BC Nexus Model

Impacts of electrification on land and water resources through 2050

NASTARAN ARIANPOO, FELIPE P. SINGH, ANDREW S. WRIGHT, TACO NIET

ΔE+ Research Group

Simon Fraser University

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SFU SIMON FRASER UNIVERSITY

ABSTRACT

This report presents the progress and current results in the development of an open-source model referred to as BC Nexus. The BC Nexus model has been developed to provide decision-makers in British Columbia (BC) with insight into the synergies and trade-offs of climate policies and their impact on land, energy and water resources. A growing number of countries are passing ambitious climate policies, especially within the energy sector. As yet, few studies have accounted for the impact that a single sector's decisions may impose on others. The nexus approach applied in this model provides insight to how integrated supply and demand issues are related to energy, land and water resources in a changing climate. BC energy, land and water systems are used to calibrate the model as a case study. The outcome of this project is an in-depth investigation of decarbonization policy options for BC, with the aim of providing clarity into the associated impacts on water and land resources and on CO_2 emissions reduction. Additionally, the project sheds light on the technology mix and costs required to apply those policies successfully.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

Climate change is the most critical challenge of our times: temperatures are rising around the world; natural disasters occur more frequently, and natural resources are scarce. Global demands for water, food and energy are predicted to increase by about 50% by 2050 due to the impacts of climate change, urbanization, and population growth [1]. To combat climate change, the decarbonization of the energy system needs to be accelerated. A growing number of governments, jurisdictions and municipalities are passing ambitious energy decarbonization policies. However, few studies have accounted for the impact of these energy transition policies on water resources as well as natural and agricultural lands, and how the changes in these sectors may impact the cost and effectiveness of these energy policies overtime [2].

This report outlines the development and initial results of the BC Nexus modelling project. The project centres around development of a nexus of water, food, energy, and a climate model calibrated with BC specification. The model will enable exploration of the impacts of various BC decarbonization policies on security of these interdependent systems. This report presents the model design and structure as well as the results of the BC policy scenarios investigated with the model. The objective of the scenarios is to evaluate the trade-offs and synergies associated with the selected BC decarbonization policies within the energy sector on water resources and natural and agricultural lands. The model was developed using the CLEWS (Climate, Land, Energy, Water Systems) modelling platform [3]. Input data collected to represent the current BC status quo includes the electricity generation portfolio (technology mix, energy supply and demand, etc.), water provision (availability, constraints), land use (types of land, agriculture, crop yields, etc.), and CO_2 emissions ratio for every activity within each of the WEF systems. The model also represents energy technologies that are missing from the current BC energy system (e.g., geothermal and nuclear power technologies) to allow optimization for the most efficacious technology selections that enable BC's energy transition. The model runs a cost optimization assessment for each decarbonization policy to choose the least-cost pathway and most reliable energy technology mix to apply those policies successfully while still meeting demand and policy constraints. The model identifies the points at which each sector interacts with the others, such as the land requirement with energy, food with water infrastructure, or the water requirements with the agriculture and energy systems.

BACKGROUND

The term "nexus", used here to describe the model, refers to the interactions among interdependent components [1]. The application of this concept within resource management is not new. The term "nexus" was applied to the concept of resource management 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 (WEF nexus) [1]. The concept is most commonly applied to required compromise in achieving resource security [4]. "Nexus" structure indicates how the changes in the availability or functionality of one component can impose pressure on security of other interdependent components within the nexus. The recognition of the interdependency between water, energy, land (food) (WEF) resources has gained momentum in both policy and research communities to change the approaches toward managing these resources. Several models and frameworks (e.g. [2], [5], [6]), including the Climate, Land, Energy, Water Systems (CLEWS) modelling framework 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 [7]. In recent years, several energy models have partially incorporated water, land use and climate elements into their analysis [8], [9]. The review of existing energy modelling approaches [10] maps two significant gaps in the representation of the cross-disciplinary and intersectoral linkages required by the nexus concept within the existing energy system models. The first gap exists within the energy system modelling itself. Energy-economy models, which directly assist policymakers with the future of energy system decisions, are not equipped to capture the full scale of flexibility and the operational curtailments required within a system that has a high penetration of variable renewable energy generation (e.g. [11] [12] [13]). The second gap, however, is identified as how energy system models define the interaction of energy system policy and investment decisions with the other elements related to health and well-being of human and ecosystems. To the best of the authors' knowledge, the current energy models that are applied to investigate Canada's climate policies only consider modest aspects of these interconnected systems. These models are often partial (components are not equally weighted) in their cross-disciplinary analysis as they mainly represent energy or water-centric perspectives, overlooking the importance of cross-disciplinary feedback mechanisms [14].

The CLEWS framework and platform, that is used in the development of BC Nexus Model, is designed to explore interlinkages between and within climate, land (food), energy and water systems. It is developed based on the United Nations' (UN) sustainable development (SD) concept; as a result, several aspects of the nexus concept are incorporated within the framework [15]. CLEWS is an open-source modelling framework created to take advantage of existing well-tested assessment methodologies for energy, water, land (agriculture) resources, combined with climate data to form an integrated analysis. The tool is used and developed in partnership with the United Nations Department of Economic and Social Affairs (UNDESA) and the United Nations Development Programme (UNDP) to assess policies targeting UN sustainable development goals. This makes the CLEWS a unique tool to enable policymakers to weigh their progress towards Paris Agreement targets [15]. Today, several completed and ongoing projects use the CLEWS platform to investigate various purposed policy questions within different special and temporal scales, and between two and more resource interactions [4]. The CLEWS modelling platform's design and structure are explained in more detail in the next section (Structure and Underlying Assumptions section).

MODEL STRUCTURE AND METHODOLOGY

This section starts with reviewing the design and structure of the CLEWS modelling platform that was used in the development of the BC Nexus model. Then, it goes through the underlying assumptions in establishing the linkages between BC CLEW systems and data used to calibrate the model with the BC energy, water, land and climate portfolios, before moving through the details of scenario development.

Structure and Underlying Assumptions

The CLEWS Modelling framework is an extended version of OSeMOSYS (the Open Source energy MOdelling SYStem) modelling framework [4]. OSeMOSYS is a bottom-up modelling framework developed to provide long-term energy system cost optimization for the user-defined regions. "The term 'modelling framework' in this context designates software that generates specific models by populating them with user-defined data" [16]. OSeMOSYS is a linear program capacity expansion model. It runs based on the exogenously provided demands portfolios, their trajectory, policy and resource constraints; it delivers the optimized power generation technology mix to meet the demand.

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 model is developed in a series of component 'blocks' of functionality. A collection of the functional component blocks combines to form a customized model" [17]. 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 to the user-design inquiry [16]. Each block interacts with the user through three levels of interface: a plain English description, an algebraic formulation, and then its code implementation. 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. Note that the CLEWS framework is not inherently system-biased (meaning no system is center of focus through the basic design) and users can tailor the analysis by defining the objective and context of each case study [4].

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. Within this approach, the WEF nexus system, and each systems' interactions with climate, are combined in a single model, allowing for efficient resource allocation and consistent price signals across all sectors to choose the least-cost energy technology mix [18].

The BC CLEWS model is made up of three major components of water, food, energy (WFE) and their interactions with the BC climate data. Figure 1 illustrates the BC Nexus model components and the affiliation of each system to the United Nations-defined SDGs. Currently, the constraints and needs of the water and climate systems are only tracked in the model.

