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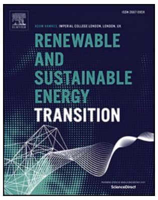

Full-length article

Electrification policy impacts on land system in British Columbia, Canada

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ABSTRACT

British Columbia (BC) is committed to transitioning to a low-carbon energy system to meet its CO_2 emission reduction targets, but this shift towards renewable energy sources may have significant implications for land use. This paper investigates the land-use impacts of different electrification pathways and technology choices in BC's energy system using the BC Nexus model. Our analysis highlights the potential increase in land-use requirements associated with transitioning from fossil fuels to renewable energy sources, with the occupied land of the power system potentially increasing up to six times larger than the current total build-up land (depending on the scale of electrification and technology choice). These findings have important implications for policymakers in terms of balancing the trade-offs between energy security, economic development, and environmental sustainability. By understanding the physical footprint of the energy transition, decision-makers can develop more effective climate policies and sustainable development strategies.

1. Introduction

As a response to climate change, an increasing number of governments, jurisdictions, and municipalities, including policymakers in British Columbia (BC) [1], are passing ambitious energy decarbonization policies. Yet, policymakers face the significant challenge of managing and optimizing (where possible) competing economic and resource management priorities and trade-offs. There is a growing need to chart technological pathways and assess the costs and scales of the transitions required to meet these political mandates. However, few studies have examined the impact of clean energy transitions on natural resources, particularly the large land area required for the deployment of utility-scale renewable energy technologies in high-scale electrification energy transition pathways [2–4].

To better capture the broader implications of electrification policies, it is necessary to integrate the interaction between interdependent resources such as land, climate, and water systems into energy planning models. Recent modelling practices, such as those outlined in [2–9], have shown that failure to consider the impact of energy transition policies on land and water resources can increase uncertainties and risks in meeting subnational climate targets, potentially affecting electricity costs and technology choices. This paper introduces an integrated water, food, energy, and climate model developed by the authors to examine the trade-offs of energy transition policies and technology choices in British Columbia, Canada.

In 2018, the British Columbia government established the Climate Change Accountability Act, SBC 2007, setting emission reduction targets for 2030, 2040, and 2050 (40 %, 60 %, and 80 % reduction below 2007 levels, respectively) [10]. Last year, the province established an even more ambitious target of achieving net-zero emissions by 2050, despite an increase in gross GHG emissions since 2015 [11,12], as shown in Fig. 1.

The planned reduction in emissions is anticipated to come primarily from the electrification of the energy system [13], which will require a

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List of Abbreviations: 100-ELC, 100 % electrification scenario; AGG, Aggressive electrification scenario; Ave., Average; BC, British Columbia; CCS, Carbon capture and storage; CLEWs, Climate, Land, Energy and Water Systems; CO_2, Carbon dioxide; CO_{2e}, Carbon dioxide equivalent; FSL, Flood safe line; GAEZ, Global Agro-Ecological Zoning; GDP, Gross Domestic Product; GHG, Greenhouse gas; GW, Gigawatt; GWh, Gigawatt hour; HFO, Heavy fuel oil; IINAS, International Institute for Sustainability Analysis and Strategy; IPP, Independent Power Producer; IQR, Interquartile; IRENA, International Renewable Energy Agency; KM^2, Square kilometre; LNG, liquefied natural gas; LPG, Liquefied petroleum gas; Max, Maximum; MW, Megawatt; MWh, Megawatt hour; NERC, North American Electric Reliability Corporation; OSeMOSYS, Open-Source Energy Modelling System; PJ, Petajoule; PV, Photovoltaics; REF, Reference scenario; RPP, Refined petroleum products; SDGs, Sustainable Development Goals; SFU, Simon Fraser University; t, tonnes; t/ha, tonnes per hectare; UN, United Nations; UNEP, UN Environment Programme; US, United States of America; WEF, Water-Energy-Food; ZEV, Zero-emission vehicles.

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two- to four-fold increase in electricity supply in a limited time frame. This presents a significant challenge, given that only 18 % of the end-use energy demand is currently supplied by electricity [12,14] (as illustrated in Fig. 2). Given that land is a finite commodity, and renewable energy technologies such as wind and solar have high land-use intensity [15] (see details in Section 2), it is crucial to explore the side effects of British Columbia's decarbonization policies on the land system. This paper investigates the impacts of various electrification and technology choices on the provincial land system, and to the best of our knowledge, it is the first such study.

Addressing literature gaps on land use in energy systems modelling, the BC Nexus Model was developed and applied to British Columbia (BC) province. The term "nexus" used in this context describes the interdependent components and their interactions in the model [16]. The application of this concept to resource management is not new, as it was first applied in the early 2000s and gained popularity after the World Economic Forum in 2008, where the challenges within the economic domain were examined through their linkages with climate change, water, food, and energy systems (Water-Energy-Food Nexus or WEF Nexus) [16]. The nexus concept is commonly applied to the required compromises needed to achieve resource security [17]. The "nexus" structure indicates how changes in the availability or functionality of one component can impose pressure on the security of other interdependent components within the nexus. The recognition of the interdependency between water, energy, and land (food) resources (WEF nexus) has gained momentum in both policy and research communities, changing the approaches toward managing these resources. Several models and frameworks have been developed (e.g., [2,4,5]), including the Climate, Land, Energy, Water Systems (CLEWS) modelling framework [17,18] applied in this project, have been developed to help policymakers better understand the complexity and interaction that comes with the nexus concept. The goal of modelling nexus systems is to maintain the resiliency of the whole system by creating feedback mechanisms between its interdependent components [19].

This paper examines the impacts of various policy pathways on the British Columbia provincial land system in response to the BC government's ambitious electrification policies. Additionally, the study explores the impact of technology exclusion/favouritism on land use within high-scale electrification policies. Notably, this analysis does not encompass the broader land impacts of the power system, including effects on biodiversity, but focuses solely on BC's energy transition's direct spatial impact (landscape disturbance).

This research enhances the current body of literature by delving into the frequently neglected side impacts of decarbonization and electrification strategies, notably their profound influence on the dynamic of regional land use. Notably, To our knowledge, this marks the first comprehensive investigation of its kind conducted for British Columbia. Our primary goal is to highlight the magnitude of the necessary transformations and the accompanying challenges, with the aim of engaging both the public and policymakers. Furthermore, we emphasize the crucial requirement to incorporate a nexus approach into energy modelling and decarbonization policies to adeptly navigate the complexities of this transformative journey.

Section 2 reviews the metrics available today to evaluate the land use of each power generation technology. Section 3 describes the model structure and methodology used in detail. Section 4 provides a thorough discussion of the results, and Section 5 summarizes the main findings.

2. Land use metrics

The literature has recognized significant advancements in renewable energy technologies over the past decade, highlighting their economic viability, efficiency, and ecological impact [19]. However, transitioning to renewables often increases land use in the power system [19], emphasizing the need for a nexus approach in energy modelling and climate policies. This paper assesses the increased land requirement in the power system based on technology choices and electrification policies, employing land-use metrics. While several methods exist for estimating land use in power generation, the three most common approaches are ecological footprint, land-use intensity, and power density [15]. Detailed definitions and distinctions amongst these metrics are included in Sections 2.1 to 2.3. Since the definition and assumptions behind each metric vary, selecting the appropriate one depends on the research's scope and objectives as well as the model structure. The metric chosen in this paper is land-use intensity, facilitating standardized comparisons and aligning with prior studies and the BC Nexus model's structure in defining interactions amongst various components. This metric quantifies the land area required to produce one unit of

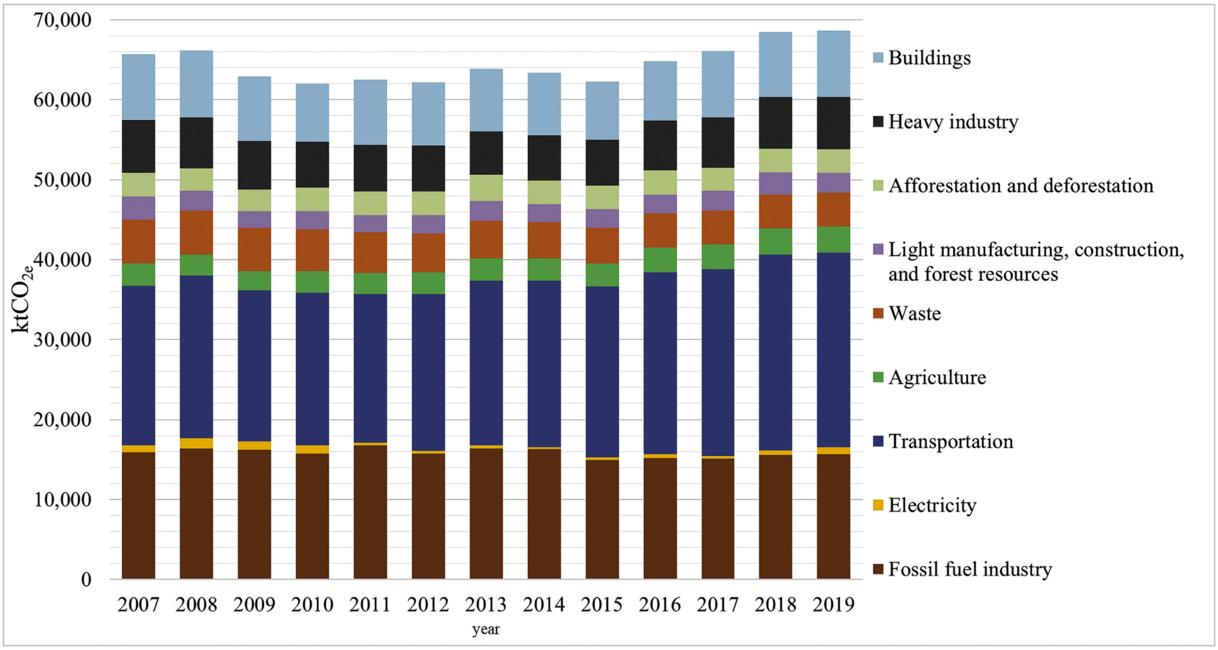

Fig. 1. BC GHG emissions by sector from 2007 to 2019 (recreated based on data provided by [11]).

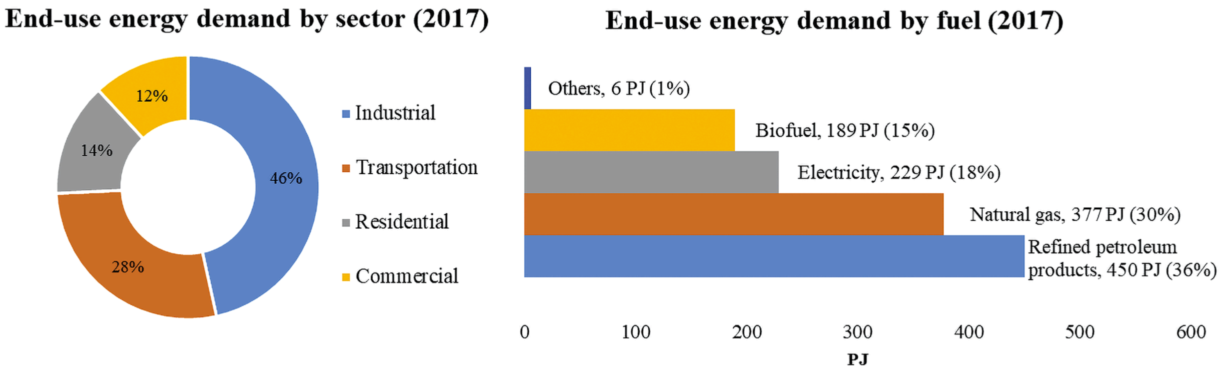

Fig. 2. BC energy demand status in 2017 by sector and by fuel source (recreated based on data provided by [12]).

energy over a technology's lifespan.

It's important to note that the literature review indicates existing land use calculations often rely on outdated data, resulting in variations in estimates due to differences in sources, methods, and assumptions [19,20]. Despite these variations, most studies rank coal, natural gas, and nuclear as having the smallest land use, while biomass, solar, wind, and hydro dams (excluding run-of-rivers) generation technologies have the largest (e.g. [19–25]). While it is acknowledged that the quantitative land-use impact of power technologies can be site-specific, it's important to highlight that due to limited available data on land-use associated with Canadian power projects, this study relies on more recent and widely applicable generic land-use data. This data, as indicated in the United Nations & IRENA [20] study (Table 1), is based on information from the US and European contexts. Figs. 3 and 4 showcase data variations in the literature reported for the land-use intensity of solar and wind power technologies.

2.1. Ecological footprint

In the 1990s, Wackernagel et al. [36] introduced the ecological footprint concept, which measures society's ability to remain within the planet's biologically productive or regenerative capacity [15]. Over the time, it has evolved into a potent indicator for assessing a society's actions in pursuit of sustainable development goals [40]. Although it was not initially designed to evaluate land use associated with the energy system, it was later adopted to suit this purpose. There are three main approaches to using this metric to quantify land use: (1) the land required to produce the same amount of energy using cultivated biomass, (2) the land needed to sequester carbon dioxide emissions produced by a technology, and (3) the land necessary to recover the natural capital used by the technology [15]. The unit used for this metric is global hectares per energy produced (ha/GJ). An example of this approach is the work by Stoglehner [40], which is further discussed in [15].

