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Demographic and Geographic Region Definition in Energy System Modelling

A case study of Canada's path to net zero greenhouse gas emissions by 2050 and the role of hydrogen

Author: Amara Slaymaker (SCIPER: 295585)

Supervisors: Professor Francois Marechal, Professor Manuele Margini, Tuong-Van Nguyen, Jonas Schnidrig

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Abstract

The urgency of reducing greenhouse gas emissions is greater now than ever, with the impacts of climate change becoming more apparent each year. Due to this, governments are setting ambitious targets such as reaching net zero GHG emissions by 2050, as announced by Canada in November of 2020. Within this context, the energy transition continues to gain momentum, as energy systems currently contribute to a large portion of these emissions. In order to support the energy transition, researchers, planners and policy makers alike are considering alternative solutions, such hydrogen, and are becoming increasingly reliant on energy system models in order to determine how the energy systems of the future should evolve.

This thesis adapts an optimization based energy system model called EnergyScope in order to model potential pathways for the production and utilization of hydrogen within an energy system. Further, different methods of the definition of regions within energy system models are considered. The EnergyScope model is adapted from a model based on regions defined by political boundaries, to a model based on regions defined by geographic and demographic characteristics. A method for defining these regions and integrating them into the model is developed. These models are then used to assess how Canada could meet its goal of reaching net zero GHG emissions by 2050 within the energy sector, and what role hydrogen could play in this future energy system.

The results highlight the importance of electrification in achieving a net zero energy system, indicating that the future system will be mainly based on renewable electricity generated by PV, wind and solar technologies. This will be used to fulfill the energy demand of the electricity sector, as well as the heating and transportation sectors, which will be mostly electrified. The results also indicate that hydrogen has a potential role to play in energy storage and heating in this net zero energy system, storing electricity when it is produced in excess and being used directly for heating (in place of electricity) when electricity generation is lower. The model indicates that hydrogen will likely be produced by emission free technologies such as natural gas pyrolysis and electrolysis, although uncertainty remains as these technologies are still maturing.

Further, it is shown that the definition of regions used in energy system models based on demographic and geographic characteristics, rather than political boundaries, can provide additional insights - particularly regarding the distribution of the potential of variable renewable technologies such as wind and solar, and how this corresponds to the distribution of demands and energy resource exchange networks.

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I would like to thank my supervisors Tivi and Jonas for supporting me through this project, as well as Francois Marechal and Manuele Margini for the opportunity to work on such an interesting project which is close to my heart.

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List of Abbreviations

AFC Alkaline Fuel Cell. 2

AMPL A Mathematical Programming Language. 2

ATR Auto-Thermal Reforming. 2

DAC Direct Air Capture. 2

DHN District Heating Network. 2

EC Electrolytic Cell. 2

ES EnergyScope. 2

ES Regional DG EnergyScope Regional - Demographic and Geographic. 2

ESR EnergyScope Regional. 2

EUD End Use Demands. 2

FC Fuel Cell. 2

GDP Gross Domestic Product. 2

GHG Greenhouse Gas. 2

GHI Global Horizontal Irradiation. 2

GIS Geographical Information Systems. 2

GWP Global Warming Potential. 2

IGCC Integrated Gasification Combined Cycle. 2

KPI Key Performance Indicator. 2

LFO Light Fuel Oil. 2

NG Natural Gas. 2

SMR Steam Methane Reforming. 2

US UltraSupercritical. 2

VRE Variable Renewable Energy. 2

CHAPTER 1

INTRODUCTION

1.1 Background

The urgency of acting to combat climate change is now more apparent than ever - highlighted most recently by the release of the IPCC's sixth report, which states that *"it is unequivocal that human influence has warmed the atmosphere, ocean and land. Widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred."*[1], and re-emphasizes that greenhouse gas (GHG) emissions are the main cause of climate change.

Within this context, the motivation of countries to act to limit GHG emissions has been increasing in recent years, with some countries announcing plans to significantly reduce their emissions, and to reach net zero GHG emissions by the year 2050. In November of 2020, Canada became one of these countries, announcing their target of reaching net zero emissions by 2050 and signing the Canadian Net Zero Emissions Accountability Act [2].

Despite these ambitious targets, the path to limiting GHG emissions and reaching net zero by 2050 is still full of uncertainty. One thing which is certain, however, is the important role of energy systems in achieving - or not - these targets. In Canada, the energy system (including buildings, electricity and transportation) accounts for almost 50% of GHG emissions [3]. Thus, a transition towards a renewable and CO_2 neutral energy system is absolutely necessary if Canada is to reach its net zero target by 2050.

This transition towards energy systems based on renewable and carbon neutral energy - popularly referred to as the "Energy Transition", has thus also been gaining in momentum in recent years, in line with efforts to reduce GHG emissions. The energy transition implies significant changes to current energy systems - which may include, for example, increased electrification in order to use renewable electricity for heating and transportation, the need for new energy storage solutions in order to account for the intermittency of renewable energies, and the production and use of alternative, carbon neutral fuels. The need to address these challenges has led to an increasing global interest in hydrogen. As it is possible to produce hydrogen via low-CO_2 or CO_2 free pathways, and hydrogen itself has no CO_2 emissions when converted into other forms of energy, this fuel has potential applications in all energy sectors, and could also be used for energy storage [4].

This being said, there is still significant debate about the role hydrogen can, and should, play in future energy systems. Already, competing visions of hydrogen production strategies are being developed - as seen in Canada where Alberta has announced plans to develop a blue hydrogen industry, producing low or carbon neutral hydrogen from fossil fuels using carbon capture, utilization and storage (CCUS) technologies, whereas Quebec has announced their interest in developing a green hydrogen industry, focusing on hydrogen production through electrolysis using renewable electricity [5][6]. The best way to integrate hydrogen into future energy systems also remains uncertain.

Energy system modelling is a useful tool for studying current and future energy systems, taking into account the demands of different sectors and the energy conversion technologies which could be used to meet these demands. Such models can allow, for example, to analyze potential impacts of different technologies on energy systems, and the identification of technology configurations which meet certain criteria - such as the ability to fulfill energy demands in a cost effective and CO_2 neutral way. This report will apply energy system modelling to the case of Canada, in order to study which resources and technologies should be prioritized in order to reach their target of net zero carbon emissions by 2050, and the potential role of hydrogen in this system.

1.2 State of the Art

1.2.1 Energy System Modelling

As the energy transition gains momentum, energy modelling has become a key tool for scientists, policy makers and planners when it comes to understanding and planning energy systems.

A review of existing large scale energy models conducted in [7] highlights that traditionally, many energy system models consider only one sector (such as electricity), and when the models to consider multiple sectors, the modelling of cross-sector interaction is limited. Further, in general energy system models can be divided into simulation and optimization models, both of which are used to analyze the costs and operations of energy systems. In general, simulation models are less computationally expensive, however they are dependent on user input conditions which influence the results. Optimization models, on the other hand, are more computationally expensive but allow the model to maintain a large number of degrees of freedom, minimizing the number of conditions that must be set by the user and allowing for an optimal configuration to be determined for complex, uncertain systems.

Another important characteristic of energy system models is spatial resolution. As the importance of location-dependent energy resources such as wind and solar gain importance, so does the need for energy system models which can account for the energy demands and potentials of specific regions [8]. Although regionalization within energy system models is becoming increasingly common, the regions are generally dictated by political boundaries, despite the fact that demands and potentials can vary significantly within one region when this definition is used. Therefore, there is a need to find new ways of defining regions within energy system models. Recent work by Siala [9] aimed to address this gap by defining regions for an energy system model of Europe based on clustering of geospatial data regarding load density distribution, solar and wind potentials.

The energy model presented in [7] is EnergyScope (ES), an energy system model which presents many advantages compared to current alternatives - it is open source, considers all energy sectors and potential interactions between them, and is optimization based while still maintaining a computational time on the order of seconds to minutes for monthly or hourly temporal resolution, respectively. Although the model presented in [7] does not account for separate regions, further work by [10] added regionalization with regions defined by political boundaries. However, additional region definition methods have not yet been implemented.

The energy system model used in this work will be ES. Due to the growing interest in modelling regions defined based on geographic and demographic features such as population and load distribution and renewables potential, an adapted version of ES will be created which implements regions defined based on these factors.

1.2.2 Hydrogen

The inclusion of hydrogen production and conversion technologies within energy system models in order to understand its potential role in, and influence on, future energy systems is also gaining interest. Recently, Evangelopoulou [11] used energy system modelling to assess the potential roles of carbon-free hydrogen in the energy system, considering three main scenarios - the use of hydrogen itself as an end use fuel, the use of hydrogen as a feedstock to produce carbon-neutral fuels, and the use of hydrogen as a carrier for chemical energy storage. This work demonstrated that the integration of hydrogen within the energy system could have benefits for future energy systems, allowing GHG emissions reductions at lower costs - although, the choice of how to produce and use hydrogen remains uncertain and depends on additional factors such as technology development and maturity, and policy decisions.

1.3 Problem Statement

This work applies energy modelling tools in order to assess how Canada's energy system might be able to reach carbon neutrality by 2050, and the role that hydrogen will play in this. In order to address this question, the ES energy system model is adapted to model various potential scenarios of hydrogen production and utilization, as well as to allow for modelling of regions defined by demographic and geographic characteristics. Thus, the main research questions addressed are:

- What are the potential pathways and relevant technologies for producing and using hydrogen?

- How can the technologies involved in these pathways be modelled and what are the relevant parameters?
- What geographic and demographic characteristics could be used to define regions within an energy system?
- How can these regions be implemented in an energy system model and used to help identify potentially optimal future energy systems?

Addressing these questions will allow for the development of an adapted ES model which will then be applied to the main case study considered, addressing the questions of:

- What are possible optimal energy system scenarios which will allow Canada to meet its goal of net zero GHG emissions by 2050?
- What role will hydrogen play in this future net zero energy system - which scenarios of hydrogen production and utilization could be the most optimal?

1.4 Project Background

This project is a Masters Thesis, completed as part of the Energy Science and Technology program of the Electrical and Electronics Engineering Section. The work has been conducted with the Industrial Processes and Energy Systems Engineering (IPESE) laboratory of Ecole Polytechnique Federale de Lausanne.

This project is part of a research project entitled *Systemic Evaluation of the Viability of Hydrogen Production and Utilization Methods for the Future of Quebec - Technical, Environmental, Economic, Social and Policy Analysis*. The project was proposed by Manuele Margini of Polytechnique Montreal, in collaboration with Francois Marechal of the IPESE laboratory of EPFL, in addition to others. It aims to use and adapt the ES model in order to perform this evaluation. This thesis represents the first stage in the project.

CHAPTER 2

METHODOLOGY

The models developed and used in this report are based on the EnergyScope Regional (ES-R) and ES Carbon Flow models. ES was first developed by Moret [12], and has since undergone various adaptations. The regional adaptation was implemented by Germano [10]. The carbon flows adaptation was developed by Li *et al* [13] . The modelling considerations specific to ES Carbon Flow were then added to ES-R, creating ES-R Carbon Flow, which was used as the basis for the basis for the models developed and used in this analysis - ES-R Canada, ES-R H_2 and ES-R DG.

The first step in the process was the development of ES-R Canada, which adapted ES-R with additional modelling considerations relevant to the Canadian context. ES-R Canada was then further adapted to ES-R H_2 through the addition of additional technologies to model the production and utilization of hydrogen. Finally, ES-R DG was developed, which adapts the region definition from one based on political boundaries (as in ES-R) to one based on clusters of similar demographic and geographic characteristics.

This section will present the additional modelling considerations implemented for each model.

2.1 General Approach

In general, the implementation of the of the ES-R Canada, ES-R H_2 and ES-R DG models has four main steps - data collection and pre-calculations, parameter and constraint selection, modelling and analysis. The first step involves determining the energy demands for the case study considered. The next step involves the selection or calculation of parameters and constraints for the case study. The case study is then modelled, and the model provides an output which is then analyzed. The ES-R DG model involves an extra step, which is the definition of the regions based on geospatial information.

The main tools used in this approach are AMPL (a mathematical programming language), the modelling language in which all ES models are written, and QGIS, an open-source GIS platform for the analysis of geospatial data, which is used for the definition of regions for ES-R DG.

2.2 Modelling

The following section describes the models - beginning with a general description of EnergyScope which is used as the basis for this work, and then an explanation of the additional constraints and considerations added for each subsequent version of the model.

2.2.1 EnergyScope (ES)

EnergyScope (ES) is an optimization based thermo-economic energy system model. The ES considered in this report is the monthly model, although an ES model with hourly time resolution also exists (ES - TD (typical days)).

2.2.1.1 Model

The model is based on "End Use Demands" (EUDs), which are defined as the energy demand at the point of use. EUDs are divided into five sectors - households, services, industry, agriculture and transportation. Within these sectors, there are 7 different end use demand types - low temperature space heating, hot water, high temperature heat, lighting, electricity, passenger mobility and freight mobility.

The model also includes various technologies which enable the conversion of resources (such as natural as, diesel wind, solar) into the EUDs. The EUDs and resources are referred to in the model as *layers*. At each time step, the model balances each layer, ensuring that the availability and production of each layer are equal to its consumption (by technologies) and EUD.

The models of the technologies consider both their thermodynamic characteristics - for example, the efficiency with which they convert one layer into another - as well as their economic characteristics, including their investment, maintenance and operation costs and lifetime.

The environmental characteristics (in terms of global warming potential (GWP)) of technologies are also considered. Various types of CO_2 layers are present in the model - including captured CO_2 ($CO_{2,c}$), point source emissions ($CO_{2,A}$), and dispersed emissions ($CO_{2,E}$). The emissions associated with the use of each technology are thus also modelled, and as with the other layers the model forces the balancing of these emissions at each time period. Any $CO_{2,C}$ (due to capture of $CO_{2,A}$ or $CO_{2,E}$ by capture technologies) must be either stored or utilized (by the appropriate carbon capture or utilization technologies), and any remaining emissions (including $CO_{2,A}$ or $CO_{2,E}$) are added to the overall GHG emissions of the energy system.

The model can then be used to determine an optimal energy system configuration based on either economic or environmental optimization, which satisfies the balance constraints as well as any other constraints defined by user-input parameters, such as constraints on the maximum potential of certain technologies.

2.2.1.2 Optimization

As mentioned, the optimization problem solved by the model can be either economic or environmental. The formulation of the respective optimization problems are as follows. The model includes variables, which are determined by the optimization, and parameters, which are defined by the user. They key outputs of the model are F_{mult} and $F_{mult,t}$ which determine the size and output of the set of technologies included in the model. The key variables, parameters and sets of ES are listed in tables 2.1 and 2.2. As discussed above, these optimization problems are also subject to constraints - the main constraint being the layer balance of the energy system, as well as additional constraints defined by user input parameters, such as the minimum and maximum sizes of technologies.

Economic Optimization:

$$\min \quad C_{tot} = \sum_i C_{inv(i)} \cdot \tau_i + C_{maint(i)} + \sum_j C_{op(j)} \tag{2.1}$$

$$C_{inv(i)} = \sum_r c_{inv(i)} \cdot F_{mult(i,r)} \tag{2.2}$$

$$C_{maint(i)} = \sum_r c_{maint(i)} \cdot F_{mult(i,r)} \tag{2.3}$$

$$C_{op(j)} = \sum_r \sum_t F_{Mult,t,(j,t,r)} \cdot c_{op(j)} \cdot t_{op(t)} \tag{2.4}$$

Environmental Optimization:

$$\min \quad GWP_{tot} = \sum_i GWP_{CO_{2,A(i)}} + GWP_{CO_{2,E(i)}} \tag{2.5}$$

$$GWP_{CO_{2,X(i)}} = \sum_r gwp_{CO_{2,X(i)}} \cdot F_{Mult_t(i,t,r)} \cdot t_{op(t)} \tag{2.6}$$

Multi-objective optimization can also be performed in order to take into account both environmental and economic objectives. In this case, the optimization problem is formulated as follows:

Multi-objective Optimization

$$\min \quad C_{tot} = \sum_i C_{inv(i)} \cdot \tau_i + C_{maint(i)} + \sum_j C_{op(j)} \tag{2.7}$$

$$\text{subject to} \quad GWP_{tot} \leq G \tag{2.8}$$

This summarizes the key elements of the ES model, which are maintained in the following adaptations of the model. Following this section, only the model adaptations are highlighted. Additional details regarding the core ES model and its other adaptations can be found in [7],[12],[10],[13].

Table 2.1: ES Model - Key Variables and Parameters

Name	**Unit**	**Description**
C_{tot}	MCAD/year	The total annualized investment cost
$C_{inv(i)}$	MCAD	Total investment cost of i
$C_{maint(i)}$	MCAD/year	Total annual maintenance cost of i
$C_{op(i)}$	MCAD/year	Total annual operation cost of j
$c_{inv(i)}$	MCAD/kW	Investment cost of i
$c_{maint(i)}$	MCAD/kW	Maintenance cost of i
$c_{op(j)}$	MCAD/kWh	Operation cost of j
$F_{mult(i,r)}$	kW	Installed capacity of i in region r
$F_{mult_t(i,t,r)}$	kW	Utilized capacity of i in r during t
$t_{op(t)}$	h	Operating time of t
GWP_{tot} $ktCO_{2,eq}$/year	Total annual GWP	
$GWP_{CO_{2,X(i)}}$	$ktCO_{2,eq}$/kWh	Emissions factor of i
τ_i	$year^{-1}$	Cost annualization factor of i

Table 2.2: ES Model - Key Sets

Symbol	**Name**
i	Technologies
j	Resources
r	Regions
t	Periods

2.2.2 ES-R Canada

Two modifications were implemented to the model in order to account for the particularities of the Canadian context. These are (1) the modelling of off-grid electricity demand, which did not exist in previous versions of the model, and (2) the modelling of resource exchange connections between regions with a separate connection parameter for each resource, whereas previously the model only included one connection parameter which was applied to all resource exchanges.

The motivation for the modifications can be seen from figures 2.1 and 2.2. Although the overall energy and electricity demands of off-grid communities are small with respect to Canada's total demands, these communities still represent a unique feature of Canada's energy system. Further, as can be seen in 2.1, a majority of off-grid communities currently rely on fossil fuel generated electricity. Therefore, they must be taken into account when planning for Canada's future net zero energy system. Further, as can be seen in 2.2, the electrical grid of Canada covers only a small portion of the country, and there are certain regions (in particular, the three territories - Nunavut, Yukon and the Northwest Territories) which are not connected to the national grid. Therefore, there are connections which exist between regions for the exchange of resources which can be transported by road or rail (such as wood, petroleum products) where no grid connection allowing the exchange of electricity is available.

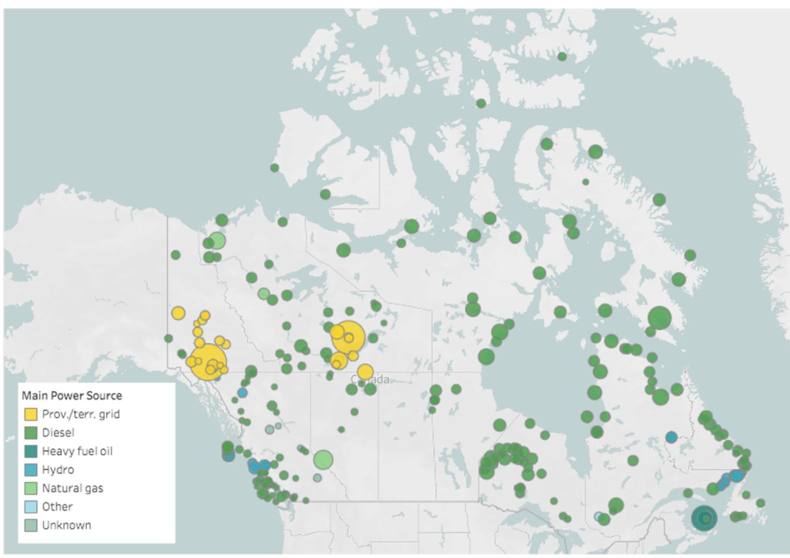


Figure 2.1: Canada's Off-Grid Communities [14]

2.2.2.1 Layers, Sets, Parameters and Variables

First, in order to model the off-grid electricity demand, the electricity layer was replaced by two separate layers - grid electricity and off-grid electricity. The additional parameters and variables

Figure 2.2: Canada's Electrical Grid (Transmission Network) [15]

added can be seen in table 2.3. The constraints added or adapted are as described below.

Table 2.3: ES-R Canada Specific Variables and Parameters

Name	Unit	Variable/ Parameter	Description
share_elec_og_min$_r$	-	Parameter	Minimum share of electricity demand that is off-grid demand (for each region r)
share_elec_og_max$_r$	-	Parameter	Maximum share of electricity demand that is off-grid demand (for each region r)
Share_Elec_Og$_r$	-	Variable	Share of electricity demand that is off-grid demand (for each region r)
connection$_{r_1,r_2,i}$	-	Parameter	Connection between regions r$_1 and r_2$ for the exchange of resource i. (1 if there is a connection, 0 if not.

This adaptation also required the addition of technologies to fulfill the off-grid electricity demand. A new set of off-grid electricity technologies was therefore created within the model. A list of the technologies added can be seen in table A.1. A description of the modelling parameters considered for each technology can be found in appendix A. In addition, off-grid versions existing ES technologies - including PV, wind, and hydro, as well as heating technologies with electricity inputs (such as heat pumps) or outputs (such as co-generation technologies), were added. In these cases, the existing parameters were maintained, with the maintenance costs increased by 5%, to account for the increase expected for smaller systems [16]. In reality, the investment costs per kW for smaller systems may also be higher, however this was not considered and could be investigated

Table 2.4: Off Grid Electricity Technologies Added in ES-R Canada

Name	Description	Input	Output
DIESEL_GEN	Diesel Generator	Diesel	Electricity
NG_GEN	Natural Gas Generator	NG	Electricity

further in the future.