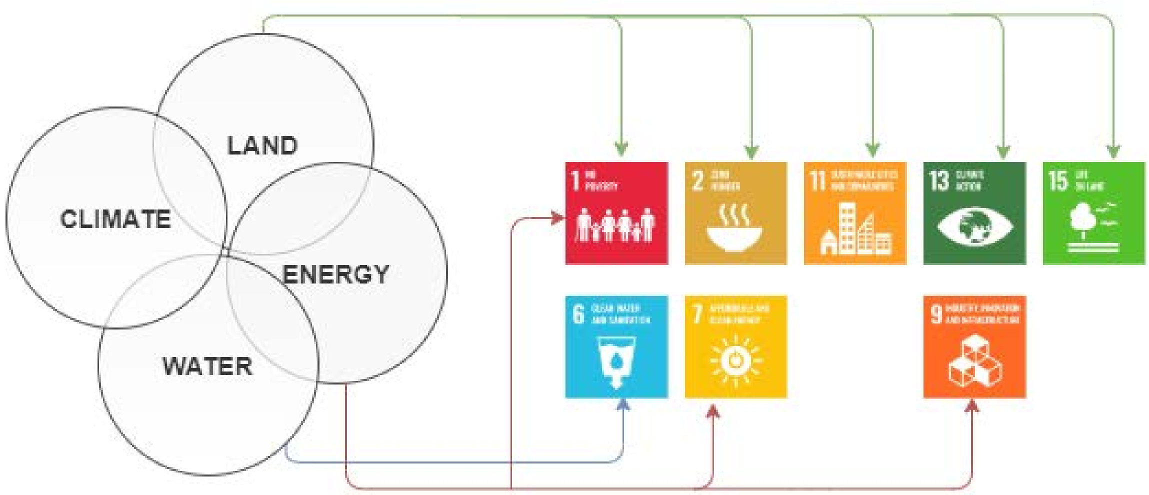

Figure 1: BC Nexus model components and affiliation to the SDGs (after [19])

In developing the model, the energy and land systems were designed and developed individually, based on the BC data sources. Then, the linkages between pairs of systems were defined for the model. For instance, the interactions of the water and energy systems were defined by the amount of water needed in generating power from each energy resource as well as the amount of energy that is required in activities such as water treatment facilities. Another example is the relationship between the energy and land systems, defined by the amount of energy required in agricultural activities (e.g., water pumping, running agricultural heavy trucks, etc.) and vice versa, for instance, the amount of land use in meeting biofuel demands in the energy system. Later, the activity ratio of CO_2 emissions produced from every activity (e.g., power production from various energy sources) within and between systems was added to the model.

The BC Nexus model, like other models developed in CLEWS and OseMOSYS, are policy driven. When carrying out a scenario within a BC Nexus model, 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, and policy constraints within each system, this identifies the boundaries, drivers and pressure points for each system. Then, each system's interactions with the others can be evaluated to identify the trade-off and synergies causing 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 the system.

Data

BC Nexus model is a multi-disciplinary analysis tool and requires a wide range of data for the energy, land (agriculture), water, and climate systems to calibrate the entire representation for BC. As much as possible, most of the information (for instance, within the energy system) was collected from BC Hydro, public datasets and other governmental sources. Only data sources of reliable providence were utilized. On occasions reasonable technically qualified assumptions were made to substitute missing or inaccurate data for the model. This section reviews the main data included in the BC Nexus model and their references and assumptions.

› ENERGY SYSTEM

Data within the energy system was divided into two categories: the power system portfolio and the demands for other types of fuels (imported and exported sources) within the province. Note that there are about 150 active power projects in BC. The majority of them are IPP (Independent power producer) projects, mainly very small to medium run-of-river stations. To simplify the model structure, many of these projects were aggregated together and represented as one larger power generation element within the model.

Aggregation of the hydropower projects has been done through careful investigation and data analysis. Firstly, the largest generators (bigger than 5% of the total provincial hydro capacity) were identified. Five large projects are recognized in this step. Due to the significant effect of these larger generators on the power system, they are represented individually within the model power system. The remaining hydro projects were investigated based on the region, capacity size, capacity factor, and generation technology. 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 South East BC region. Unfortunately, not all data was available for every project. Consequently, the hydro projects were merged to represent 12 larger generation boxes in the model. The same process applies to natural gas and bioenergy power stations. However, for the variable renewable power projects (wind and solar), due to their sensitivity to location and vary capacity factors, all projects are represented individually within the model. Table 1 indicates the list of data gathered to shape the energy system portfolio of BC.

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

	Collected data	**Data analysis and assumptions**
Power System		
Components (each power generation stations)	- Location, capacity, nominal annual generation, actual annual generation, operational life span	- Capacity factor - Efficiency - Residual capacity
Cost	- Capital, fixed, and variable costs - Generic technology cost info [20]	- 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 [21]	- Availability factors - Time slices (daily) and year split (seasonal) - Specified annual demand for each time slice - Specified demand portfolio within each time slice - Specified power demand for each sector (residential, commercial, industry, transportation)
Other information	- Transmission loss (10%) [22] - Reserve margin (10.4%) [23]	- Reference data was allocated
Rest of the energy system		

Non-electrical fuels	- Accumulated annual end-use fuel demand [24] - Domestic fuel productions - Import/export fuel supplies	- For non-electrical fuels that can be stored, the demand projected on annual basis rather than for each time slice
Cost	- Fuel cost and annual forecast to 2050	- 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 machineries) 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 inquiry. This is especially important in the case of variable renewable power sources such as solar and wind, where the production at different times of a year and site locations are significantly different. For the version of the model reported in this document, 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 2 outlines the temporal data structure used.

Table 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 2 is shown in Table 3. This represents the annual fraction of the total power demand required for each time slice.

Table 3: Electrical Demand Profile of BC.

	Spring		Summer		Fall		Winter	
	D	N	D	N	D	N	D	N
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

› LAND SYSTEM

Two main categories of data were collected to build the land-use representation of BC Nexus Model: availability and allocation of land and existing land-used to meet current food and energy demands. Table 4 summarizes the main data collected for the land portfolio of BC:

Table 4: 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 main crops growth in BC - Clustered data for crop yield (t/ha) o crop-specific agro-climatic assessment o soil/terrain limitations o Water use (rained fed vs irrigated) o Agricultural intensity (low, intermediate, high input level)	- Future growth in land use for built-up and agricultural lands based on population growth and historical trends - Choosing 10 crops that covers more than 90% of agricultural lands for clustering and analysis of future growth - Majority of the data collected using GAEZ model (Global Agro-Ecological Zoning):
Linkages data: Land-use on energy and water systems	- Land needed for biofuel production	

To reduce the computational complexity, gridded land data is clustered to establish areas of similar crop suitability for the BC land system. Clustering organizes land with similar properties: general agro-climatic indicators, crop-specific agro-climatic indicators, and water-limited and soil/terrain limitations were combined as one group to reduce the computational complexity of the modelling analysis in simulating large area data. The GEAZ model (Global Agro-Ecological Zoning) was used to collect crop suitability estimation data for BC land. An agglomerative hierarchical clustering method was then used to cluster lands (cell) with a similar achievable yield potential together. Figure 2 shows the clusters used for the BC Nexus Model, as well as the attainable yield for two representative clusters.

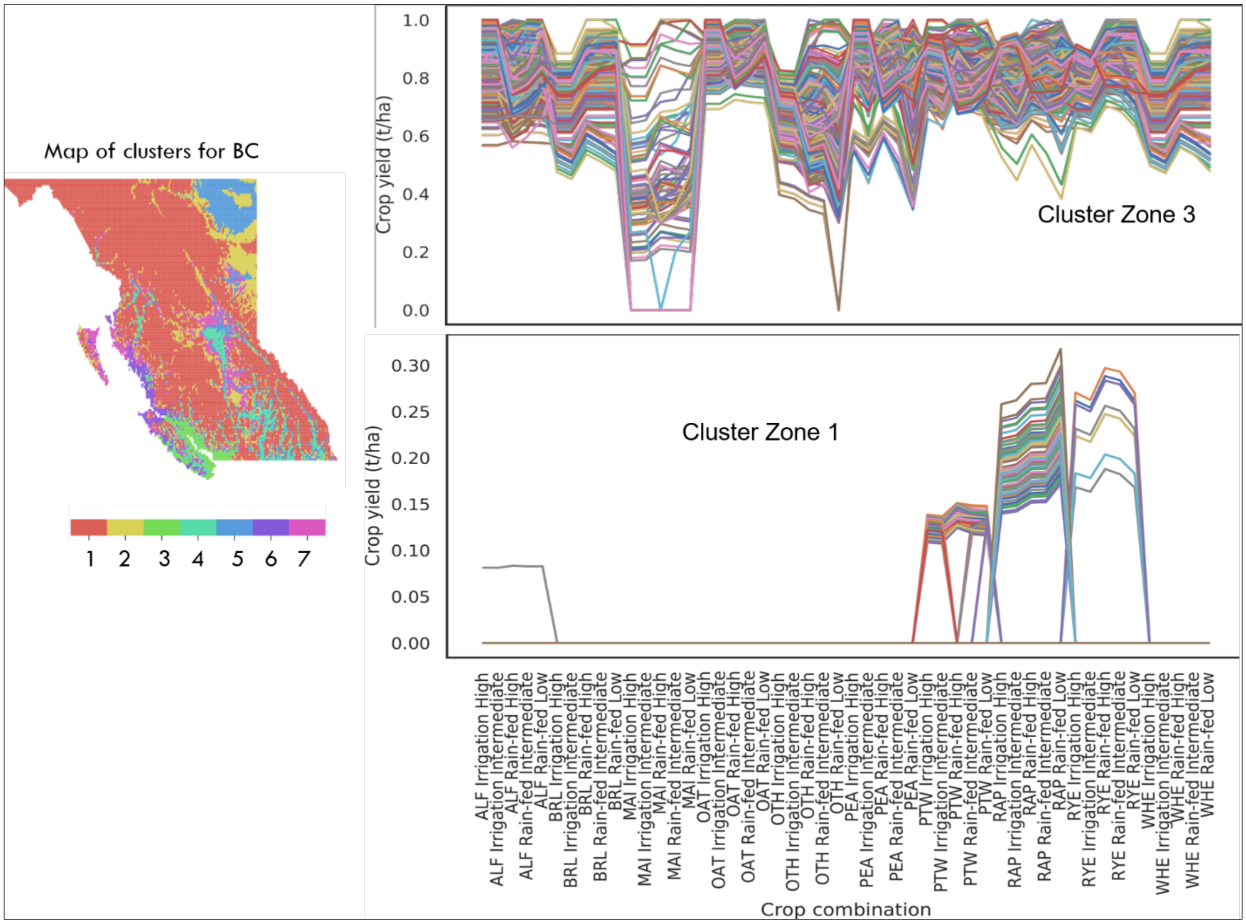

Figure 2: BC crop attainable yield clusters based on similar irrigation and intensity combinations.