2.2. Land-use intensity

The land-use intensity metric, which measures the amount of land required to produce one unit of energy over the entire lifespan of a technology, is another useful tool for assessing the impact of power generation on land use [15]. To quantify the land-use intensity, the installed area used for power generation (direct footprint) is divided by the number of years (asset lifetime) and the yearly production of technology (example of standard unit: m^2 per MWh). One advantage of this method is that it takes into account the full life cycle of a technology. However, it has been noted that the lack of a temporal boundary on land use can favour renewable sources over strictly annual metrics "since an installation receives full credit for its lifetime power generation" [15]. Previous studies, such as Fthenakis and Kim [28] and McDonald et al. [32], have used this approach to evaluate the land-use intensity of power generation technologies in the US. However, the data used in these studies date back to the 1980s and 2000s, and it is crucial to validate whether they still accurately represent the technology for both renewable and non-renewable sources [15].

Recently, Lovering et al. [33] calculated the land-use intensity of various power generation technologies using data from real-world projects reported within the literature, public records, datasets, and original geospatial data, from 66 countries, including 45 US states. Their work estimated median, mean, and interquartile (IQR) values for each technology. Their finding was later used in this study for the sensitivity analysis of the impact of electrification policies on BC's land system, as discussed in Section 3.1.1. Table 1 summarizes examples of land-use intensity data found in the literature.

2.3. Power density

The power density metric is a measure of the power output generated per unit of land on an annual basis (example of standard unit: W_e per m^2). In 2015, Smil [35] presented the first systematic and quantitative approach for calculating power density for energy technologies. This method employs annual generation, allowing for a better comparison of energy technologies with different life spans. Wachs et al. [15] provide a more detailed comparison of the three methods used to evaluate the land use impact of power generation technologies, including the power density metric.

2.4. Literature gaps

The primary gap in existing literature, at the core of our study, involves the impact of technology choices and exclusions within electrification policies on regional land use. This paper presents a distinctive empirical perspective by examining this relationship, emphasizing the urgent requirement for comprehensive research on land use dynamics within evolving energy systems, particularly in regions like British Columbia with ambitious electrification objectives.

3. Methodology

This section begins by reviewing the BC Nexus model's structure, including its framework, components, data collection methods, and assumptions. It then explores the defined scenarios for assessing the impacts of electrification policies and technology choices on land use.

3.1. Modelling structure and assumptions

The BC Nexus model ([43]) is made up of three major components of water, food, and energy (WFE) and their interactions with the CO_2 emissions level. Each of these components was designed and developed individually using BC-specific data sources. Then, the linkages between pairs of systems were defined for the model. For example, the water and

Table 1

Examples of land-use intensity (km^2/PJ) of power technologies by various studies.

Land-use intensity >>> (km^2/PJ)		Electricity (km^2/PJ)										Liquid fuel (km^2/PJ)			
Source	**Secondary (original data) source**	Biomass	Wind	Hydropower	Solar Photovoltaic	Solar Thermal	Geothermal	Nuclear	Natural gas	Coal underground	Coal surface	Fossil fuel	Biofuel-Soy	Biofuel-corn (maize)	Biofuel-Sugarcane
UN & IRENA [26]	U.S. (data based on Trainor et al. (2016)) [27]	225.0	0.36	4.69	4.17	5.36	1.42	0.03	0.28	0.17	2.28	0.17	82.22	65.83	76.11
	U.S. (data based on Fthenakis and Kim (2009)) [28]	3.61	0.28	1.14	0.08			0.03	0.08	0.06	0.06				
	EU (data based on IINAS (2017)) [29]	125.0	0.19	0.97	2.42	2.17	0.69	0.28	0.03	0.06	0.11	0.03	133.0	61.11	66.39
	UNEP (data based on UNEP (2016)) [30]		0.08	0.92	3.61	3.89	0.08		0.06		4.17				
	UN Estimation-Typical (own estimate for the unspecified region) (i.e., generic)) [31]	138.8	0.28	2.78	2.78	4.17	0.69	0.03	0.06	0.06	1.39	0.11	111.1	63.89	69.44
Note that data include land use for spacing and from upstream life cycles (e.g., mining). For further details, refer to [26]															
McDonald et al. (2009) [32]	U.S. (Estimation for new assets in 2030)	150.9	20.03	15.00	10.25	4.25	2.08	0.67	5.17		2.69		248.3		
Note that this study calculates land-use intensity by considering area requirements for energy production, energy sprawl, and new generating capacity across different energy production methods. Excluded are site preparation, reclamation, end-use electricity generation on developed sites, energy efficiency improvements, and the effects of new long-distance transmission lines. For further details, refer to [32]															
Lovering et al. (2021) [33] **and through personal conversation with the author**	Median	162	0.36	1.80	5.47		0.13	0.02	1.13	0.19					
	Average	447	0.47	40.79	5.92		0.39	0.04	1.14	0.17					
	Q1 (IQR technique-1st quartile value)	117	0.23	0.28	4.20		0.05	0.01	0.69	1.71					
	Q3 (IQR technique-3rd quartile value)	281	0.56	6.63	6.55		0.45	0.03	1.28	6.24					
Note that included in the land-use intensity calculation in this study are the land areas occupied by electricity-producing facilities (direct area) and, if applicable, the land required for sourcing power plant fuel (indirect area), though the specifics of what is encompassed vary depending on the technology. For further details, refer to [33].															

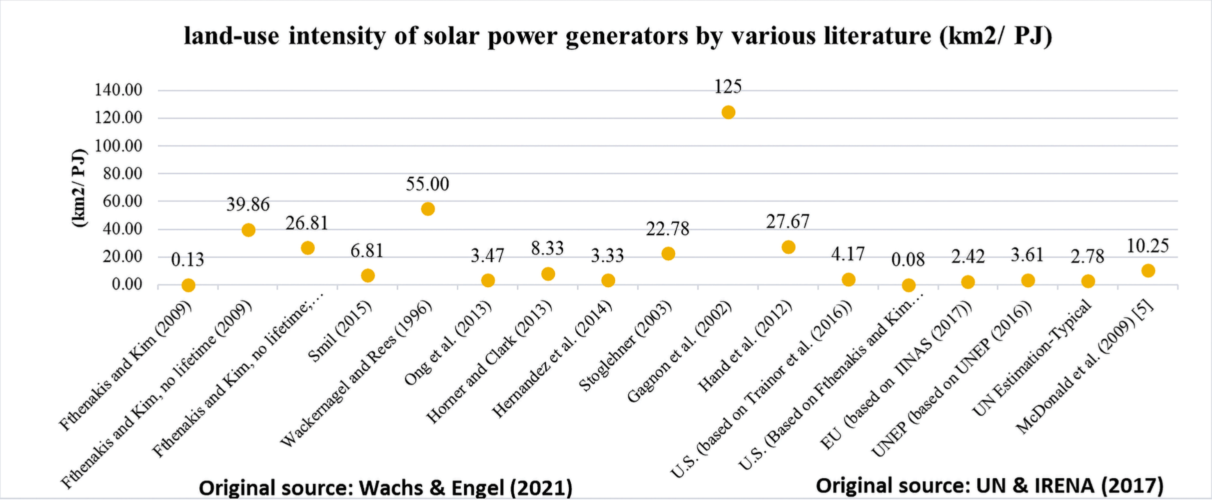

Fig. 3. Illustrating the range of land-use intensity for solar power generation found in the literature (data references: Wachs & Engel [15], Fthenakis and Kim [34], Smil [35], Wackernagel and Rees [36], Ong et al. [37], Horner and Clark [38], Hernandez et al. [39], Stoglehner [40], Gagnon et al. [41], Trainor et al. [27], IINAS [29], UNEP [42], U.N. & IRENA [26]).

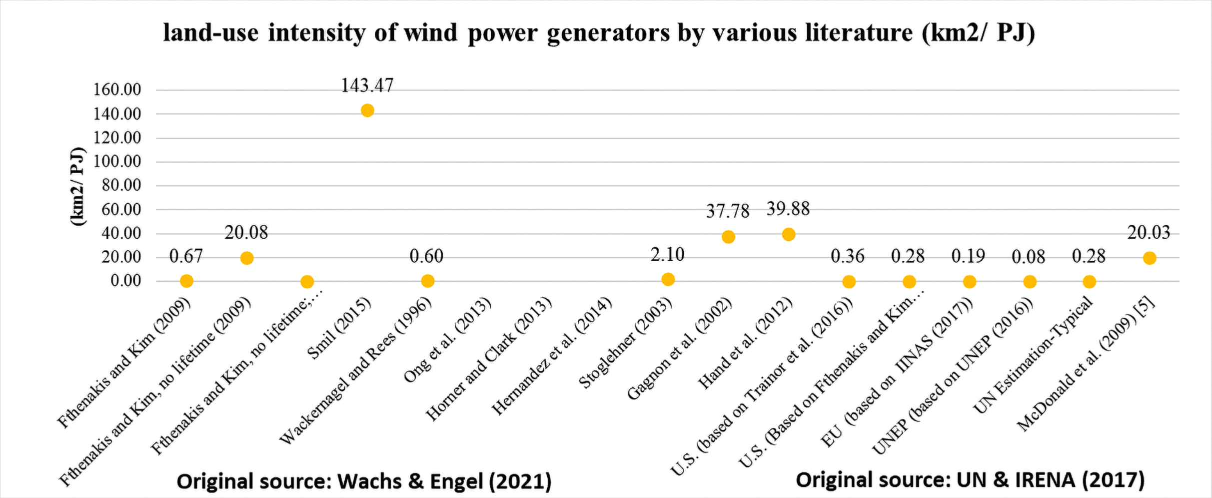

Fig. 4. Illustrating the range of land-use intensity for wind power generation found in the literature (data references: Wachs & Engel [15], Fthenakis and Kim [34], Smil [35], Wackernagel and Rees [36], Ong et al. [37], Horner and Clark [38], Hernandez et al. [39], Stoglehner [40], Gagnon et al. [41], Trainor et al. [27], IINAS [29], UNEP [42], U.N. & IRENA [26]).

energy systems were linked by identifying the amount of water needed to generate power from various power generation technologies, as well as the energy required for activities like water treatment. Similarly, the energy and land systems were connected by examining the energy needed for agricultural activities like water pumping and running heavy equipment, as well as the land required to meet biofuel demands in the energy system. As the model evolved, the activity ratio of CO_2 emissions produced by each activity within and between systems was incorporated. This allowed for a more complete analysis of the impacts of changes in each system on BC's carbon footprint.

The BC Nexus model was developed using the CLEWS (Climate, Land, Energy, Water Systems) modelling framework and platform. CLEWS is an extended version of the energy capacity expansion modelling framework named OSeMOSYS (the Open-Source energy MOdelling SYStem) [17]. OSeMOSYS is a bottom-up linear modelling framework developed to provide long-term energy system cost optimization for user-defined regions. "The term' modelling framework' in this context designates software that generates specific models by populating them with user-defined data" [44].

The energy system in "OSeMOSYS [and hereditary CLEWS] is designed to be easily updated and modified to suit the needs of a particular analysis. To provide this capability, the […OSeMOSYS framework] is developed in a series of component 'blocks' of functionality. A collection of the functional component blocks combines to form a customized model" [45]. Each block contains a stand-alone set of equations and variables that can be plugged into the model's core code to create specific insights into the user-design enquiry [46]. This unique structure of the modelling framework makes the tool easy to use/learn and accessible to a wide range of audiences. The method used in designing the structure of the OSeMOSYS energy framework can be extended beyond the energy system to include other nexus components. The same approach has been taken to embed the water, land-use, and climate systems with the energy system in the CLEWS framework [17].

The CLEWS modelling framework can be applied through the two different approaches of soft-linking and hard-linking (integrated) between systems [18]. In the BC Nexus model, a fully integrated approach is used to define and design the interlinkages between CLEW systems. The model is policy-driven, and when carrying out a scenario, the analysis proceeds within each system based on the exogenous user-defined data. This phase includes assessing resource availability, demand trends on energy, agriculture products and water, plus policy constraints within each system to identify each system's boundaries, drivers, and pressure points. Then, each system's interactions with the others can be evaluated to identify the trade-off and synergies caused by each policy. Additionally, the model provides a least-cost technology mix (optimization) to meet power demand during the modelling period, along with total CO_{2eq} emissions emitted by all systems.

Appendices A, B, and C provide an overview of the primary data and assumptions made to calibrate the model with BC's land, water, and energy systems representations. The data used to shape the energy system portfolio of BC was gathered from public datasets and governmental sources. Reasonable, technically qualified assumptions were made to substitute missing or inaccurate data for the model in some cases.

3.1.1. *Land-use intensity of power generation*

In the BC Nexus model, the interactions between systems (Water ↔ Land-use ↔ Energy) define by the amount of input from one system to produce the desired output from another system - for instance, how much water is required to produce one unit of power in a natural gas power plant. As discussed in Section 2, the land-use intensity (direct landscape impact) of power generator technologies varies in the literature, mainly for renewable energy technologies such as wind and solar. Data clean-up and normalization techniques (interquartile range) are used on the sample literature data represented in Table 1 to improve data integrity, lessen data redundancy, and create a common scale. The focus of the interquartile-range technique is to minimize the influence of outliers on the estimation of average value. This method separates data between the 25th (Q1: Quartile 1) and 75th (Q3: Quartile 3) percentile values, and the average value is calculated for these sorted data.

To estimate the central tendency of land-use intensity for each technology, the authors compared their normalized data collected from literature with Lovering et al.'s study [33] and the research conducted by UN & IRENA [26]. There were similarities between the results. However, considering the data used in the Lovering et al. and UN & IRENA works is more updated, the information they provided was used to define a range for conducting a sensitivity analysis. Table 2 provides the values used in this study, with the middle column representing the average between values from Lovering et al. and the UN estimation of typical values for generation technologies. (See Table 1).

