able to see the benefits, limitations, and trade-offs of the switchgrass biofuels pathway and its impact on electricity, land, and water. In the Supplementary Material, additional scenarios are provided to test the Nuclear and Hydropower Maximum Capacity Constraints, Switchgrass Biofuels Energy Efficiency, and Cost on Forest Land.

3. Results

We first discuss the electricity system changes for each scenario in section 5.1, then the impact on emissions in section 5.2. Next, we look at the land use implications of the switchgrass biofuels pathway compared to the net zero scenario without biofuels in section 5.3, as well as the impact on crop yields of the increased land use for biofuels and the water limiting constraint. Section 5.4 highlights the impact of biofuels on water use, as well as how the water limit scenario constrains the uptake of biofuels in the model.

3.1. Electricity generation

As seen in Fig. 3, for the baseline scenario gas and hydropower provide nearly 100% of the electricity by 2050 as they have the lowest costs with a relatively long operational life and can meet the baseload requirements. Note that Figs. 3 and 4, Fig. 5, and Fig. 6 and figures in the supplementary materials all show the electricity system based on electricity generation, which has to meet the exogenously defined electricity demand. As the operational life of technologies with a residual capacity is reached, the model will switch to the lower-cost options that allow it to meet all other constraints (namely the emission and water limits).

In Fig. 4, the net zero scenario without biofuels is now applied. Once the emissions limit is introduced, without biofuels, hydropower and nuclear are the only technologies able to provide carbon free baseload generation in the model. As such, both hydropower and nuclear reach their maximum capacity by 2050. To meet the rest of the demand, the model chooses a mix of solar PV, wave, and onshore wind.

The results shown in Fig. 5 is for the net zero with biofuels scenario. In this scenario, biofuels from switchgrass are generating at first a small and increasing portion of the overall electricity generation consistently throughout the model period, with BECCS contributing a small amount to the energy mix. Biofuels from switchgrass particularly seem to replace onshore wind, which is greatly reduced in the biofuels scenario. Biofuels, now available, have the advantages of having zero emissions (or negative for BECCS) and can meet baseload demand when hydropower and nuclear reach their maximum available capacity. BECCS has the highest capital cost of any of the technologies, though biomass has a

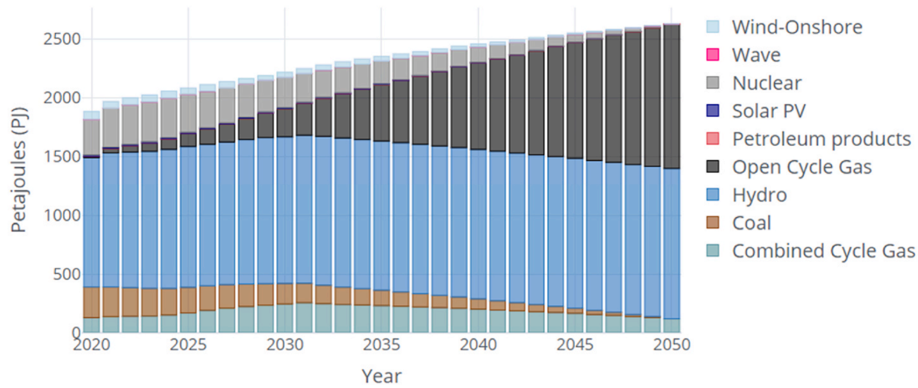

Fig. 3. Electricity Generation in Canada for the baseline scenario.

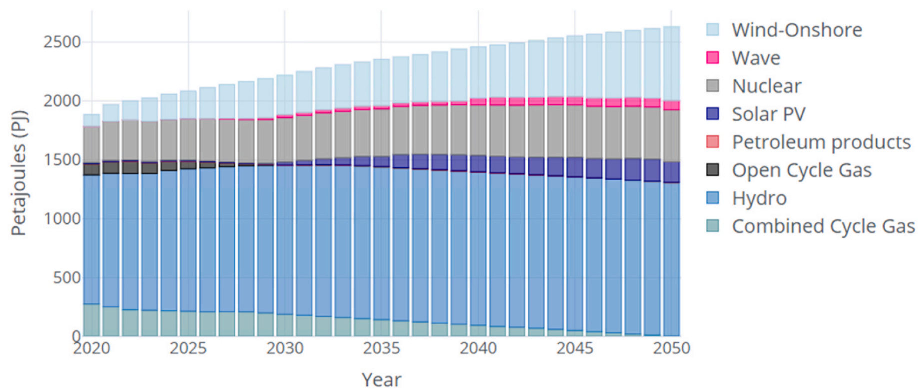

Fig. 4. Electricity generation in Canada for the net zero scenario.