As shown on the left side graph of Figure 2, a total of seven clustered zones were defined for BC. Each cluster indicates the area in which there is a similar possible crop yield due to similar irrigation and intensity combinations. To match BC agricultural production, nine main crops that represent 90% of the agricultural production in BC (namely alfalfa, barley, maize, oat, pea, potato, rapeseed, rye, and wheat) are included. The remaining crops are lumped together into an 'other' category to represent the full agricultural output of the province. On the right side of the figure, crop suitability is compared for two clusters: 1 and 3. In these charts, each differently coloured line represents a cell (a land unit) in BC. The vertical axis shows a combination of a crop type, the water use (either rain-fed or irrigated), and the crop's yield intensity level (high, intermediate, or low). The horizontal axis represents crop yield (tonnes per hectare). As reflected, in cluster zone 1, most of the crops show zero to a low yield potential. This makes sense as the cluster zone 1 mainly covers the mountainous regions of BC. Cluster zone 3, on the other hand, represents a much more fertile area of BC.

› WATER AND CLIMATE SYSTEMS

Water and climate data only get tracking in the current version of the model. This means, for instance, water availability in BC and change in demand for water in various sectors (e.g., power sector, public sector, agriculture based on the type of crop and yield, etc.) are only monitored to assess the impacts of various policies on water (one-way interaction). In the case of climate, the amount of CO_2 emission for each activity within and between systems gets tracked by the model. One of the important items of activity within the model is forestry. Forests can play important role in climate change acts by absorbing CO_2 from atmosphere. By assigning a negative value of variable cost to the forest lands within the model area, the model includes the reforestation consideration within its optimization analysis. However, at the time of preparing this report, there is ambiguity around the role of Canadian/BC forests in absorbing CO_2 from the atmosphere in contrast with the amount they emit. Given this uncertainty, negative emission ro forests were not included in the model at this time.

Scenarios

Three decarbonisation scenarios were investigated for BC between 2030 to 2050. The scenarios were developed to investigate the synergies and trade-offs of the selected BC decarbonization policies and actions and their impact on land and water resources. Another scope of the investigation was to find out whether these policies and actions would allow BC to meet its CO_2 emission reduction targets. Two types of decarbonisation 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 carbon tax, cap-and-trade and clean fuel standards that invoke economic driven action and emission reductions.

The projection of demand in residential, commercial, industrial and transportation sectors outlined in the Canada's Energy Future report of 2019 [24] was selected as a reference scenario (BAU-business as usual scenario). The reason behind this choice is a moderate approach with regard to the projection towards decarbonisation of BC's energy system, energy price and technological improvement trends, as well as climate and energy policies. Figure 3 shows the projection of the demand in the Business as Usual (BAU) scenario.

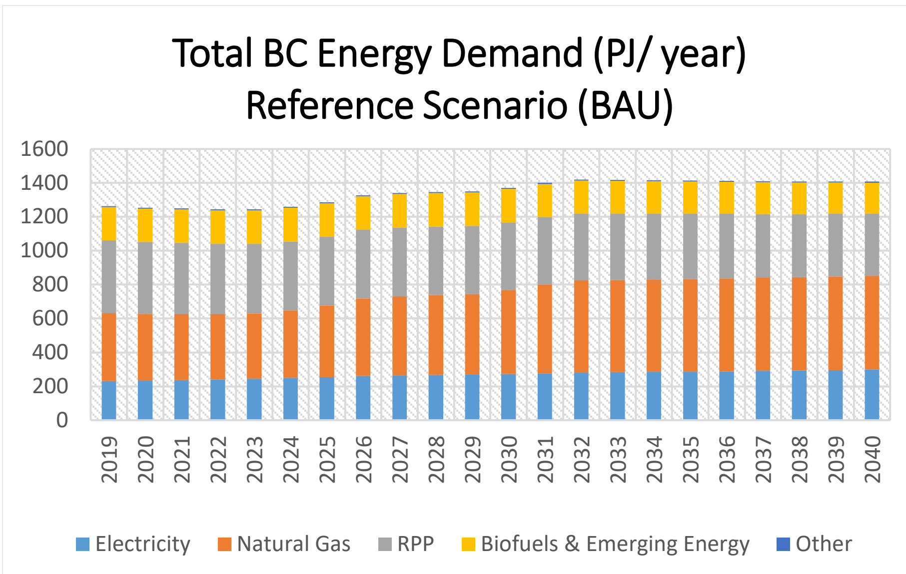

Figure 3: BAU scenario- BC's energy outlook (PJ/year) based on the 2019 Canada's Energy Future report.

Based on the report, the total energy growth of 11% was estimated between 2019-2040, breaking down into 29% growth in electricity demand, 39% growth in natural gas demand, followed by 15% and 7% decline in demand for refined petroleum products (RPP) and biofuels respectively. The demand was projected to 2040, and to match the modelling period, the demand trends linearly extrapolated to 2050.

The demand growth trends in all sectors and WEF systems, allows the model to compute an optimization analysis that finds the least-cost technology mix to meet the demand. The power system's assessment centres around the residual energy capacity in BC, facility operating life span, cost information, demand projection and policy directions. Considering the sensibility of the interaction between the reserve margin value in the technology mix choices for power sector, this scenario was run twice with and without a reserve margin value of 10.4% for comparison. As

Figure 4 shows, without reserve margin, the model cost optimization analysis indicated that, in addition to the current BC power capacity portfolio (site C included), the least cost energy option to meet the demand between 2030 and 2050 is by investing in wind power. Importantly, by adding the reserve margin requirement, the geothermal power generation is gradually adopted as the least-cost baseload power generator when the hydro capacity becomes fully utilized around 2040. Due to the importance of reserve margin in planning and managing the power supply, it is included in all subsequent analysis scenarios.

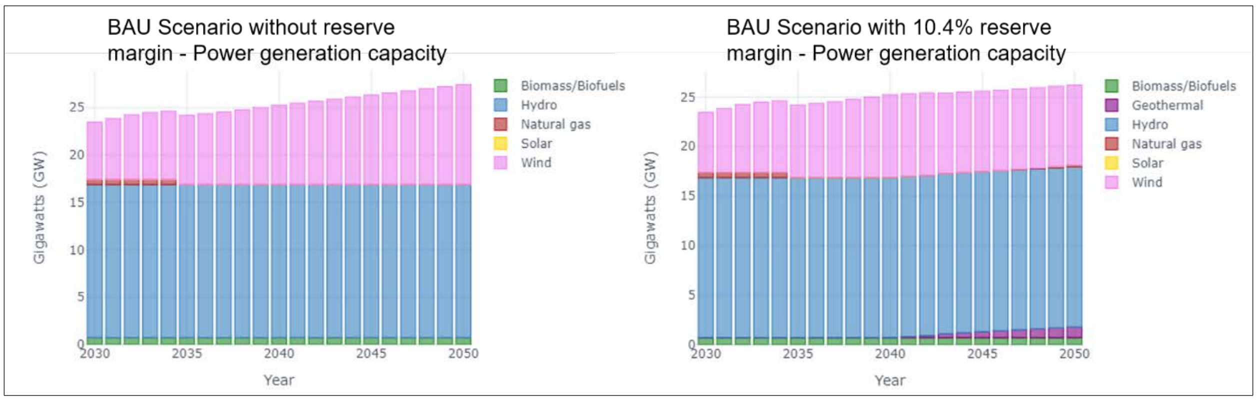

Figure 4: BAU scenario – power generation capacity to meet the demand between 2030-2050 with and without reserve margin value of 10.4%.