Given the significant role of hydro energy in British Columbia's (BC) power system (90 %), the authors examined the practicality of the selected land-use intensity range for the sensitivity analysis of hydropower technology in the BC Nexus model. To this end, the authors conducted a case study of Site C, one of the ongoing large dam projects in BC. However, obtaining land-use impact data for BC's power projects posed a significant challenge, with the only available data being an internal report [47] from the Ministry of Environment prepared in the 1980s. While the total proposed capacity of Site C in the 1980s was 875 MW (~4460 GWh), the current projection is 1.1 GW.

Table 2
Land-intensity value range chosen for the sensitivity analysis (based on Lovering et al.'s [36] study and UN & IRENA [13]).

	Minimum (Km^2/PJ)	Average (Km^2/PJ)	Maximum (Km^2/PJ)
Nuclear	0.01	0.03	0.04
Geothermal	0.05	0.54	0.69
Wind	0.23	0.38	0.56
biomass	117	293	447
Natural gas	0.06	0.60	1.28
Hydroelectric (single-purpose dams)	0.28	21.8	40.8
Coal	0.17	0.78	6.24
Solar PV	2.78	4.35	6.55

According to the Ministry of Environment report [47] at the time, the Site C project is estimated to affect a land area of approximately 280 km^2. A detailed breakdown of the estimated affected land area can be found in Table D1, located in Appendix D. The land-use intensity of 17 km^2/PJ for Site C was calculated using this information. This estimation aligns well with the range of values suggested by Lovering et al.'s [33] and UN's works [26] for large-scale hydro dam projects, as shown in Table 2. However, the limited availability of data on the land-use impacts of BC's power projects underscores the need for more comprehensive data collection and reporting efforts to support sustainable decision-making.

3.2. *Scenarios*

Three main electrification scenarios are identified for BC. The first Scenario, the reference scenario (REF), assumes a low electrification rate based on Canada's Energy Future projection published in 2019 [48]. In the second scenario, denoted as the aggressive electrification scenario (AGG), it is assumed that the replacement of 100 % of natural gas will occur in both the residential and commercial sectors. Additionally, within the transit sector, the assumption is that 50 % of passenger cars and 50 % of transit vehicles will be electrified, in alignment with the BC ZEV mandate [49]. Finally, the third Scenario, the 100 % electrification scenario (100-ELC), aims to meet BC's net-zero decarbonization target by 2050 through 100 % electrification of all sectors' energy demand [1].

These scenarios were developed to investigate the synergies and trade-offs of the selected BC's energy decarbonization policies and actions and their impact on the land system. Two types of decarbonization directions were explored in BC. First, the governmental actions (policy acts) that target the alteration of energy supply and demand portfolios, such as electrification plans and improving energy efficiency standards, to cause GHG emission reduction. Second, market policies of the carbon tax, cap-and-trade and clean fuel standards result in economic-driven action and emission reductions.

To establish the reference scenario, the demand projections for residential, commercial, industrial, and transportation sectors outlined in Canada's Energy Future report published in 2019 [48] were used. This Scenario was selected because of its moderate approach to decarbonizing BC's energy system, considering the price and technological improvement trends, climate and energy policies, and other factors (Fig. 5). Based on the report, a total energy growth of 11 % was estimated between 2019 and 2040, with 29 % growth in electricity demand, 39 % growth in natural gas demand, followed by a 15 % and 7 % decline in demand for refined petroleum products (RPP) and biofuels respectively. The demand trends were linearly extrapolated to 2050 to match the modelling period. Within the transportation sector specifically, the report projected a 12 % decline in the total end-use energy demand. This projection included substantial escalations in electricity (2624 %) and natural gas (741 %) demand, as well as declines in other energy demands such as biofuels, diesel, motor gasoline, and heavy fuel oil.

The technical and financial details of various power generator technologies, such as solar, nuclear and coal, are added to the BC Nexus model. The demand growth trends in all sectors and WEF systems allow the model to compute an optimization analysis that finds the least-cost technology mix to meet the power demand. The optimization analysis takes into account the residual energy capacity in BC, facility operating life span, cost information, demand projection, and policy directions. One critical factor in determining the direction of investment in the technology mix pathway for the power sector is the reserve margin value. The reserve margin is the amount of unused capacity in the system that serves as a buffer against unexpected changes in demand or supply. Note that intermittent renewable technologies such as wind and solar are not fit for addressing reserve margin obligations as they are not baseload generators, at least without coupling with storage technologies. The North American Electric Reliability Corporation (NERC)

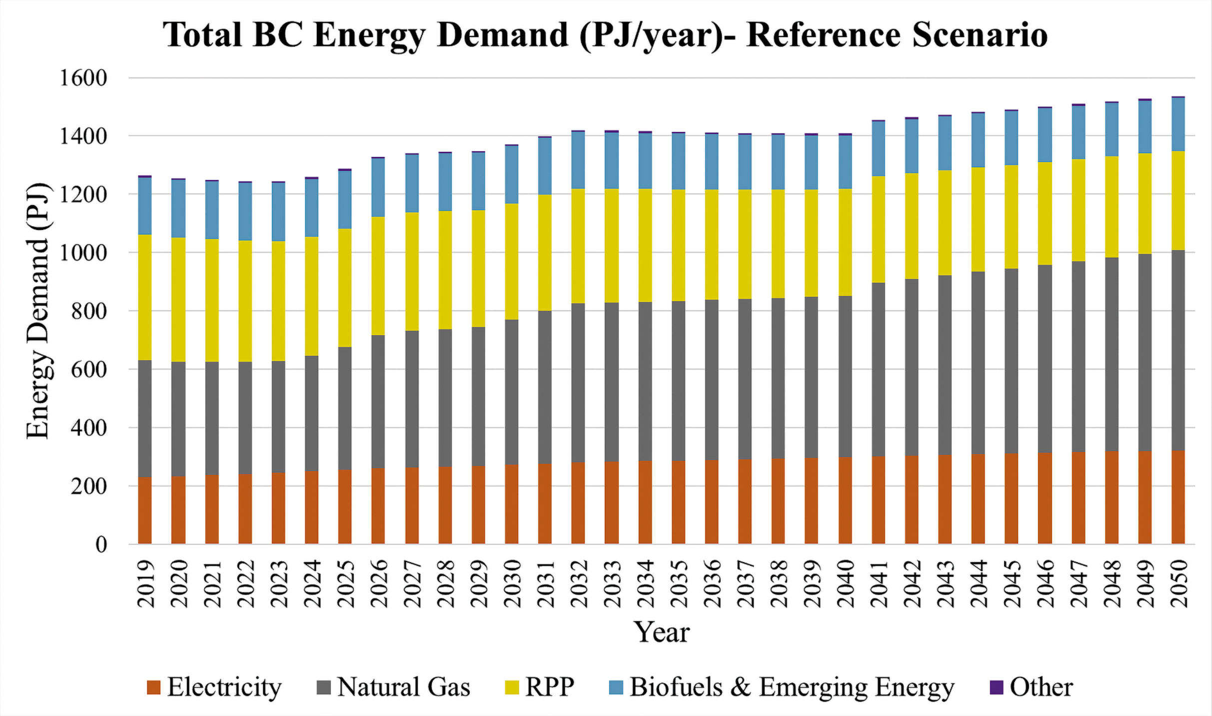

Fig. 5. Historical data and the projection of BC's energy demand (PJ) based on the 2019 Canada's Energy Future report [48] used in the reference scenario.

published a Long-Term Reliability Assessment report in 2020 [50], which set the anticipated, prospective, and reference reserve margin values for BC from 2021 to 2030.

As illustrated in Fig. 6, the value of anticipated and prospective reserve margins closely follows, reaching its peak in 2025 at 24.1 %. The value of the reserve margin in the reference scenario fluctuates between 12.3 % and 14.1 %, with an average value of 13.55 %. For this paper, the value presented in the NERC reference scenario [50] for BC between 2021 and 2030 was used and linearly extrapolated to 2050 to match the modelling period.

Table 3 below provides an overview of the scenarios' directions and assumptions examined in this paper. As mentioned above, three

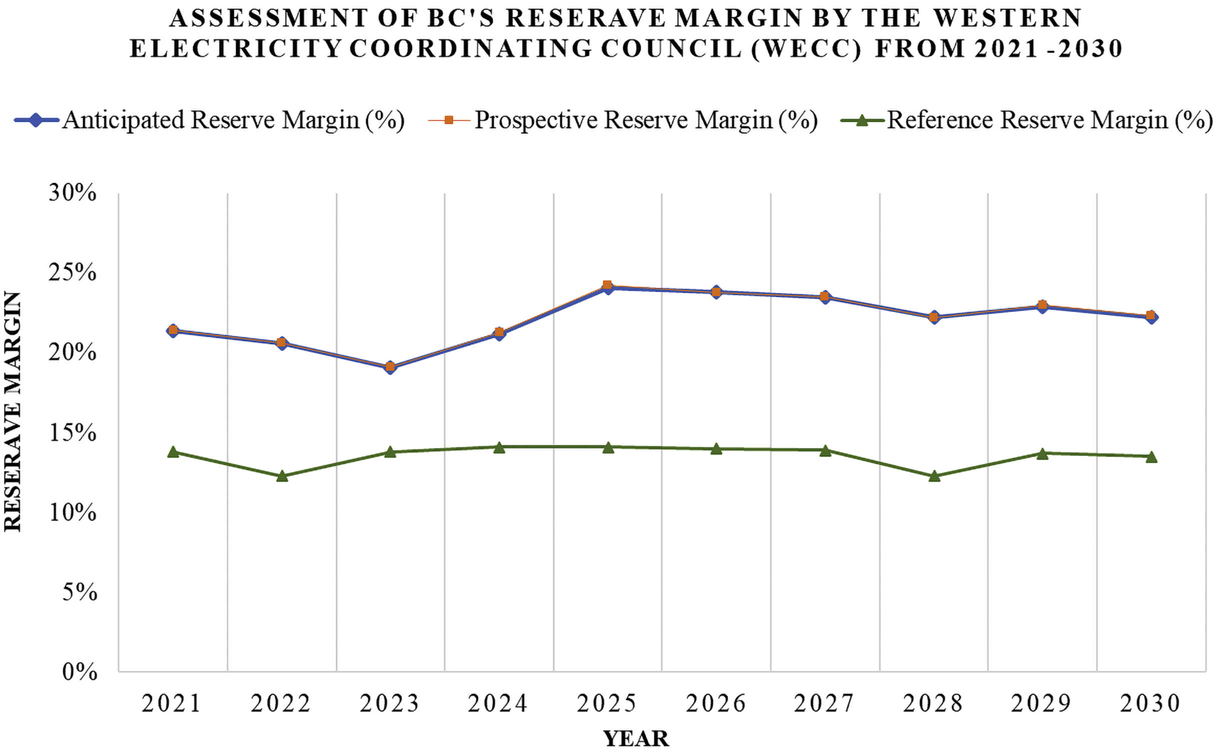

Fig. 6. Anticipated, prospective, and reference reserve margin for BC from the 2020 Reliability Assessment report by the North American Electric Reliability Corporation [50].

Table 3
The summary of the scenarios' directions and assumptions.

No	Scenario name	Policy direction (see Table 4 for more details)			Land-use intensity value	Technology exclusion and favouritism
		Reference	Aggressive	Net-zero	Average (from Table 2)	
1	REF	✔			✔	No exclusion or favouritism
2	AGG		✔		✔	No exclusion or favouritism
3	100-ELC			✔	✔	No exclusion or favouritism
4	100-ELC-NoNGS			✔	✔	No fossil fuel (in BC, this means no natural gas)
5	100-ELC-W&S			✔	✔	Only wind & solar technology allowed for new capacities
6	100-ELC -NoGEO			✔	✔	Geothermal technology is excluded from technology options
7	100-ELC-NoNu			✔	✔	Nuclear technology is excluded from technology options

electrification policy directions were studied. Land-use intensity sensitivity analyses were conducted for each policy. Later, the 100-ELC Scenario with the land-use intensity value of the average was expanded. This new set of scenarios (scenarios 4 to 7 in Table 3) was used to explore the influence of energy technology exclusion and favouritism on land use, as well as to bring a discussion to the public about the less-discussed side effect of energy transition toward renewable sources. The authors examined the scenarios in which the model was restricted in choosing only wind and solar in addition to no fossil fuel as well as no geothermal technology or nuclear to serve as baseload to address the future demand as summarized in Table 3.

The second policy direction in this paper, the aggressive Scenario (AGG), explores a more aggressive approach to electrifying the energy system compared to the reference scenario. In this scenario, the energy consumption by fuel type and application was closely examined based on 2019 Canada's Energy Future projection [48]. Within the residential and commercial sectors, the demand for natural gas for space heating is assumed to be 100 % electrified by 2050, using heat pump technology for space heating. In transportation, 50 % of passenger cars and 50 % of transit vehicles are electrified, following the BC ZEV mandate [49]. The BC ZEV mandate requires that 30 % of new light-duty vehicle sales in BC be zero-emission vehicles (ZEVs) by 2030, with a target of reaching 100 % ZEV sales by 2040. Given this mandate, the rapid adoption of electric vehicles and the typical service life of gasoline-powered cars, a transition towards an all-electric vehicle landscape within the transportation sector is a reasonable expectation by 2050. To project the AGG Scenario's new demand trend, gasoline and diesel demand in the transportation sector is linearly reduced from 2020 to zero by 2050, with corresponding adjustments in electricity demand. Note that the transition will not be a joule-by-joule substitution for the higher efficiency of the electrical heating technologies (heat pumps, insulation, etc.) must be accurately represented. It is important to acknowledge the vast array of scenarios and assumptions that can be explored using our model. While our aggressive scenario does not encompass significant changes in the industrial sector, it aligns with the changes projected in Canada's Energy Future, staying within those bounds. The sole modification involves incorporating BC Hydro's three-terawatt/hour LNG power agreement into the industry sector's electricity demand projection [51]. The LNG agreement allows LNG Canada access to electricity from BC Hydro for the power needed for its proposed liquefied natural gas (LNG) export. The project will be online in 2024. This scenario serves a specific purpose: to underscore the critical importance of adopting a more aggressive approach within the industrial sector. This emphasis is essential for effectively achieving British Columbia's GHG reduction targets.