2.2.2.2 Constraints

The end-use demand calculation constraint for electricity in ES Canada was adapted from [12] to include the share of off-grid electricity demand, such that:

$$EndUse_{elec_g,t,r} = \left(\frac{EndUsesInput_{elec,r}}{8760} + \frac{EndUsesInput_{lighting,r} \cdot Share_{lighting,t,r}}{t_op_t}\right) \cdot (1 - Share\_Elec\_Og_r) + Losses_{elec_g,t,r} \tag{2.9}$$

and

$$EndUse_{elec_{og},t,r} = \left(\frac{EndUsesInput_{elec,r}}{8760} + \frac{EndUsesInput_{lighting,r} \cdot Share_{lighting,t,r}}{t_op_t}\right) \cdot (Share\_Elec\_Og_r) \tag{2.10}$$

One additional constraint was added to maintain the share of off-grid electricity demand between the minimum and maximum values.

$$share\_elec\_og\_min_r \leq Share\_Elec\_Og_r \leq share\_elec\_og\_max_r \tag{2.11}$$

2.2.3 ES-R H_2

As discussed in section 1, the potential role of hydrogen in Canada's future net zero energy system is of particular interest for this analysis. While the previous versions of ES-R include some general technologies for hydrogen production as well as hydrogen mobility technologies and power to gas storage, ES-R H_2 built upon this to include additional technologies and represent more completely the possibilities for the production and utilization of hydrogen.

2.2.3.1 Layers, Sets, Parameters and Variables

A representation of the technologies added to the model can be seen in 2.3. Only the technologies added to existing sets, and the new sets included, are shown. The adaptation required the creation of two new sets - a set of technologies for ammonia production and a set for steel production. These sets were included in ES-R H_2 because these are two of the industries with significant hydrogen demand in Canada [4], and the non-energy use demands for hydrogen may impact the role of hydrogen in the overall energy system. Further, these industries can contribute significantly to CO_2 emissions, depending on the method of hydrogen production, and thus the production of hydrogen for these industries is also an important aspect of achieving net zero GHG emissions in Canada. In general, the technologies added were selected with reference to Canada's national hydrogen strategh [4], which provides a very complete overview of the potential strategies for producing and using hydrogen. Other technologies which were already included in the ES model include mobility technologies (such as hydrogen freight trucks, fuel cell cars and fuel cell buses), as well as methanation, which reacts carbon dioxide with hydrogen to produce natural gas.

As can be seen in figure 2.3, five new layers were also created - $H_2, 100bar$, $H_2, 200bar$, $H_2, 300bar$ were added in addition to the existing H_2 layer, which represents hydrogen at atmospheric pressure. These were included in order to model the fact that depending on the technology, hydrogen must be used and stored at pressures above atmospheric pressure. Ammonia and steel layers were also added, to account for the industry demand as described previously.

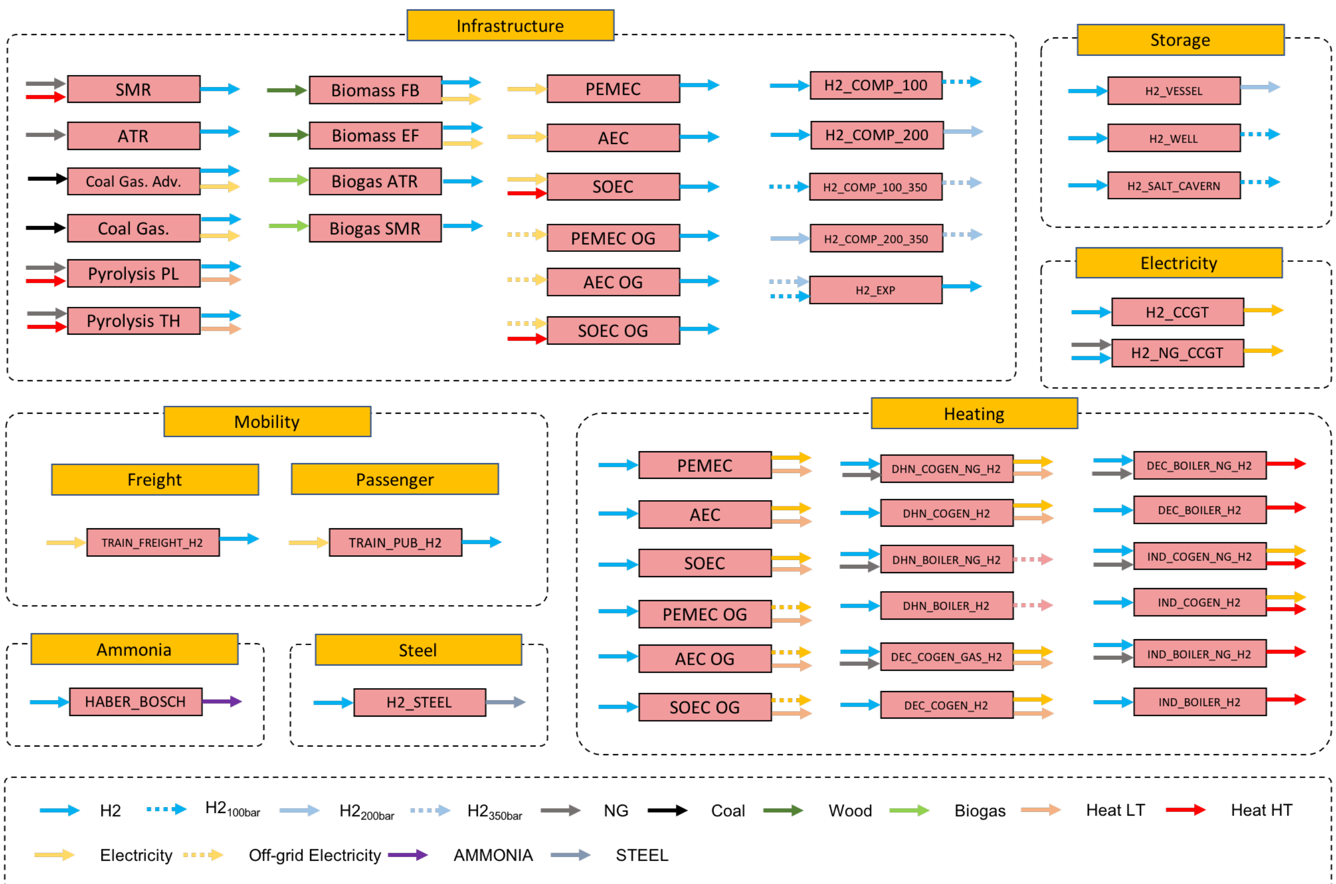


Figure 2.3: Hydrogen Technologies Added to ES Technology Sets

More details regarding the parameters used for modelling of these technologies can be found in appendix B.

2.2.3.2 Constraints

No specific constraints were added for the ES-R H_2 model.

2.2.4 ES-R DG

As introduced in section 1, there is a growing interest grouping energy systems into regions based on demographic and geographic characteristics, rather than political regions. The interest of this can be further seen in figures 2.1 and 2.2. Within a single province, there are separate off-grid communities, regions which are not connected to the electrical grid and regions very sparsely, or not at all, inhabited. The potentials of renewable energy resources such as hydro, solar and wind, as well as their availability (considering access to the grid and other land uses) can also very significantly across a single province. With this motivation in mind, ES-R DG was developed in order to model the energy system with regions defined by similar demographic and geographic characteristics. The following section describes the adaptation of the ES model to account for this new type of regionalization. The method used to define these regions is described in section 2.3.

2.2.4.1 Layers, Sets, Parameters and Variables

The main sets and layers of the ES-R model (including the modifications described previously for ES-R Canada and ES-R H_2) were maintained for the ES-R DG model. One additional set was added containing the demographic/geographically defined regions - hereinafter referred to as "clusters", due to the clustering methodology used to define them (section 2.3).

The parameters and variables which were previously defined for each region were adapted to be defined for each cluster. For the regions, the set regions was maintained as well as the parameter regarding the end uses demands per region, as end use demands are still input into the model for regions, and then calculated within the model for each cluster. The additional variables and parameters added are described in table 2.5.

Notably, this version of the ES model changes the transportation network connection from a parameter defined by the user (ES-R) to a binary variable selected during the solving of the optimization problem (ES-R DG). The other variables are mainly used in the constraints linked to distribution of the demand.

The end_uses_demand_year$_{i,s,c,r}$ parameter was calculated based on the input data for regional end use demands (end_uses_demand_year$_{i,s,r}$ as follows. It was assumed that the household and services demand was distributed proportionally based on population, the agricultural demand was distributed proportionally based on agricultural area, and the industrial and transportation demands were distributed proportionally based on the extended ecumene area, where ecumene refers to inhabited areas.

Table 2.5: ES-R DG Specific Variables and Parameters

Name	Unit	Variable/ Parameter	Description
cluster_composition$_{c,r}$	-	Parameter	The percentage of cluster c in region r (based on area)
area$_r$	km^2	Parameter	Total area of each region r
area$_c$	km^2	Parameter	Total area of cluster c
pop_dens$_c$	cap./km^2	Parameter	Population density of cluster c
agri_perc$_c$	-	Parameter	Percentage of agricultural area of cluster c
ecu_perc$_c$	-	Parameter	Percentage of extended ecumene area of cluster c
pop$_r$	cap.	Parameter	Population of region r
agri_area$_r$	km^2	Parameter	Agricultural area of region r
ecu_area$_r$	km^2	Parameter	Extended ecumene area of region r
cost_connection$_i$	MCAD/km	Parameter	Investment cost associated with connection infrastructure for the transportation of resource i
connection_distance$_{i,c}$	km	Parameter	Average distance of cluster c from the transportation network of resource i
end_uses_demand_year$_{i,s,c,r}$	GWh	Parameter	The annual end use demand for end use category i, in sector s, of cluster c, within region r
connection_c$_{i,c}$	-	Variable	Binary variable for the existence of a connection to the transportation network of resource i within cluster c. (1 if connected, 0 if not)
cost_connection_tot$_c$	MCAD/year	Variable	Total cost of extending the resource transportation connections in cluster c

When sector s is households or services:

$$end\_uses\_demand\_year_{i,s,c,r} = \frac{end\_uses\_demand\_year_{i,s,r} \cdot pop\_dens_c \cdot cluster\_composition_{c,r} \cdot area_r}{pop_r} \tag{2.12}$$

When sector s is agriculture:

$$end\_uses\_demand\_year_{i,s,c,r} = \frac{end\_uses\_demand\_year_{i,s,r} \cdot agri\_perc_c \cdot cluster\_composition_{c,r} \cdot area_r}{agri\_area_r} \tag{2.13}$$

When sector s is industry or transportation:

$$end\_uses\_demand\_year_{i,s,c,r} = \frac{end\_uses\_demand\_year_{i,s,r} \cdot ecu\_perc_c \cdot cluster\_composition_{c,r} \cdot area_r}{ecu\_area_r} \tag{2.14}$$

2.2.4.2 Constraints

The creation of the binary connection variable necessitated the following additional constraints. While previously the share of off grid electricity demand was determined within a minimum and maximum range input into the model, the new model must determine the share based on whether the optimization determines that the cluster is connected to the electrical grid or not.

$$Share\_Elec\_Og_{(c)} = (1 - connection\_c_{(elec_{grid},c)}) \tag{2.15}$$

The same logic applies to the import and export of electricity, which must be prevented if a cluster is not connected to the electrical grid, which implies the following constraints:

$$\sum_t F_{Mult,t(import,c)} \cdot t_{op(t)} \leq availability_{(import,c)} * connection\_c_{(elec_{grid},c)} \tag{2.16}$$

$$\sum_t F_{Mult,t(export,c)} \cdot t_{op(t)} \leq availability_{(export_{elec},c)} * connection\_c_{(elec_{grid},c)} \tag{2.17}$$

As the availability of location-independent resources such as wood and biogas were not defined on the cluster level and only known on the provincial level, an additional constraint was added to limit the total use of resources, whereas the maximum availability of resources per cluster is not constrained:

$$\sum_c \sum_t F_{mult,t(j,t,c)} \cdot t_{op(t)} \leq \sum_r availability_{j,r} \tag{2.18}$$

The total cost associated with any new connections to resource transportation networks is determined as follows:

$$cost\_connection\_tot_c = \sum_i connection\_c_{i,c} \cdot connection\_distance_{i,c} \cdot cost_connection_i \cdot \tau \quad (2.19)$$

The total connection cost is then added to the calculation of total cost, such that the decision of whether or not to connect is determined during economic optimization.

2.3 Demographic and Geographic Regionalization for ES DG

As mentioned briefly previously, the demographic and geographic regionalization was performed using a clustering method applied on geospatial data. The following section describes the selection of demographic and geographic attributes, and the clustering method. Details regarding the data sources and the data processing are described in section 2.3.3.

2.3.1 Attribute Selection

The geographic and demographic features selected for clustering are listed in table 2.6.

In terms of potentials, wind, solar and hydro were considered as these resources are location dependent and cannot feasibly be moved from one region to another. Although other resources - such as biomass - may be more prominent in some regions than others, transportation between regions is easily feasible. The actual available potential was considered by taking into account both the capacity factors and the area available - in order to account for the possibility that although some areas may have a high capacity factor for wind or solar, that area may be dedicated to other uses which render capturing that potential difficult or infeasible (for example, they may be forested or protected areas).

In terms of demographic characteristics, the population density and urban area, agricultural area and ecumene area were considered. These factors were selected in order to model the distribution of energy demands of different sectors, which were considered proportional to these areas as discussed above.

Finally, the distance from the electrical grid was considered. Given the limited reach of the electrical grid in Canada and the potential importance of electrification in future energy systems, consideration of this parameter allows to model on versus off-grid energy demands, and the interest of connecting off-grid regions.

2.3.2 Clustering

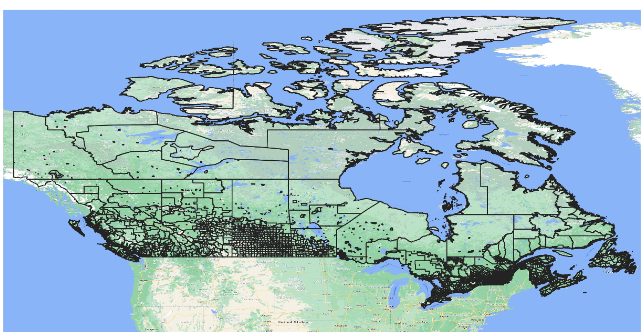
The map of Canada was first divided into smaller sub-regions defined by Canada's Census Subdivisions (CSDs) (figure 2.4a). Although the CSDs are still a form of political region definition,

Table 2.6: Demographic and Geogrphic Features Selected for the Definition of Energy System Regions

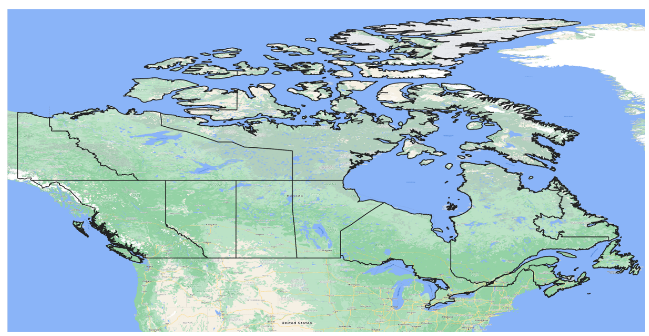
Name	Unit	Description
$C_{p,solar}$	-	Capacity factor of solar PV
$C_{p,wind}$	-	Capacity factor of wind
$C_{p,hydro}$	-	Capacity factor of hydro
$Area_{\%,solar}$	-	Percentage of land area available for solar PV
$Area_{\%,wind}$	-	Percentage of land area available for wind
$Hydro_{potential}$	GW/km^2	The hydro potential per square kilometer
$Area_{\%,agri}$	-	Percentage of land area which is agricultural
$Area_{\%,ecu}$	-	Percentage of land area within the extended ecumene
$Area_{\%,urban}$	-	Percentage of land urban land area
Pop_{dens}	cap./km^2	Population density
$Grid_{distance}$	km	Average distance from the transmission network

these are simply used as a basis for assigning attributes. As can be seen in figure 2.4, the CSDs are much smaller than the provinces, and there would be too many CSDs to model all of them in an energy system. Therefore, they are only starting point for the analysis.

The value of each selected attribute was determined and assigned to each CSD based on geospatial data analysis (2.3.3). A clustering method was then used to assign CSDs with similar geographic and demographic characteristics (the attributes discussed above). The CSDs belonging to the same cluster are then modelled as a single cluster/region within the ES-R DG model.



(a) Census Subdivisions



(b) Provinces

Figure 2.4: Maps of Canada

Once the value of each attribute was determined for each CSD, the attributes were prepared for clustering by scaling using the min max method, which normalizes the data between 0 and 1 as follows:

$$X_i^{'} = \frac{X_i - X_{min}}{X_{max} - X_{min}} \tag{2.20}$$

where $X^{'}_{i}$ is the scaled value i of attribute X, X_i is the original value, and X_min and X_max are the minimum and maximum values of attribute x, respectively.

Following this, the k-means clustering algorithm was applied. The k-means algorithm solves the following optimization problem:

$$min \sum_{j=1}^{k} \sum_{i=1}^{n} \|x_i^{(j)} - c_j\|^2 \tag{2.21}$$

which is where k is the number of clusters, n is the number of cases, c_j is the centroid of cluster j and $x_i^{(j)}$ is case i in cluster j.

The number of clusters must be selected by the algorithm user. In order to select the number of clusters, following indicators were considered for different values of cluster number k:

The total sum of errors squared (SES):

$$SES = \sum_{j=1}^{k} \sum_{i=1}^{n} \|X_i^{(j)} - C_j\|^2 \tag{2.22}$$

The average error squared (AES):

$$AES = \frac{1}{n} \sum_{j=1}^{k} \sum_{i=1}^{n} \|X_i^{(j)} - C_j\|^2 \tag{2.23}$$

The average relative error (ARE):

$$ARE = \frac{1}{n} \sum_{j=1}^{k} \sum_{A}^{a=1} \sum_{i=1}^{n} \frac{|x_{i,a,j} - c_{a,j}|}{x_{i,a,j}}$$

(2.24)

The average inter-cluster distance (AICD):

$$AICD = \frac{1}{k^2} \sum_{j=1}^{k} \sum_{i=1}^{k} \|c_i - c_j\|^2 \tag{2.25}$$

2.3.3 Geospatial Data Processing

As mentioned, the geospatial data used for cluster definition was processed using the geographical information systems tool QGIS. The GIS data and sources used for determining the attributes discussed above are listed in table 2.7.

The GHI and wind speed data were available for environmental weather stations spread across Canada. Each CSD was assigned the average GHI and wind speed values based on the closest stations. The solar c_p was calculated from the GHI as:

$$c_{p,solar} = \frac{GHI_{avg}\frac{kW}{m^2}}{1000\frac{kW}{m^2}} \tag{2.26}$$

The wind c_p was calculated using the approximation in [17], which relates the capacity factor to the wind speed (μ_v) in m/s , turbine rotor diameter (D) in m and turbine rated power (P_r) in kW. A rotor diameter of 110m [18] and a rated power or 2MW [19] were assumed.

$$c_{p,wind} = (1-0.087)\{tanh\frac{0.087\cdot\mu_v^2}{2\pi\cdot(1+(P_R/D^2))+P_R/D^2} - \frac{0.087}{2\pi\cdot(1-(P_R/D^2))\cdot\mu_v}\} \tag{2.27}$$

GIS data regarding the location and capacity of existing hydro plants was used to determine hydro capacity. First, total existing hydro capacity (MW) of each CSD was determined based on the GIS data. Canada's additional, undeveloped hydro potential (as defined in [20]) was assumed to be distributed proportionally to existing hydro potential. The potential per km^2 was then calculated according to the area of the CSD. It should be noted that this assumption is a limitation of the cluster definition method, as there may be hydro potential in areas which currently have no developed hydro plants - however, GIS regarding the distribution of undeveloped hydro potential was not available. Additional analysis regarding this should be considered in the future.

The hydro c_p was determined for each province based on data regarding annual installed capacity [21] and generation [22]. The hydro c_p of each CSD was assumed to be equal to that of the province the CSD is in.

A map of the transmission network was used to determine the average distance from the transmission grid for each CSD. This was achieved using the distance calculation tool in QGIS, which calculates the distance from the center of each cluster to the closest network point.

The population density was calculated based on the area and population of each CSD, as provided by Statistics Canada. The percentage of each CSD's area corresponding to urban, agricultural and ecumene areas was determined using the CSD map data, as well as the ecumene maps provided by Statistics Canada and Natural Resources Canada. This was achieved using the difference tool in QGIS, which can calculate the overlapping area of two shapes overlaid on the map. This allowed the calculation of the urban, agricultural and ecumene area of each CSD.

The area available for wind and solar was calculated based on the data regarding the urban and agricultural land area, as well as the land cover type. First, the urban and agricultural areas of each CSD were excluded. Then, the overlapping area corresponding to forest was also excluded. The remaining area was considered 100% available for wind or solar development. Of the other area, it was considered that agricultural area was 100% available for wind development, and 20% available for solar [23]. Finally, it was considered that an additional area of 13 m^2/capita was available for development of rooftop solar installations, based on [24] which analyzed the per capita area suitable for rooftop PV in Ontario, Canada. Using these factors, the total value and percentage of each CSD's area available for wind and solar technology was calculated.

Table 2.7: Geospatial Data - Data Sources

Geospatial Data	**Unit**	**Source**
Average annual GHI	kW/m^2	Government of Canada [25]
Average annual Wind Speed	m/s	Government of Canada [25]
Land Cover Type	-	Government of Canada [26]
Transmission Network	-	Natural Resources Canada [15]
CSD Area and Population	-	Statistics Canada [27]
Hydro Plants	-	Natural Resources Canada [15]
Urban Ecumene	-	Statistics Canada [28]
Agricultural Ecumene	-	Statistics Canada [29]
Extended Ecumene	-	Natural Resources Canada [28]

CHAPTER 3

CASE STUDIES

The following section describes the specific modelling considerations and parameter estimations applied for the case studies analyzed in this work. The main case studies considered include (1) the 2018 Canadian energy system, used to validate the ES-R Canada model, as well as (2) the 2050 Canadian energy system as implemented in the ES-R H_2 model, and (3) the 2050 Canadian energy system as implemented in the ES-R DG model.

3.1 2018 Canadian Energy System - ES-R Canada

The 2018 Canadian energy system was selected as the reference system to use for validation of the ES-R Canada model as data regarding the energy demands and energy generation of this system are well documented and can be used for comparison in order to validate that the model is functioning as expected. The parameters used for this model are explained below.