The first scenario (S1) investigates more aggressive electrification of the energy system when compared to the BAU reference scenario. In this scenario, close examination of the energy consumption by fuel type and applications was undertaken at the energy demand outlined in Canada's Energy Future projection. Within the residential and commercial sectors, the demand for natural gas is often for space heating. An aggressive electrification approach was taken, assuming 100% of this demand will be electrified by 2050, switching to heat pump technology for space heating. The same aggressive approach has been taken within the transportation sector, assuming all vehicles turn into 50% electrical passenger cars and 50% efficient electrical transit vehicles. This assumption will not be far from the BC ZEV mandate outcome. In this mandate, by 2040, all the new car sales should be electric cars. Considering the common shelf life of gas cars, it is reasonable to assume that in 10 years, almost all vehicles shift to the electrical options. To project the new demand trend for S1, we linearly reduced gasoline and diesel demand within the transportation sector from 2030 value to zero in 2050. The new electricity demand is calculated accordingly. 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. The industry sector demand remains untouched, except the additional three-terawatt hour LNG power agreement signed by BC Hydro in 2014 will be added to the sector's electricity demand. The LNG agreement allows LNG Canada access to electricity from BC Hydro for the power needed for its proposed liquefied natural gas (LNG) export from the Kitimat facility. The project will be online after 2024.

The next scenario (S2) adds the BC carbon tax policy to explore its effect on the technology mix. Currently, the BC carbon tax is \$40 per tonnes of CO2eq emissions and is expected to increase to \$50/tCO2eq by 2022 to meet the federal backstop carbon tax. Note that due to the Coronavirus pandemic, the increase paused for one year or until further notice. Due to the uncertainty in the BC carbon tax trend after 2022, we projected the carbon tax increase based on the federal backstop value of \$15 per year to meet the minimum requirement for BC, as shown in Figure 5.

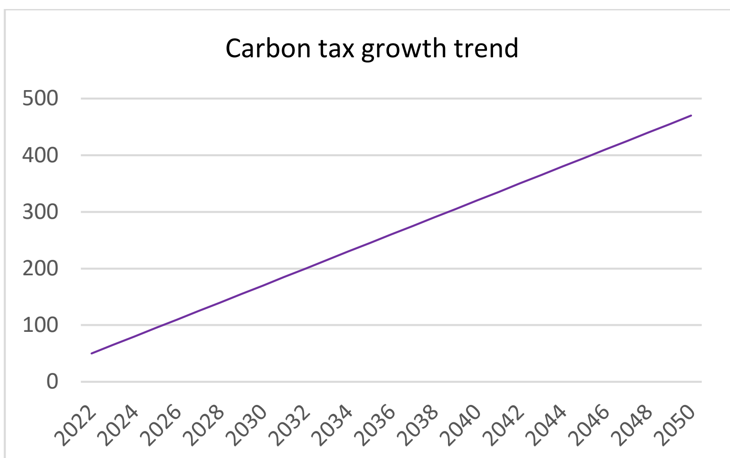

Figure 5: S2 – BC carbon tax prediction based on federal policy.

Table 5 summarizes the different scenarios assessed in this report.

Table 5: The summary of the scenario's directions and assumptions

<table>
<tr><td>Scenario</td><td>Direction</td><td>Assumptions</td></tr>
<tr><td>Reference scenario (BAU)</td><td>Based on Canada's Energy Future projection of 2019</td><td>- slow total energy use growth of 11% to 2040 in BC
Canada wide:
- Population growth of 20%
- GDP growth of 40% (leading to reduction in energy use per person and per dollar of economic activity)
- 50% and 30% growth in crude oil and natural gas respectively.</td></tr>
<tr><td>Scenario 1 (S1)</td><td>Reference scenario (BAU) + more aggressive electrification without carbon tax</td><td rowspan="2">- 100% transition from natural gas in residential and commercial sectors
- 100% transition to electric vehicles
- Additional 3 Terawatt hr. electricity demand in the industry sector due to LNG sector</td></tr>
<tr><td>Scenario 1 (S2)</td><td>Reference scenario (BAU) + more aggressive electrification with carbon tax</td></tr>
</table>

MODELLING RESULTS AND ANALYSIS

This section reviews the main results of the investigation on the selected scenarios explained in previous section (BAU, S1, S2).

Reference Scenario (BAU)

Figure 6 illustrates the main results of the assessment on the energy system in the BAU scenario. In row one, the "gross final energy consumption" graph projected the BC energy demand between 2030 and 2050. Based on the reference scenario in the Canada Energy Future report (2019), issued by the government of Canada, the demand for the natural gas remains high throughout the scenario, followed by electricity. The "power generation capacity" graph indicates that the least-cost technology mix to meet the power demand is the combination of hydro power, wind, geothermal and biomass. A close look at the capital investment graph highlights that on top of the current BC power portfolio, the model cost optimization analysis leads to a huge investment into wind power till 2040 to increase the share of this energy from

0.7 GW currently to 8 GW (~7 times more than Site C) in 2050. The model also indicates the need for the investment in natural gas; however, the comparison between the power generation capacity graph, the power generation graph and the power generation by time slice graph indicates that the model uses natural gas as a stand-by option to cover a fraction of the required reserve margin.

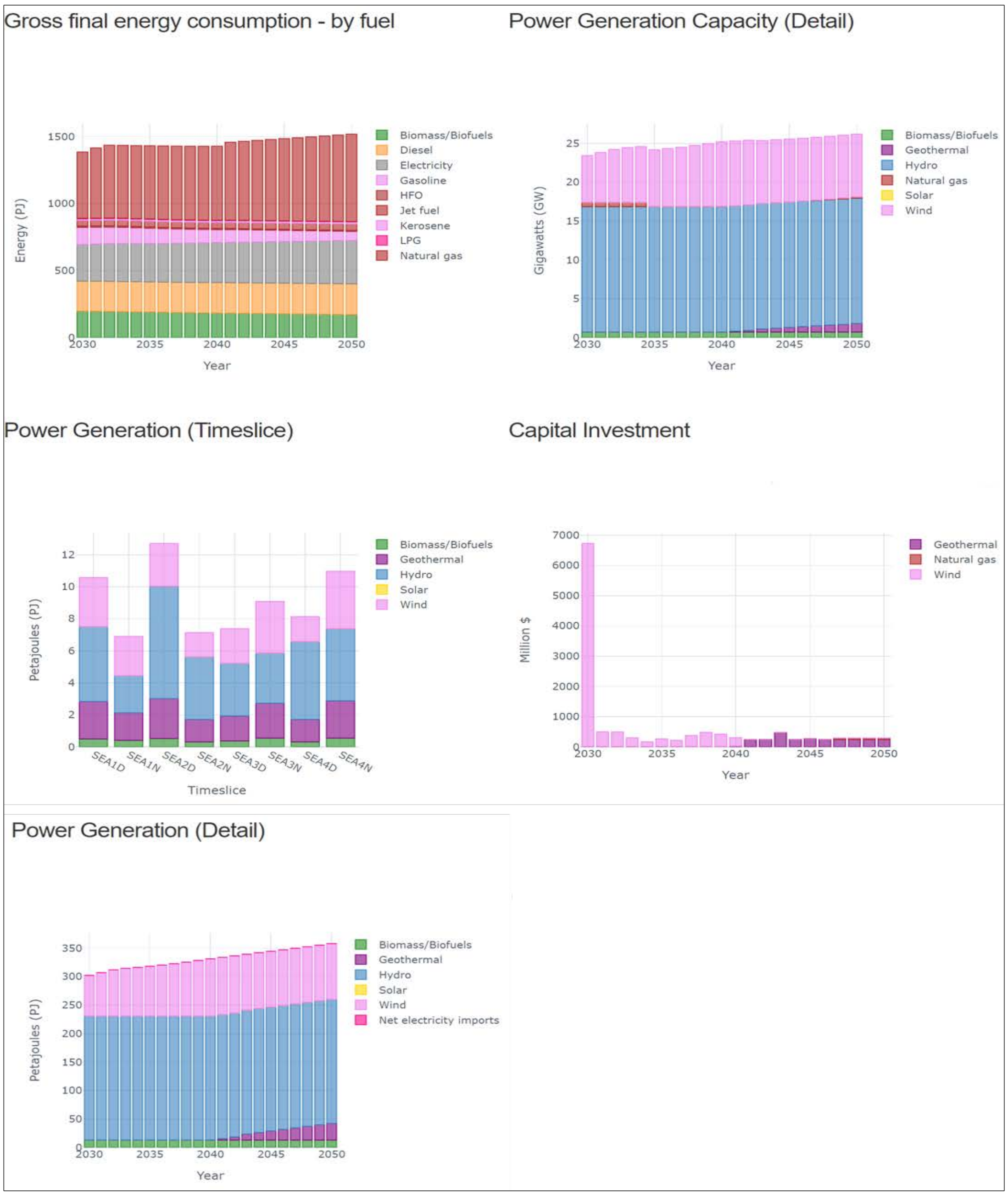

Figure 6: BAU scenario results- Energy system assessment

After 2040, the result shows the investment in development of 1GW capacity of geothermal energy and small (0.14 GW) capacity of natural gas by 2050. It is noteworthy that Site C is included in the portrayal of residual capacity in the model. Currently, hydro power generates about 90% of the BC power supply and Site C (1.1 GW) is expected to be completed in 2025. However, in less than 10 years, in 2030, hydropower generation will not be sufficient to meet the gap between energy demand and supply, even in the most modest power growth scenario explored in this investigation. In this scenario, the share of hydropower within the BC power supply reduces to about 65% of the total generated.