In addition to the policy directions mentioned above, BC's carbon tax regulation (carbon pricing) is included for AGG and 100-ELC scenarios. Carbon pricing is how the government directly puts a price on pollution to influence the energy market. BC's current (April 01, 2022) carbon tax rate is $50 per tonne of carbon dioxide equivalent (CO_{2e}), with a scheduled increase of $15 per year until 2030, reaching $170 per tonne of CO_{2eq} following the federal backstop carbon tax rate [52]. Due to the uncertainty in the BC and federal carbon tax trend after 2030, a constant rate of $170 is maintained from 2030 to 2050. Table 4 summarizes the different policy directions in the scenarios assessed in this report.

4. Results and discussion

This section summarises the detailed results of the modelling scenarios explained earlier in Section 3.1.2 and discusses the findings revealed by the results for each electrification pathway.

4.1. Energy consumption

The results of the modelling scenarios are shown in Fig. 7, which demonstrates how the energy consumption (demand portfolio) changes by sector and fuel type based on the various electrification scales. The charts on the left side of Fig. 7 illustrate the energy demand portfolio by sector in each scenario. As previously mentioned, the AGG and 100-ELC scenarios investigate the impact of more aggressive electrification within residential, commercial, transportation, and industry sectors by 2050. Due to the higher efficiency of electric cars and heat pumps when employed to replace traditional gas-powered cars and natural gas furnaces, the transition reduces the total end-use energy demand in these two scenarios, as illustrated in Fig. 7.

The charts on the right compare the transition in the energy demand by fuel type based on the scale of electrification. The 100-ELC scenario shows a linear transition from 2025 to 2050 toward near 100 % electrification of BC's energy system, except for the industry sector and electrification of aviation and heavy fuel in the transportation sector. Due to the complexity of the energy shift in these sectors, the electrification process begins in 2030 within these sectors to have a more realistic time scale for optimization analysis of BC's energy system.

4.2. Technology mix

This section summarizes the technology mix shift based on the policy assumptions and electrification scale for the main scenarios (REF, AGG, 100-ELC). In these scenarios, no technology option has been excluded: the only constant is the cost and availability of the energy source within BC's geographical boundaries. Fig. 8 demonstrates two sets of findings for REF and AGG scenarios. The charts on the left-hand side illustrate the magnitude of the electricity system capacity that will need to be scaled up to meet electrification goals. The charts on the right-hand side are the power generation technology mix supplying the demand.

In the reference scenario (REF), there is no cap on the untapped potential of energy sources for future expansion, and the model selects technological pathways based solely on cost optimization analysis. In

Table 4
Overview of the energy decarbonization assumptions for each policy direction investigated in this work.

Policy direction	Direction	Assumptions
Reference (REF)	Based on Canada's Energy Future projection published in 2019 (no carbon tax)	- Slow total energy use growth of 11 % to 2040 in BC Canada wide: - Population growth of 20 % - GDP growth of 40 % (leading to a reduction in energy use per person and per dollar of economic activity) - 50 % and 30 % growth in crude oil and natural gas, respectively. - Note: Additional hydropower capacity is added to the residual capacity in the model in 2025 due to the expectation that the proposed Site C dam project will be coming online
Aggressive electrification (AGG)	Reference scenario (REF) + current long-term policies such as carbon tax + more aggressive electrification carbon tax	- 100 % transition from natural gas in residential and commercial sectors - 100 % transition to electric vehicles for non-heavy cars - Additional 3-Terawatt hr. electricity demand in the industrial sector due to the LNG sector - Carbon tax: 45 in 2020 + $15 each year till 2030; from then, a flat rate of $170 - plus, no new natural gas/ fossil fuel power plant development after 2030
100 % electrification to achieve Net-zero by 2050 (100-ELC)	100 % electrification in all sectors	- AGG's assumptions, except there is no ban on using natural gas as long as zero-emission by 2050 is achieved - 100 % electrification of all sectors' energy demand in addition to the electrification pathway explained in the aggressive scenario - Due to the complexity of the industry sector, the joule-by-joule energy transition to electricity is applied - CO_2 emission limit set at 0 for 2050

this scenario, no policy constraint on carbon emission (e.g., carbon tax) leads to the investment in natural gas after 2039. When the installed hydropower and geothermal capacity are fully utilized by 2035 to serve as baseload power sources, the model starts deploying and investing in the least-cost technology available (in this case, natural gas) to fulfil the requirement for the reserve margin constraints. Note that the variable renewable energy sources are not baseload energy providers and the development of other baseload technology options such as nuclear, hydro, and geothermal will require more significant investment. As shown in the power generation chart, natural gas capacity is only built to serve as and stand-by reserve margin, not as a day-to-day power provider. The 1.1 GW jump in the hydropower capacity in 2025 is due to the expectation that the proposed Site C dam project on Peace River will be coming online by then.

By introducing the carbon tax policy and restricting the model from investing in fossil fuel technologies after 2030 in the aggressive Scenario (AGG), the investment direction shifts from natural gas resources to nuclear, geothermal, and solar energy. The natural gas capacity shown between 2020 and 2034 is the current residual capacity expected to reach the end of its operational life span around 2034. However, the comparison between the power generation capacity and the power generation charts indicates that the model uses existing natural gas capacity as a stand-by option to cover a fraction of the required reserve margin. Except in 2024, a year before Site C comes online, the model uses the existing natural gas capacity to address the increase in power demand. Despite assuming a more aggressive electrification policy, which involves transitioning 100 % of natural gas in residential and commercial sectors, a 100 % shift to electric vehicles in the transition sector for non-heavy vehicles, and an increase of 3 Terawatt-hours in electricity demand due to the expansion of the LNG sector, the power system's capacity in 2050 shows a growth of only 1.5 times the current capacity.

The results from the Scenario of achieving net-zero emissions by 2050 through 100 % electrification (100-ELC) show a significant increase in the power system capacity required by that year. The expansion needed is about four times greater than the current capacity, as shown in Fig. 9. Our analysis also illustrated that the cost of electricity generation exhibits a twofold rise during the shift from the reference scenario to the aggressive scenario, and surges fourfold in the 100 % electrification scenario. The model suggests investing in untapped geothermal capacity, which is cheaper than nuclear power in the model, followed by the expansion of nuclear and natural gas generation technologies to meet the rising demand. However, despite a carbon tax rate of $175 after 2030, natural gas power technologies are still used, indicating that it is not a financially adequate incentive. Fig. 9 also shows that biomass production remains constant in all scenarios, regardless of electrification scale. This is because of the limited supply of carbonaceous materials like wood or agricultural crop residues available within BC for this particular energy sector. BC has legislated emission targets for 2030, 2040 and 2050 [10] of 40 % (≈40 million tonnes of CO_2), 60 % (≈25 million tonnes of CO_2), and 80–100 % (≈12–0 million tonnes of CO_2) below the 2007 levels (=64.76 million tonnes of CO_2), respectively. In Fig. 9, these emission reduction targets are annotated with red circles. In the 100-ELC Scenario, BC's climate targets are linearly interpolated between defined points (2030, 2040, and 2050) to achieve emission reduction targets, as shown in Fig. 10. However, it is important to note that the optimization analysis proved to be infeasible and unsuccessful. This outcome can be attributed to several factors within the model's framework, including the ambitious scale of electrification being considered, the distinct energy prerequisites such as those for high-temperature processes, the magnitude of the necessary transformations, and the rate at which these changes are likely to be accepted and implemented within BC's industrial sector. Given these parameters, BC is unlikely to achieve its targets within the specified timeframe spanning from 2030 to 2040, as illustrated in Fig. 9. However, it may still be possible to achieve net-zero by 2050 as illustrated in Fig. 9 if the industrial sector sharply reduces its greenhouse gas (GHG) emissions from energy consumption. This can be accomplished by enhancing energy efficiency, selectively electrifying processes, integrating solutions such as CCS and green hydrogen, and adopting circular economy practices.

Furthermore, as shown in Fig. 11, the REF and AGG scenarios, even with aggressive electrification, will not meet the legislated targets without significant changes within the industry sector, requiring a 50 % reduction in emissions by 2040 and another 50 % by 2050, as explored in the 100-ELC Scenario. Carbon pricing and cap-and-trade policies can trigger more profound actions and faster transitions within the industry sector.

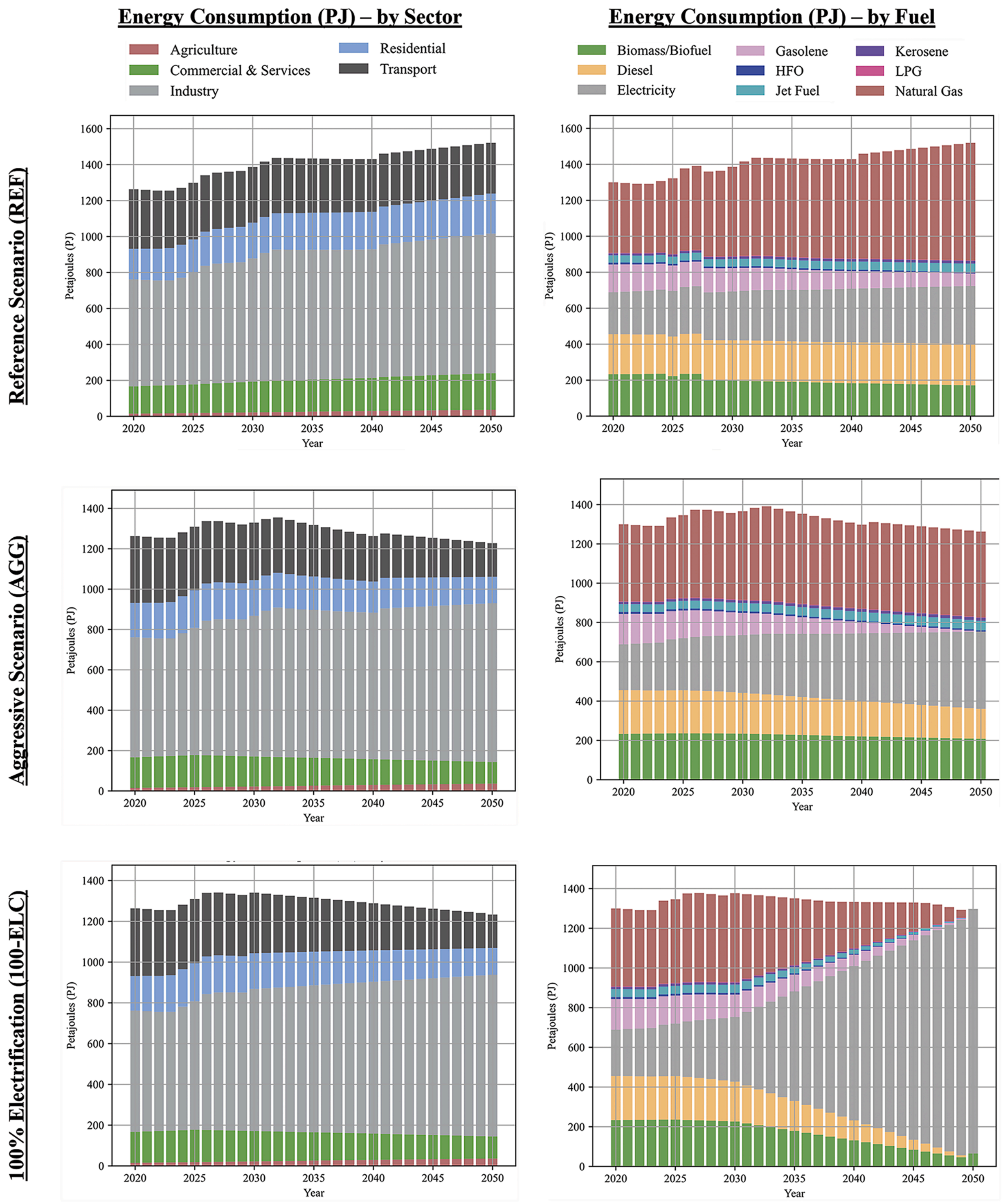

Fig. 7. Change in energy consumption based on various electrification pathways.4.2. Technology mix.