3.1.1 End-Use Demands

As discussed in the previous section, the main input to the ES model are the end use demands (EUDs). The EUDs for the reference year of 2018 were obtained from Natural Resources Canada's *Comprehensive Energy Use Database* [30]. This database provides end-use energy demand data for five sectors - residential, commercial, industrial, transportation and agriculture - and for different regions (provinces, territories, or groups in some cases a group of provinces and/or territories). In order to relate the data available in this database to the main sectors and demand types that describe the EUDs within the ES-R Canada model, the following additional assumptions were made.

3.1.1.1 Residential:

For the residential sector, data was provided according to the following categories: space heating, water heating, appliances, lighting and space cooling. Space heating, water heating and lighting already correspond to ES EUS types. It was assumed that the energy demand of appliances was electricity demand. In reality, a small portion of this demand is for natural gas - for example for use in gas cooking stoves - however, this represents a small portion and was neglected. Space cooling demand was neglected, as cooling technologies are not yet integrated into ES and space cooling represents a small percentage of the total residential energy demand in each province (between 0 and 1.62% in every province and territory except for Ontario and Manitoba, where it represents 4.18% and 4.10% respectively). However, it is recommended to include this in future work.

Data was available for each province, however the data regarding the three territories (YT, NT, NU) was grouped together. The total end-use demand for the territories was therefore allocated as follows:

$$EndUseDemand_{rc,i} = EndUseDemand_{rc,territories} \cdot \frac{Demand_i}{\sum_{j=1}^{3} Demand_j} \tag{3.1}$$

where $EndUseDemand_{c,i}$ is the end use demand of territory i in residential category rc, $EndUseDemand_{c,territories}$ is the total end use demand of all territories in residential category cc, $Demand_i$ is the total annual energy demand (excluding industrial energy demand) of territory i and $Demand_j$ is the total annual energy demand (excluding industrial energy demand) of territory j. The total annual non-industrial energy demand of each territory was obtained from the Canada Energy Regulator [31]. It should be noted that this data was only available for the year 2017, however the relative proportions were assumed to remain relatively constant. The total annual non-industrial energy demand was used for allocation as opposed to the population due to the fact that energy consumption per capita varies significantly between the different Canadian provinces and territories.

3.1.1.2 Commercial/Services:

For the commercial sector - referred to as the services sector in ES - data was available for the following categories: space heating, water heating, auxiliary equipment, auxiliary motors, lighting, space cooling and street lighting. Street lighting demand was attributed to the lighting demand in ES. It was specified in the database that the auxiliary motors consumed only electricity, therefore this demand was attributed to electricity demand [30]. Finally, the auxiliary equipment demand was further analyzed according to energy source and further broken down into electricity, which was therefore attributed to electricity demand, and natural gas, coal and propane, which was attributed to high temperature heating demand.

Data for the four Atlantic provinces (NL, NB, NS, PE) was grouped together, and data for BC and the three territories (YT, NT, NU) was grouped together. This grouped data was allocated as follows:

$$EndUseDemand_{cc,i} = EndUseDemand_{cc,group} \cdot \frac{GDP_{services,i,2018}}{\sum_{j=1}^{n_{group}} GDP_{services,j,2018}} \tag{3.2}$$

where $EndUseDemand_{sc,i}$ is the end use demand of province or territory i in services category cc, $EndUseDemand_{sc,group}$ is the total end use demand of the group in services category cc, $GDP_{services,i,2018}$ is the GDP of the services sector of province or territory i in 2018, $GDP_{services,j,2018}$ is the GDP of the services sector of province or territory j, and n_group is the number of provinces or territories in the group. The GDP of the services industry was obtained from Statistics Canada [32].

3.1.1.3 Industry

: For the industrial sector, data was available either per industry (for example pulp paper, construction, cement, etc.) or per energy source (for example electricity, natural gas, coal, fuel oil). Therefore, additional assumptions were made to divide this into the ES EUD types of electricity, lighting, high temperature heating, space heating, and water heating.

For the electricity energy source, it was assumed that 6% of the total electricity was lighting demand[33], and that the remaining 94% was electricity demand. It was further assumed that energy demand from all other sources was heating demand. In order to separate this heating demand further into high temperature (HT), space heating (SH) and water heating (HW) demand, the percentages in table 3.1. The percentages were approximated according to the findings of Naegler et al.[34]. Where there were differences between the industry types found in Canada's energy demand database and those studied by Naegler et al., the following assumptions were made. Smelting refining was assumed to be equivalent to metal processing. Petroleum refining was assumed to be similar to the cement and iron steel industries.

Table 3.1: Heating Demand in Industry - High Temperature, Space Heating and Water Heating Demand Percents of Total Heating Demand, according to Industry Type [34]

Industry Category	**HT Demand (%)**	**SH Demand (%)**	**HW Demand (%)**
Construction	84.00	13.60	2.40
Pulp and Paper	97.50	2.50	0.00
Smelting and Refining	83.00	14.96	2.04
Petroleum Refining	97.50	2.50	0.00
Cement	97.50	2.50	0.00
Chemicals	82.00	18.00	0.00
Iron and Steel	97.50	2.50	0.00
Other Manufacturing	84.00	13.60	2.40
Forestry	87.00	13.00	0.00
Mining, Quarrying, Oil and Gas Extraction	96.00	4.00	0.00

In terms of groups, similarly to the services sector, the industry sector data had two groups - Atlantic provinces (NL, NB, NS, PE) and BC and Territories (BC, YT, NT, NU). The grouped data was allocated as follows:

$$EndUseDemand_{isc,i} = EndUseDemand_{isc,group} \cdot \frac{GDP_{industry_{cat},i,2018}}{\sum_{j=1}^{n_{group}} GDP_{industry_{cat},j,2018}} \tag{3.3}$$

where $EndUseDemand_{isc,i}$ is the end use demand of province or territory i in industrial energy demand of energy source category isc, $EndUseDemand_{isc,group}$ is the total end use demand of the group in industrial energy source category isc, $GDP_{industry_{cat},i,2018}$ is the GDP of the relevant industry category of province or territory i in 2018, $GDP_{industry_{cat},j,2018}$ is the GDP of the relevant industry category of province or territory j, and n_group is the number of provinces or territories in the group. The GDP data was obtained from Statistics Canada [32]. It should be noted that for the energy source natural gas, n_group for the BC and Territories group was taken as 3 and included BC, YT and NT. NU was excluded from the group as NU does not consume any natural gas [31].

3.1.1.4 Transportation:

The energy demand for transportation was available for several transportation types, including both passenger transportation modes (car, passenger light trucks, motorcycles, school buses, urban transit, inter-city buses, passenger air, passenger rail and off-road) and freight transportation modes (freight light trucks, freight medium trucks, freight heavy trucks, freight air, freight rail, and marine). For the purposes of this thesis, air transportation (both freight and passenger), marine transportation and off-road transportation were excluded from the analysis.

The database also provided the energy intensity of each transportation mode, in terms of MJ/pkm (passenger transport) or MJ/tkm (freight transport). This data was therefore used to convert the demand into passenger-kilometers (pkm) or tonne-kilometers (tkm) for ES.

The transportation sector had one data group - BC and Territories (BC, YT, NT, NU). The grouped data was allocated as follows:

$$EndUseDemand_{tm,i} = EndUseDemand_{tm,group} \cdot \frac{Pop_{i,2018}}{\sum_{j=1}^{n_{group}} Pop_{j,2018}} \tag{3.4}$$

where $EndUseDemand_{tm,i}$ is the end use demand of province or territory i for transportation mode tm, $EndUseDemand_{tm,group}$ is the total end use demand of the group for transportation mode tm, $Pop_{i,2018}$ is the population of province or territory i in 2018, $Pop_{j,2018}$ is the population of province or territory j, and n_group is the number of provinces or territories in the group. The population data was obtained from Statistics Canada [35]. Data was provided on a quarterly basis, therefore the population of 2018 was taken as the average population over the four periods.

3.1.1.5 Agriculture:

The agricultural end use demand data was broken down into non-motive energy demand (with energy resources electricity, natural gas, light fuel oil, kerosene, heavy fuel oil, propane and steam), and motive energy demand (with energy resources motor gasoline and diesel fuel oil).

Regarding the motive energy demand, it was assumed that all of this demand was linked to transportation, and this was therefore attributed to freight transportation demand. The energy demand provided was converted into tonne-kilometers (tkm), the unit used to describe freight transportation demand, using the average energy intensity (in terms of MJ/tkm) of freight trucks (light, medium and heavy) provided in the transportation section of the database, as discussed above. Regarding the non-motive energy demand, it was assumed that 4% of the electricity source demand was lighting demand, with the remainder being electricity demand [36]. It was further assumed that the energy demand from all remaining sources was heat demand, with 10% being water heating demand and the remainder being space heating demand [36].

Again, the agricultural sector data had two groups - Atlantic provinces (NL, NB, NS, PE) and BC and Territories (BC, YT, NT, NU). The grouped data was allocated as follows:

$$EndUseDemand_{ac,i} = EndUseDemand_{ac,group} \cdot \frac{GDP_{agriculture,i,2018}}{\sum_{j=1}^{n_{group}} GDP_{agriculture,j,2018}} \tag{3.5}$$

where $EndUseDemand_{ac,i}$ is the end use demand of province or territory i in agriculture energy source category ac, $EndUseDemand_{ac,group}$ is the total end use demand of the group in agriculture energy source category ac, $GDP_{agriculture,i,2018}$ is the GDP of agriculture of province or territory i in 2018, $GDP_{agriculture,j,2018}$ is the GDP of agriculture of province or territory j, and $n_g roup$ is the number of provinces or territories in the group. The GDP data was obtained from Statistics Canada [32]. Again, NU was assumed to have no demand for natural gas.

3.1.2 Resources

The main resource parameters considered in ES are annual availability (GWh/year) and operating costs (MCAD/GWh). The method used to estimate these parameters is described below.

3.1.2.1 Availability:

Specific values of availability were calculated for the following ES resources: waste, wood, dry wood, wet biomass and biogas. Key sources are summarized in table 3.2.

The availability of waste in terms of kg/province/year was determined from [37] for 2016. Increase in waste availability (for the year 2018) was assumed to be equivalent to population growth. An average value of 10 MJ/kg[38] was used to determine the annual availability in terms of GWh/year.

The availability of residual biomass resources from foresty, crop agriculture and animal agriculture were determined from [39] for the year 2001 in terms of GWh/year. The increase in availability for the year 2018 was considered equivalent to the GDP growth between 2001 and 2018 of the forestry and logging, cop production and animal and aquaculture industries respectively. Further, the distribution of the overall Canadadian availability was assumed to be proportional to these GDPs. This GDP data was obtained from Statistics Canada [32]. The availability from crop and animal agriculture was considered wet biomass. Of the availability from forestry, 57% was considered wood and the remaining 43% was considered dry wood (assuming Canada has a similar wood to dry wood ratio to for Switzerland, where this value was available from adaptations of the ES model).

The total biogas potential in Canada was determined from [40]. As determined by the report, 68% of the biogas potential comes from agriculture - therefore, the biogas potential per province was assumed to be proportional to the agricultural GDP (accounting for both crop production and animal and aquaculture).

Table 3.2: Resource Availability Data Sources

Resource	**Source**
Waste	Environmental & Climate Change Canada [37]
Biomass	BIOCAP Canada Foundation [39]
Biogas	Biogas Association [40]

3.1.2.2 Operating Costs:

A summary of the operating costs used in the model can be found in table 3.3. As resource prices are not fixed and depend on market variations, values within the fluctuation range were selected. Generally, prices in the higher range were selected.

3.1.3 Technologies

Technology potentials were considered for renewable energies - including geothermal, solar, wind, hydro and solar - as the potential of these technologies is variable in terms of both time and space.

The geothermal potential was determined from the Canadian Geothermal Energy Association (CanGEA) database [47]. Data is only provided for Alberta, British Columbia, the Yukon and Nunavut. These were selected for CanGEA's study as they are the provinces and territories with

Table 3.3: Resource Operating Costs

Resource	**Cost** (CAD/kWh)	**Source**
NG	0.011	[41]
LFO	0.037	[41]
Gasoline	0.14	[42]
Diesel	0.13	[42]
Coal	0.011	[43]
Wood	0.0016	[44]
Electricity Import	0.040	[45]
Electricity Export	0.039	[45]
Biogas	0.18	[44]
H_2	0.06	[46]

the greatest geothermal resource potential. It was assumed that other provinces have no geothermal potential. Data is provided for both technical and theoretical potential at different recovery percentages and depths. The values of technical potential for 14% recovery at a depth of 3'500m were assumed.

The wind potential was determined from a study performed by the Canadian Wind Energy Association [48]. Their study considered three different scenarios of wind energy development in Canada. The highest potential out of the three scenarios was assumed for each province. This study did not consider the territories. The study also included a detailed analysis of the potential monthly generation at various wind sites This data was used to determine the capacity factor of each province in each month, which was taken as an average of all the wind sites within a given province included in the study. The wind energy potential of the Northwest Territories from [49] was used, and the other two territories (Yukon and Nunavut) were assumed to have the same potential as the Northwest Territories. The capacity factors were considered to be the same as that of their nearest province - Quebec in the case of Nunavut, Alberta in the case of the Northwest Territories, and British Columbia in the case of Yukon.

The solar PV and solar thermal potentials were determined according to the following assumptions. First, the rooftop potential for each province was calculated assuming an area of 13 m^2 per capita [24], and the population of each province [35]. For solar thermal, it was assumed that only rooftop space would be used. The potential was then calculated assuming a solar radiation of 1 kW/m^2, and a solar thermal efficiency of 30% [50]. For solar PV, the total urban area (already accounted for with the rooftop PV assumption), as well as the farm areas, and protected areas and forest areas were subtracted from the total province area. It was assumed that the remaining land could be available for PV. The potential was the calculated from the total land area, assuming again a solar radiation of 1 kW/m^2 and a solar PV efficiency of 20%.

The capacity factor for solar PV was determined based on environmental weather station data

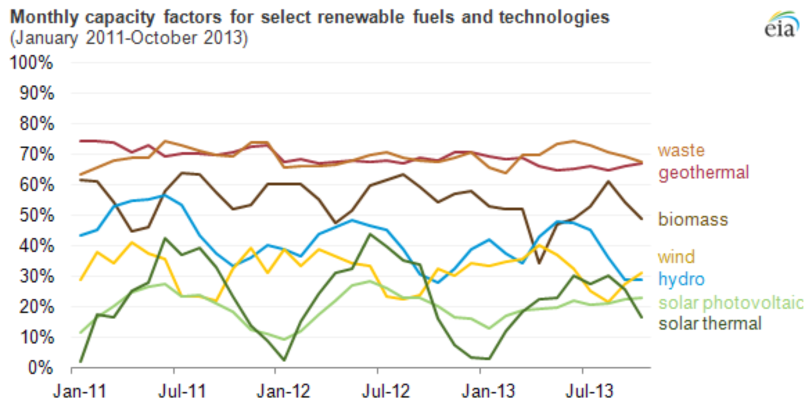


Figure 3.1: Monthly Capacity Factors of Renewable Fuels and Technologies [51]

which provided hourly GHI values (kW/m^2) [25]. The average monthly GHI value was determined for each province, taking an average of all the weather stations in the province. The monthly capacity factor was then determined by dividing the average monthly GHI by 1 kW/m^2. The capacity factor for solar PV was used to determine a reasonable assumption for the capacity factor of solar thermal based on figure 3.1, where it can be seen that the capacity factor is almost double that of PV in the summer months, and almost half of that of PV in the winter months. The cp values of solar PV were thus adjusted accordingly in order to obtain values for the cp of solar thermal.

The installed and potential hydro capacity for each province was provided by [20]. As this data was not divided between river and dam hydro (as in ES), an review of existing hydro installations in each province was performed in order to determine the proportion of river versus dam hydro. The new hydro potential was assumed to follow the same proportions.

The monthly capacity factor of hydro for each province was determined based on data regarding the installed capacity [21] and monthly generation [22]. As this data was not separated into river and dam hydro, the following assumption was made. The calculated values were used for the c_p of both river and dam hydro for existing hydro technologies. For new hydro technologies, the monthly c_p of Alberta was taken for new dam hydro and the monthly c_p of Saskatchewan was taken for new river hydro, as these provinces have almost exclusively dam and river hydro respectively, and are therefore considered representative.

3.1.4 Energy System 2018 Parameters and Constraints

In order to model the 2018 Canadian energy system, additional constraints and parameters were specified in order to re-create a modelled system close to the actual one.

For electricity. the total electricity generation by each resource in 2018, as in [52], was used to determine the percentage contribution of each resource to the total electricity demand. For heating, the total use of each resource was available from [30] which was again used to determine the percentage contribution of each resource to the total heating demand. As data was available according to resource use rather than specific technologies, the following additional constraint was then added in the model:

$$\sum_{n_{j,i}}\sum_{t} F_{Mult_t(n,t,r)} \cdot t_{op(t)} \cdot layers_{in,out(n,i)} \leq f_{maxperc_{j,i}} \cdot \sum_{x_j}\sum_{t} F_{Mult_t(x,t,r)} \cdot t_{op(t)} \cdot layers_{in,out(x,i)} \quad (3.6)$$

$$\sum_{n_{j}}\sum_{t} F_{Mult_t(n,t,r)} \cdot t_{op(t)} \cdot layers_{in,out(n,i)} \geq f_{minperc_{j,i}} \cdot \sum_{x_j}\sum_{t} F_{Mult_t(x,t,r)} \cdot t_{op(t)} \cdot layers_{in,out(x,i)} \quad (3.7)$$

where $n_{j,i}$ is the set of conversion technologies n which generate layer i from layer j, $layers_{in,out(n,i)}$ is the amount of layer i generated per kW of unit n utilized, $x_{j,i}$ is the set of all conversion technologies which generate layer i, and $f_{minperc_{j,i}}$ $f_{maxperc_{j,i}}$ are the maximum and minimum percentages of layer i generated from layer j. $f_{minperc_{j,i}}$ $f_{maxperc_{j,i}}$ are defined based on the percentages calculated previously, ±5%.

For transportation, data regarding the use of specific transportation technologies was available from [30]. Thus, the use of each technology within its respective end use type was calculated. The end use types defined in ES for transportation include private passenger mobility, public passenger mobility, road freight mobility and train freight mobility. The ES parameters $f_{minperc_x}$ $f_{maxperc_x}$, which represent the minimum and maximum share of a given technology within its end use type, was defined based on the calculated percentages ±5%.

Additional parameters specific to the 2018 system include the maximum and minimum shares of public transportation (within passenger transportation) and maximum and minimum shares of train freight transportation (within freight transportation), which were again calculated based on data from [30]. The maximum and minimum shares of district heating networks (DHNs) (within low temperature heating) were set to 0.1 and 0 respectively, as the share of heating capacity provided by DHN technologies was reported as less than 7% [53]. The maximum and minimum shares of off-grid electricity demand (within electricity demand) were determined from the remote communities energy database [54].

Finally, the efficiencies of transportation technologies (in terms of pkm or tkm delivered per kWh input) were updated. Given that the initial values were developed for Switzerland, and transportation behaviour is quite different in Canada due to the differences in transportation network, distances and population density, these values are impacted. The values corresponding to the Canadian system were available in [30].

3.2 2050 Canadian Energy System - ES-R H_2

Following validation of the ES-R Canada model, the 2050 energy system was modelled using ES-R H_2. Modelling of the energy system in 2050 requires the extrapolation and modification of certain parameters and constraints.

3.2.1 End-Use Demands

The end uses demands for 2050 were extrapolated from those determined for 2018 according to projections for population and GDP growth for Canada.

The projection for population growth was taken from Statistics Canada's medium growth (M1) scenario, which projects a population of 48.76 million in 2050[55]. Based on this, the percent increase was calculated as:

$$\%_{increase,pop} = \frac{Pop_{2050} - Pop_{2018}}{Pop_{2018}} \tag{3.8}$$

The projection for GDP growth was taken from PwC's *The World in 2050* report, which projects that Canada will reach a GDP of 3.1 trillion USD_{2016} by 2050, compared to a GDP of 1.5 trillion USD_{2016} in 2016 [56]. Based on this, an annual growth rate, r, was calculated assuming constant annual growth, as follows:

$$GDP_{2050} = GDP_{2016}(1+r)^{(2050-2016)} \tag{3.9}$$

According to this growth rate, the 2018 GDP in USD_{2016} was calculated and from this, the overall increase from 2018 to 2050 was determined:

$$GDP_{2018} = GDP_{2016}(1+r)^{(2018-2016)} \tag{3.10}$$

$$\%_{increase,gdp} = \frac{GDP_{2050} - GDP_{2018}}{GDP_{2018}} \tag{3.11}$$

Based on this, the end use demands for 2050 were calculated from the reference 2018 demands, where household, services, and passenger mobility demands were multiplied by $\%_{increase,pop}$ and the industry (including the demands for ammonia and steel), agriculture and freight mobility demands were multiplied by $\%_{increase,GDP}$ in order to obtain the values for 2050.

As mentioned above, the ES-R H_2 model also includes the demand for steel and ammonia. The data sources used for the demand for steel and ammonia production in Canada in 2018 can be seen in table 3.4. The data regarding production for the entire country was found, and distributed on a provincial level according to the GDP of the relevant industry (chemicals for NH_3, iron and steel for steel).

Table 3.4: Canadian Ammonia and Steel Demand in 2018 - Data Sources

Parameter	**Source**
NH_3 Production (Canada)	Statistics Canada [57]
Chemicals Industry GDP (Provincial)	Statistics Canada [32]
Steel Production (Canada)	International Trade Administration [58]
Iron & Steel Industry GDP (Provincial)	Statistics Canada [32]

3.2.2 Technologies

The costs of wind and solar PV were updated according to [59]. Multiple scenarios of the price of PV and wind costs are presented - the more conservative reference scenario was selected. The extrapolation (currently until 2040) was extended to 2050.

Additionally, the electrical freight train technologies existing in ES were updated. Given that as of 2018, Canada's freight trains are entirely diesel operated and the line is not at all electrified, as well as considering the differences in network and distances within the transportation system as discussed previously, there was a need to update the freight train data in order to model the potential of electrifying transport in 2050. Three electrical freight train technologies were added - overhead line electrified (OLE), fast charging battery electric and full battery electric. The efficiencies and costs were determined from a study regarding the electrification of train lines in Norway and the US [60]. The US parameters were taken, assuming that this is comparable to the case of Canada.