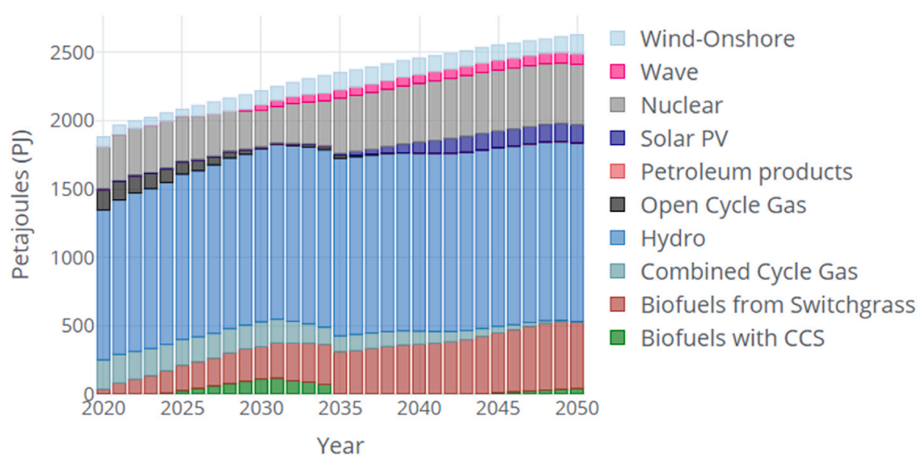

Fig. 5. Electricity generation in Canada with an emission limit for net zero by 2050, with biofuels and BECCS from switchgrass.

lower capital cost than many of the renewable energy sources. While neither technology has a set fixed or variable cost, the cost on agricultural land use further limits use of these technologies. They are also both limited by the need for land to produce switchgrass, and the cost of producing it. Compared to the net zero scenario (Fig. 4) the biofuels are not replacing emitting electricity sources, indicating that biofuels are more expensive than existing emitting generation, but are valued for their dispatchability to meet carbon restrictions.

Finally, Fig. 6 shows the electricity generation for the water limit scenario, where there is still an emission limit and biofuels from switchgrass present in the model. While there is still some generation from biofuels, it is greatly reduced when compared to Fig. 5 and more closely resembles Fig. 4. As the switchgrass biofuels requires an input of land and water, with heavily restricted water use it is much more difficult for the biofuels to be used in the model. If there is no water for irrigation, much of the crops can only be grown using rainwater, and as rainfed crops have a lower yield than irrigated crops this will also require increased land use for the same amount of output. While the model could theoretically use much more land and still have biofuels in the model, as agricultural land area is not free, this will increase the cost of biofuels. Consequently, biofuels are no longer selected as the optimal source to generate as much electricity in the water limited scenario as in the scenario without a water limit.

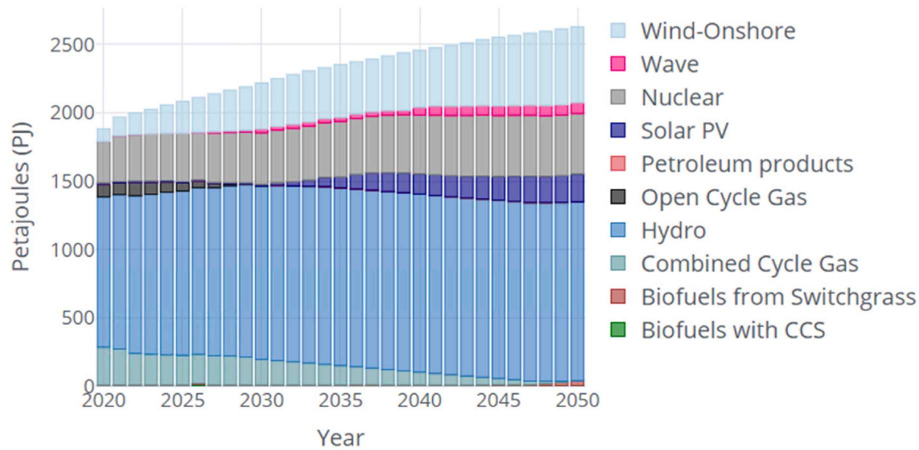

Fig. 6. Electricity generation when the agricultural water use is limited to 6 billion m^3.