Scenario 1 (S1): Aggressive electrification

S1 scenario investigates the impact of more aggressive electrification within residential, commercial and transportation sectors by 2050. As previously mentioned, in this scenario, the natural gas used in space heating is substituted with electrical heat pumps and insulation strategies. The same aggressive approach has been taken within the transportation sector, assuming all vehicles turn into 50% electrical passenger cars and 50% efficient electrical transit. The higher efficiency of electrical 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. Figure 7 compares the change in the gross energy consumption in BAU and S1 scenarios. The chart at the right bottom of the graph shows how electrification of space heating in residential sectors reduced the total energy demand in this sector. For more information on the logical steps taken to convert the value of reduced fossil fuel demands within each sector and added to the electricity demand after electrification action, please see Appendix A.

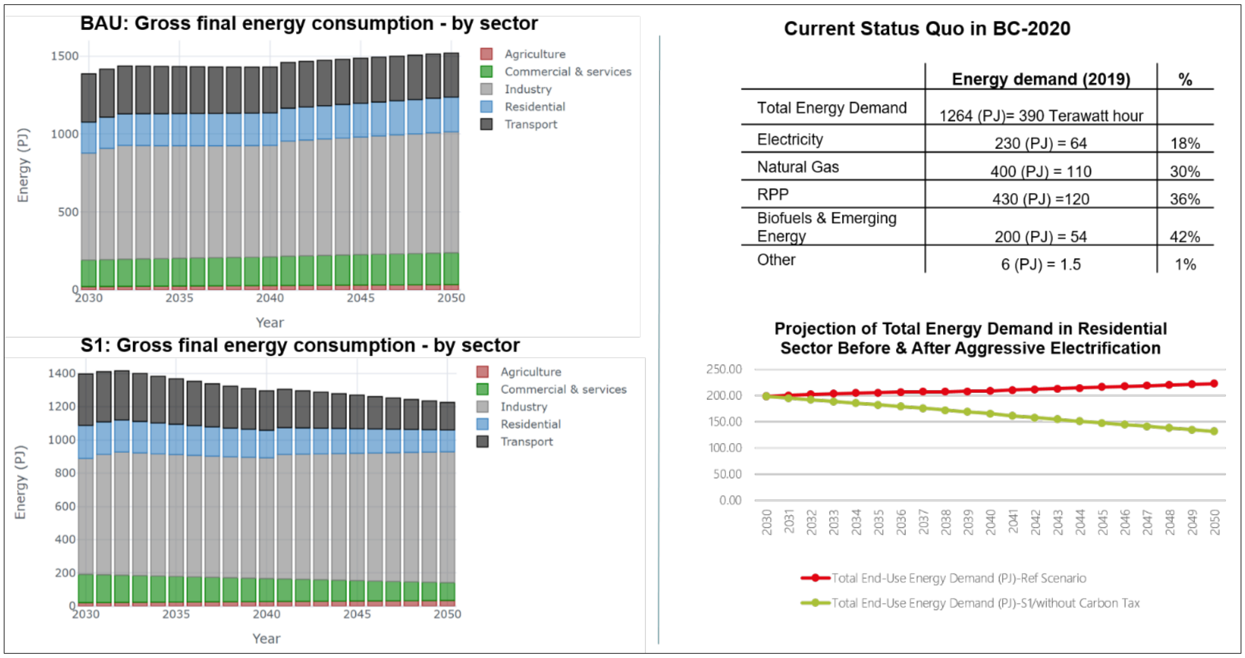

Figure 7: Comparing BAU and S1 scenarios- final energy consumption.

Figure 8 compares the change in demand portfolio in Scenario BAU and S1. As shown on the right graph representing the differences, about 300 PJ of fossil fuels can be substituted with almost 70 PJ of electricity.

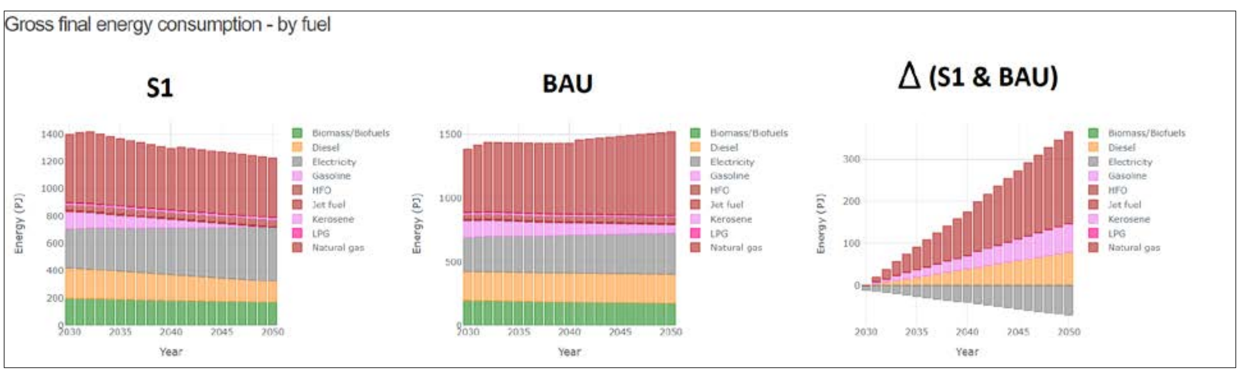

Figure 8- BAU vs. S1 scenario results- gross energy consumption by fuel.

Another important result comparing BAU and S1 scenarios was how the increase in electricity demand reduced the wind power share in the power generation capacity portfolio, as shown in Figure 9. In the capacity graph of Figure 9 one can see that increased natural gas and geothermal generation are used to meet the increased demands and reserve margin, while in the power generation graph, before 2035, natural gas is no longer needed for stand-by capacity.

When the hydropower capacity is fully utilized by 2033 to serve as baseload power source, some natural gas generation is installed to meet the reserve margin. However, this installed natural gas generation does not persist and is quickly replaced by geothermal in 2036.