4.3. Impact of technology choice on the land-use

This section delves into a frequently overlooked implication of technology selection and the direction of electrification in British Columbia's land system. The focus of this paper centers on examining the ramifications of technology choices made to fulfil electricity demand within diverse electrification scenarios on the corresponding land occupancy requirements. Fig. 12 depicts the land-use sensitivity analysis (Ave. and Max based on the categories defined in Table 2) for the main electrification scenarios (REF, AGG, and 100-ELC as specified in Table 4) for the year 2050. As previously mentioned in Section 3.1, the technology pathways were chosen based on the least-cost optimization assessment without constraints on technology type. To provide perspective on the magnitude of land required for BC's energy transition, the area of land currently occupied by major cities in the province is included on the graph. As illustrated, except for the REF with an average land-use intensity scenario (650 km^2), the land needed to implement the energy transition pathways in all scenarios surpasses the combined area of six major cities in the province (about 750 km^2) by 2050. Given that the current built-up land area in BC, encompassing

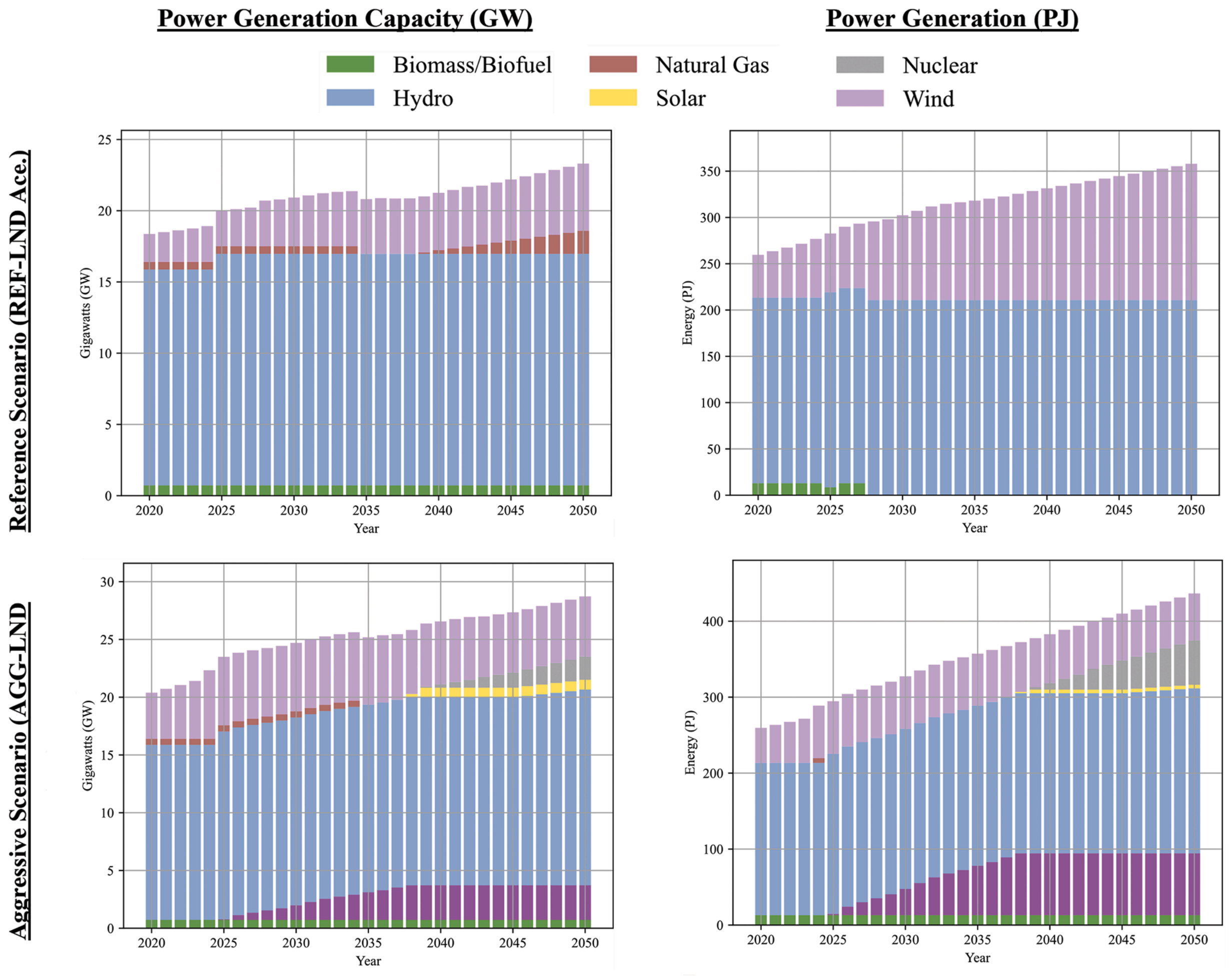

Fig. 8. power system technology mix to address the growing demand in the reference scenario (REF), aggressive (AGG), and net-zero (NET) pathways.

cities, roads, power plant facilities, mines, and agricultural land, is approximately 4000–6100 km^2 [53] as per GAEZ 2021 data, it is crucial to emphasize that the land-use impact of any of these scenarios is substantial, particularly concerning the 64 % of BC's land covered by forests.

Considering the popularity of the idea of 100 % renewable energy systems and negative publicity for certain technologies, such as nuclear and large hydropower projects in Canada, it is essential to examine the impact of technology exclusion and favouritism on land use when assessing the future of the energy system in a climate change era. First, the feasibility of the notion of 100 % electrification with 100 % wind and solar is explored and deemed unfeasible due to the lack of a baseload capacity to meet the reserve margin requirement. Bear in mind that the reserve margin used in this study is conservative (~13 %), with the actual reserve margin potentially reaching as high as 24 %. Next, the exclusion of technology based on social and political directions is also investigated. In the 100-ELC Scenario, as shown in Fig. 9, the technical solution to address the demand and achieve zero-emission in 2050 heavily relies on nuclear technology expansion in the province. The critical questions to consider are whether building 30 GW of nuclear power generation capacity for BC would be socially and politically acceptable and what the reasonable cap on nuclear power would be to make the model's results more realistic socially and politically.

In 2022, the Canadian government released a report (Towards Net-Zero: Electricity Scenarios [54]) outlining their investigation into achieving net-zero emissions by 2050. The report proposes that a maximum of 17 GW of nuclear power capacity be developed by 2050 for the entire country, representing approximately 5 % of the total capacity. To evaluate the impact of social and political technological exclusion on nuclear development, three scenarios were developed using BC Nexus Model: a 4 GW cap on nuclear capacity (5 % of the total capacity required in 2050 based on the 100-ELC Scenario), a 10 GW cap on nuclear (the middle ground between 4 GW and 30 GW), and no nuclear development allowed (100-ELC-NoNu).

Our study suggests that achieving net-zero emissions is not feasible in the case of a 4 GW cap on nuclear capacity, given our current assumptions and limitations in the model, as well as the 100-ELC-NoNu Scenario. In the 10 GW cap scenario, a power system twice the current size is required to meet the demand by 2050, with solar technology being the only available option. However, as depicted in Fig. 13, substituting nuclear power with solar power technologies significantly increases the land required for the power system (more than double in size). This raises concerns about where the extra 10-20 thousand square kilometres of land required to produce this magnitude of solar power will come from. According to the solar map of BC [55], areas with the highest solar photovoltaic (PV) generation potential are mainly located in the south and southeast of the province, where most agricultural lands are situated. This highlights potential conflicts between energy and food security, as well as the choice of technology mix in achieving BC's climate targets.

Additionally, the political reluctance to develop geothermal power projects in Canada is examined. Despite being situated on the ring of fire [56], there are no geothermal power plants in BC. In the recent net-zero blueprint report (Towards Net-Zero: Electricity Scenarios [54]) published by the government, geothermal power technology is not included. Given the limited untapped baseload technology available in BC,

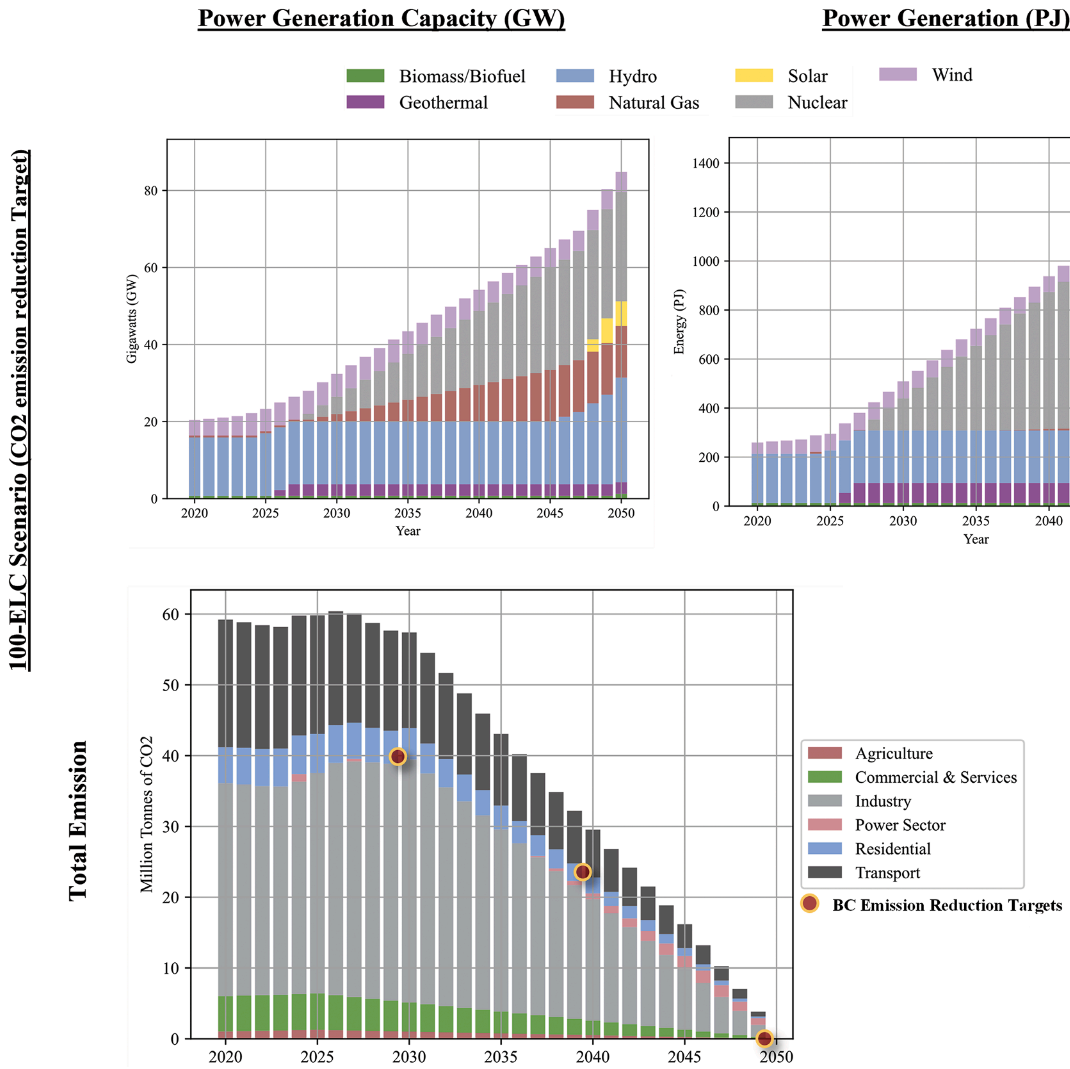

Fig. 9. Technology pathway to net-zero (100-ELCScenario) with limitation on using natural gas after 2030- the figure shows the power generation capacity (GW) results.

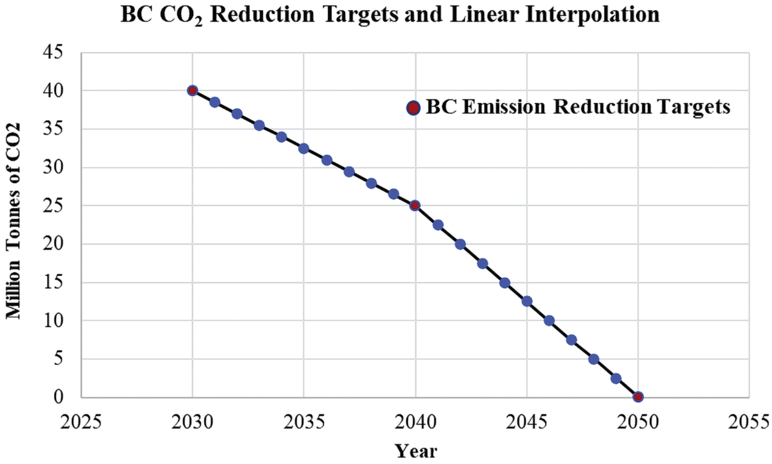

Fig. 10. BC climate targets for 2030, 2040, and 2050. The data for missing years are linearly interpolated between these targets.

excluding such a reliable energy source with low land-use intensity may exacerbate the conflict between energy, food, and ecosystem security. As shown in Fig. 14, excluding geothermal power technologies only slightly affects the total capacity required to meet the demand. However, as geothermal technology is replaced with hydropower and solar technologies, the impact on land-use becomes more noticeable.

Fig. 15 provides valuable insights into the share of each technology in generating power to meet the electricity demand in 2050 for different

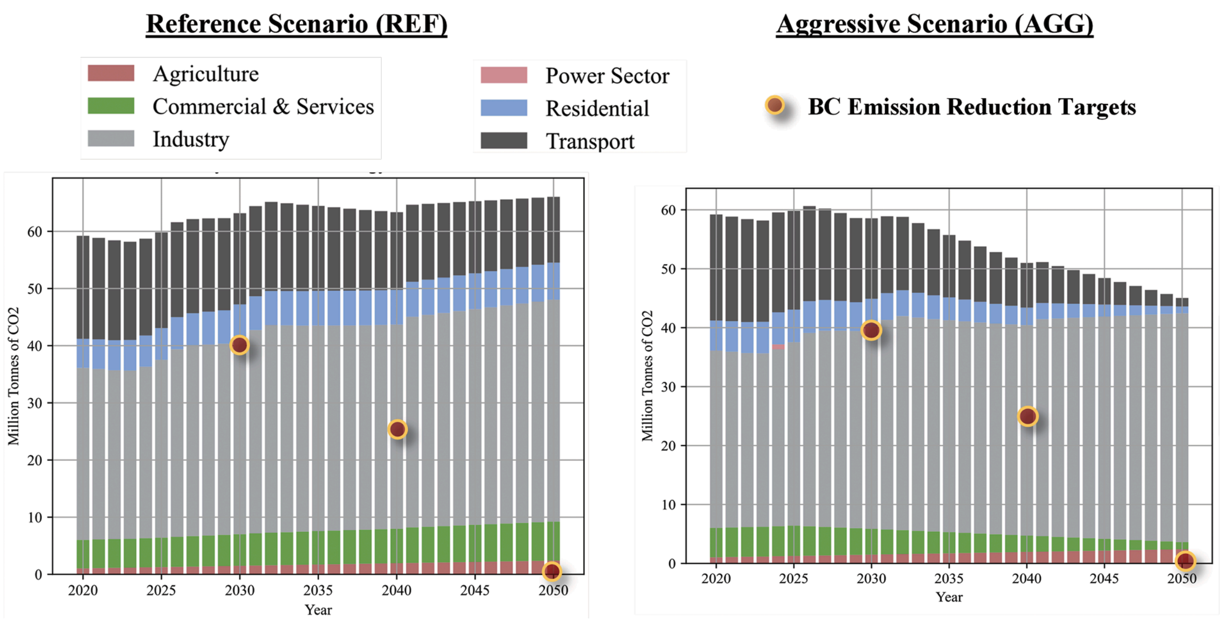

Fig. 11. CO_2 emission reduction in the Reference, Aggressive, and Net-zero scenarios. Red circles indicate the provincial emission reduction targets in 2030 and 2040.