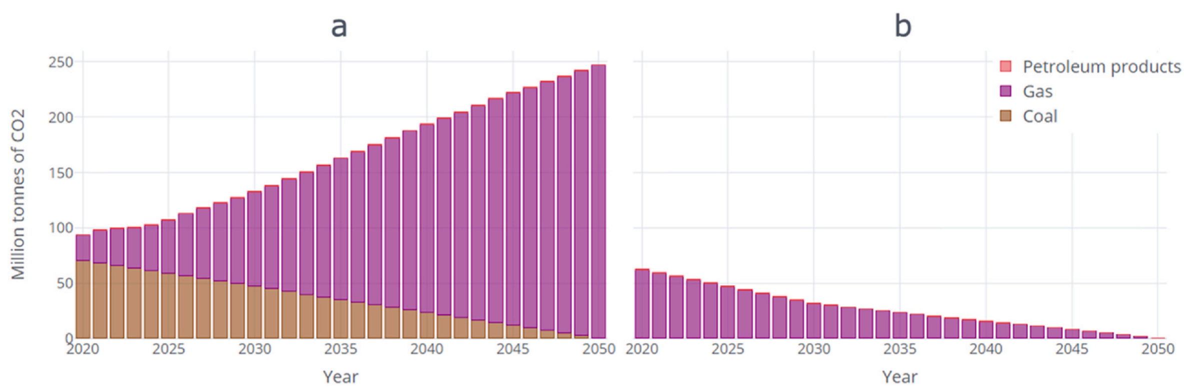

Fig. 7. CO_2 emissions in the baseline (left) and net zero (right) scenario (emissions in the net zero with biofuels scenario are the same as in the rightmost figure, the net zero scenario).

3.2. Emissions

Fig. 7 shows the emissions in the baseline scenario with no emission intervention on the left, and the net zero emission limit on the right. Compared to the baseline emissions, an exogenously defined emission limit in the net zero scenario dictates that emissions are significantly reduced, with the emissions at the maximum allowed value for each year. The scenario emissions for an emission limit have essentially the same results with or without the biofuels, expressing that it is the emission intervention, and not the biofuels per se, that have an impact on emissions. The biofuels allow the model to meet the emission limit with a lower overall cost than without biofuels. For the emission limit scenarios both with and without biofuels the emission limit is a binding constraint, producing emissions equal to the limit annually. Just as the biofuels alone do not limit fossil fuel generation, they do not reduce emissions on their own. As shown in the graphs from Fig. 7, the emission limit immediately removes coal as this limit is already too strict for coal generation in 2020.

3.3. Land use implications of biofuels

Fig. 8 shows the land area by cover type for the net zero scenarios that do not (left) and do (right) include biofuels. Without biofuels, agriculture uses 246,310 km^2 in 2050 and forest cover 3,414,700 km^2, and with biofuels agriculture jumps to 892,500 km^2, with a corresponding reduction in forest cover to 2,768,300 km^2. While all energy technologies come with their own trade-offs and require land to operate on, biofuels have the disadvantage of competing directly with food