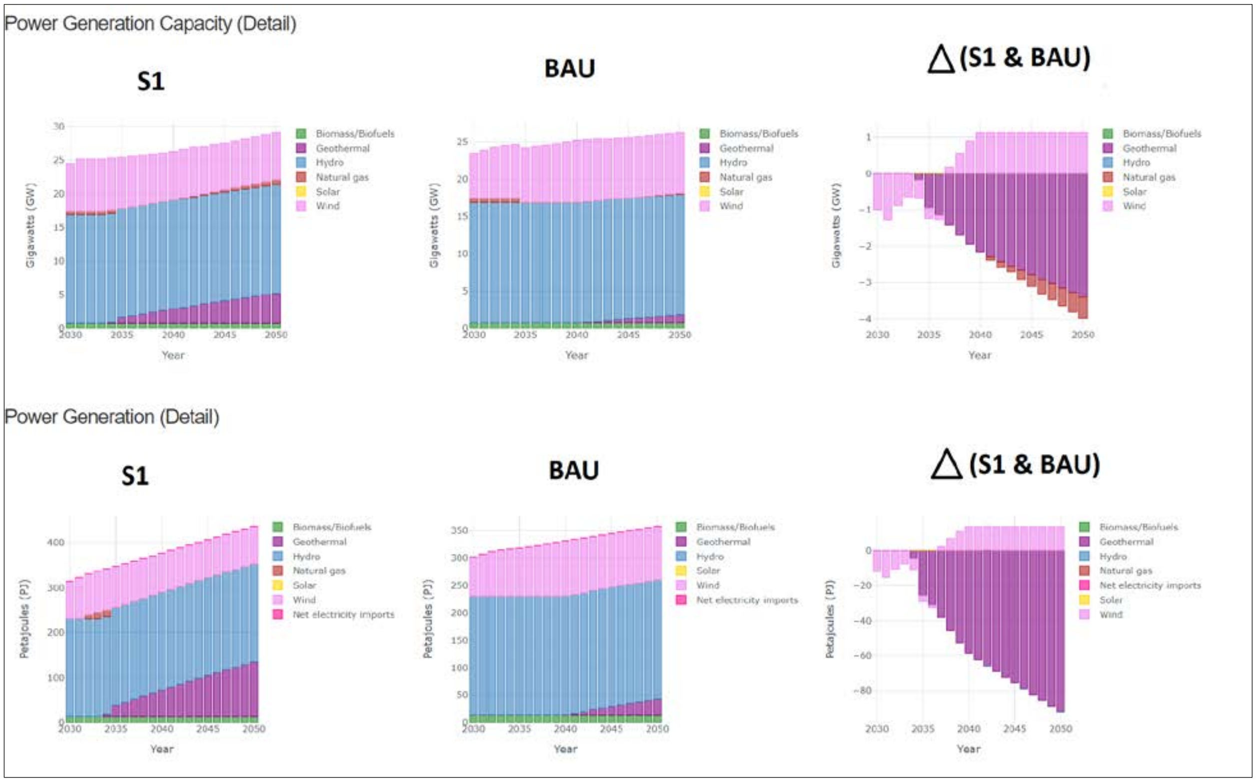

Figure 9: BAU vs. S1 scenario results- power system technology mix and generation details.

This shift in the share of the technology mix can be explained by the 10.4% reserve margin requirement. The variable energy sources, wind and solar, cannot provide reserve margin capacity. Thus, when the hydropower capacity becomes fully utilized in 2031, the model starts deploying and investing in other baseload options available in the region. In the case of BC, the options are geothermal power, more hydropower generation, and natural gas, and between these options, the least-cost pathway is the combination of natural gas and geothermal power, as shown in Figure 10.

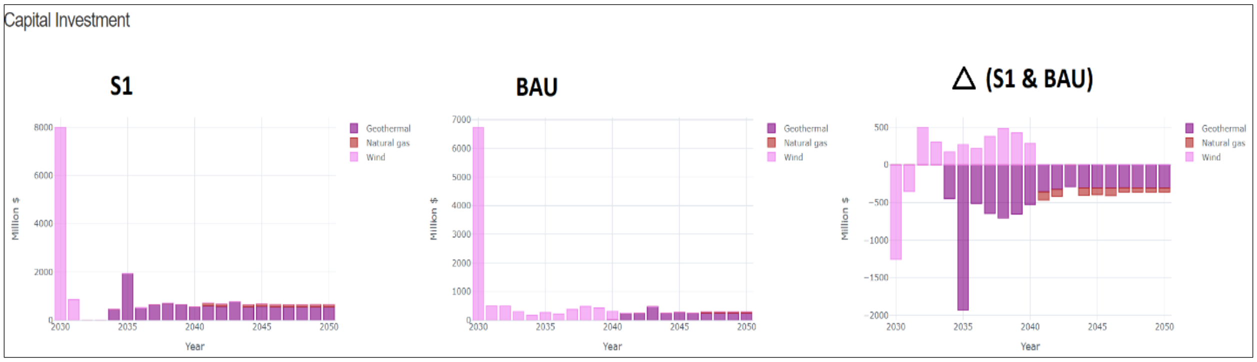

Figure 10: S1 vs BAU- Change in sectoral electrification.

Figure 11 compares the installed generation mix of the current system in 2019, the BAU 2050 projection and the S1 2050 projection.

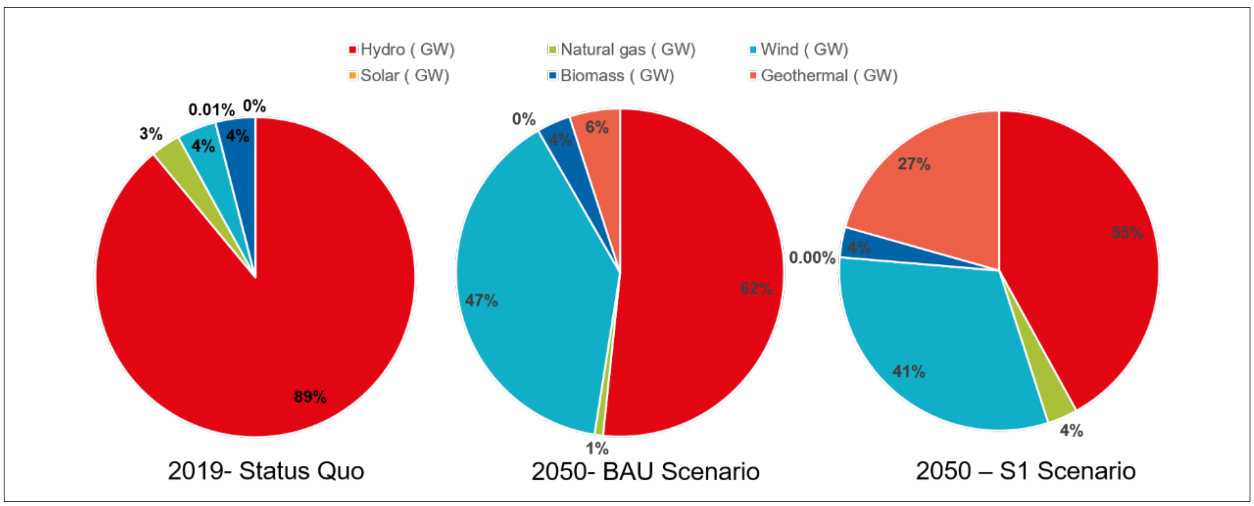

Figure 11: Installed generation mix for BC: 2019 status quo vs. 2050 BAU and 2050 S1.

Scenario 2 (S2): Aggressive electrification plus carbon tax

Scenario S2 uses the same demand portfolio as S1, along with adding a carbon tax to the optimization. Putting a penalty on carbon emissions encourages the model to reduce its dependence on fossil fuel options. Note that in 2050, the generation capacity in S2 is similar to S1. However, as shown in Figure 12, the natural gas generation is not used but acts as standby to meet the reserve margin (Figure 12, rows 2 and 3). Geothermal capacity is built earlier (starting in 2031) to replace natural gas generation (compared to 2034 in S1).