3.2.3 Energy System 2050 Parameters and Constraints

For the 2050 energy system, the maximum share of freight was set to 0.80 for each province, and the maximum share of public transportation was set to 0.30 for each province (in both cases, a value was selected which is slightly higher than province with the maximum value in the 2018 system). The maximum share of DHN was maintained at 0.1.

Although the minimum and maximum shares of specific technologies are not constrained for the 2050 model, as the goal is to identify the optimal technologies for the system, a constriant is imposed on the maximum penetration of VREs (including wind and PV) in the grid. The maximum share is limited to 70% and is formulated as follows. The constraint must hold for each region.

$$\sum_{t}(F_{mult,t(PV,t,r)}+F_{mult,t(Wind,t,r)})\cdot t_{op(t)} \leq 0.7\cdot\sum_{t}\sum_{m} F_{mult,t(m,t,r)}\cdot t_{op(t)}\cdot layers_{in,out(n,elec_{grid})} \quad (3.12)$$

where m is the set of all technologies generating on-grid electricity.

3.3 2050 Canadian Energy System - ES-R DG Model

In general, the parameters and modelling considerations for the 2050 system are the same as described previously, unless otherwise stated below.

3.3.1 Technologies

As discussed previously, the geospatial data analysis and clustering process led to the definition of the parameters including cluster area and percent area available for wind and solar developments. Regarding solar, the overall potential (in terms of GW) was calculated using the same method described previously, assuming a solar irradiation of 1 kW/m^2 and efficiencies of 20% and 30% for solar PV and solar thermal respectively. For wind, a rated turbine power of 4MW/km^2 was assumed [19].

The capacity factors of wind, solar and hydro determine for each cluster were average annual values, as clustering based on monthly values for each parameter would result in an overly large number of attributes to cluster. Therefore, the annual values were converted into monthly values as follows. The average annual capacity factor, and the variation of the monthly capacity factors from the average annual value, was determined based on the provincial values calculated previously, and the average deviation for a given month and technology was calculated considering all the provinces. These average deviation values were then used to calculate monthly capacity factors for each cluster from the average annual value.

3.3.2 Energy System 2050 Parameters and Constraints

The maximum shares of public mobility and freight train mobility are maintained at 0.3 and 0.8 per cluster, respectively. In this case, the maximum DHN share is assumed to be proportional to the percentage of urban area of each cluster,

As before, a constraint regarding the maximum grid penetration of VREs is implemented. However, in this case the constraint is imposed over the entire system, rather than at the level of a single cluster:

$$\sum_c \sum_t (F_{mult,t(PV,t,c)} + F_{mult,t(Wind,t,c)}) \cdot t_{op(t)} \leq 0.7 \cdot \sum_c \sum_t \sum_m F_{mult,t(m,t,c)} \cdot t_{op(t)} \cdot layers_{in,out(n,elec_{grid})} \tag{3.13}$$

CHAPTER 4

RESULTS AND DISCUSSION

The following section discusses the results obtained for the three case studies considered. First, the ES-R Canada model validation using the 2018 reference system is presented. Then, the results obtained for 2050 using ES-R H_2 and ES-R DG are discussed and compared.

4.1 Model Validation - 2018 Reference System

In order to verify the validity of the model, the adapted ES Canada model was used to model a reference energy system - in this case, the energy system of Canada in 2018 - with known parameters. Comparing the model output with the known parameters of the energy system allows for validation of the model. Tables 4.2 and 4.2 show the results of the model validation.

The values of the model objectives - total cost and GWP - for the cost minimized system - are also shown in Table 4.1. Canada emitted a total of 728 Mt CO_{2eq} in 2018 [3], with 336 Mt $COCO_{2eq}$ from the transport, buildings and electricity sectors. The remaining emissions are divided between the oil and gas sector (191.4 Mt), and waste and others (51.3 Mt) - which are not accounted for in ES - as well as heavy industry (77.1 Mt) and agriculture (73.1 Mt), of which only the emissions due to energy consumption are accounted in the model, while other emissions - such as the emissions due to cement production or animal manure - are not considered. Therefore, the model result seems to be within the range expected based on the actual system.

Table 4.1: 2018 Reference System - MILP Model Objectives (Minimized Total Cost)

Total Cost	[BCAD/year]	700
Total GWP	[MtCO_{2eq}/year]	344

It can be seen from the validation results that the ES model is able to represent quite closely the reference system, with a percent difference between the model output and the actual system of less than 10% in many cases when considering total resource use as well as electricity generation.

This being said, there remain some cases for which the percent difference is greater - in particular, the total use of coal, LFO and wood, as well as the electricity generated by coal, gas, petroleum

Table 4.2: Model Validation for 2018 Reference System - Resource Use

Resource	**MILP Model** TWh	**Actual** TWh	**Delta** TWh	**Delta** %
Coal	126	176	50	0.28
NG	1193	1233	39	0.03
Diesel	327	354	26	0.07
Gasoline	437	424	-14	-0.03
LFO	123	144	21	0.15
Uranium	245	249	3	0.01
Wood	161	133	-28	-0.21

Table 4.3: Model Validation for 2018 Reference System - Electricity Generation

Resource	**MILP Model** TWh	**Actual** TWh	**Delta** TWh	**Delta** %
Uranium	91	95	4	0.04
Hydro	364	382	18	0.05
Solar	2.9	3.1	0.2	0.05
Wind	30	32	2	0.05
Coal	44	53	8	0.16
NG	47	66	19	0.29
Petroleum	2	4	2	0.56
Biomass	2	9	6	0.74
Total	584	644	60	0.09

and biomass.

These differences can be explained as follows. First, the lower value of electricity generation by gas, petroleum and biomass determined by the model as compared to the actual system - and the lower overall electricity generation - can be attributed to an assumption made when defining the end use demands. As discussed in section 3.1.1, for industrial energy demand it was assumed that the electricity demand was only the direct electricity consumption by industry, and the demand fulfilled by other resources was attributed to heating. In reality, it is likely that a percentage of resource use - in particular, a percentage of the use of coal, NG, petroleum and biomass - was used for electricity generation rather than heating. Thus, it is likely that the electricity demand is slightly underestimated and the heating demand slightly overestimated in the model. However, as additional data regarding the percentage of demand attributed to electricity versus heating was not available, the original assumption was maintained.

The differences in overall resource use may be explained by differences in the efficiencies of technologies used by the actual energy system, and those energy scope model. For example, the efficiency of coal power plants in ES are 0.49 and 0.54 for US and IGCC plants respectively. However, these are relatively modern and efficient coal electricity generation plants, and many existing plants likely have a lower efficiency, thus resulting in a higher primary energy consumption in order to fulfill the same end use demand.

Further, it is important to recall that the model output is based on optimization of the total cost of the energy system, whereas the actual system has evolved in a way that is not necessarily optimal. Therefore, the model may present a configuration that uses more or less of a certain resource or technology in order to optimize the costs of the system. Although constraints were added in order to force to some extent the use of certain resources and technologies and mitigate this effect, some degree of flexibility was maintained, and this can also explain some of the differences observed between the model output and the actual system.

4.2 2050 Canadian Energy System - ES-R H_2 Model

4.2.1 Overall Results

The ES-R H_2 was then used to model the energy system of Canada in 2050, in order to address the two main questions of this work - how can Canada achieve its goal of net zero GHG emissions in 2050, and what role could hydrogen play in Canada's future energy system.

The initial results of multi-objective optimization for the 2050 energy system can be seen in figure 4.1. The extreme right points represent the optimized system based on total cost minimization, and the extreme left points represents the optimized system based on total cost minimization with the constraint that the total GWP of the system must be less than or equal to zero.

In figure 4.1, two systems are compared - one which considers the GWP associated with the construction of the technologies, and one which does not. It can be seen that the impact of the construction GWP on the system is very minimal, with a negligible increase in total annual GWP and a maximum total cost increase of 0.07% for the net zero GWP system. As the influence on the system is small and there is a high degree of uncertainty regarding the emissions due to construction in 2050, as this is highly dependent on the location and processes used in construction as well as the resources and conversion technologies used to provide the energy required during the construction process, these emissions were excluded in the subsequent analysis.

The energy systems corresponding to the two extreme points are represented in figure 4.2. It can be seen that the system relies heavily on the use of natural gas, which can be expected due to the low natural gas price. Further, it can be observed that there is very little change in the selected energy conversion technologies - with the most notable changes being a slight increase in the electricity production from wind turbines and AFCs. The decrease in emissions (and increase in costs) is rather due to the implementation of carbon capture and storage technologies - including point source and direct air carbon capture. Given the low price of gas and the relatively low cost and high efficiency of carbon capture technologies modelled, this most cost effective way to reach zero

CO_2 emissions, rather than switching to emission-free technologies.

It should be noted, however, that this implies that it is possible to capture all CO_2 emissions with carbon capture technologies, which is not very realistic as carbon capture technologies are not able to capture CO_2 with 100% efficiency. While point source carbon capture technologies are limited to 90% efficiency in the model, direct air capture (DAC) technologies are not. Therefore, an additional constraint was added to the model in order to limit DAC technologies to 90% carbon capture efficiency. This was also compared to an extreme case where DAC technologies are removed from the model. The resulting pareto curves are shown in figure 4.3.

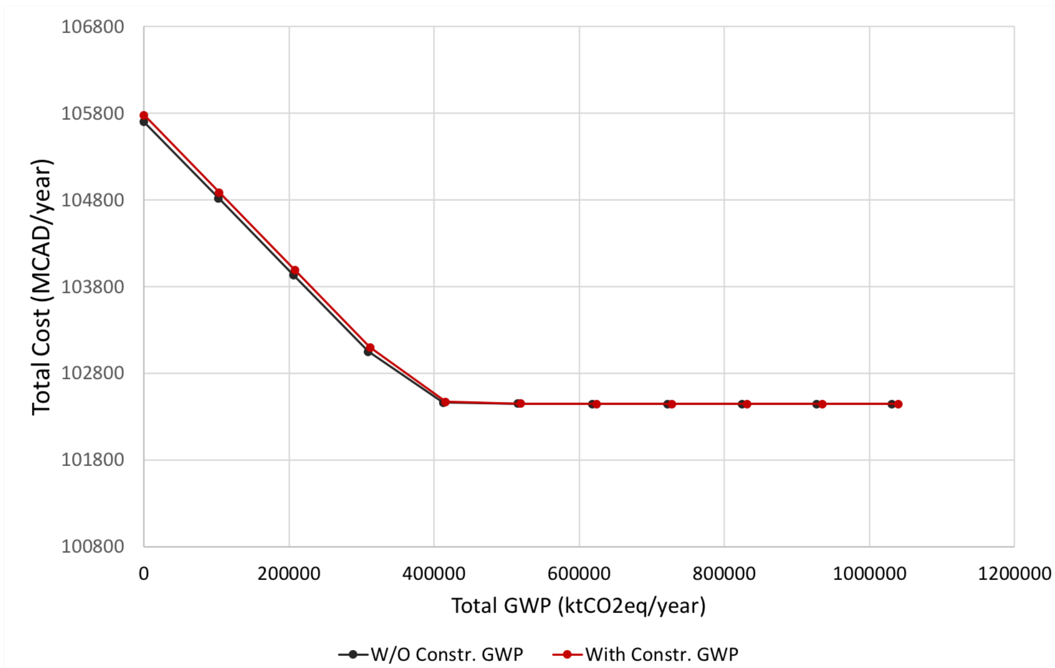
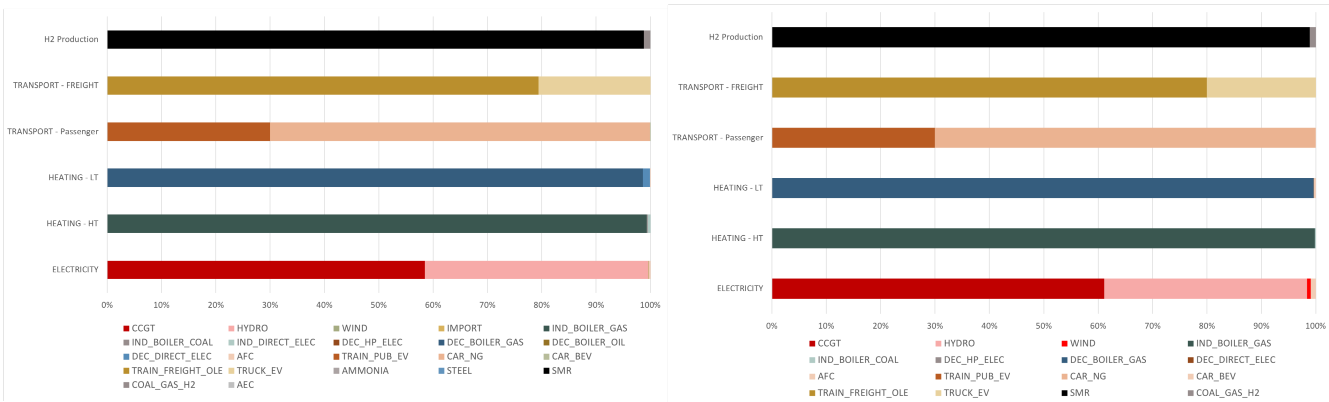


Figure 4.1: Pareto Curve With and Without GWP due to Construction

It can be seen in 4.3 that limiting the carbon capture efficiency or the availability of the DAC technology results in a significant increase (more than 200%) in the cost of the net zero GWP system. It can also be seen that at the net zero point, there is no difference between the system in which DAC is completely unavailable, compared to the system in which DAC efficiency is limited to 90%. This is due to the fact that DAC is no longer used. In this case, the most cost effective option becomes avoiding emissions as much as possible through the use of emissions free energy conversion technologies, with the remaining emissions reductions achieved through biomass conversion with carbon capture. There is also no difference for the cost minimized system, as at this case DAC is also not used given that there is no constraint limiting the emissions. The energy systems represented by these two extreme points can be seen in figure 4.4.
As can be seen in 4.4, the system now changes significantly between the two extreme points. For example, while natural gas and hydro technologies are the predominant electricity generation



(a) Cost Minimized System

(b) Net Zero System

Figure 4.2: Comparison of Cost Minimized and Net Zero Energy Systems

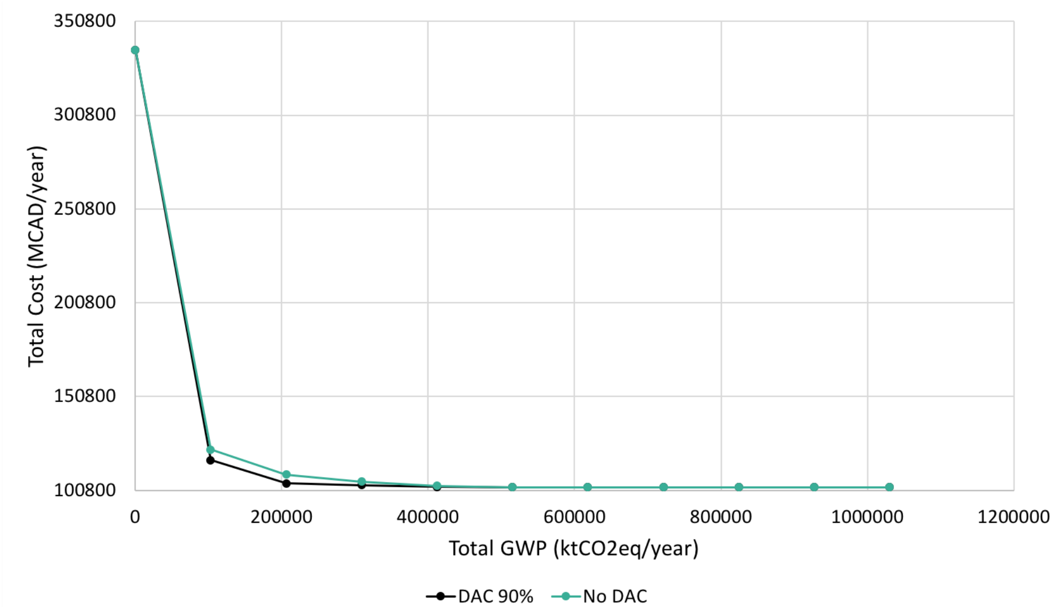
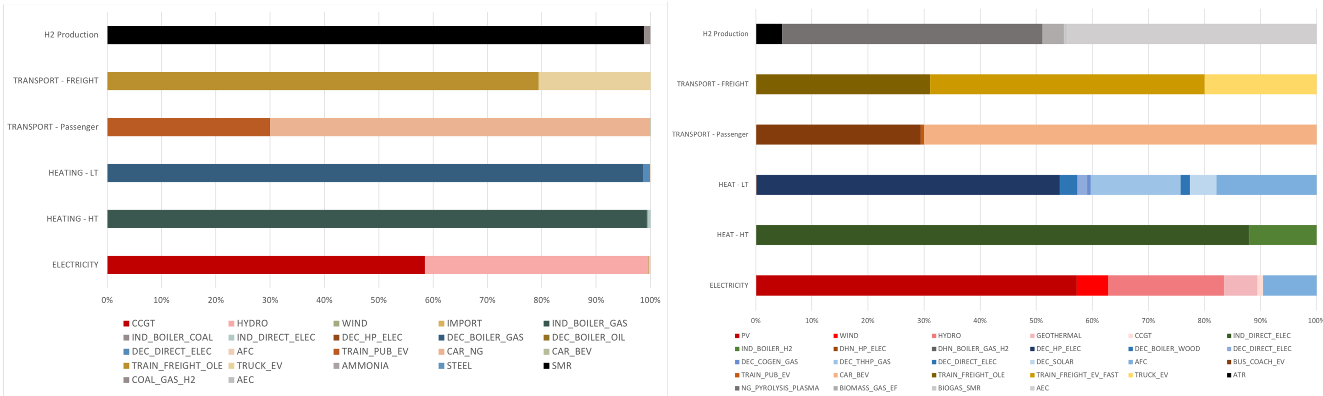


Figure 4.3: Pareto Curve With No DAC and DAC Limited to 90% Efficiency

technologies in the cost minimized system, PV becomes predominant in the net zero system, with wind and hydro also accounting for a significant share. In the heating sector, electrical and hydrogen heating technologies take up a larger share. Further, emissions-free methods of hydrogen production - including natural gas plasma pyrolysis and alkaline electrolysis - become the preferred methods of hydrogen production.

The emissions which are released are captured through point source carbon capture on fossil fuel generation plants (for example, for the combined cycle gas turbine), as well as through point source carbon capture on biomass based hydrogen production plants, which generates negative net



(a) Cost Minimized System

(b) Net Zero System

Figure 4.4: Comparison of Cost Minimized and Net Zero Energy Systems with DAC Constraints

emissions to compensate for the dispersed emissions which are no longer captured by direct air capture. In further analysis, the DAC capture efficiency constraint is maintained at 90% as this more accurately reflects the potential of the technology, which typically ranges from 83-95% [61].

It can also be noted in figure 4.3 that there is a significant increase cost between the second lowest GWP point and the net zero point. Thus, it may be possible to achieve significant CO_2 reductions at lower costs, and achieve the additional GHG reductions by other means - for example, offsetting and relying on carbon sinks. However, given the fact that, as discussed in the introduction, the energy system accounts for approximatly 50% of Canada's overall GHG emissions, it must be noted that to achieve the overall goal of net zero, there are other significant GHG reductions to achieve. Further, although one may have a vision of Canada as a country with a significant carbon sink due to its forested areas, in recent years Canada's forest have actually been emitting more CO_2 than they have absorbed [62], particularly due to the increase in forest fires as the effects of climate change begin to impact Canada. Therefore, a true net zero energy system is prioritized in this analysis.

4.2.1.1 Net Zero and the Role of Hydrogen

The following section analyzes further the potential energy system configurations which would allow Canada to meet its goal of net zero GHG emissions, as well as the role of hydrogen in a potential future net zero energy system.

For initial analysis, key performance indicators (KPIs) assessed for nine reference scenarios were assessed, which are described in 4.4. They include the four scenarios discussed above, as well as additional scenarios in which the price and availability of natural gas is varied. The key performance indicators considered include four general parameters - total cost, primary energy consumption, natural gas consumption, and CO_2 captured - as well as four hydrogen specific parameters - hydrogen production, hydrogen consumption by end use, share of hydrogen technologies in end uses, and hydrogen storage capacity. The KPIs are assessed for the net zero (zero GWP) system, therefore there is no KPI specific to GWP as it is zero in all cases.

Table 4.4: Description of Reference Scenarios

Scenario	**Description**
With GWP Constr.	GWP of constr. is included. No limit on DAC. NG price is 3 CAD/GJ.
No GWP Constr.	GWP of constr. not included. No limit on DAC. NG price is 3 CAD/GJ.
DAC 90%	GWP of constr. not included. DAC limited to 90%. NG price is 3 CAD/GJ.
No DAC	GWP of constr. not included. DAC not available. NG price is 3 CAD/GJ.
NG 3.5 CAD/GJ	GWP of constr. not included. DAC not available. NG price is 3.5 CAD/GJ.
NG 4.7 CAD/GJ	GWP of constr. not included. DAC not available. NG price is 4.7 CAD/GJ.
NG 5.8 CAD/GJ	GWP of constr. not included. DAC not available. NG price is 5.8 CAD/GJ.
NG 8.5 CAD/GJ	GWP of constr. not included. DAC not available. NG price is 8.5 CAD/GJ.
No NG CAD/GJ	GWP of constr. not included. DAC not available. NG is not available.

The resulting key performance indicators for each reference scenario can be seen in figures 4.5 and 4.6. It can be observed, as seen previously, that the total cost of the system increases significantly in the scenarios which limit DAC capture efficiency, and that this cost increase corresponds to a significant increase in primary energy consumption from VREs (including wind, solar and hydro in this case), and a decrease in fossil primary energy consumption, including natural gas consumption. The CO_2 capture KPI also highlights the role of biomass plants with carbon capture in achieving a net zero system when DAC capture efficiency is limited. It should be noted that the CO_2 captured is used rather than stored for all of the reference scenarios considered. It is used for the generalized direct use technology implemented in the model, rather than for conversion of hydrogen into natural gas via methanation..

The role of hydrogen is highlighted in figure 4.6. It can be seen that as the primary energy consumption of fossil fuels decrease and VREs increase, hydrogen take up a relatively more significant share in the energy system, particularly in the heating sector. Within this sector, hydrogen is predominantly used in industrial boilers to provide high temperature heat for industry. It is also used for cogeneration in alkaline fuel cells, producing low temperature heat as well electricity (which accounts for the share of hydrogen in the electricity sector). In the scenarios considered, hydrogen is not used in the transportation sector, which is instead de-carbonized entirely through electrification and the production of renewable electricity.