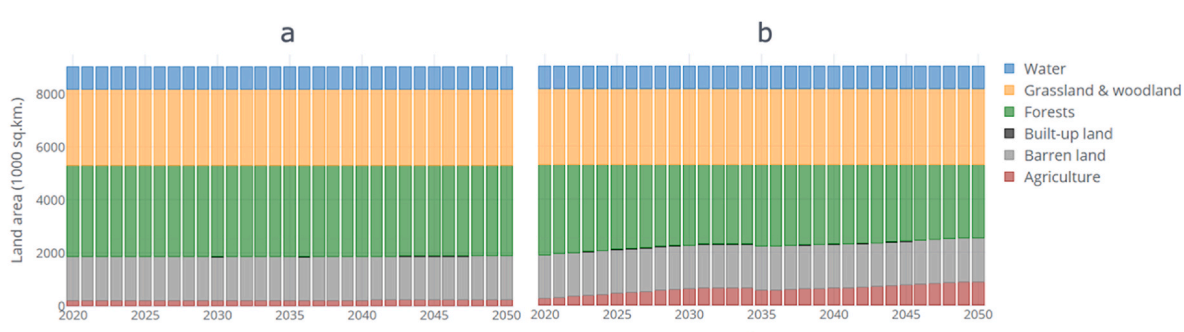

Fig. 8. Area by land cover type for the net zero scenario without biofuels (a) and with biofuels (b).

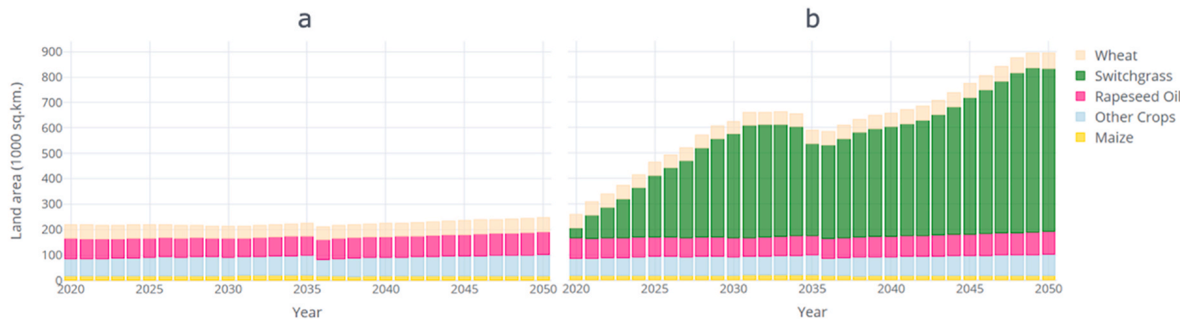

Fig. 9. Area by crop for the net zero scenario without (a) and with (b) switchgrass biofuels.

demand and resources. While biofuels can provide dispatchable energy to replace fossil fuel sources, they require significant land area for fuel production.

In Fig. 9 the land area by crop demonstrates the large increase in land use for switchgrass, with the non-biofuel scenarios on the left and biofuels scenarios on the right. Note that the right graph has a significantly different vertical scale. Even though the impact on the electricity system of biofuels is not enormous, the impact on land use is significant. While Canada is geographically a large country with plenty of land, the difference in land use from switchgrass alone covers an area roughly equivalent to the area of Ukraine.

In 2050, while the difference in land use for switchgrass is 643,400 km^2 with biofuels, the difference in agricultural land overall is 646,190 km^2. There is an additional 2790 km^2 needed for crops other than switchgrass, even though the demand for these crops has not changed. The details for all crop, forest, and agriculture land areas as a comparison for the net zero, net zero with biofuels, and water limit scenarios can be found in the Supplementary Material Table 8.

Fig. 10 is showing the crop yields for years 2035–2050 for the net zero and net zero with biofuels scenarios. The value of each crop's yield in 2050 for each scenario is also shown in Table 2. Comparing the net zero and net zero with biofuels scenarios, only wheat's yield is lowered by about 5%. However, once the water limit is applied in the model, all crops have a lower yield. While, in the biofuels scenario, wheat's yield is lowered due to being pushed to more marginal crop land, the impact of using less irrigation and more rain fed crops from the water limit is much greater.

In the model results the switchgrass yield is generally about 1.8 t/ha, as shown in Fig. 10 and Table 2, a rather low yield for the crop. Reviewing literature values for the yield of switchgrass, a range of 0.9–40.3 t/ha is found [84,92–94]. While yields of about 10 t/ha can be found in south-eastern Canada [92], other studies focused on the US show low yields for switchgrass in areas close to the Canada-US border, decreasing in more northern areas [95]. Given that there is considerable uncertainty in these values, a Sensitivity Analysis for the switchgrass yield is provided in the supplementary material.

Table 2
Crop yield in 2050 with and without biofuels [t/ha].