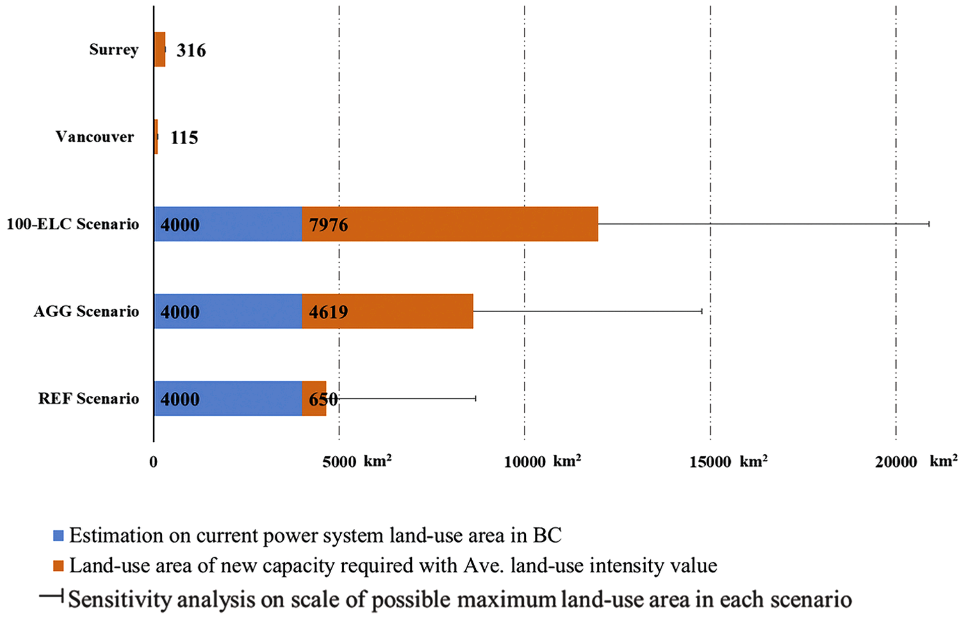

Fig. 12. Land-use sensitivity analysis based on various electrification rates in 2050. Each colour represents a different land-use intensity level based on the categories defined in Table 2. The sub-categories of REF, AGG, and 100-ELC represent policy scenarios (electrification scale) specified in Table 4. The scale of land-use impact is compared with the total area of major cities in the province.

scenarios, as well as the share of each technology in occupying the land required to implement these scenarios. In the second row of the figure, land-use requirements are compared across different electrification scenarios, with the "100-ELC-10 GW Cap on Nuclear" scenario serving as the baseline due to its largest land requirement. The figure showcases the effect of technology choice on land-use requirements across different scenarios. The results in the first row demonstrate that as electricity demand increases, the significance of nuclear technology as a baseload energy source amplifies. As shown, while biomass has a relatively small share in the technology mix, it is a major contributor to the amount of land required to electrify BC's energy system in all scenarios, along with hydropower. In the Reference (REF) scenario, hydroelectricity is responsible for almost all of the land-use required. This includes both current hydroelectricity and the Site C dam, which is expected to be online by 2025. It is important to note that in the amount of land-use illustrated for the REF scenario, Site C accounts for only 1/16th of the total land-use. On the other hand, the results of the AGG scenario show that biomass leaves a significant footprint on land with similar power production, which may not be an efficient use of land resources in the long term. In contrast, in 100-ELC scenarios, nuclear technology plays a significant role in the technology mix for power generation while requiring an insignificant amount of land use.

In the context of the energy transition, paying attention to the land required by energy technologies is crucial as it has the potential to

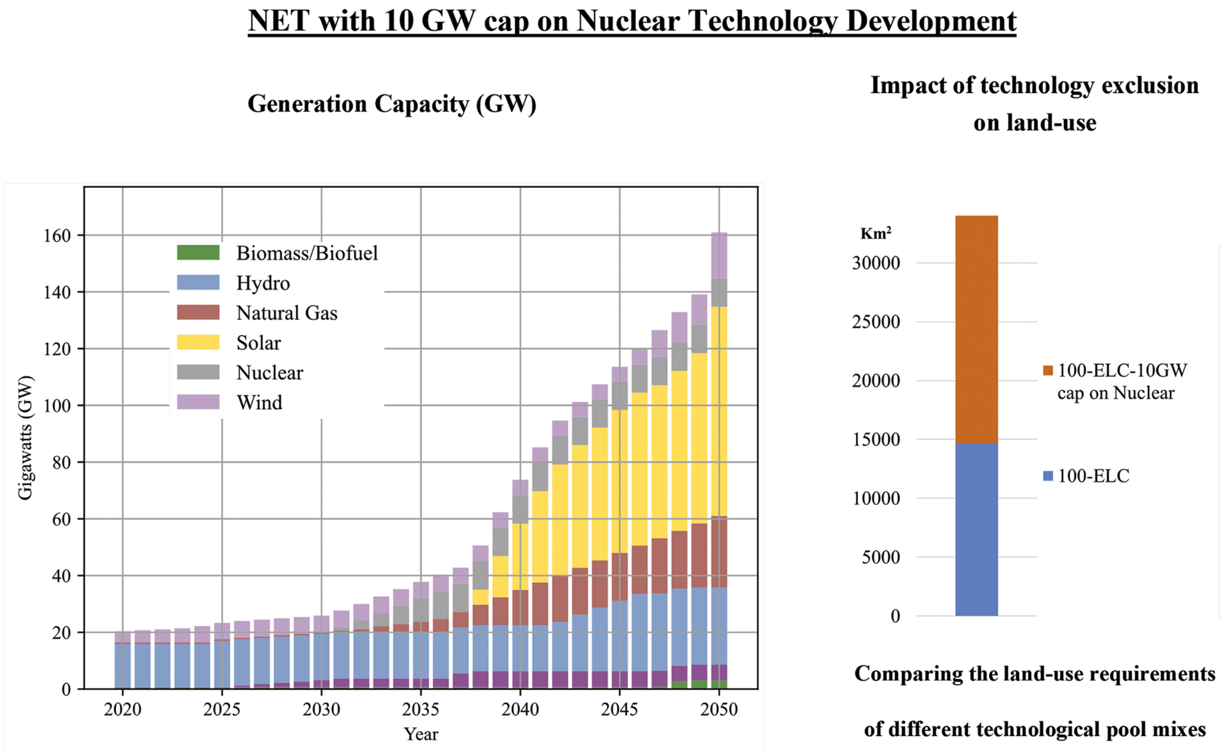

Fig. 13. Power generation capacity (GW) and its associated land-use impact in the 100-ELC Scenario with a 10 GW of cap on nuclear power development.

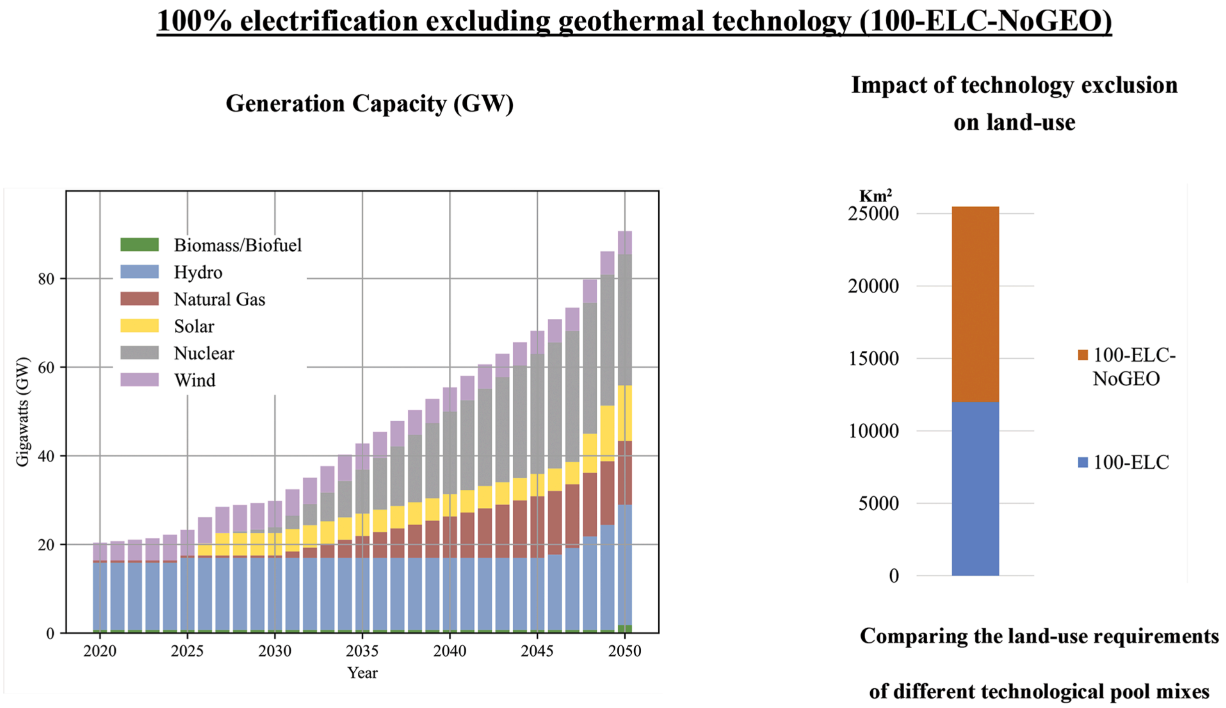

Fig. 14. Power generation capacity (GW) and its associated land-use impact in the 100-ELC-NoGEO Scenario.

impact food and water security, which are already under threat from climate change. While transitioning to a more sustainable energy system is essential to mitigate climate change, the interaction between the energy system and food and water security must also be considered. It's particularly important given that energy sources like biomass may compete with agriculture for land use and can also have significant impacts on the health of forests and ecosystems, which provide important services such as clean air and water, carbon storage, and biodiversity conservation. For instance, as demonstrated in Fig. 15, by simply excluding the biomass option from the power technology mix, the required land for the '100-ELC with 10 GW cap on Nuclear' Scenario drops by approximately 50 % (two last scenarios). These research findings can provide better insight for policymakers and stakeholders in making informed decisions about excluding or promoting technology

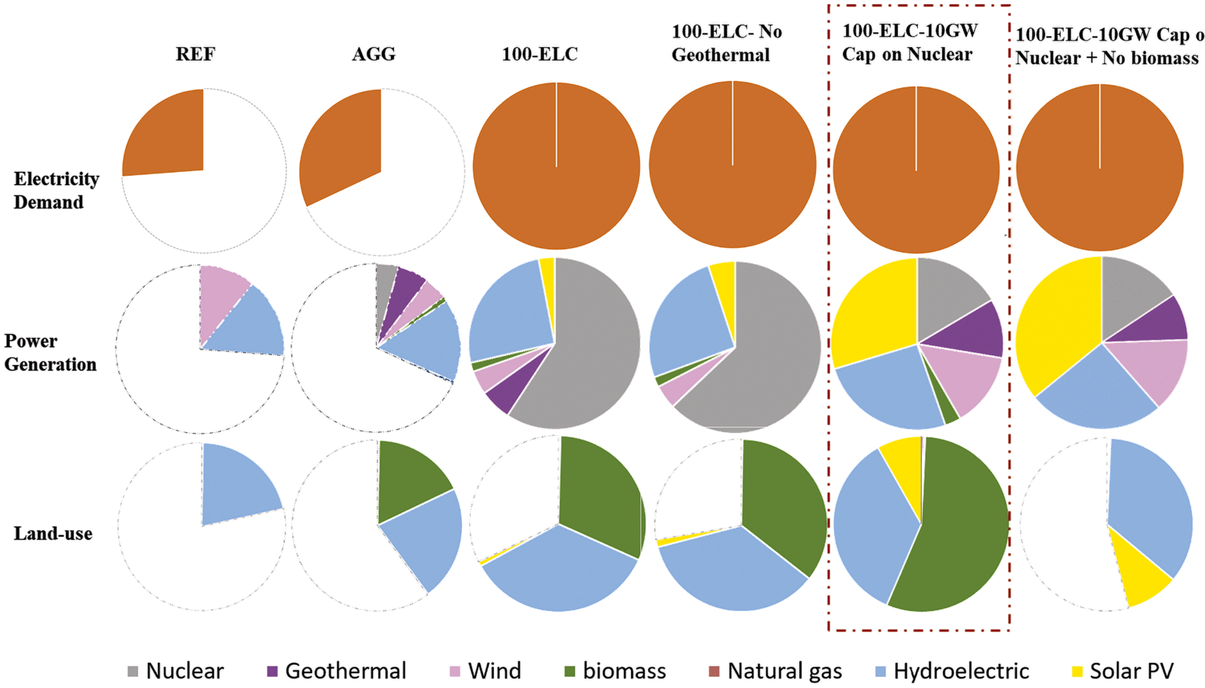

Fig. 15. Comparison of electricity demand, power generation and land-use in 2050. The size of the circles represents the maximum power generation or the largest land-use (100-ELC-10GW Cap on Nuclear).

options for BC's future power system.