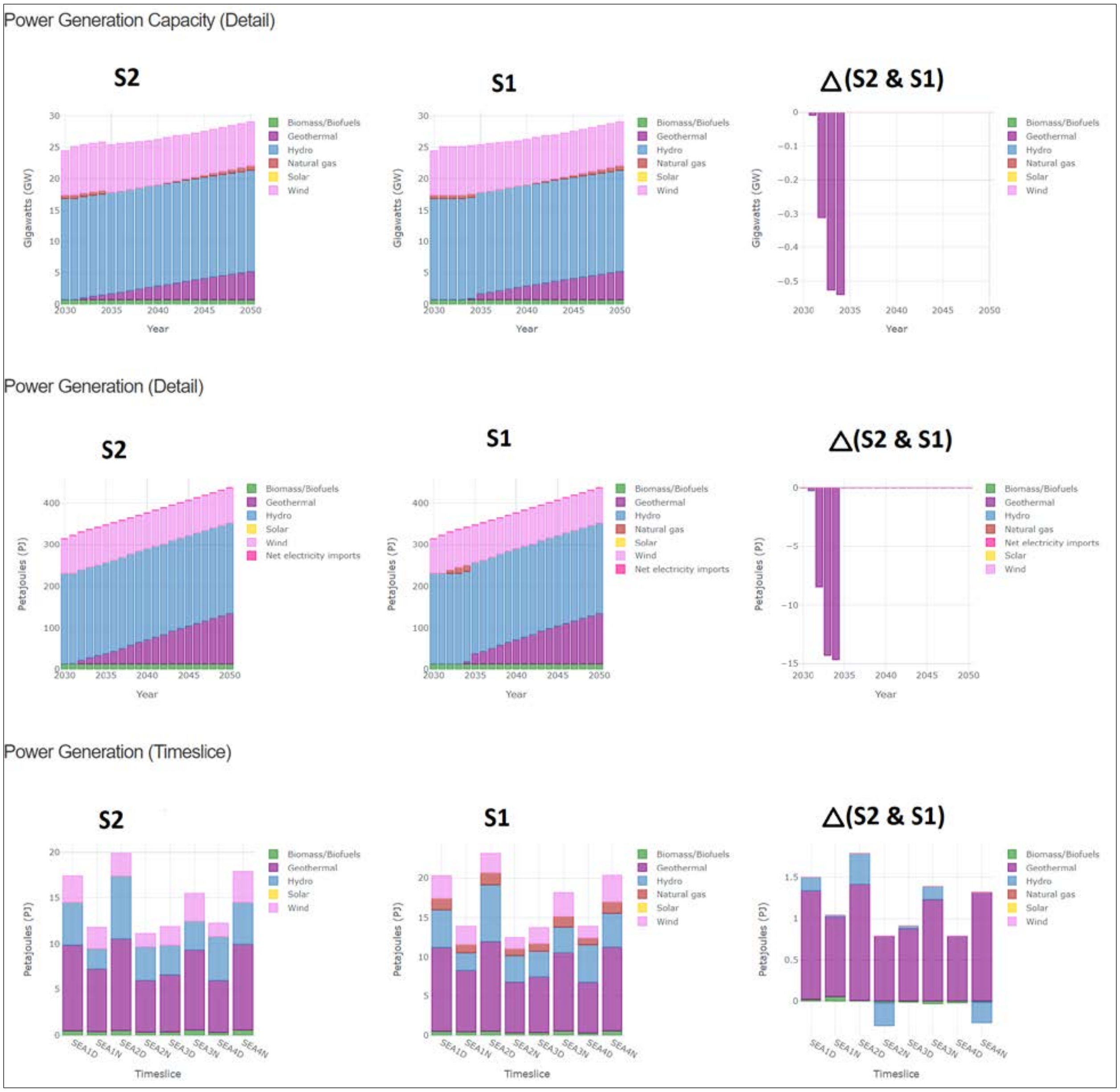

Figure 12: S2 vs. S1-Investigating the effect of carbon tax on the energy system.

Land and water use

Figure 13 compares the effect of electrification and technology choice on land and water use according to S1 and BAU scenarios. Since the biomass power generation is decreasing in all scenarios, as well as the demand for biofuel from agricultural products in both scenarios (as well as S2), the power system change did not affect the agricultural land. The reason is, in BC, most of the biomass comes from forest (wood-products) and the future reports indicates the biofuel industry moves towards non-agricultural biomass sources such as animal manure, food waste, as well as municipal waste streams, and algae in future [25]. Note that the land-use effect by non-biomass power generation activities is under development and has not yet been fully embedded within the model. Considering the huge impact of variable renewables (such as wind and solar farms) on land, including this option can bring significant insights into the technology mix options and a full assessment of decarbonization policies.

The third row of Figure 13 indicates the increase in the demand for water within the power sector. A closer look within the power generation details (Figure 9, row 2) shows the use of natural gas between 2031 and 2033 (the sudden increase in Figure 14 of the same year), as well as a gradual increase in the geothermal power generation, which match the gradual increase in water demand. By adding the carbon tax to the equation in S2, the increase in water demand related to natural gas production has disappeared.

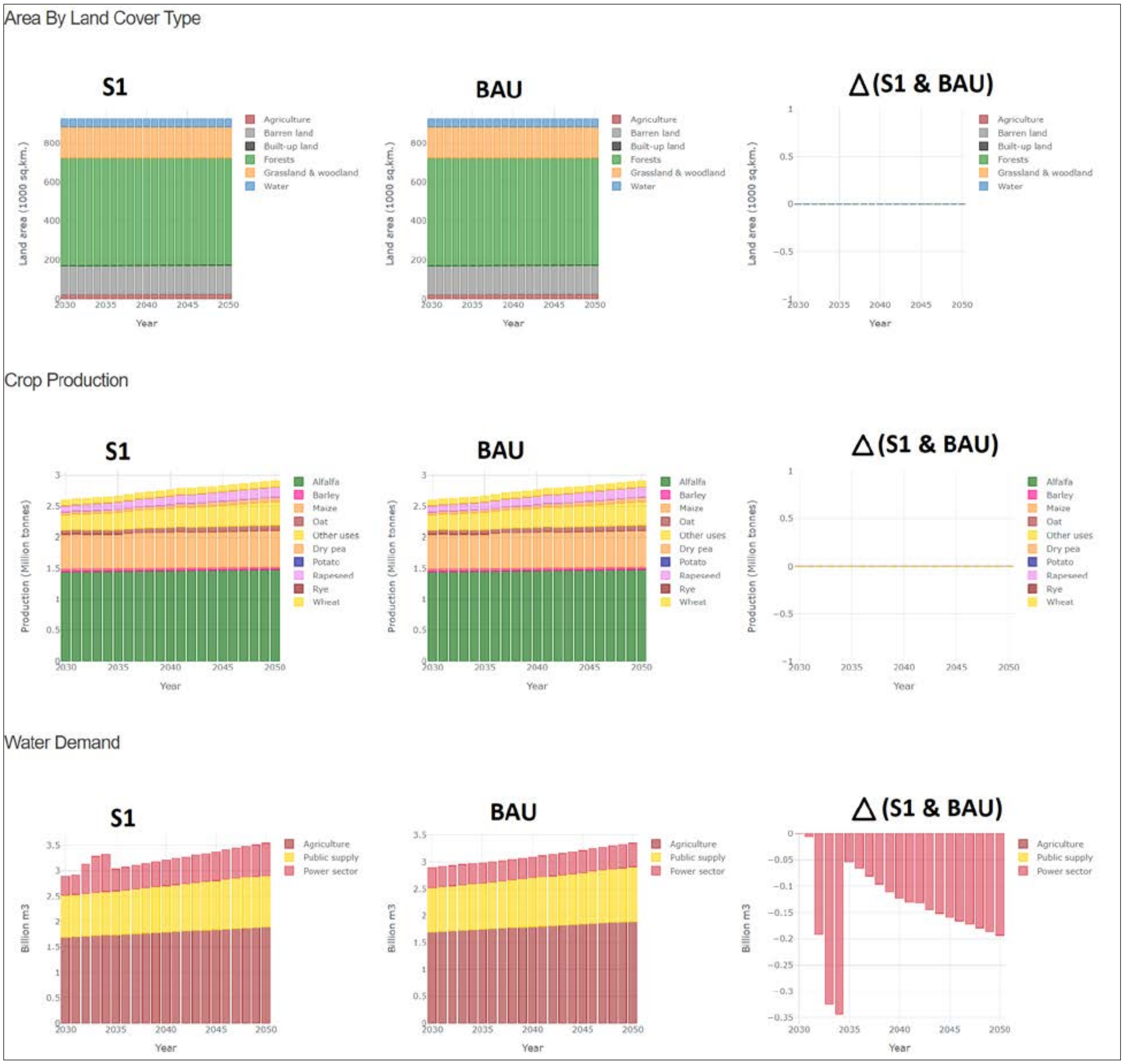

Figure 13: Land and water use- comparison between S1 and BAU scenario.

CO_2 emission targets

The model also shows the shifts in emissions as different energy strategies are employed. BC.'s legislated emission targets for 2030, 2040 and 2050 of 40% (≈ 40 Million tonnes of CO_2), 60% (≈ 25 Million tonnes of CO_2) and 80% (≈ 12 Million tonnes of CO_2) below 2007 (= 64.76 Million tonnes of CO_2) levels, respectively. Figure 14 highlights these targets, annotated with dark red circles. As shown, despite aggressive electrification within residential, commercial, and transportation sectors, without considerable change within the demand portfolio of the industry sector, BC will not be able to meet the legislated targets. Meeting the provincial CO_2 emission reduction targets can only be met if industry cuts emissions by half by 2040 and another half by 2050. Policies, such as carbon pricing and cap-and-trade approaches by setting a limit on pollution and creating a market, cause the deeper actions and faster transitions within the industry sector. Due to the complexity of the industry sector energy demand, further careful investigation is needed to identify proper substitutions for the fossil fuel demand within this sector. Such investigation is part of our team's future scope. In scenario 2, adding carbon tax to the model constraints triggered a minor emission reduction between 2032 and 2034, as a result of eliminating natural gas from the power system generation during that period. This is consistent with the fact that currently 95% of the BC power system (not energy system) is generated from clean, renewable sources.