Crop	Without Biofuels	With Biofuels	Biofuels w/Water Limit
Maize	7.80	7.80	7.50
Other Crops	2.95	2.95	2.74
Rapeseed	3.90	3.90	3.48
Switchgrass	n/a	1.75	1.06
Wheat	8.39	7.98	7.80

3.4. *Water use implications of biofuels*

In Fig. 11 is the agricultural water use without biofuels, with biofuels, and with biofuels and a water limit of 6 billion m^3 imposed. In Fig. 12, the water balance for these same scenarios are shown. As seen in Fig. 6, a water limit of 6 billion m^3 heavily restricts the uptake of biofuels in the model. Even without switchgrass in the model, the agricultural water use for the net zero scenario is higher than in the restricted water scenario, and with biofuels from switchgrass the water use peaks at 238.4 billion m^3 in 2049. For the biofuels scenario, though the land use impacts were large, they were likely feasible given the significant land resources available in Canada. The water impact, however, is less likely to be feasible, even with the significant freshwater resources available in Canada.

Fig. 12 gives the water balance for the scenario without biofuels (a), with biofuels (b), and with the water limit (c), showing where water is being used in the model, and where it is coming from. The water balance graphs put the water use into the broader context, further demonstrating how this singular biofuel pathway can impact water systems in the model. The water use increase is due to the increased irrigation requirements, primarily for switchgrass, with a smaller additional amount needed to account for the decrease in crop yields. Irrigation is used over rainfed as it allows the crop to have a higher yield. For the water limited scenario, irrigation is not an option after a certain point, and crops must be rainfed. This leads to lower yields and higher costs for crop production.

The additional water is taken from ground and surface water, indicating that aquifers would be a key resource. These results are limited, particularly due to the data limitations on irrigated and rainfed crops in

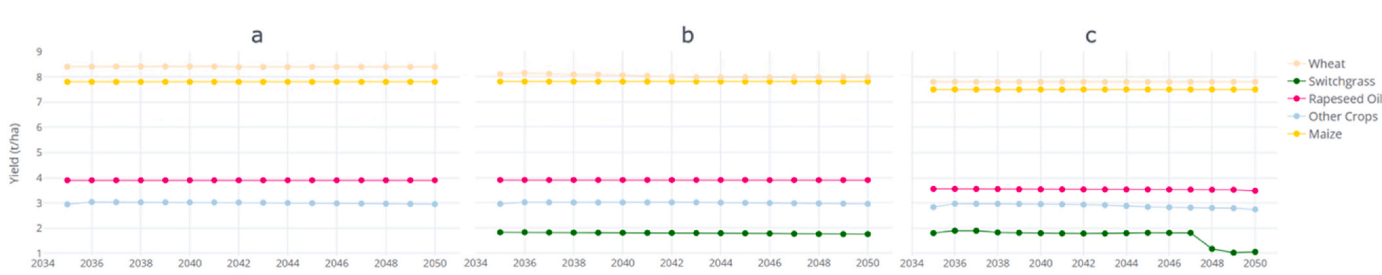

Fig. 10. Crop yields for the net zero without (a) and with (b) biofuels, and for the water limit scenario (c).

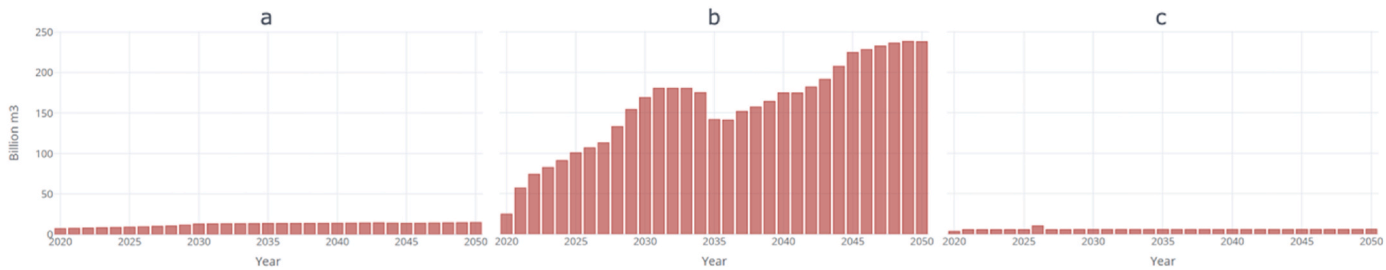

Fig. 11. Agricultural water use without biofuel (a), with biofuels (b), and with a water limit of 6 billion m^3 imposed (c).