It can also be seen that even as the overall use of fossil fuels decreases in reference scenarios which consider limited DAC or increased price of natural gas, hydrogen production from fossil fuels still accounts for approximately half of the overall production. However, the technology used changes. In the first two scenarios (GWP Constr. and No GWP Constr.), hydrogen is produced almost entirely through steam methane reforming with carbon capture. In the other scenarios, natural gas plasma pyrolysis is the most predominant method, as this method decomposes methane into hydrogen and solid carbon, and thus does not produce CO_2 emissions.

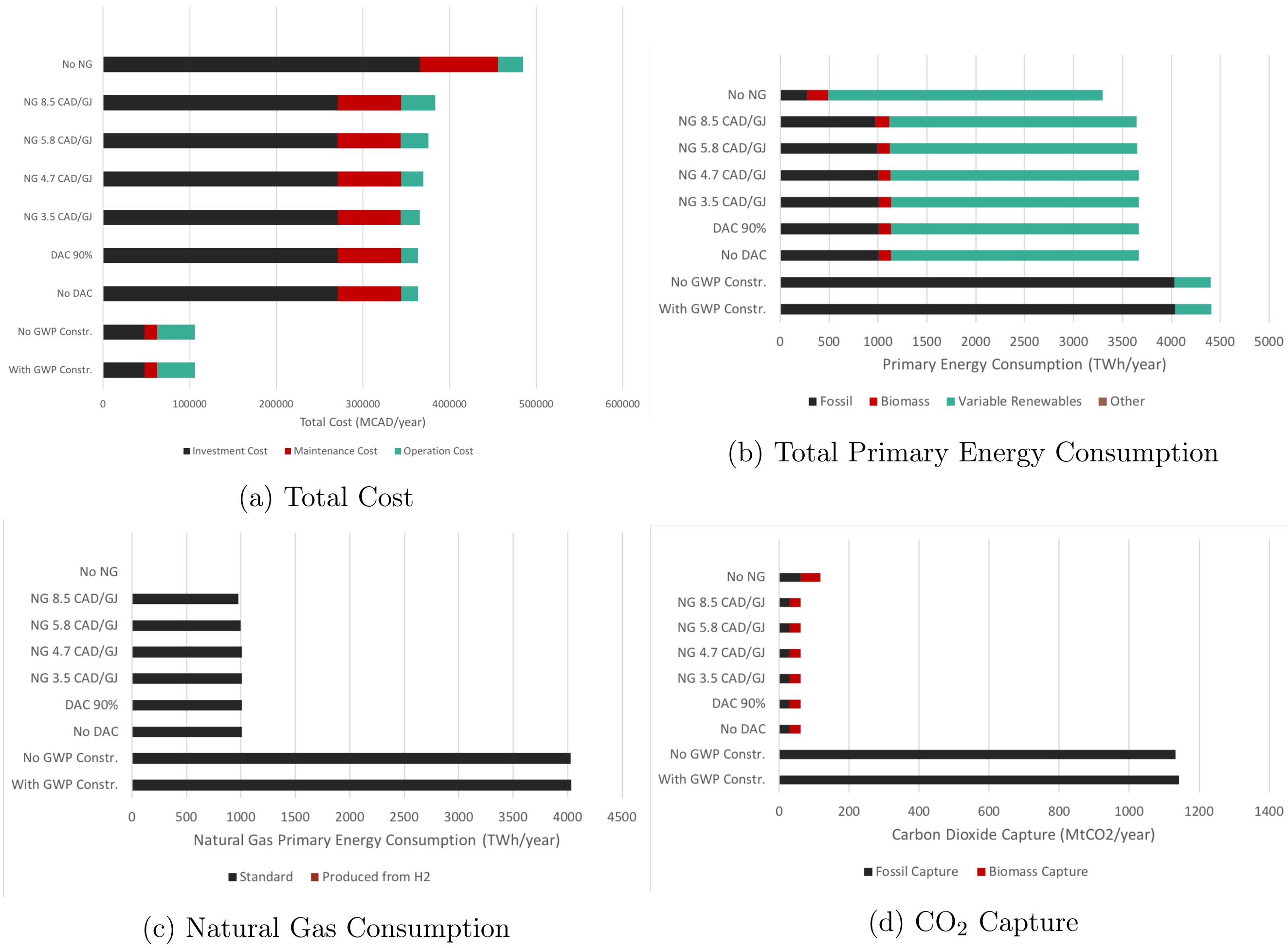
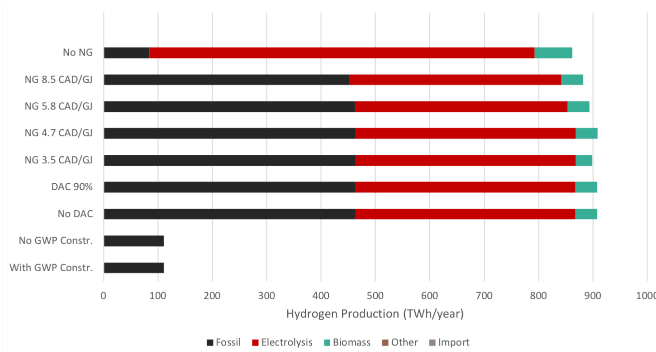


Figure 4.5: General Key Performance Indicators of Reference Scenarios

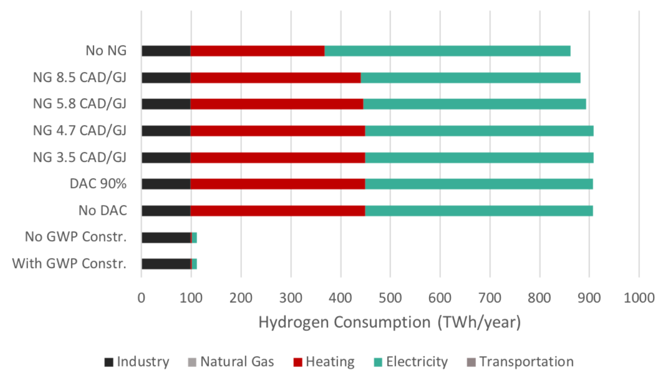
The role of hydrogen in energy storage in Canada's potential future net zero energy system can also be seen in figure 4.6d, where the hydrogen storage capacity of the energy system increases along with the increased dependence on VREs. This role is further highlighted with a specific example from Nunavut (based on reference system NG 4.7 CAD/GJ), shown in figure 4.7. It can be seen that hydrogen is produced in the months when electricity generation is increased (due to a higher monthly capacity factor), and this hydrogen is then used to supplement electricity based heating with hydrogen boilers in order to meet demand for high temperature heating in the months when electricity generation is lower.

4.2.1.2 Competing Hydrogen Strategies

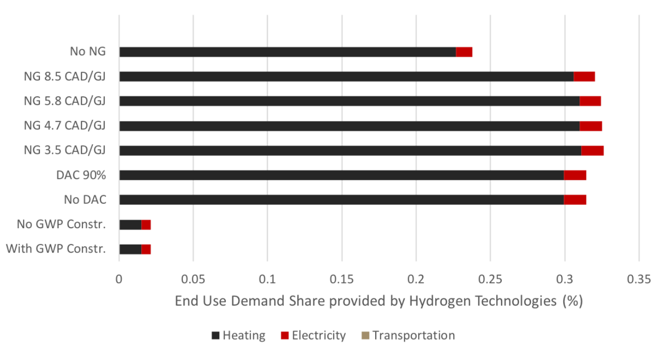
As discussed in section 1, two major competing hydrogen strategies exist in Canada, with Alberta wanting to develop a "blue" hydrogen strategy, based on hydrogen production from fossil fuels



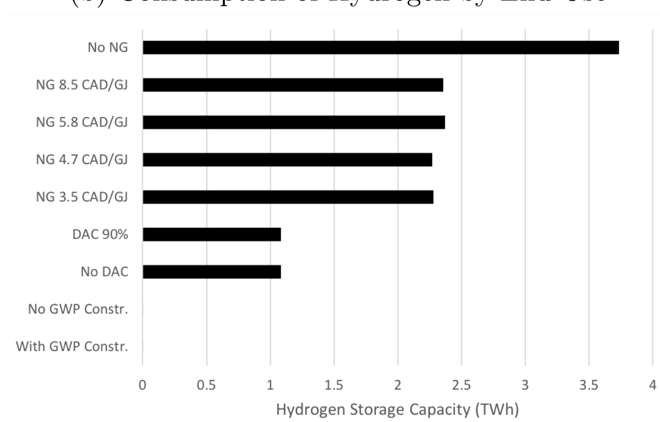
(a) Hydrogen Production



(b) Consumption of Hydrogen by End Use

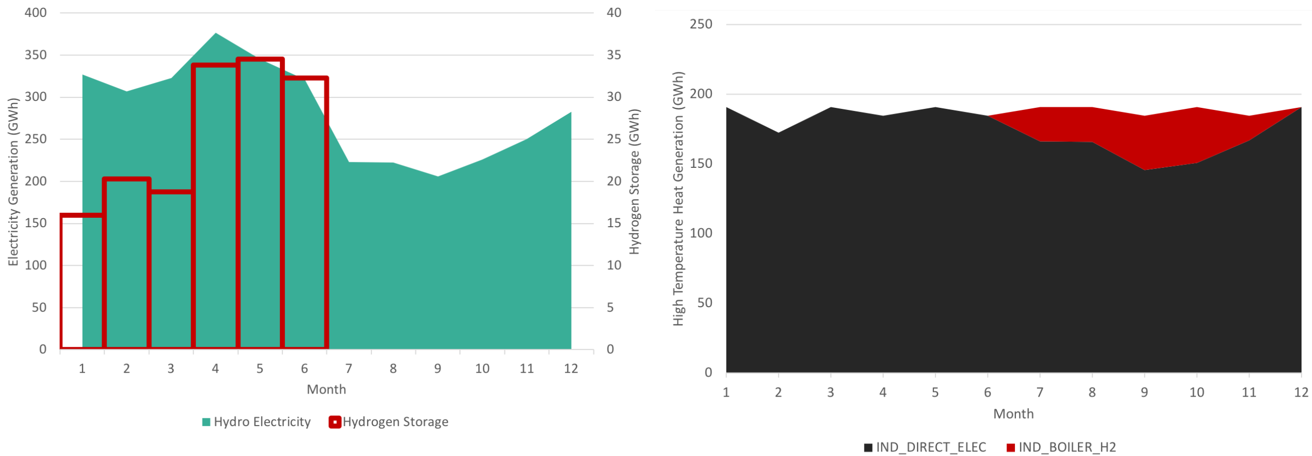


(c) Share of Hydrogen Technologies by End Use



(d) Hydrogen Storage

Figure 4.6: Hydrogen Specific Key Performance Indicators of Reference Scenarios



(a) Monthly Electricity Generation and Hydrogen Storage

(b) Monthly High Temperature Heat Generation

Figure 4.7: The Role of Hydrogen in Energy Storage in Nunavut. (Taken from reference system NG 4.7 CAD/GJ).

and Quebec pushing a "green" hydrogen strategy focused on production of hydrogen via electrolysis using renewable electricity. Based on the scenarios considered, a combined strategy seems preferred, with hydrogen production from fossil fuels and electrolysis accounting for close to 50% each. However, the fossil fuel production method is natural gas pyrolysis, rather than traditional methods such as SMR and ATR with carbon capture.

This being said, this result is sensitive to several factors - although the price of natural gas has already been considered, it may also be influenced by the prices of renewable electricity conversion technologies, the prices of the hydrogen production technologies as well as their efficiencies, as well as the long term availability of natural gas. Further, this is based on the assumption that the pyrolysis reaction proceeds without side reactions, whereas in reality some CO_2 may be released due to side reactions during the pyrolysis reaction. The sensitivity of the results will be discussed further in the following section.

4.2.1.3 Sensitivity

The parameters used in the model - such as resource prices, technology costs and efficiencies - are subject to a certain degree of uncertainty, particularly when extrapolating to 2050. In order to account for this, the following section assesses the sensitivity of the model to some of these parameters.

The first parameter considered is natural gas. The price of natural gas is quite volatile and difficult to estimate with certainty in the future, however it is a relatively important resource in the energy system, as seen in the previous results. As in the reference scenarios, the results are compared at five different natural gas prices, which represent the 2019 price (3 CAD/GJ) and four higher values based on different future projection scenarios. The details regarding these scenarios can be found in appendix B.

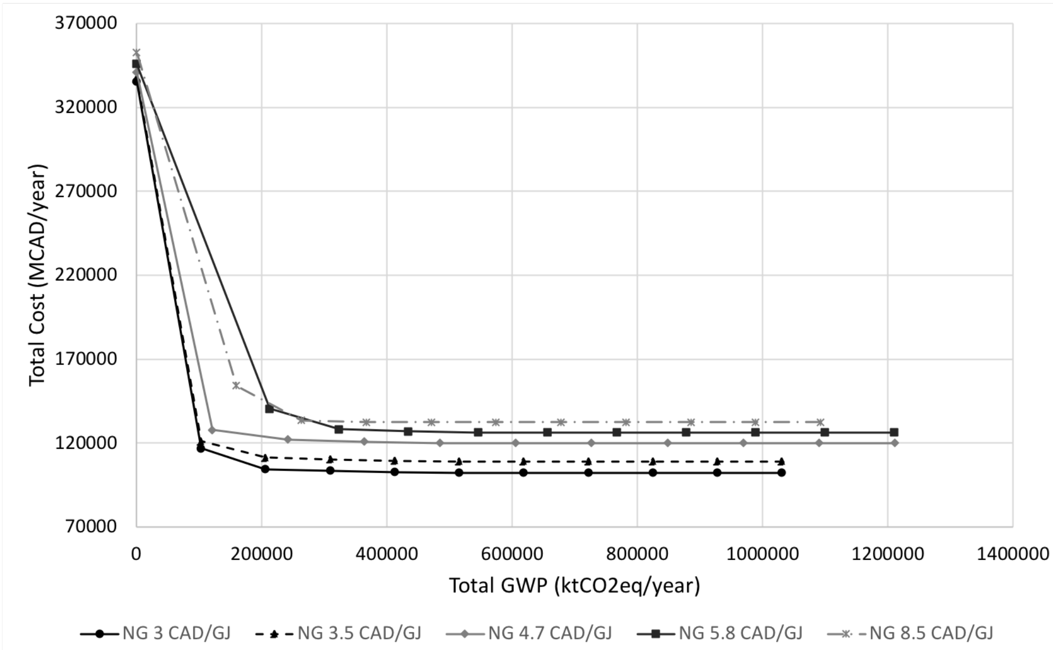


Figure 4.8: Pareto Curve - Influence of Natural Gas Price

The results shown in figure 4.8 highlight that the price of natural gas has a relatively significant influence on the cost optimized system, leading to increased overall costs and emissions. The increase in cost can be attributed to both the increased cost of natural gas, which is still used in the system, as well as the introduction of other resources and technologies, including both wind and coal for electricity, and coal for heating. The increased use of coal compared to natural gas also leads to an increase in emissions.

This being said, the influence of the price of natural gas on the GWP minimized net zero energy system is relatively small, with an increase in total cost of only 5% despite an NG price increase of over 180% between the minimum and maximum NG prices. This can be explained by the fact that although NG still plays a role in the net zero energy system, its role is less significant - as was also confirmed previously in figure 4.5c.

Although as demonstrated the NG price does not have a large effect on the net zero energy system, which is the focus of this report, it should be noted that an intermediary natural gas price of 4.7 CAD/GJ (0.0125 CAD/kWh) will be used in all subsequent analysis unless otherwise stated, as an increase in price compared to the base value is considered in all 2050 projection scenarios reviewed.

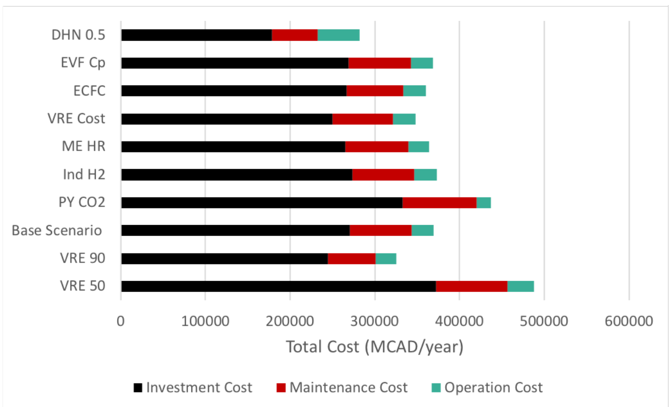
Additional parameters which may have a significant influence on the net zero energy system, and the role of hydrogen in that system specifically, were selected based on the results presented in the previous section. These include the maximum grid penetration of VREs (in this case, PV and wind), the investment costs of PV and wind, the CO_2 emissions released during natural gas pyrolysis, the efficiency of the high temperature hydrogen boiler, the implementation of energy recovery during methanation, the cost and efficiency of electrolyzers and fuel cells, the capacity factor of EV freight trucks and the maximum share of district heating networks (DHN). A summary of the scenarios considered is presented in table 4.5. More details relevant to the selection of these scenarios can be found in B.

Table 4.5: Sensitivity Scenarios Description

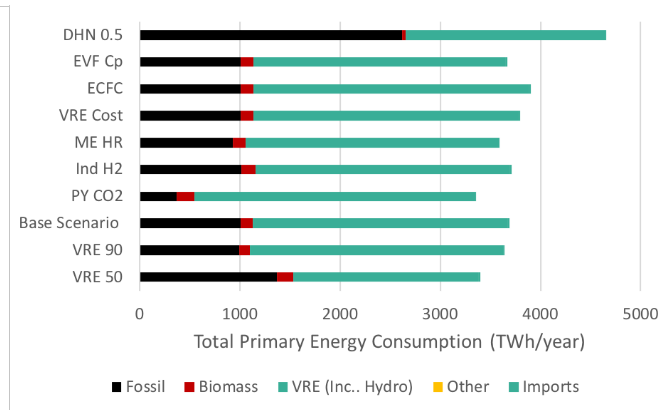
Scenario Name	**Parameter**	**New**	**Original**
VRE 50	VRE Grid Penetration	50%	70%
VRE 90	VRE Grid Penetraion	90%	70%
PY CO_2	NG Pyrolysis Emissions	5 tCO_{2eq}/kg_{h2}	0 tCO_{2eq}/kg_{h2}
Ind H_2	Industrial H_2 Boiler Efficiency	93%	97%
ME HR	Methanation Heat Recovery	0.8 kW_{el}/kW_{CH_4}	0 kW_{el}/kW_{CH_4}
VRE Cost	PV and Wind Investment Cost	740 CAD/kW (PV) 858 CAD/kW (Wind)	986 CAD/kW (PV) 1'145 CAD/kW(Wind)
ECFC	FC, EC Investment Costs and Efficiency	Efficiency: +5% Costs: -25% to -50%	- -
EVF C_p	EV Freight Truck Capacity Factor	-25%	-
DHN 50	Maximum DHN Share	50%	10%

The scenarios described in table 4.5 are compared for the net zero energy system only. The resulting KPIs can be seen in figures 4.9 and **??**. The following points of interest can be observed. First, it can be seen that further limiting the penetration of VREs increases the system's use of fossil fuels, leading to an increased dependency on carbon capture for maintaining a net zero system. The reverse is true for increasing the penetration of renewables. Increasing renewables penetraion also decreases the costs of the system - however, the costs associated with renewables penetration at this level may not be fully accounted for, as the model captures only monthly variations and does not account, for example, for the short term storage solutions that may be required to compensate for variations on the scale of hours or seconds. Additional work is therefore needed to assess this - for example using the typical days (TD) ES model. Further, the impact of very high renewables penetration on additional factors such as grid grid stability are still uncertain, and require further analysis.