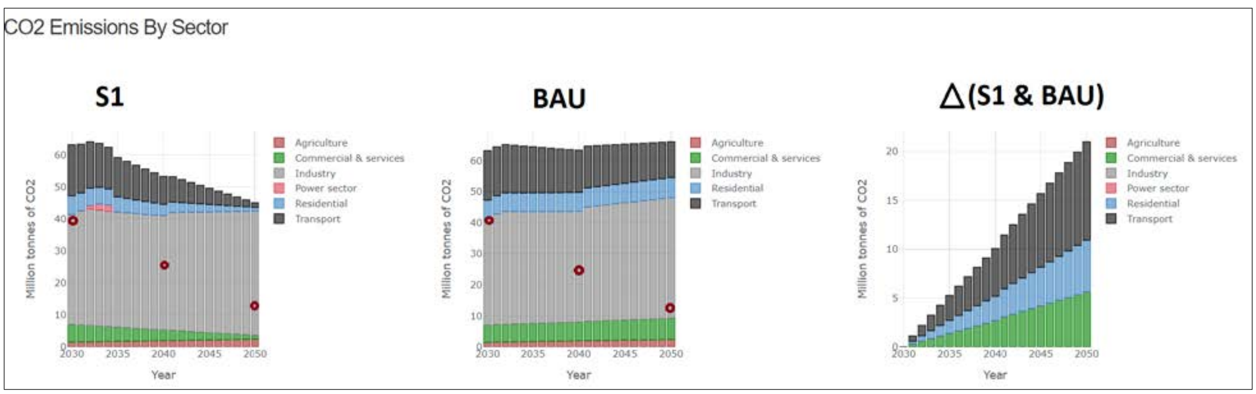

Figure 14: CO_2 emission reduction in S1 and BAU scenarios.

DISCUSSION

This section discusses the usability of the BC Nexus model for policy design and integration in the national modelling platform, along with the current status of the model and future works. The challenges with accessibility and availability of data in the nexus modelling are also discussed.

Accessibility and Transparency

Accessibility and transparency of modelling in the CLEWS platform was one of our motivations in choosing it. CLEWS platform is an open-source model which does not require big time investments to build and operate, making it suitable for people with various background to use it. To align with this open source philosophy at the heart of CLEWs, we will be releasing the model on GitHub free and open source, as well as open data, once the model reaches maturity and passes validation testing.

Usability for Policy Design and integration in a national modelling platform

To combat climate change, one of the significant challenges that policymakers are facing is to manage and optimize (where possible) competing economic and resource management priorities and trade-offs. As fossil fuels are responsible for emitting a large share of GHGs, decarbonisation of the energy system is at the core of most climate policies. Recent modelling practices (e.g. [2], [5], [6], [26]) show that a failure to consider the impact of energy transition policies on land and water resources can increase uncertainties and risks in meeting subnational climate targets, as well as affecting electricity costs and technology choices. The review (e.g. [27]–[29]) of the current energy system models and their capabilities in representing the nexus concept also indicates that these inadequacies in energy system modelling may mislead policy decisions and, consequently, the flow of investment into new technologies and future power capacity plans. While intersectoral interaction between energy economy, capacity expansion and power system models are getting more attention, the cross-disciplinary interactions of energy domain with factors such as water, food and natural securities remain relatively underrepresented in existing energy models. The BC Nexus model, upon completion, will be better equipped to assist BC policymakers and provide a more accurate picture of climate change actions. The result of two change-based scenarios, S1 and S2, shows that how changing in the demand portfolio shifts the technology mix and the share of each energy source to meet the demand. The impacts of this large shift to wind and geothermal on land use is beyond the scope of the current modelling work but is included on the development path of the BC Nexus Model.

Analyzing decarbonisation policies with the BC Nexus model to reveal the impacts and interactions of energy, water and land system not only prevents unintentional trade-offs, but also facilitates coordinating action between governments and private sector stakeholders. This is vital for cost effective, action where the timeline for mistakes has no margin of error. This makes the BC Nexus model a unique tool; integrating it in the national modelling platform could provide broader insights in assessing the decarbonisation policies and directions, as well as progress towards sustainable development goals.

Current Status and Envisioned Future Work

The BC nexus model outlined in this report is part of a larger and longer research modelling endeavour designed to tackle the gaps in representing the nexus concept within the modelling paradigm to support effective policy development. This particular project aims to expand the local and regional representation of the nexus within Canada CLEWS, since climate and geography have a tremendous influence on supply and demand synergies, which in turn impacts the effectiveness of policies, their costs and trade-offs. Water and land systems are the most sensitive to the level of spatial resolutions. Current results show the importance of incorporating these trade-offs into the modelling paradigm.

Two major directions are envisioned for future work. The first will address the gaps within the CLEWS modelling platform in representing the energy transition. Incorporating grid flexibility and reliability considerations with a high penetration of intermittent renewable resources. This is achieved by increasing the temporal and special resolution, as well as provisioning energy storage representation within the BC Nexus model. Incorporating operational and installed capacity limits on various technologies will also enhance the energy system representation. The second direction focuses on gaps in the representation of the cross-disciplinary linkages required by the nexus representation within the model. Some of these gaps include health impacts, natural security (e.g., biodiversity), individual well-being and cultural values. It also considers missing linkages within water and land systems, such as a better representation of land use related to energy system impacts, the impact of changes in water and land systems on climate and economy, and a closer look at the role of forestry in BC with respect to CO_2 emissions.

Finally, further scenarios and sensitivity analysis will be performed to identify the impacts of a variety of input parameters including, but not limited to, varying carbon tax levels, varying costs parameters and varying resource options to identify synergies and trade-offs. Once fully developed, the model will be available and accessible for free on GitHub with all used data and calculations.

CONCLUSION

This report presents the results and progress made in the development of the BC Nexus model. The model is developed to provide insights to BC policymakers about the underlying linkages and relationships among energy, water, food and climate systems in response to the challenge that provincial and municipalities worldwide face in tracking their progress towards the United Nations Sustainable Development Goals (SDGs). The nexus approach used in the design and development of the model allows policymakers to better recognize solutions for low-carbon energy systems and, in turn, provision economies that achieve United Nations SD goals. The key conclusion from the scenarios examined in this report are:

- Due to the low solar irradiance recorded in the only solar power project in BC, the model did not choose further investment in the solar generation capacity in any of the scenarios despite the low development cost.
- The aggressive electrification examined in the S1 scenario highlights the significant role that the baseload energy options (such as geothermal, hydropower, and natural gas) are playing in the power grid's stability with a large amount of variable renewable energy sources.
- Despite the aggressive electrification in the residential, commercial, and transportation sectors, the results of S1 and S2 scenarios indicate that meeting the provincial CO_2 emission reduction targets can only be met if the industry sector cuts emissions by half by 2040 another half by 2050.
- The results of the S2 scenario did suggest that policies such as carbon tax and cap-and-trade approaches by setting a limit on pollution and creating a market can change the timeline and direction of investment in the energy technology mix.

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APPENDIX A

The table below shows the formula used to convert PJ of energy demand for fossil fuels consumed in space heating and passenger and heavy-duty vehicles to electricity demand in the scenario 1 and 2. The translations are compliant with Clean BC initiatives.

Residential and commercial sectors
Converting PJ of demand for natural gas in space heating systems to electricity in heat pumps: Additional Electricity $Demand_{2050}$ = $Fossil\_Fuel\_Demand_{2050}$ * efficiency chain * Scenario Adoption_Efficency Assumption: S1 scenario: Scenario Adoption_Efficency = 100% $Demand_{electricity\ 2050} = Demand_{fossil\_fuel2050} * \eta_{chain} * \eta_{scenario}$ Where efficiency chain η_{chain} is: $\eta_{chain} = \eta_{furnace\ efficiency} * \eta_{heat\ pump\ efficiency} * \eta_{insulation}$ $\eta_{furnace\ efficiency} = 0.9$ $\eta_{heat\ pump\ efficiency}$ =0.25 (1:3 / 1:4 Coefficient of Performance (COP)) $\eta_{insulation} = 0.6$
Transportation sector
Converting PJ of demand for gasoline in motor-gas cars to electricity in EVs: New_Additional_Electricty $Demand_{2050}$ = $Fossil\_Fuel\_Demand_{2050}$ * efficiency chain * Scenario Adoption_Efficency <u>For Motor Gas</u> Assumptions: Assume of 100% car journeys turn into 50% electrical car journeys and 50% efficient electrical transit $Demand_{electricity\ 2050} = Demand_{motor\text{-}fuels\text{-}2050} * (\eta_{chain} * \eta_{scenario}) * transportation\_car + Demand_{motor\text{-}fuels\text{-}2050} * (\eta_{chain} * \eta_{scenario}) * transportation\_transit$ Where efficiency chain $\eta_{chain\ is:}$ $\eta_{chain} = \eta_{ice\text{-}engine\text{-}} * \eta_{electrical*motor} * \eta_{transit\text{-}mode}$ $\eta_{ice\text{-}engine}$ = 0.3 (ice stands for internal combustion engine) $\eta_{electrical\ motor}$ =0.9 $\eta_{transit\text{-}mode\ =}$ 1 for car 0.1 for transit transportation_car = 0.5 transportation_transit =0.5 <u>For Diesel Motors</u>: transportation_heavy_goods = 0.9 transportation_buses =0.1