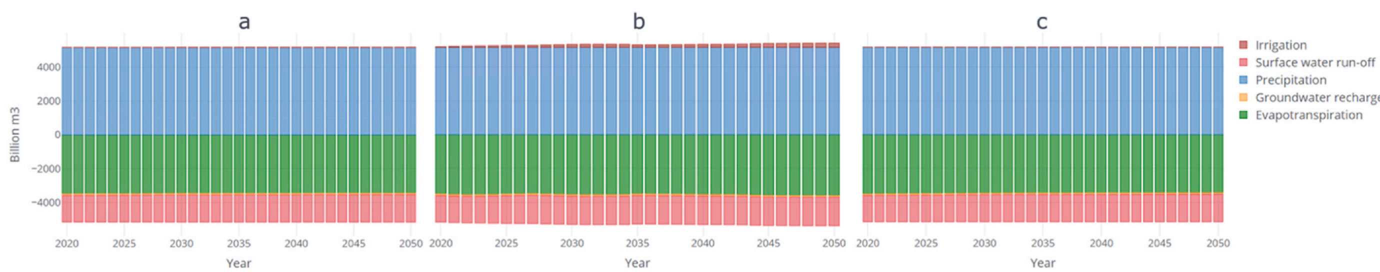

Fig. 12. Water balance without biofuel (a), with biofuels (b), and with a water limit of 6 billion m^3 imposed (c).

Canada. Even in a water-rich country such as Canada, careful resource allocation for renewable energy, food, and water will likely be key. It is beyond the scope of this study to assess the availability of water resources, but they are already known to be stressed [96,97].

4. Discussion and conclusions

With the CLEWs Canada model, we analysed several decarbonization scenarios and compared them with and without switchgrass biofuels implemented in the model. As discussed in section 2, Canada's electricity is generated from 61% hydroelectricity, 15% nuclear, 18% fossil fuels, and only about 7% from non-hydro renewables [48]. Hydropower, nuclear, and fossil fuels have the benefit of providing dispatchable, baseload energy, whereas other renewables such as wind and solar are highly variable and the electricity produced from these technologies must be used immediately or stored [98]. Switchgrass biofuels can contribute low carbon dispatchable electricity to Canada. As CLEWs Canada is a least-cost optimization model, in the baseline scenario with no switchgrass biofuels and no emission limit (Fig. 3), the model is choosing a mix of technologies based on the least cost outcome. For the net zero scenario that does not contain biofuels (Fig. 4), the model first uses the available capacity for nuclear and hydropower before variable renewable sources are used. For the net zero scenario with biofuels (Fig. 5), the switchgrass biofuels can meet the net zero electricity demand with a baseload energy supply at a lower system cost compared to the net zero scenario without biofuels. Having low carbon baseload generation is critical to decarbonizing the system while maintaining resiliency. This is a concern with electrification and decarbonization in general and highlights one of the main draws of biofuels as an energy source. In the decarbonization scenarios, while an emission limit dictates greatly reduced emissions, biofuels alone do not decarbonize the modelled electricity system - decarbonization requires strong carbon constraints, and policies, first and foremost. As all technologies have their trade-offs and appropriate uses, different technology options are required to support emission reduction policy.

While biofuels have the benefit of providing a baseload energy source in the transition to a net zero electricity system, the impact on land and water from biofuels much also be considered. As seen in Figs. 8 and 9, the land area used for crop production increases dramatically with the introduction of switchgrass biofuels. Since most other land types are not as easily converted, this would likely have ramifications in particular for Canada's forest land. While the direct impact from increasing switchgrass production is a land use increase of over 643,400 km^2, an additional amount of land is also used for wheat as the most fertile, highest yield land is used up and crops are forced into land area not previously chosen by the model for production. These indirect land use impacts from the switchgrass indicates that the land required for biofuels is not just the land used to grow the crops for biofuels. These impacts are demonstrated in the yields for each crop over the model period in Fig. 10. As switchgrass is not already a crop produced in Canada and has more flexible land requirements (eg soil composition), the land use does not as significantly affect other crops as much as other biofuel feedstocks might. However, even the 5% decrease in yield for wheat would likely affect the cost to consumers. When considering biofuel crops, those that can be grown on land not currently used or highly valued for other purposes may offer less land use trade-offs than others. Even when contributing only a small share of energy generation to the mix, the impact on land use from biofuels is significant in the model.