5. Conclusions

This paper presents the development of the BC Nexus capacity expansion model, emphasizing the lesser-explored implications of the transition to a high penetration of renewable energy sources on land use in BC, Canada. It underscores the importance of adopting a nexus approach to inform effective policy decisions. Three scenarios have been developed, ranging from a business-as-usual scenario with low electrification pathway, to a scenario aiming for 100 % electrification of the energy system in BC by 2050. These scenarios illustrate the model's capability to inform decision-making processes related to climate change mitigation, especially in situations where economic considerations, technology choices, and land use impacts intersect with societal constraints.

The findings emphasize the scale of land required to transform the energy system away from fossil fuels and toward renewable and clean energy sources in BC. The transition may increase the occupied land of the power system up to six times larger than the current total built-up land. This highlights the magnitude of land-use trade-offs that will be required to transform BC's energy system. Even though a wide range of direct and indirect environmental trade-offs, such as biodiversity and ecosystem services, were excluded, the findings remain conservative regarding the land impacts of the energy transition.

The utilization of this model highlights the formidable choices that must be made to attain net-zero emissions by 2050 in British Columbia. These choices primarily revolve around scale, cost, and land usage. Firstly, the scale of absolute capacity expansion, which aims to increase the electrical system from 20 GW to 80 GW, is projected to be three to four times the size of the current electricity system. To put this in perspective, the capacity of the controversial Site C project is nominally a 1 GW device, indicating the need for 60–80 of these generators. Achieving this scale in the limited timeline demands immediate and sustained capital investment if the net-zero target by 2050 is to be met.

One of the pivotal considerations in the context of energy transition, particularly on a substantial scale, is the escalating cost of electricity generation and its impacts on consumers. Our analysis underlines a significant trend, revealing that the cost of electricity generation experiences a twofold increase when transitioning from the reference scenario to the aggressive scenario and a fourfold surge in the 100 % electrification scenario. Consequently, thoughtful decision-making in terms of specific technology choices carries substantial implications for cost dynamics. For instance, imposing a limitation on the development of nuclear power capacity to 10 GW translates to a fivefold spike in electricity costs between the reference and 100 % electrification scenarios. Furthermore, technology choices such hydro and biofuel cause extensive expansion of land use which causes significant biodiversity loss and contrasts dramatically with the insignificant impact of nuclear and geothermal technologies upon land use.

Finally, the limited wind, solar, geothermal, and bio-fuel resources in the province constrain technology choices, pushing for the consideration of expanding of either hydro, geothermal or nuclear. Counter intuitively, system costs can be reduced if rarely utilized gas turbine generators are considered for ensuring reserve margin is available for rare but probable renewable outage occurrences. A fast track to net zero + 1 by 2050 might be a very cost effective rapidly deployed solution. This model allows consideration of these options for policy development.

This work showcases the power of decision-assisted nexus energy modelling in revealing tough trade-offs. It suggests that all technologies, including nuclear, undergo evidence-based evaluation, facilitated by this tool. This tool also assists in revealing the weaknesses and costs of the everything all at once everywhere solution which is aspirational and popular but replete in potential harm with high-cost poor utility choices.

6. Limitations and future works

This study contributes to the existing body of literature by exploring the often-overlooked consequences of decarbonization and electrification policies, specifically their substantial impact on regional land-use dynamics. To our knowledge, this is the first comprehensive study of its kind conducted for British Columbia. Our primary objective is to highlight the scale of the transformations required and the associated challenges, aiming to capture the attention of both the public and policymakers. Moreover, the critical need for integrating a nexus approach into energy modelling and decarbonization policies is stressed to effectively address the intricate complexities of this transition. However, the current version of the model used in this paper has some limitations that will be addressed in future work. These include gaps in representing energy storage technologies, inter-regional interconnections, energy trading with neighbouring regions, and grid reliability. To address these gaps, the BC Nexus model will be expanded to include storage and interconnection capabilities and will be coupled with a power systems model to evaluate the operational feasibility of suggested long-term pathways. Additionally, future enhancements to the model should also incorporate a more comprehensive representation of renewable energy sources' contribution to grid stability in a high-penetration renewable energy system. Currently, the model primarily relies on base-load technologies to provide the required reserve margin, and further research is needed to accurately capture the dynamic nature of grid stability with a significant share of renewable energies. Another gap in the model is that it calculates land use based on production units, not installed capacity.

Another area for future research is the role of forest carbon uptake in energy modelling. Forests play a critical role in mitigating climate change and adapting to its impacts. Recent wildfire events in British Columbia and elsewhere have had devastating consequences, with the 2017 and 2018 wildfires in BC alone responsible for emitting three times more CO_2 than all sectors combined [57]. Future research should explore the potential for forests to contribute to carbon capture and storage, with the aim of informing effective climate change policy development and nexus modelling projects.

In addition, this study focused solely on the impact of the energy transition on land use. Future research should expand on this by investigating a broader range of land-use impacts, including the effects of the energy transition on biodiversity, land quality, and other direct and indirect impacts on ecosystem services.

It is worth noting that once the BC Nexus model is fully developed, it will be freely available on GitHub, along with all applied data and calculations.

List of recommended reviewers

1. Dr. Manuel Welsch, International Atomic Energy Agency
2. Dr. Nilay Shah, Imperial College London
3. Dr. Falko Ueckerdt, Potsdam Institute for Climate Impact Research

CRediT authorship contribution statement

N. Arianpoo: Data curation, Investigation, Methodology, Software, Validation, Writing – original draft, Writing – review & editing. **M.E. Islam:** Visualization, Writing – review & editing. **A.S. Wright:** Conceptualization, Funding acquisition, Investigation, Project administration, Supervision, Writing – review & editing. **T. Niet:** Conceptualization, Funding acquisition, Investigation, Project administration.

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.

Data availability

Data and model used in the research, along with user guide, assumptions, input data, and references, will be available on the model's GitHub page after paper publication.

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Appendix A. Energy System- Modelling Structure and Assumptions

Data within the energy system was divided into the power system portfolio and the demands for other types of fuels (imported and exported energy sources) within the province. The BC Nexus model includes a comprehensive representation of the energy system portfolio in British Columbia, which includes about 150 active power projects. These projects are mainly IPP (Independent Power Producer) projects, with the majority being small-scale to medium run-of-river stations that were later aggregated into one larger unit within the model to simplify the model structure. The hydropower projects were carefully investigated and analysed, and the five largest generators were represented individually within the power system due to their significant effect on the system. Eight regions have been defined: Peace River region, Northern BC region, Prince Rupert and Graham Island region, Prince George and Jasper region, Vancouver Island region, Lower Mainland and Pemberton region, and Kamloops and Southeast BC region. The remaining hydro projects were merged within these areas to represent 12 larger generation units in the model based on region, size, capacity factor, and generation technology. Unfortunately, not all data (actual capacity, life span, etc.) was available for every project, and the missing values were replaced using reasonable assumptions based on similar projects.

Similar processes were applied to natural gas and bioenergy power stations. However, for variable renewable power projects like wind and solar, all projects were represented individually within the model due to their sensitivity to location and varying capacity factors. Table A.1 provides a summary of the data used to shape the energy system portfolio of BC in the model.

Table A.1
Main data used to calibrate the energy system for BC.

Power System	Collected data	Data analysis and assumptions
Components (power stations)	Location, capacity, nominal annual generation, actual annual generation, operational life span	Capacity factor, Efficiency, and Residual capacity of the energy system
Cost	Capital, fixed, and variable costs. Generic technology cost info [58]	Due to the lack of information, generic cost data assigned for each technology
Demand	Hourly production loads from BC hydro and potential hourly load for wind and solar projects at each specific site location [59]	Availability factors Time slices (daily) and year split (seasonal) Specified annual demand for each time slice. Specified demand portfolio within each time slice The specified power demand for each sector (residential, commercial, industrial, transportation)
Other information	Transmission loss (10%) [60] Reserve margin (~13%) [50,61]	Reference data was allocated
Rest of the energy system		
Non-electrical fuels	Accumulated annual end-use fuel demand [62] Domestic fuel productions Import/export fuel supplies	For non-electrical fuels that can be stored, the demand is projected on an annual basis rather than for each time slice
Cost	Fuel cost and annual forecast to 2050	The assumption has been made to project the fuel cost to 2050
Linkages data: energy on land and water systems	Energy demand in agriculture (e.g., diesel used to run agricultural machinery) and water systems (e.g., water pumping, water treatment facilities, etc.)	

Temporal Representation and Demand for the Power System

In the BC Nexus model, temporal representation is a user-defined option and can be changed based on enquiry. This is especially important in the case of variable renewable power sources such as solar and wind, where the production at different times of the year and site locations are diverse. To represent the energy demand and supply, temporal resolution defines by two elements of "time slices" and "seasons" in the model. The demand and supply for other systems, e.g., agriculture and water, are on an annual basis. For the version of the model reported in this paper, temporal resolutions are simplified to the four seasons per year (Spring, Summer, Fall and Winter) and two day-splits of day and night to reduce computational complexity. Table A.2 outlines the temporal data structure used.

Table A.2
Temporal data structure of the BC. Nexus Model.

	Spring (Mar 20-Jun19)		Summer (Jun 20-Sep 21)		Fall (Sep 22-Dec 20)		Winter (Dec 21-Mar19)	
	Day	Night	Day	Night	Day	Night	Day	Night
Seasonal days	93.00		93.00		90.00		89.00	
Ave. Seasonal hrs.	13.90	10.10	15.36	8.64	10.00	14.00	8.75	15.25
Year split	0.15	0.11	0.16	0.09	0.10	0.14	0.09	0.15
Daylight time (start, end)	6	20	6	21	8	18	8	17

Based on the hourly electrical load of BC in 2019 and 2018, the demand profile corresponding to the temporal structure of Table A.2 is shown in Table A.3. This represents the annual fraction of the total power demand required for each time slice.

Table A3
Electrical Demand Profile of BC.

	Spring		Summer		Fall		Winter	
	Day	Night	Day	Night	Day	Night	Day	Night
Daylight time (start, end)	6	20	6	21	8	18	8	17
Specified Demand (%)	0.15	0.08	0.16	0.07	0.12	0.13	0.13	0.16

BC's Renewable Energy Potential

While BC has the potential to develop most renewable energy technologies, the literature on the technical and commercial potential of these energy sources is limited. The University of Alberta's report [63], which summarizes the reported data on the geographic potential of renewable energy sources in BC, is used as a reference in this version of the model (Table A.4). However, it should be noted that this is a conservative estimate, and actual technical potentials may be higher with technological advancements in the future. It is worth noting that some renewable energy technologies, such as geothermal and ocean energy sources, have not yet been commercially developed in BC. Therefore, there is limited information available on their potential capacity. Further investigation and development of these technologies may provide significant opportunities for the province to diversify its energy mix and reduce greenhouse gas emissions. Detailed information on the assumptions and data used in the model can be found on our GitHub page, including comprehensive documentation, codes, and structures.

Table A4
Untapped potential of renewable energy sources in BC ([68]).

	Total capacity (MW.)		Currently, economically feasible (MW.)	The value used in the model
	Min	Max		
Solar	–	–	–	- No information has been provided - No constrain are set for this energy source in the model
Wind	–	16,425	5250	Three sets of wind power generation technologies - varying capital costs & untapped potential capacities - were defined within the model as: 1. One is defined with the max capacity cap of the current economically feasible value (5250 MW) and the current levelized cost of the technology. 2. Another set with an untapped potential capacity of 5500 MW and twice the capital cost of the 1st set 3. Another set with an untapped potential capacity of 5500 MW and three times of capital cost from the 1st set
Geothermal	133	5700	400	- 18 economically ’favourable’ sites have been identified with a total capacity of 400 MW- Three set of geothermal power generation technologies - varying capital costs & untapped potential capacities - was defined within the model: 1. One is defined with the max capacity cap of the current economically feasible (400 MW) and the current levelized cost of the technology. 2. Another set with an untapped potential capacity of 2600 MW and twice the capital cost of the 1st set 3. Another set with an untapped potential capacity of 2600 MW and three times of capital cost from the 1st set
Biomass	–	2300	–	- Considering the future technological advancements, max potential capacity has been considered as the technological limit of this energy source
Hydropower (run-of-river)	–	12,000	–	- As in the model, the BC hydropower merged into 12 large units, and there is no discussion in the near future to add more large dams in the area besides Site C; we used the 12GW limit defined for untapped run-of-river projects as the future potential of the hydro energy source in the model
Hydropower (dams)	–	–	–	

Appendix B. Land System- Modelling Structure and Assumptions

The BC Nexus Model’s land-use representation was built based on two main categories of data: the availability and allocation of land and the current utilization of land to fulfil food and energy demands. Table B.1 summarizes the primary data collected for the land portfolio of BC:

Table B1
Main data used to calibrate the land system for the BC Nexus Model.