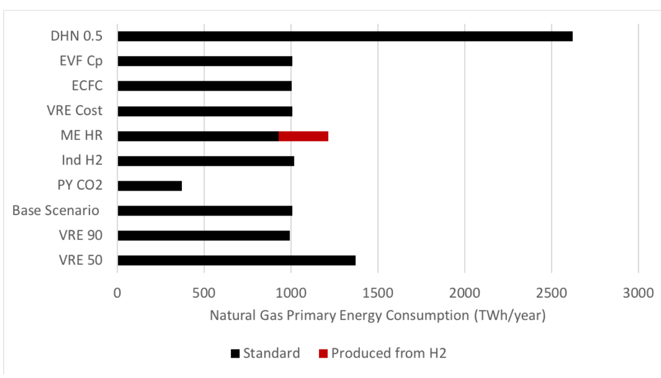
It can also be seen that if natural gas pyrolysis is not 100% free of CO_2 emissions, the production of hydrogen via fossil fuels decreases considerably, and the share of hydrogen produced by electrolysis increases. Further, it should be noted that in this scenario, the hydrogen which is produced via



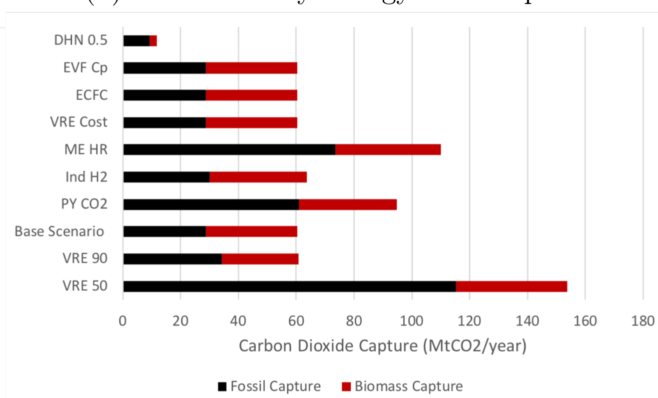
(a) Total Cost



(b) Total Primary Energy Consumption

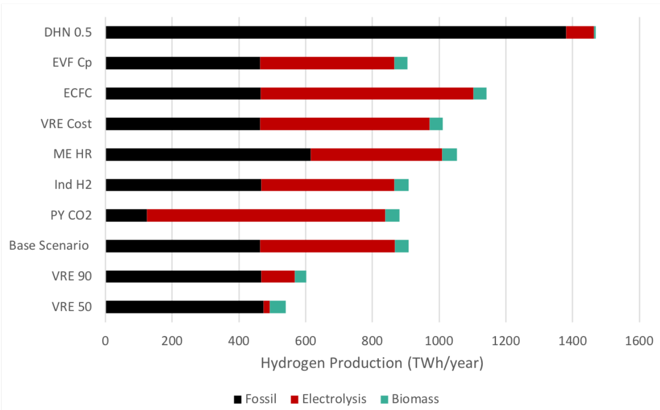


(c) Natural Gas Consumption

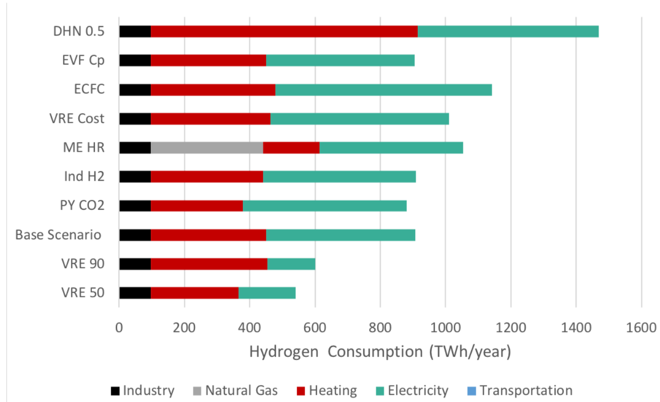


(d) CO_2 Capture

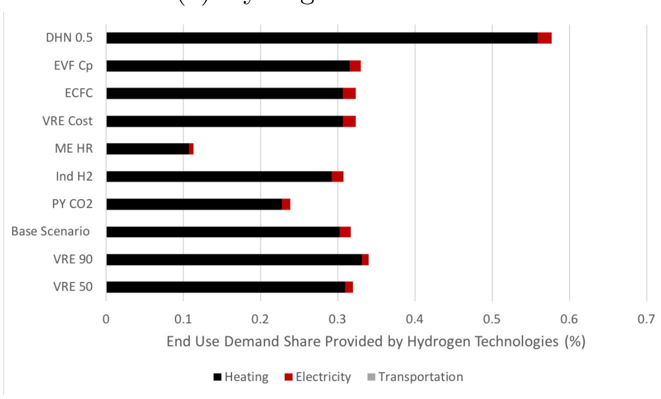
Figure 4.9: General Key Performance Indicators of Reference Scenarios



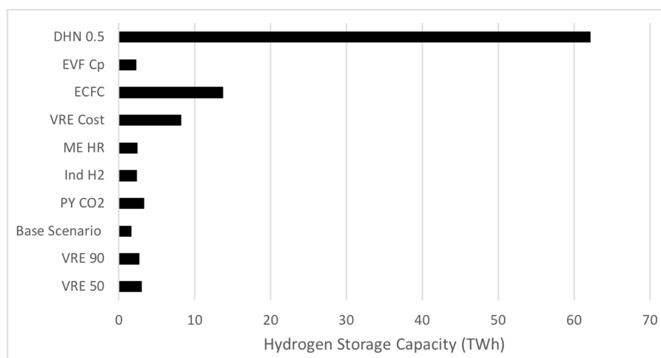
(a) Hydrogen Production



(b) Consumption of Hydrogen by End Use



(c) Share of Hydrogen Technologies by End Use



(d) Hydrogen Storage

Figure 4.10: Hydrogen Specific Key Performance Indicators of Reference Scenarios

fossil fuels is produced through autothermal reforming with carbon capture and storage, leading to the increase in carbon capture which can also be seen in the figure.

Interestingly, it can be observed that if energy recovery is implemented for the methanation reaction, the interest in converting hydrogen into natural gas increases significantly, and the share of hydrogen used directly for end use energy demand - particularly heating demand - decreases, indicating that instead the hydrogen that is converted into natural as is used in this purpose. However, the direct use of hydrogen is not completely eliminated.

Decreasing the costs of VREs does not have a significant impact on the system other than to slightly decrease the cost, as these technologies are already highly utilized in the system at the base cost considered. However, decreasing the costs while increasing the efficiency of ECs and FCs increases the production of hydrogen via electrolysis, as well as the amount of hydrogen consumed for electricity production.

Regarding transportation, it can be seen that even if the capacity factor of electric freight vehicles are reduced, they are still the preferred technology over hydrogen freight trucks. Although hydrogen freight trucks may have an advantage in terms of charging time (leading to a higher effective capacity factor), in this case the trade-off associated with the low overall efficiency (considering hydrogen production and compression) means that they are not the preferred alternative based on the system considered.

It can also be observed that the allowable share of DHNs has a significant impact on the system. Increasing the maximum share of DHN technologies reduces overall costs of the system, while increasing the use of fossil fuels - which can mainly be attributed to an increase in hydrogen production via natural gas pyrolysis, as the hydrogen production by fossil fuels increases although the carbon capture decreases. The additional hydrogen production is mainly used for heating, as is seen by the increased share of hydrogen in heating. This is due to the use of DHN hydrogen technologies - in particular, DHN hydrogen boilers.

4.3 2050 Canadian Energy System - Es-R DG Model

As seen in the previous section, a future net zero energy system will be highly dependent on renewable energy technologies - in particular PV, Wind and Hydro technologies. These technologies are highly location dependent. Therefore - particularly in a country such as Canada with an extremely low population density - this leads to the question, for example, of whether the areas of high energy demand correspond with areas of high renewable potential.

It was also demonstrated that electrification of heating and transportation are key components of achieving a net zero energy system. However, full electrification of the energy system - particularly the transportation system - may pose challenging in a country such as Canada, where the transportation network extends beyond the limits of the current electrical grid.

As discussed previously, this work proposes a new way of regional energy system modelling which enables users to investigate these challenges, where the regions are defined by their demographic and geographic characteristics, rather than political boundaries. While the issues discussed above are difficult to address using the previous model, this new type of regionalization allows for such questions to be assessed. The following section discusses the results relevant to the development of this model, and finally the results obtained using the model.

4.3.1 Geographic and Demographic Characteristics of Canada

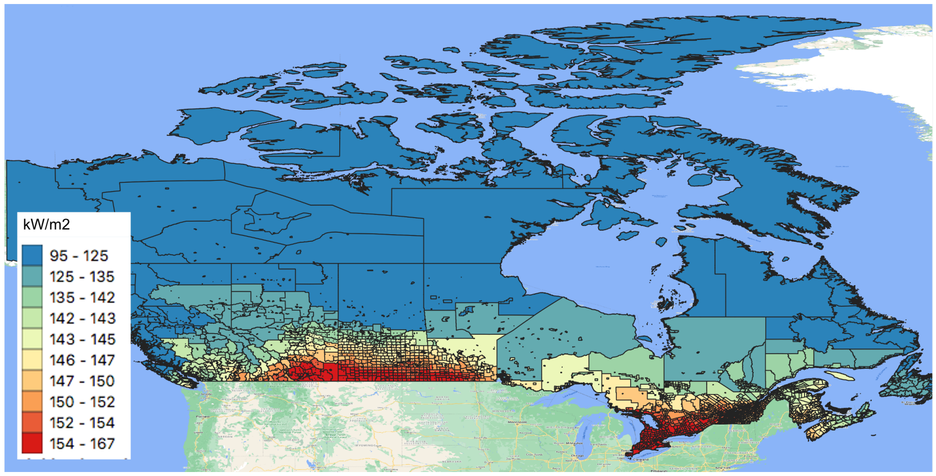
The results of the analysis of Canada's geographic and demographic characteristics can be seen in figures 4.11 - 4.13. Comparing the geographic distribution of the potentials (4.11) with the energy demand (which is considered to follow the distribution of inhabited areas), as well as access to the electrical grid (4.13), it can be seen that the places with the highest solar and hydro potential are indeed near to the most inhabited areas (although in the case of hydro, it should be noted that this result is likely heavily affected by the assumption explained previously that the additional hydro potential would be distributed according to the existence of the current potential. Additional future analysis with more detailed data is required in order to confirm this). Regarding wind potential, many of the places with the highest potential are uninhabited areas, and out of the range of the electrical grid. However, there are still some pockets of high wind potential closer to the grid and the inhabited areas.

It must also be noted that the maps in 4.11 do not consider the land use, and whether the areas with high potential also have the space required for renewable energy projects, or are actually already occupied by urban areas, agriculture, or forest. Due to this, the availability of land for a particular technology was also considered. The resulting availability of land according to technology type (wind or solar) can be seen in figure 4.14. Here it can be seen that the are available for wind corresponds quite well with the wind potential, particularly since wind can be more readily be developed on agricultural land. On the other hand, the area available for solar is quite low in the areas with the highest potential.

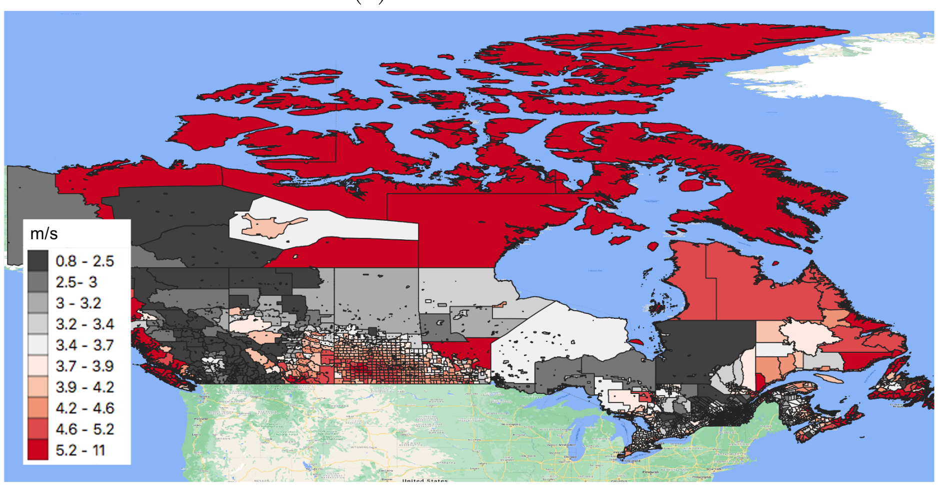
4.3.2 Clustering

The following section discusses the results of the k-means clustering method applied to the selected set of geographic and demographic attributes of Canada, which was used to define a new set of regions based on these attributes.

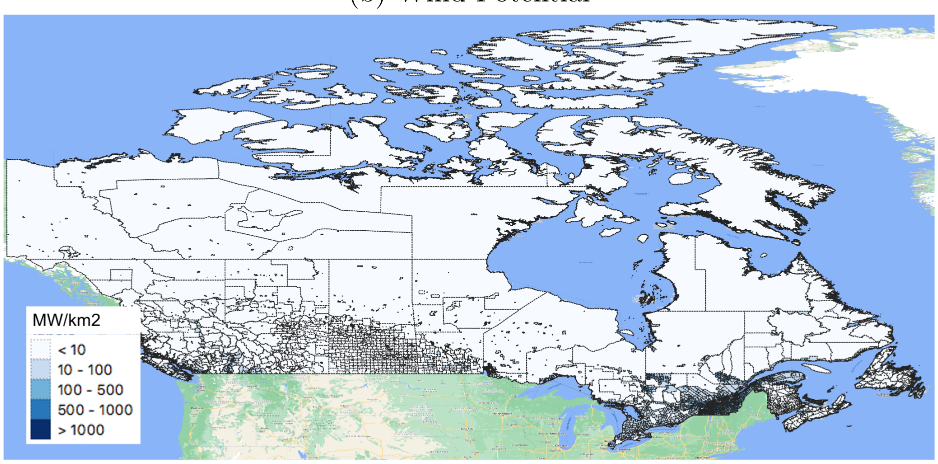
The k-means clustering algorithm was tested for 1-25 clusters, and the resulting distortion (sum of normalized errors squared), as well as the percent improvement in distortion for each increase in cluster number (figure 4.15) was analyzed. As can be seen, the distortion improves significantly when going from 1 to 3 clusters, and remains above 10% improvement with each added cluster until 5 clusters. The percent improvement with each added cluster then remains above 5% until



(a) Solar Potential



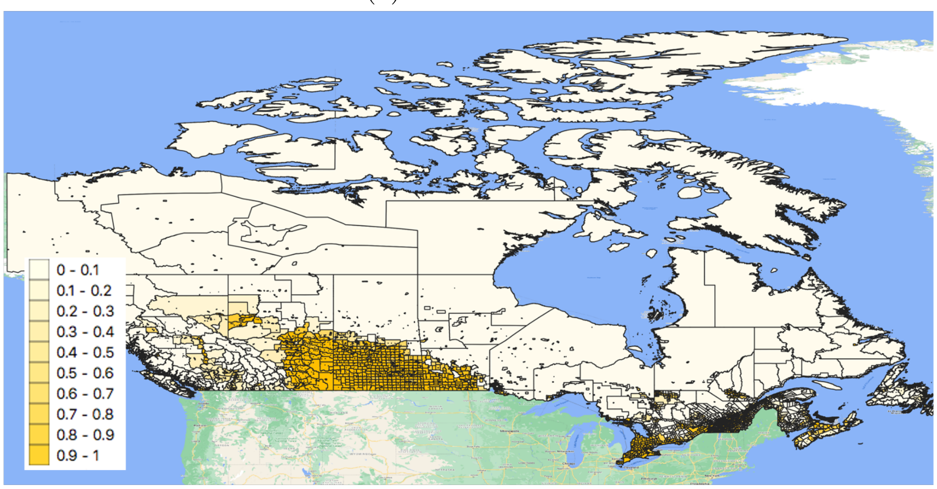
(b) Wind Potential



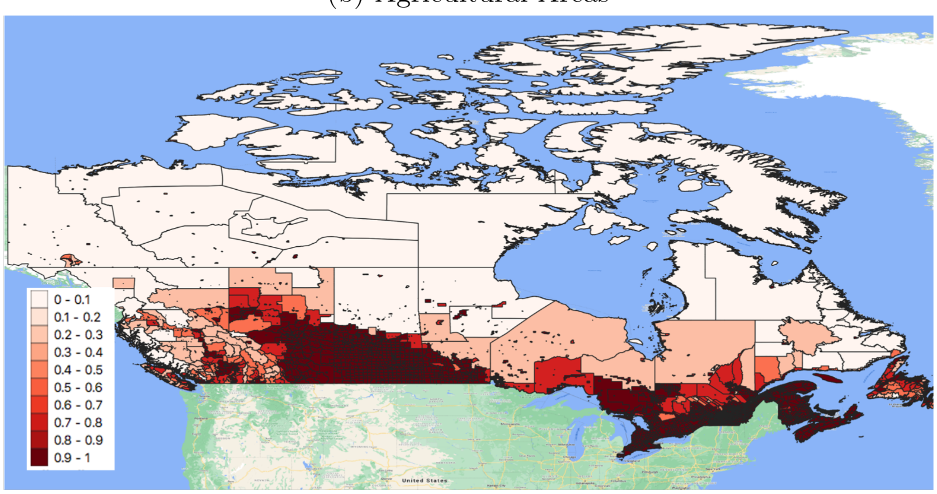
(c) Hydro Potential

Figure 4.11: Distribution of Renewable Energy Potential in Canada.

(a) Urban Areas



(b) Agricultural Areas



(c) Ecumene Areas

Figure 4.12: Distribution of Urban and Inhabited Areas in Canada.

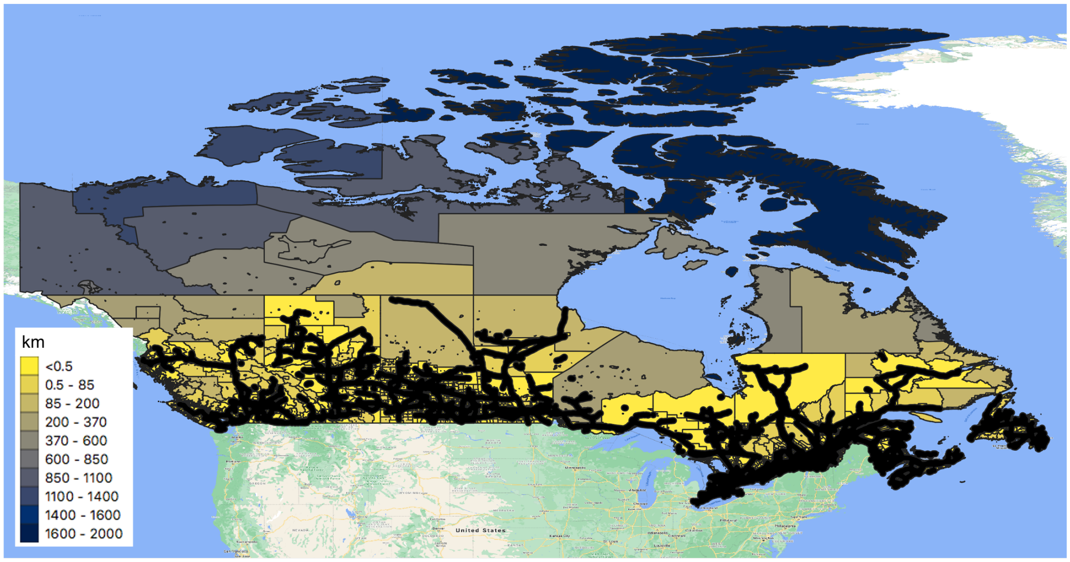
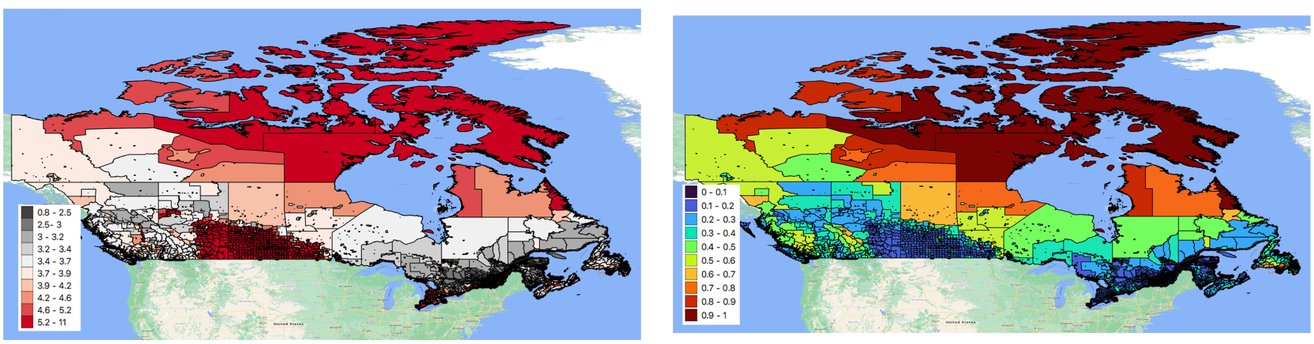


Figure 4.13: Electrical Transmission Network of Canada



(a) Area Available for Wind Technologies

(b) Area Available for Solar Technologies

Figure 4.14: Distribution of Available Area for Wind and Solar Technologies

the 12th cluster, after which it decreases further. A number of clusters between 5 and 12 is thus likely ideal, as with less than 5 the error is very high and above 12 the decrease in error is small and may not be worth the increased computational time required.

The error squared, relative error and inter-cluster distance of each individual cluster was also analyzed for 5, 10, 15 and 20 clusters. The percent change observed for the average value of each of these parameters is shown in figure 4.16. The ideal cluster number should minimize the average squared and relative errors, while maximizing cluster distance. Here it can be seen that increasing from 5 to 10 clusters significantly reduces the errors (by more than 20%) while minimally reducing the inter-cluster distance (by less than 10%). When increasing from 10 to 15 clusters, however, this balance is reversed - there is a smaller reduction in errors with a trade-off of a larger decrease in inter-cluster distance.