For Canada specifically, the major limitation of biofuels is likely not land use, but water use. While current agricultural water use is around 2.95 billion m^3, with biofuels and no water limit this value increases to 238.4 billion m^3. As the water use in the biofuels scenario went up about 80 times, and even in the baseline without biofuels it increased about 5 times the current amount, the water use implications of biofuels may be highly restrictive for the feasibility of this energy source. When water is limited in the model to 6 billion m^3 more crops must be rainfed rather than irrigated, resulting in the yields for every crop decreases by 2050. Due to climate change, water and land systems will already be under unprecedented stress. The impacts on crop yields from restricted water capacity and increased land area are especially important to consider as climate change will increasingly destabilize crop production and water supply, exacerbating all of these with feedback loops and making it more important than ever to consider our energy system policy in conjunction with our natural resource system. As noted, Canada has relatively large amounts of land and water compared to other countries. Given that other countries have more limited land and water resources, this could have even more significant policy implications for other countries.

Based on the CLEWs Canada case study, biofuels might be more appropriately applied in hard to decarbonize sectors, such as transportation and industry, prior to using them for electricity. Given the limited availability of water for growing biofuels, low carbon electricity generation may not be the most efficient or appropriate use for biofuels. As we are only examining a technology pathway in the electricity sector, there are other areas where biofuels would likely be more useful, and they have the benefit of using retrofitted existing fossil-fuel infrastructure. They are likely to be more beneficial in sectors other an electricity, including transportation and industry, as this would ease the burden of the electricity sector as Canada transitions to a low carbon energy system. Further research with the CLEWs Canada model should incorporate these other sectors to better examine the impacts of biofuels on the broader energy system.

The CLEWs Canada model is developed to support more effective sustainable development by considering the interlinkages of the climate, land, energy, and water systems, and to examine how energy system policy can impact water and land systems in unforeseen ways. CLEWs modelling can highlight interactions between land, water and energy that are not included in typical energy modelling scenarios nor in energy-economy modelling but are critically important for making effective policy decisions. Water and land use for biofuels is a clear example of these interactions. Utilizing a nexus modelling approach and incorporating system interactions allows for policy and strategy development while identifying trade-offs and synergies in the nexus. Given the current climate crisis, there is an ever-growing need for efficient policies that protects all our resources. Having a nexus model for Canada is an important step in making better policy decisions and considering the land and water use impacts of electricity from biofuels.

Limitations of the model and method used in this study should be noted, and the results must be considered in the context of what the model is and is not intended for. While we examine the trade-offs of switchgrass biofuels, all technologies have impacts on land and water systems. Including more of these trade-offs into a national model, including refining the land and water use parameters for all technologies, will help to better consider the trade-offs as a whole and compare outcomes for capacity planning. The model is not intended for thorough economic analysis, though this can be an important component in the trade-offs of different energy technologies. As a least-cost, linear optimization model there are many societal and economic factors that are not incorporated into the model but that do impact and are impacted by the energy system.

Future work will explore adding more biofuel pathways to the model, including more crops and different types of biofuels. Other energy end use sectors, such as transportation, will also be added. Future work will also seek to ease the subsequent steps required to make any country CLEWs model from OSeMOSYS Global, using the CLEWs Canada model as a base case study.

Credit author statement

Kamaria Kuling: Conceptualization, Methodology, Software, Investigation, Data curation, Writing (Original Draft, Review and Editing), Visualization, **Trevor Barnes**: Data curation, Visualization, Software. **Abhishek Shivakumar**: Visualization, Software. **Maarten Brinkerink**: Visualization, Software. **Taco Niet**: Supervision, Conceptualization, Methodology, Software, Writing (Original Draft, Review and Editing).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esr.2022.100929.

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