	Collected data	Data analysis and assumptions
Type of land available in BC.	- Sizes of agriculture, forests, barren, water body, and built-up lands in BC.	
Agriculture	- Type of crops in BC per hectares - Annual demand for primary crops growth in BC. - Clustered data for crop yield (t/ha) ○ crop-specific agro-climatic assessment ○ soil/terrain limitations ○ Water use (rain-fed vs irrigated) ○ Agricultural intensity (low, intermediate, high input level)	- Future growth in land use for built-up and agricultural land based on population growth and historical trends. - Choosing ten crops that cover more than 90% of agricultural lands for clustering and analysis of future growth. - Most of the data was collected using the GAEZ model (Global Agro-Ecological Zoning) [53]
Linkage’s data: Land-use on energy and water systems	- Land needed for biofuel production. - The land-use intensity of the power generation technologies - A unit of water is required to grow a unit of each main crop type in BC	- A sensitivity analysis scenario was conducted to explore the impact of power technology choices on land transformation

Clustering approach is used to define the current and future potential of BC’s agricultural system. The GAEZ model (Global Agro-Ecological Zoning) [53] is a tool used in the BC Nexus Model to cluster and collect crop suitability for BC, which helps to reduce computational complexity. This clustering approach groups together areas of land with similar properties based on general agro-climatic indicators, crop-specific agro-climatic indicators, and water-limited plus soil/terrain limitations [64]. The agglomerative hierarchical clustering method is used by the GAEZ model to cluster cells with similar irrigation need and achievable yield potential. The number of clusters in the GAEZ model is determined by the user. To aid in this determination, GAEZ provides an elbow graph for the study area. The elbow graph depicts the decrease in total "error" in clusters as the number of clusters increases. This means that the user should select a number of clusters (elbow point) such that adding another cluster does not significantly improve the modelling outcome.

Fig. B.1 shows the clustered regions used in the model for BC. Based on the elbow graph of the clustering algorithm shown on the left top side of the figure, seven cluster zones is chosen to divide BC crop attainable yield clusters. The map of BC on the left bottom of the figure shows the distribution and size of each cluster. In this map, areas with similar colours indicate similar possible crop yields due to similar irrigation. To represent BC’s agriculture production, the study considered nine main crops that accounted for 90% of the province’s agricultural output, including alfalfa, barley, maize, oat, pea, potato, rapeseed, rye, and wheat. Other crops were lumped together under the ’other’ category to represent the province’s full agricultural output.

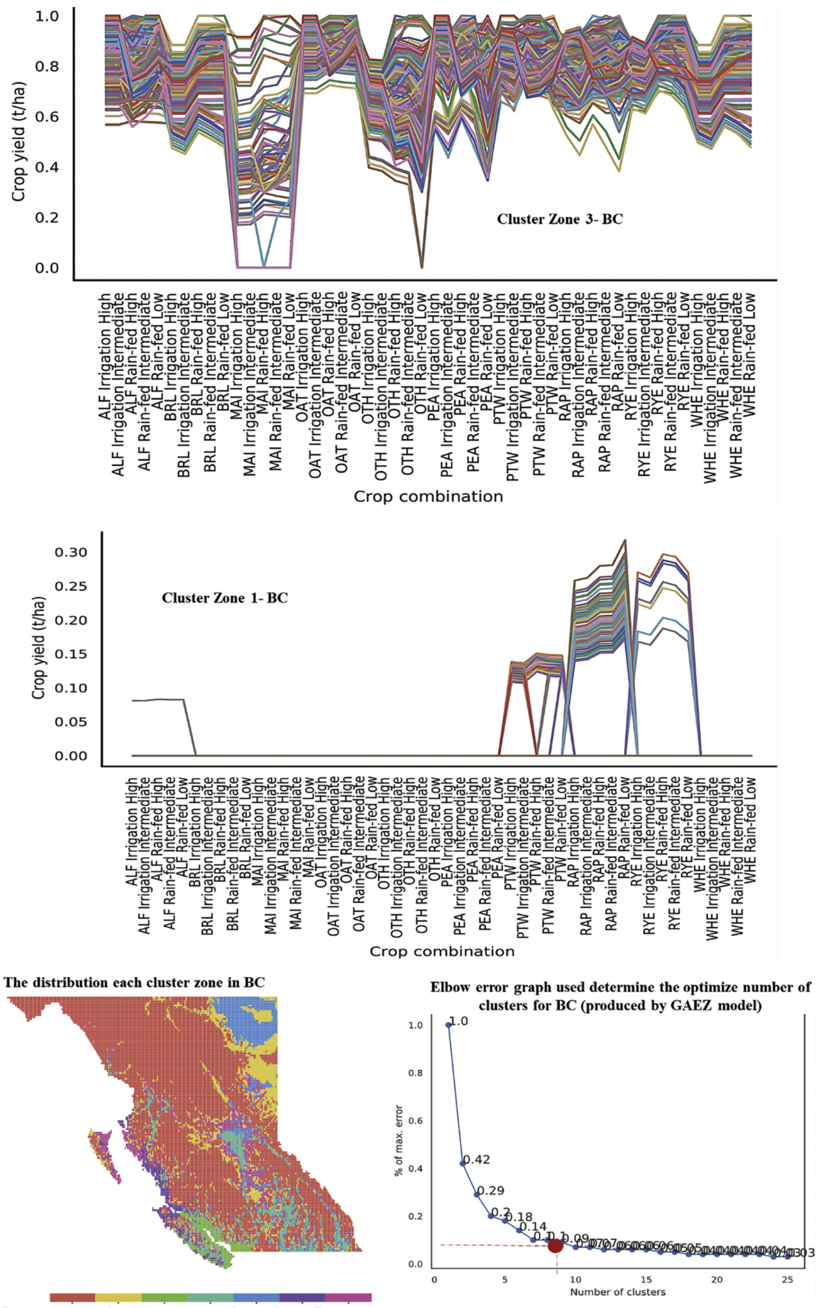

Fig. B.1. BC clustered based on similar irrigation and intensity combinations.

The two graphs on the right side of Fig. B.1 compares crop suitability for cluster zones 1 and 3, with each differently coloured line representing a land unit in BC. The vertical axis displays a combination of a crop type, water use (either rain-fed or irrigated), and the crop's yield intensity level (high, intermediate, or low). The horizontal axis represents crop yield in tonnes per hectare. As shown, cluster zone 1, which mainly covers BC's mountainous regions, exhibits zero to low yield potential for most crops, while cluster zone 3 represents a much more fertile area of BC.

Data accessibility was a significant challenge in modelling BC's agriculture sector, particularly in estimating future growth and water demand for irrigation based on crop types. The study relied on historical data to project production growth for each crop, but as shown in Fig. B2, understanding the growth trajectory was difficult due to the scale of data fluctuation. To address this issue, the study linearly extrapolated the production rate from 5 to 10 years prior to the modelling period, predicting slow growth for most crops. This method aligns with the low estimated population growth rate of 1.1% in BC and produces satisfactory results.

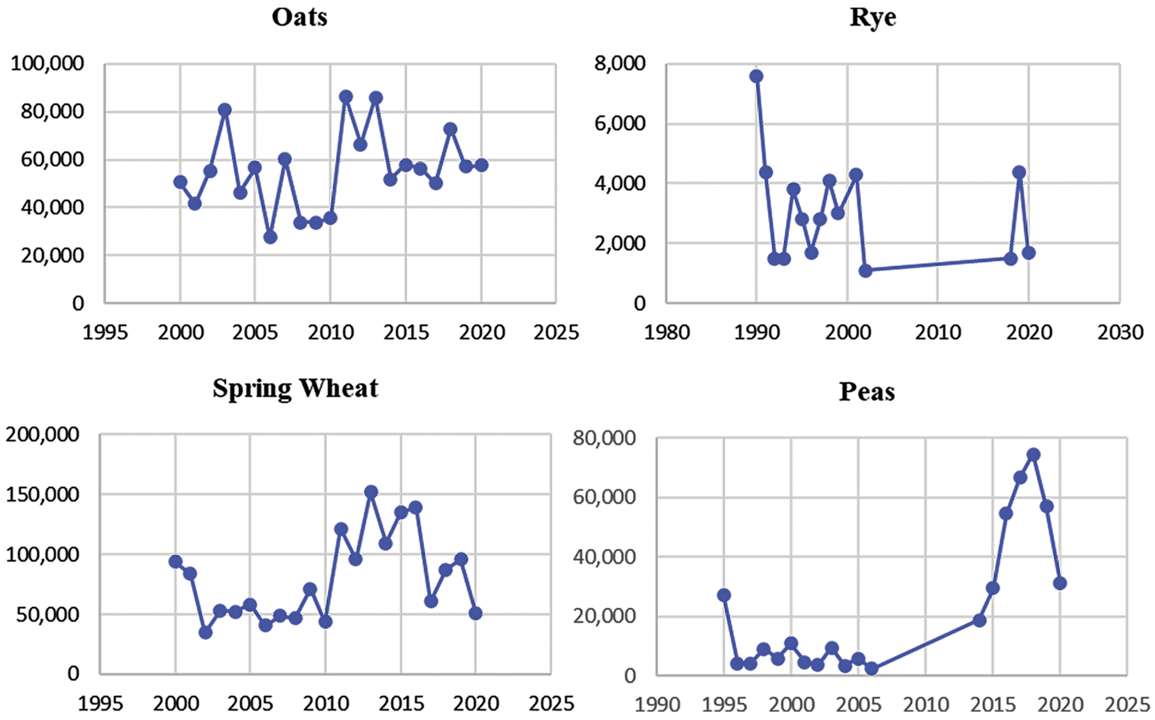

Fig. B2. Historical production data for selected BC crops [65].

Appendix C. Water and Climate Systems- Modelling Structure and Assumptions

In the current version of the model, water and climate data are only tracked. As a result, the model is limited to just monitoring water use in British Columbia, and changes in demand for water in various sectors such as the power sector, public sector, and agriculture, depending on the crop type and yield. This allows for assessing the impacts of various policies on water resources, but the interaction is only one-way. Regarding the climate system, the model tracks the amount of CO_2 emissions generated by each activity within and between the water, food, and energy systems.

The role of BC Forests as CCS Technology in the model

One of the crucial elements in the model is representing the climate mitigation role that BC forests play by capturing and storing carbon dioxide. Forests are treated as a carbon capture and storage technology (CCS) in the model, and their reforestation and deforestation considerations are included in its cost optimization analysis by assigning a negative value of variable cost to forest lands. However, ongoing debates exist around the true climate mitigation value of Canadian/BC forests in absorbing CO_2 from the atmosphere compared to the amount they emit.

Appreciation for the magnitude of the Total Ecosystem Carbon sequestration of old growth forests can be understood when the afforestation of fallow or bare land is considered. The range of carbon sequestration of new and young forests varies dramatically but the youngest and most productive stands only reach a total of 800 tonnes/ha of total storage over a 150-year growth window, the poor performing forests only reach 200 tonnes/ha in this time frame [66]. Afforestation Total Ecosystem carbon storage could optimistically reach 150/200 tonnes per hectare over the first 50-year growth period from seedlings to forest. When compared to additional sequestration rates of in excess of 200 tonnes/ha per annum for old growth established forests their value is manifest. Thus, the use of old growth biomass for wood pellets can not be regarded as a net-zero option in any meaningful time frame as sequestration rates are measured in centuries compared with yearly consumption burn rates. Thus, old growth should be regarded as a critical resource for carbon capture and afforestation is an important but significantly less productive secondary sequestration option.

For the purpose of this paper, even though the data is rather uncertain, reasonable values of BC's forest in absorbing and storing CO_2 is estimated. According to the Government of BC [67], approximately two-thirds of the province (roughly 600 thousand km^2) is covered by forest, of which an estimated 43% are old-growth trees. The Sierra Club reported in 2019 [68] that BC's old-growth forests store over 100,000 tonnes of carbon per square kilometre and absorb an additional 200 tonnes per square kilometre each year. BC forest was estimated to observe about 20–28 million tonnes of CO_2 from the atmosphere in 2016 [68]. Considering the set provincial carbon tax value ($50–170 from 2020 to 2050), forests can provide the CCS services with an approximate value of 1000–5000 million dollars per year in addition to what is already sequestered. However, the amount of carbon emission from BC's forests is increasing due to human activities and climate change. Wildfire emissions have also dramatically increased by about 650% in recent years, and BC's forests were estimated in 2017 to emit about 203 million tonnes of CO_2, with 42 million tonnes from logging and 117 million tonnes from wildfire [68].

For the results presented in this paper, the annual value of BC's forest CCS service is estimated using data from the 2019 Sierra Club report [68], as shown in Table C.1. The impact of recent wildfires is excluded from the calculation, as is the value of the carbon already stored in the forest. However, further research is required to better represent the true value of the CCS service provided by BC forests, both old-growth and new forests, within the model.

Table C1
Value of BC's new growth forest CCS service in $million per unit of land (1000 km^2) based on the provincial carbon tax rate between 2020 and 2050.

Year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030–2050
carbon tax rate ($)	45	45	50	65	80	95	110	125	140	155	170
Value ($Million dollars) of BC's annual forest CCS service per each 1000 km^2 of land	2	2	2	3	4	4	5	6	7	7	8

Appendix D. Supplementary Information

CASE STUDY: ESTIMATED LAND AREAS AFFECTED BY SITE C DAM PROJECT IN BRITISH COLUMBIA, CANADA

Table D1
Estimated land and watercourse areas affected by Site C and associated development (reported in 1980 [47]).

Estimated land and watercourse areas affected by Site C and associated development (reported in 1980 [27])	km^2
1. Areas flooded by the reservoir to flood safe line (FSL)	
total reservoir	94.4
total watercourse	48.4
total land	46
woodland	35.44
uncultivated forage and grassland	4.24
cultivated farmland	4.6
unproductive rock, banks	0.8
recreation reserves	0.32
developed farmstead and residential sites	0.6
wildlife reserve	20
2. area between reservoir FSL and residential safe-line on low banks	8.4
3. predicted the extent of actual sliding and erosion	2
4. area temporarily or permanently affected at the dam site	2.8
5. highway and access roads	1.42
6. transmission line	9.6
The total affected area (km^2)	**279.02**

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