Considering these factors, a cluster number of 10 was ultimately selected and is used in further analysis. A summarized description of each cluster can be seen in table 4.6. A more detailed description of the cluster data can be found in appendix C

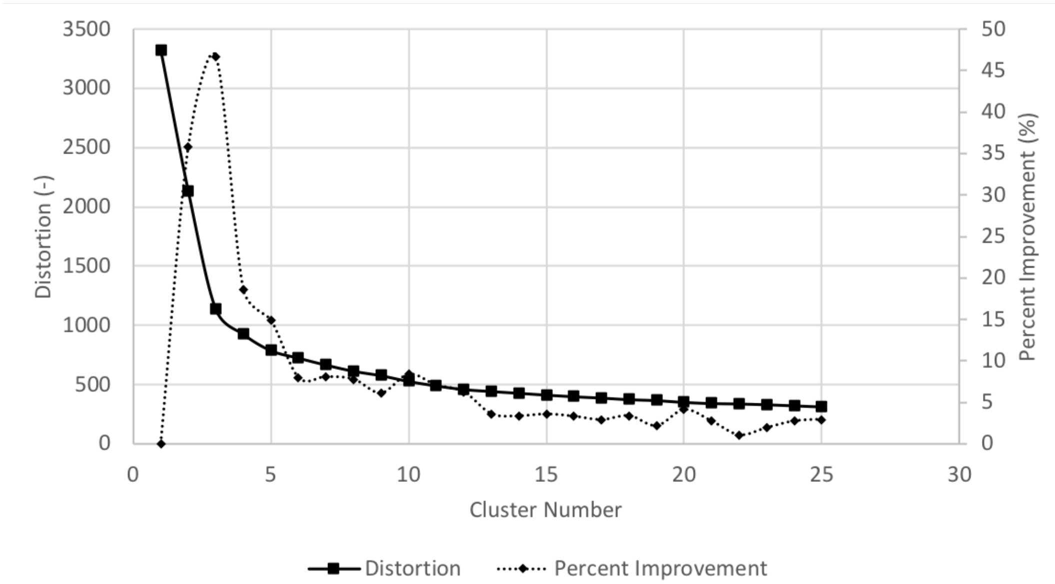


Figure 4.15: Cluster Number vs Distortion for K-Means Clustering

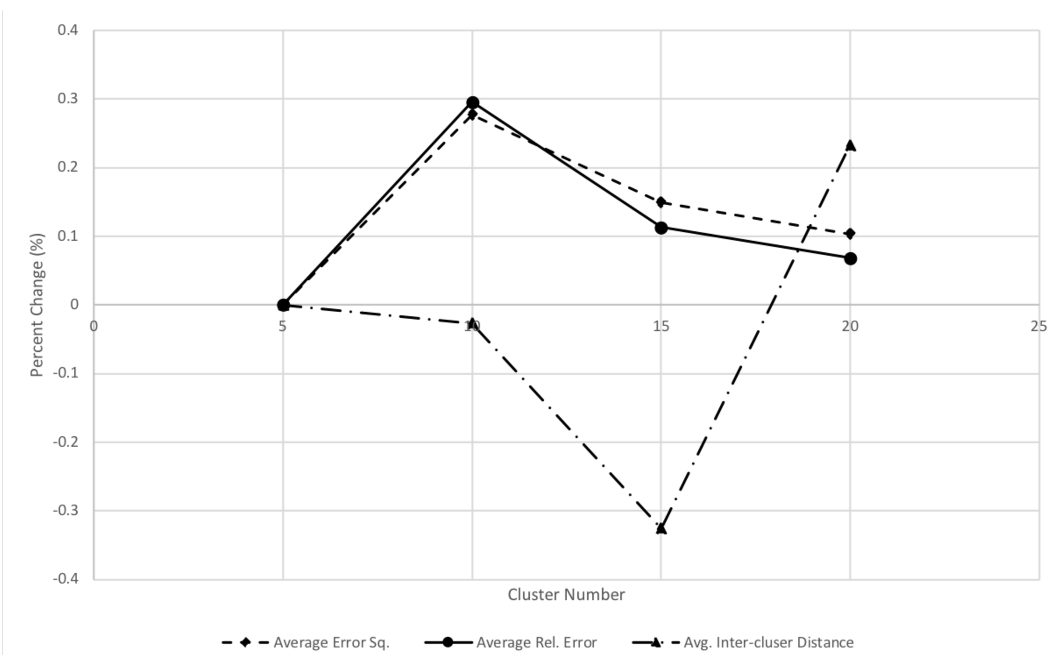
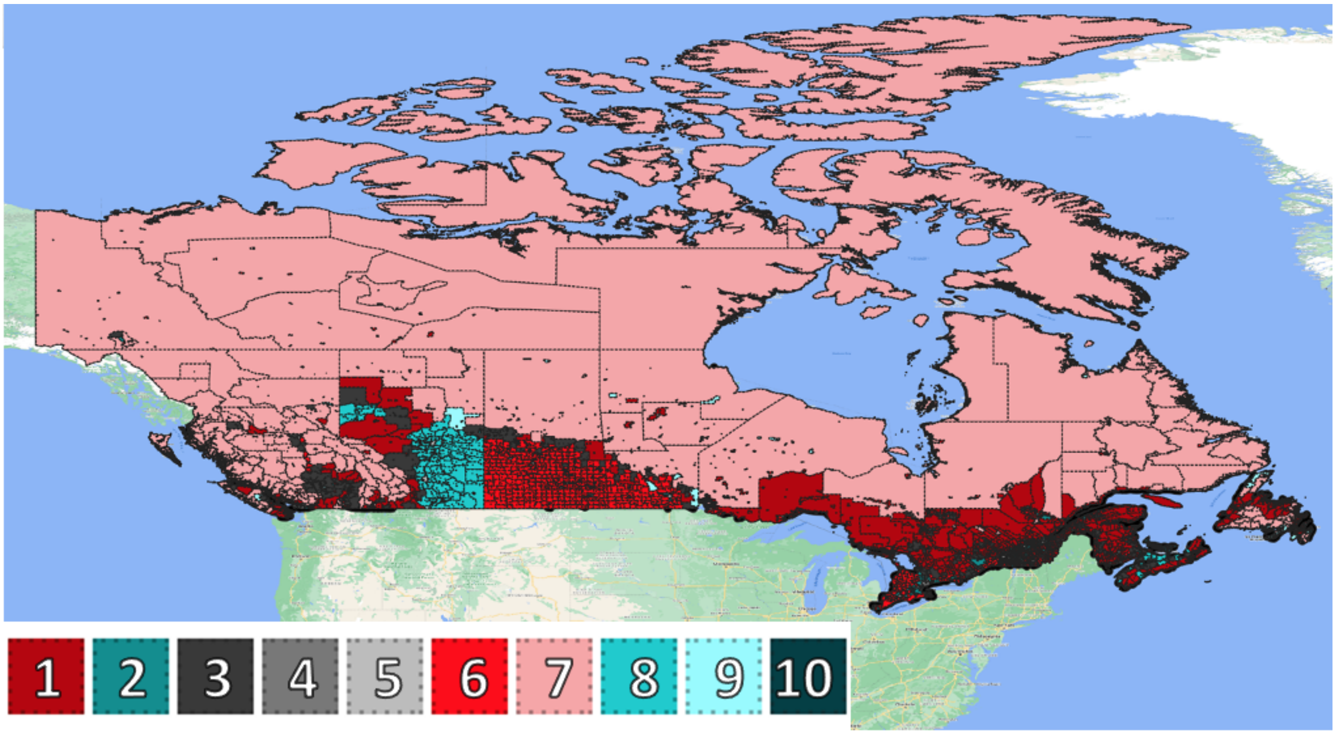
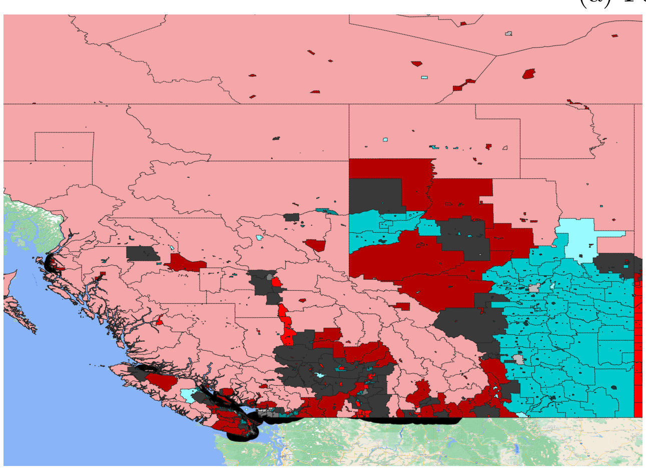


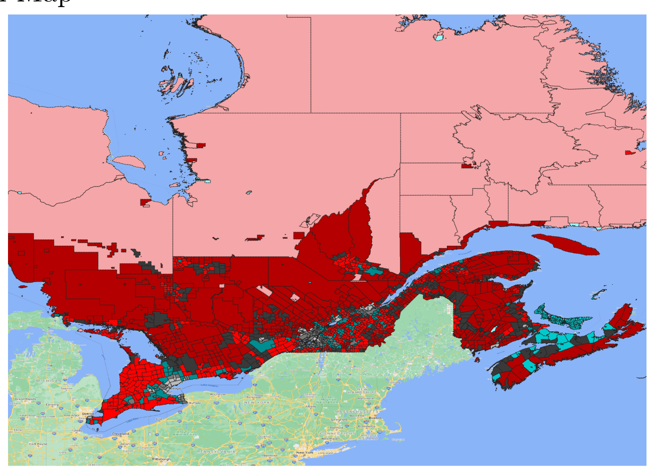
Figure 4.16: Cluster Number vs Average Errors and Inter-Cluster Distance



(a) Full Map



(b) Zoom - Southern Quebec and Atlantic



(c) Zoom - Alberta and British Columbia

Figure 4.17: Mapped Cluster Distribution

Table 4.6: Cluster Centroids

Cluster	Description
1	Sparsely inhabited area with medium grid distance and high wind and hydro potentials
2	Agricultural area close to the grid with medium wind and high solar potentials
3	Sparsely inhabited agricultural area close to the grid with high solar potential
4	Urban area near the grid with high solar, wind and hydro potentials
5	Urban area with medium grid distance and high hydro potential and wind potential
6	Agricultural area near the grid with medium solar, wind and hydro potentials
7	Sparsely inhabited area far from the grid with high wind potential
8	Agricultural area near the grid with high wind potential
9	Sparesely inhabited area far from the grid with high wind and hydro potential
10	Urban area near the grid with medium solar, wind and hydro potentials

4.3.3 Case Study: Canada 2050

In the following section, the two main case study questions considered above - how can Canada achieve net zero GHG emissions by 2050 and what role could Hydrogen play in this - are assessed using the ES-R DG model. The results will be compared to those presented previously, and the additional insights which can be obtained using this type of model, as well as potential limitations, will be discussed.

4.3.3.1 Overall Comparison

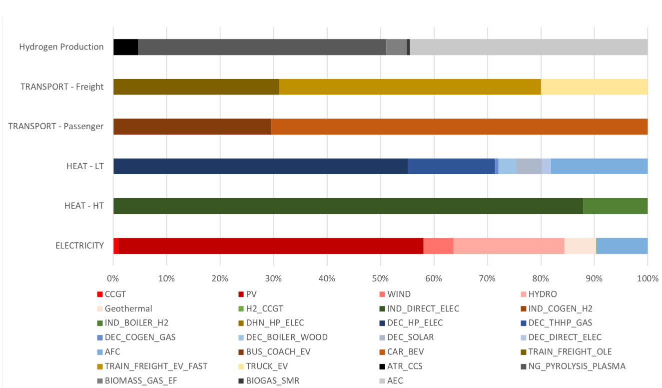
An overall comparison of the results obtained with the ES H_2 model compared with the ES-R DG model can be seen in table 4.7. It can be seen here that the results obtained using the two models are relatively close for the cost optimized system, where the slight increase in cost and emissions observed in the cluster regions model can be attributed to the additional costs of grid connection which were not considered in the previous model, as well as the different way of modelling on-grid and off-grid demands (previously as a portion of the overall demand of a province, whereas now cluster is considered entirely on or off grid depending on whether it is connected), leading to slightly different system configurations.

For the net zero energy system, however, the cluster system has a significantly lower cost. Upon further comparison of the system configurations as seen in 4.18, it can be seen that the share of electricity generated by wind is much higher in the cluster regions system. In fact, further analysis revealed that wind was reaching the maximum potential capacity defined in the ES-R H_2. This is understandable, as the wind potential was defined based on a study which considered sites within range of the electrical grid. The clustered model, however, considers a higher potential based on the country's entire available area, as described previously, and also considers the option of extending the grid if needed to access this potential. This result demonstrates the potential that wind energy has for economically reducing GWP emissions emissions in Canada, as well as the interest in considering extending the electrical grid in order to access this potential. In fact, it should be noted that for the cost optimized system, only those clusters close to or at a medium distance from the grid are connected. However, for the net zero system, all clusters are connected to the grid. This further highlights the importance of electrification for achieving a net zero energy system.

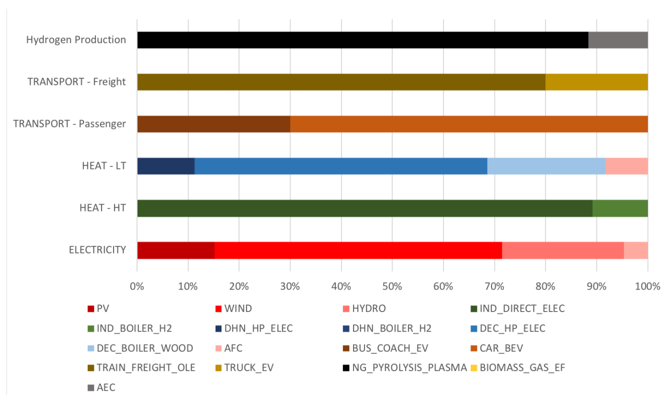
Another difference between the ES-R H_2 and the ES-R DG results is the use of DHN. While in the reference scenario for the ES-R H_2 system, DHN was limited to 10% (with a sensitivity analysis increasing thisto 50%), the ES-R DG model considered a maximum DHN share of a cluster proportional to the urbanized area of a cluster, as the implementation of DHNs is more realistic in densely urbanized areas. This allowed an overall higher share of DHNs for low temperature heat generation. As with the sensitivity analysis, this result further confirms the potential of DHNs in the future net zero energy system for providing cost effective, carbon free heating based on electricity and hydrogen.

Table 4.7: Comparison of Models

Model		**Total Cost** (MCAD/year)	**Total GWP** (ktCO_2/year)
Political Regions	Cost Optimized	120’000	1’211’080
	Net Zero	341’000	0
Cluster Regions	Cost Optimized	120’400	1’230’700
	Net Zero	286’760	0



(a) Political Boundary Regions



(b) Cluster Regions

Figure 4.18: Energy System Composition for Cluster Based Regions Energy System Model versus Political Boundary Based Regions Energy System Model

4.3.3.2 Net Zero Energy System and the Role of Hydrogen

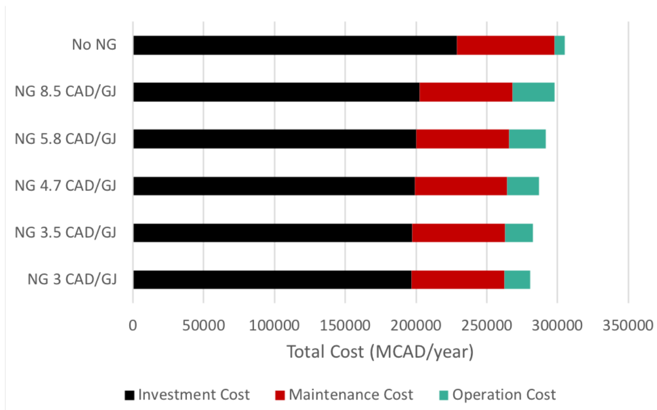
The key performance indicators for reference scenarios as described previously can be seen in figures 4.19 and 4.20. It can be noted that in this case, there is no graph regarding CO_2 capture in all cases, CO_2 emissions were avoided entirely rather than through carbon capture technologies, which is one of the main differences seen in the results with this model. This is likely due to the differences in system configuration observed in figure 4.18 - for example, the increased use of DHN which means that fossil fuel based decentralized heating technologies (such as natural gas based systems) are no longer used. Further, the increased availability of wind electricity means that there is no longer a small portion of electricity generated by combined cycle gas turbines.

It can also be seen that the total production of hydrogen is decreased compared to the results obtained with the previous model - with a slight increase in the fossil based production (via natural gas pyrolysis), and a significant decrease in the production via electrolysis. This is coupled with a decrease in the overall consumption of, and share of, hydrogen in the heating and electricity sectors. This seems to be due mainly due to the reduced share of AFCs and industrial hydrogen boilers in the system. Interestingly, the storage capacity for hydrogen increases despite the decrease in overall hydrogen share used by the system. This may be due to the fact that the constraints only limit the overall share of VREs (PV and wind) in the etire system, and not within an individual cluster, which means that some clusters rely exclusively on either wind or solar, creating greater variations between periods. Although in some cases this is balanced out by exchange of hydrogen between regions (discussed further below), in others it is stored instead.

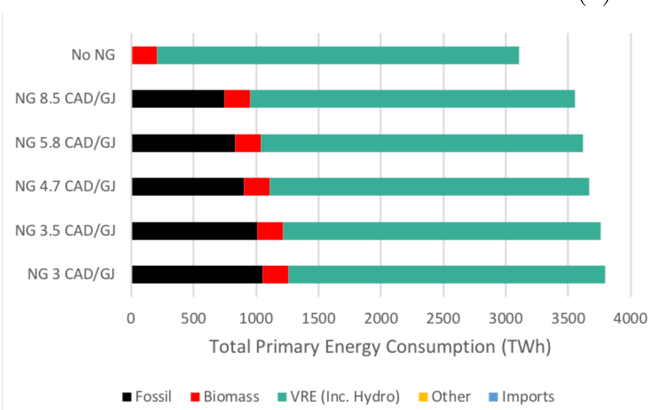
It can also be noted that in all scenarios except for the scenario with no availability of natural gas, all clusters are connected to the electrical grid, allowing for full electrification of both passenger and freight mobility. In the scenario without natural gas, cluster 9 (the cluster with the furthest average distance from the electrical grid) is not connected. In this case, it is interesting to realize that the preferred transportation technologies are hydrogen based (fuel cell cars and buses for passenger transport, with freight transport split between hydrogen trucks and hydrogen trains), demonstrating the potential of hydrogen for enabling carbon neutral transportation in off-grid areas.

The only resource exchanged between clusters is hydrogen, as demonstrated in 4.21, where the energy exchanged between cluster 3 and cluster 7 is represented. Cluster 3 relies on electricity generation from PV, which is highest in the summer months, while cluster 7 relies mainly on wind electricity generation, which is highest in the fall and winter months. When cluster 7 has excess electricity generation and cluster 3's electricity generation is lower, hydrogen is imported by cluster 3 from cluster 7 (and vice versa).

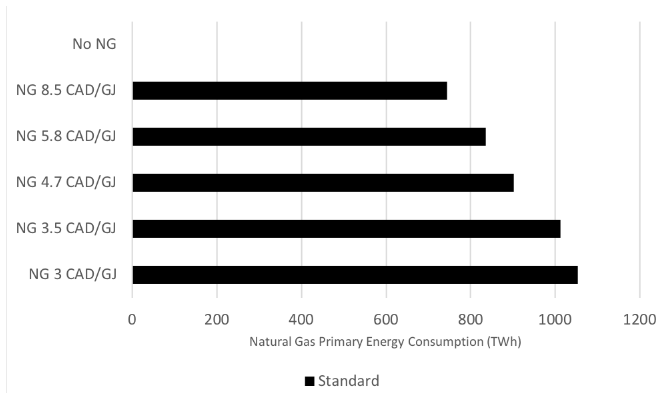
It is important to note, however, that over the entire year, each cluster exports as much hydrogen as it imports - therefore, the seasonal exchange between clusters is highly dependent on the cost of hydrogen transportation versus hydrogen storage. In this case, it appears cheaper to transport as much hydrogen as possible to locations where it can be used directly, storing only the remainder (as hydrogen storage is also still an important aspect of the energy system, as seen from the kpis. However, this may also be because the modelling of transportation distance is limited in this model as it is difficult to model the distance between clusters, which varies depending on their distribution across the country. Therefore, additional work is required to understand whether this is truly the



(a) Total Cost

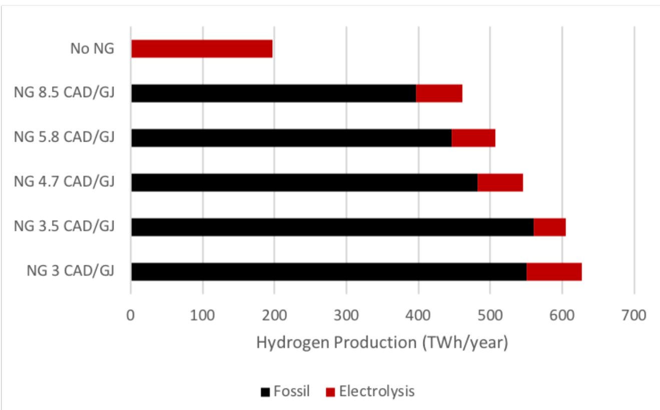


(b) Total Primary Energy Consumption

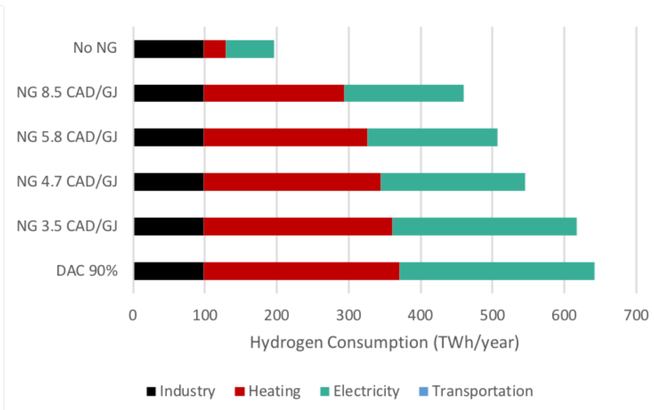


(c) Natural Gas Consumption

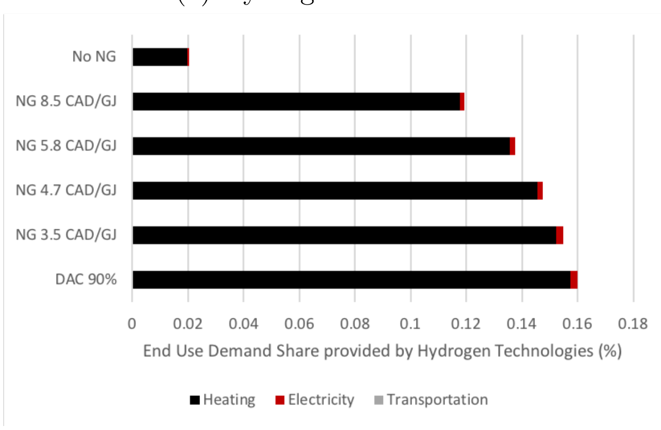
Figure 4.19: General Key Performance Indicators of Selected Reference Scenarios for Demographic and Geographic Regionalization ES Model



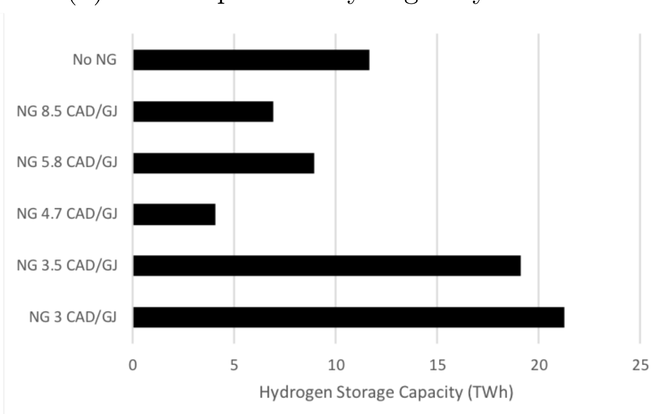
(a) Hydrogen Production



(b) Consumption of Hydrogen by End Use

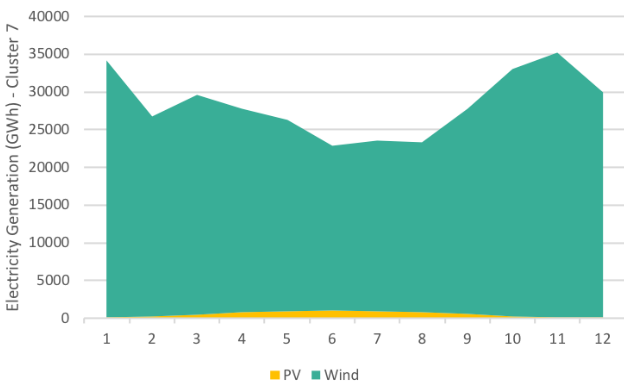


(c) Share of Hydrogen Technologies by End Use

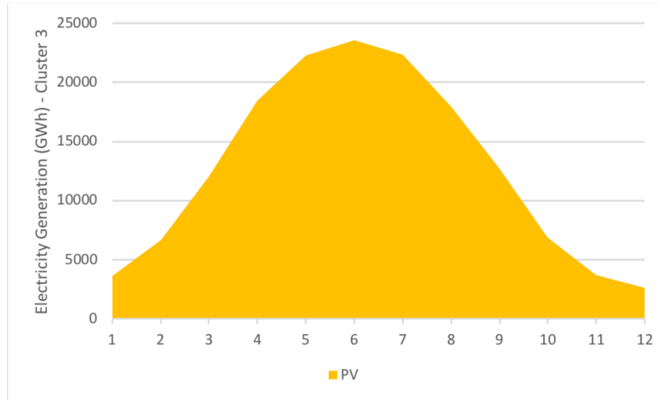


(d) Hydrogen Storage

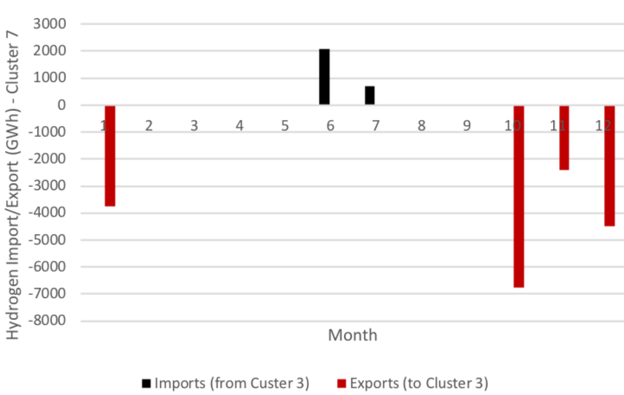
Figure 4.20: Hydrogen Specific Key Performance Indicators of Selected Reference Scenarios for Demographic and Geographic Regionalization ES Model



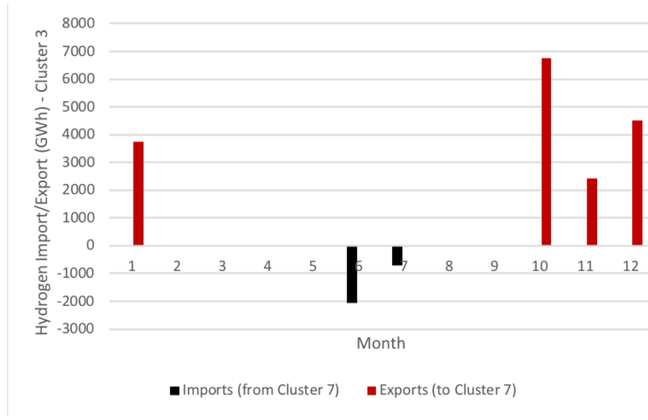
(a) Monthly Electricity Generation - Cluster 7



(b) Monthly Electricity Generation - Cluster 3



(c) Hydrogen Imports and Exports - Cluster 7



(d) Hydrogen Imports and Exports - Cluster 3

Figure 4.21: Season Energy Exchange through Hydrogen between Clusters 3 and 7

best option or if it would be more realistic that the clusters store their own hydrogen to use in months where electricity generation is lower. This may also depend on the storage capacity of the clusters, as underground storage may be limited in certain geographic areas - however, this was not explicitly taken into account either, and could be considered further in the future.

4.4 Summary

As can be seen from the results presented above, it is at least theoretically possible for Canada to meet its goal of net zero GHG emissions within the energy sector by 2050. This can be enabled by an energy system based mainly on renewable electricity generation - in particular hydro, wind and PV - and through the electrification of the heating and transportation sectors. The system might also include a minimal use of fossil fuels, combined with point source carbon capture and storage on fossil fuel generating plants, as well as point source carbon capture and storage on biomass generating plants. Regarding the role of hydrogen, the results demonstrate that it could play an important role in the energy system when it comes to energy storage and heating. In a mainly electrified system, hydrogen can be generated in months with excess electricity and used directly for heating in months when electricity is lower. This hydrogen would likely be produced mainly through the pyrolysis of natural gas, as well as electrolysis.

The model results suggest that hydrogen should be used as an energy vector itself, rather than converted into another energy carrier, such as natural gas. Hydrogen was only converted into natural gas when considering heat recovery implementation with the methanation reaction. This being said, there are additional factors not fully taken into account in this model - for example, the costs associated with changing or upgrading technologies and distribution networks currently designed for natural gas in order to accept hydrogen, rather than utilizing the existing infrastructure. Further, although factors such as the compression and storage of hydrogen were accounted for in the model, this was a first implementation and there may be additional complexities in the hydrogen supply chain which are not accounted for, and could reduce the overall efficiency, making other pathways more appealing. Therefore, additional analysis should be performed regarding this.

This sensitivity to heat recovery also demonstrates the influence that considering (or not) heat recovery can have on the optimal energy system configuration, and the role of hydrogen. The actual heat recovery which can be realized at a large scale by many of the hydrogen production and utilization technologies is still uncertain, and values are mainly based on research and smaller scale test systems. Therefore, additional analysis should be performed to assess the importance of heat recovery, and at which levels of heat recovery certain technologies and pathways become economical or not.

Another limitation regarding the modelling of hydrogen in the energy system is that while the technologies for producing hydrogen are modelled, and thus the effective price of hydrogen is related to the installation and operation of these technologies, the technologies for extracting and producing other resources (for example, natural gas) are not, and their costs are rather modelled based on market prices. Thus, there is an imbalance in the comparison. Although the system was proven to be relatively insensitive to the price of natural gas, it would still create a more equal comparison to model both resources using the same method. Therefore, this should be considered and implemented in the future.

In general, the most cost effective method of producing hydrogen while maintaining a net zero system appears to be the pyrolysis of natural gas. However, it should be noted that this technology is not yet implemented on a large scale, and is possibly susceptible to side reactions which create CO_2 emissions even though stoichiometric the reaction does not produce CO_2 . As seen in the sensitivity analysis, electrolysis may be the preferred method if this is the case. Further, the availability of natural gas may be a factor, as this resource is more abundant in some provinces (such as Alberta) than others. Therefore, both methods will likely have a place in the future energy system.

Although the ES-R DG model indicated that the optimal scenario would be to connect all clusters (i.e. all of Canada) to the electrical grid, it must also be noted that this may not be realistic. The clusters represent only the average distance from the grid within each cluster, and there are still some places and communities at the outer limits where it may not make sense, or may not be possible, to extend the electrical grid. Therefore, alternative solutions should also be considered within Canada's net zero strategy. As seen with this model, in the case that a cluster was not connected to the grid, the main aspect affected is transportation - where hydrogen transportation options are implemented rather than electrical ones. This represents another potential role of hydrogen in the net zero system. It should be noted, however, that the model did not allow the supply of electricity for electric mobility by off-grid electricity sources. However, off-grid electric mobility may be another option that could be further explored.

The results have also demonstrated the potential to gain additional insights using an regional energy system model based on a demographic and geographic definition of regions, rather than political ones. First, it enables location-specific renewable resource potentials to be better modelled, as was seen with the increase in wind potential and utilization in the cluster model results. It also allows for synergies to be observed between clusters with complementary potentials - for example wind and solar, as seen in 4.21. Further, it can enable a more detailed modelling of energy resource transportation networks, and the interest of expanding these networks. In this case, the electrical grid was the focus, but this could also be expanded to other analysis in the future. Further, knowing where the populations and demands are the most dense can also help estimate where certain technologies - such as district networks can be implemented, in order to more accurately model the potential penetration of such technologies, which may have an important influence on the energy system as demonstrated by the results.

This being said, this form of region definition also has certain drawbacks. For example, although network connections can be modelled, the model regarding the transportation of resources between clusters was not complete, as the distance between one cluster and another cluster was not defined. This is due to the fact that a single cluster type could be spread across many parts of Canada. Further, there are certain constraints that exist at the level of political boundaries - such as biomass or fossil resource availabilities - which are also not as precisely modelled using this method. Additional work could consider optimizing simultaneously both the cluster regions and the political regions, with the political regions described as a sum of the clusters which compose them. This adds an extra level of complexity which creates a computationally expensive model. However, applying a decomposition such as Dantzig Wolfe to the model definition could be explored in order to reduce computation time. Finally, the analysis using this model was only performed for one set of clusters. Additional analysis varying the cluster number and the attributes considered should be performed in order to better understand the influence of these choices on the modelling results.

CHAPTER 5

CONCLUSION

The main research questions addressed by this thesis, as introduced previously, are focused on two main points - hydrogen, and the definition of regions in energy system models. Within hydrogen, this work aimed at identifying the potential pathways and relevant technologies for producing and using hydrogen, identifying the relevant parameters for modelling these technologies and pathways, and integrating them into an energy system model. Regarding the definition of regions for energy systems, this work aimed at developing a method for defining energy systems based on geographic and demographic characteristics, and integrating these regions within an energy system model. The energy system models developed through this research were then used to analyze energy system of Canada, and particularly to address the case study of how the energy system of Canada could reach net zero GHG emissions by 2050, and what role hydrogen might play in this future energy system.

Overall, the analysis of this case study demonstrated that a net zero energy system in Canada would be based primarily on renewable electricity generated by wind, PV and hydro, with heating and transportation technologies predominantly electrified. This would also involve a significant expansion of the electrical grid. In this system, hydrogen will most likely play a role in energy storage and heating, and potentially transportation in off-grid areas, and this hydrogen would be produced by non-CO_2 emitting processes (natural gas pyrolysis and electrolysis). This being said, as many hydrogen technologies are still not implemented on a large scale, and the results are affected by variations in operating strategy, efficiencies and costs, further analysis is required.

The modelling of hydrogen production and utilization revealed the many complexities of these pathways that must be considered. Hydrogen can be produced from many resources, and can be used across all energy sectors, either directly or through the conversion of hydrogen to another energy vector. In the future, additional considerations - such as heat recovery from technologies, pressure levels, and transportation options - could be considered in more depth in order to better understand their impacts on the overall energy system and the corresponding role of hydrogen.

Further, the comparison of two models - one based on political regions and one based on demographic and geographic regions - revealed the potentials and limitations of both models. Using the demographic and geographic regions has the potential to allow better representation of renewable energy potential, consider energy resource transportation network connections, and identify places of concentrated population and demand for the implementation of certain technologies. However, political boundaries and physical proximity can also influence the energy system. Therefore, additional work is needed to explore how the benefits of these two types of models could be combined. Further, this work presents only one set of demographic and regional clusters. Additional methods of attribute selection, cluster number and cluster definition should also be explored further.

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APPENDIX A

ES-R CANADA

Table A.1: ES-R Canada Off-Grid Technology Parameters

Name	$\mathbf{c}_{inv}$ MCHF/kW	$\mathbf{c}_{maint}$ MCHF/kW	$\mathbf{c}_{p}$ -	**Lifetime** years	**Efficiency** -
DIESEL_GEN	314[63]	376[63]	0.28[63]	0.36[63]	25[64]
NG_GEN	177[63]	200 [63]	0.20[63]	0.34[63]	25[65]

APPENDIX B

ES-R H_2

B.1 Hydrogen Technology Data

The parameters of the hydrogen technologies added to the model are listed in tables B.1 and B.2. The references also provided the efficiencies of the technologies, although these are not explicitly listed in the table.

Certain natural technologies which were already in the model were adapted to hydrogen, or hydrogen and natural gas mixture, technologies. In this case, it was assumed that the cost increased proportionally between 30% hydrogen and 100% hydrogen, according to the costs reported in [66].

B.2 Sensitivity

The evolution of the natural gas price until 2030 in Canada was obtained from [81], which considers both a low, base and high scenario. Then, three scenarios for the evolution of the US natural gas price were obtained from [82] - the National Energy Board (NEB)'s reference and evolving scenarios, and the Energy Information Administration (EIA)'s scenarios. Starting with the low, base and high natural gas prices for Canada in 2030, these prices were extrapolated to 2050 using each of these three scenarios. This resulted in figure B.1. For the sensitivity analysis, the minimum, maximum and two intermediate values were selected.

Table B.1: Hydrogen Technoloy Parameters - Part 1

Technology	$\mathbf{c}_{inv}$ CHF/kW	$\mathbf{c}_{maint}$ CHF/kW	**lifetime** Years	$\mathbf{c}_p$ -	**References**
SMR	407.72	20.39	30.00	0.85	[67]
SMR_CCS	1405.87	70.29	30.00	0.85	[67]
ATR	551.52	27.58	30.00	0.85	[67]
ATR_CCS	1062.44	53.12	30.00	0.85	[67]
NG_PYROLYSIS_THERMAL	564.85	39.21	25.00	0.95	[16]
NG_PYROLYSIS_PLASMA	790.79	33.52	25.00	0.95	[16]
COAL_GAS_H2	1191.28	59.56	25.00	0.85	[68]
COAL_GAS_H2_CCS	1486.50	74.32	25.00	0.85	[68]
COAL_GAS_H2_ADV	2597.01	129.85	25.00	0.85	[69]
COAL_GAS_H2_ADV_CCS	2640.28	132.01	25.00	0.85	[68]
BIOMASS_GAS_FB_H2	1061.78	53.09	30.00	0.85	[68]
BIOMASS_GAS_FB_H2_CCS	1635.15	75.92	30.00	0.85	[68]
BIOMASS_GAS_EF_H2	2016.90	100.84	30.00	0.85	[68]
BIOMASS_GAS_EF_H2_CCS	3106.02	144.21	30.00	0.85	[68]
BIOGAS_SMR	1390.82	69.54	30.00	0.86	[70]
BIOGAS_SMR_CCS	2141.86	99.44	30.00	0.86	[70]
BIOGAS_ATR	1705.87	85.29	30.00	0.86	[70]
BIOGAS_ATR_CCS	2627.04	121.97	30.00	0.86	[70]
SOEC	1059.35	74.15	20.00	0.97	[16]
PEMEC	640.96	25.64	30.00	0.97	[16]
AEC	376.57	7.53	35.00	0.97	[16]
H2_CCGT	887.72	55.41	25.00	0.85	[71]
H2_NG_CCGT	887.72	55.41	25.00	0.85	[71]
H2_NG_CCGT_CCS	1371.03	79.49	25.00	0.85	[71]

Table B.2: Hydrogen Technoloy Parameters - Part 2

Technology	$\mathbf{c}_{inv}$ CHF/kW	$\mathbf{c}_{maint}$ CHF/kW	**lifetime** Years	$\mathbf{c}_p$ -	**Reference**
PAFC	675.14	33.76	20.00	0.97	[72] [73]
SOFC	1059.35	74.15	20.00	0.97	[16]
PEMFC	640.96	25.64	30.00	0.97	[16]
AFC	376.57	7.53	35.00	0.97	[16]
TRAIN_FREIGHT_H2	49.23	4.47	40.00	1.00	[60]
TRAIN_FREIGHT_H2_HYBRID	107.51	4.47	40.00	1.00	[60]
TRAIN_PUB_H2	517.89	0.02	40.00	1.00	[74]
H2_Haber_Bosch	0.00	0.00	40.00	0.90	[75]
H2_Steel	0.00	0.00	40.00	0.90	[76]
H2_COMP_200	489.76	29.39	20.00	0.95	[77] [78]
H2_COMP_200_350	489.76	29.39	20.00	0.95	[77] [78]
H2_COMP_100	489.76	29.39	20.00	0.95	[77] [78]
H2_COMP_100_350	489.76	29.39	20.00	0.95	[77] [78]
H2_VESSEL	8.79	0.44	30.00	0.95	[79]
H2_SALT_CAVERN	0.05	0.00	50.00	0.95	[80]
H2_WELL	0.04	0.00	50.00	0.95	[80]
H2_EXPANSION_100	0.00	0.00	10.00	0.95	-
H2_EXPANSION_200	0.00	0.00	10.00	0.95	-
SOEC_OG	1059.35	127.12	20.00	0.97	[16]
PEMEC_OG	640.96	44.87	30.00	0.97	[16]
AEC_OG	376.57	18.83	35.00	0.97	[16]
PAFC_OG	675.14	81.02	20.00	0.97	[72] [73]
SOFC_OG	1059.35	127.12	20.00	0.97	[16]
PEMFC_OG	640.96	44.87	30.00	0.97	[16]
AFC_OG	376.57	18.83	35.00	0.97	[16]

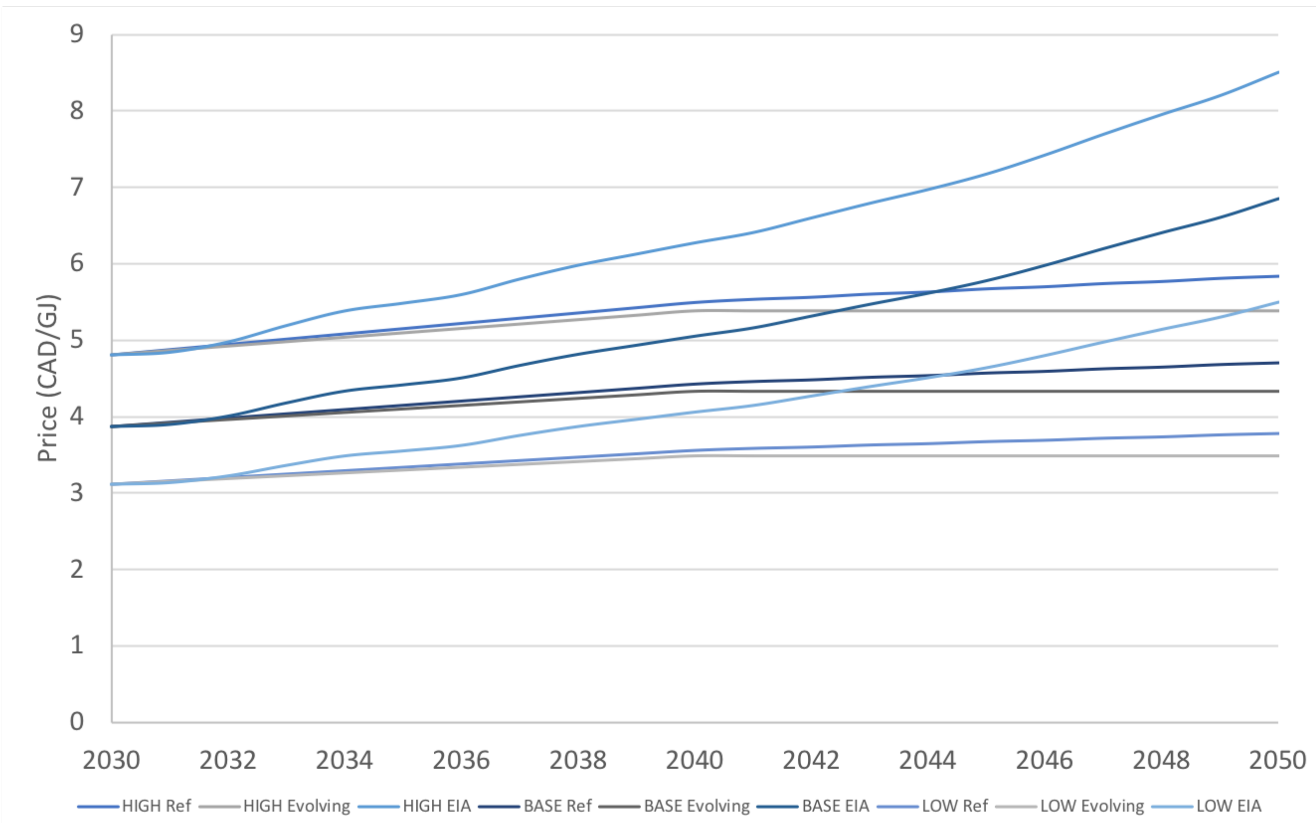

Figure B.1: Predicted Evolution of the Price of Natural Gas between 2030 and 2030

APPENDIX C

ES-R DG

Table C.1: Cluster Parameters - Part 1

Cluster	$\mathbf{C}_{p,wind}$	$\mathbf{C}_{p,solar}$	$\mathbf{pop}_{dens.}$	**Grid Dist.**	$\mathbf{Area}_{\%,urban}$	$\mathbf{Area}_{\%,agri}$	$\mathbf{Area}_{\%,ecu}$
	-	-	cap./km^2	km	-	-	-
1	0.16	0.14	18.03	37.28	0.09	0.03	0.95
2	0.15	0.15	82.65	3.57	0.44	0.97	1.00
3	0.13	0.15	13.40	4.82	0.07	0.48	0.96
4	0.16	0.15	382.42	1.36	0.95	0.98	1.00
5	0.17	0.14	564.71	41.20	0.85	0.04	0.97
6	0.15	0.15	18.57	3.79	0.05	0.98	0.99
7	0.18	0.13	3.50	156.48	0.01	0.02	0.23
8	0.19	0.14	21.77	4.98	0.06	0.96	0.99
9	0.19	0.13	37.67	237.94	0.06	0.01	0.92
10	0.15	0.14	320.91	4.34	0.94	0.99	1.00

Table C.2: Cluster Parameters - Part 2

Cluster	$\mathbf{C}_{p,hydro}$	$\mathbf{Hydro}_{installed}$	$\mathbf{Hydro}_{river,potential}$	$\mathbf{Hydro}_{dam,potential}$	$\mathbf{Area}_{\%,wind}$	$\mathbf{Area}_{\%,solar}$
	-	GW/km^2	GW/km^2	GW/km^2	-	-
1	0.51	16.40	13.05	13.88	0.23	0.21
2	0.52	1.65	0.90	1.88	0.55	0.12
3	0.49	0.19	0.15	0.11	0.60	0.26
4	0.51	6.07	4.46	6.42	0.05	0.01
5	0.49	20.81	11.72	22.42	0.06	0.06
6	0.52	2.48	1.97	2.90	0.94	0.20
7	0.50	5.39	2.89	7.22	0.49	0.47
8	0.12	0.21	0.28	2.78	0.92	0.20
9	0.45	37.03	20.14	48.81	0.68	0.67
10	0.19	0.51	0.51	5.91	0.06	0.01