

Electricity and renewable gas energy system alternatives for fossil fuel substitution in British Columbia

A report to the Energy Modelling Initiative

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Abstract (English)

This report documents model development and data availability to investigate emission reductions in the residential and commercial space and water heating sectors of Metro Vancouver, British Columbia. Two transition pathways quantify electricity and gas system requirements to eliminate natural gas combustion. In these pathways, a one-year hourly capacity expansion and dispatch model substitutes natural gas with either renewable electricity, or biogas and electrolytic hydrogen. Historic secondary energy demand and heating system efficiency data inform on the effects of heating technology improvements. Cost-minimization reveals optimal electricity generation, gas production, and storage capacities able to supply energy demands. Results show both pathways to reduce emissions by ~ 80%, but capacity requirements are sensitive to ambient temperature profiles, and available biogas resources. Electrification is 52% lower cost than renewable gas transition when heat demand is low; renewable gas transition is 35% lower cost when biogas availability includes wood gasification.

Résumé (Français)

Ce rapport documente l'élaboration de modèles et la disponibilité des données pour étudier d'émissions dans les secteurs résidentiels et commerciaux et du chauffage de l'eau de la région métropolitaine de Vancouver, en Colombie-Britannique. Deux voies de transition quantifient les exigences des systèmes d'électricité et de gaz pour éliminer la combustion du gaz naturel. Dans ces voies, un modèle d'expansion et de répartition de la capacité horaire sur un an remplace le gaz naturel par de l'électricité renouvelable ou du biogaz et de l'hydrogène électrolytique. Les données historiques sur la demande d'énergie secondaire et l'efficacité du système de chauffage informent sur les effets des améliorations de la technologie de chauffage. La minimisation des coûts révèle des capacités optimales de production d'électricité, de production de gaz et de stockage capables de répondre à la demande énergétique. Les résultats montrent que les deux voies permettent de réduire les émissions d'environ 80%, mais les exigences de capacité sont sensibles aux profils de température ambiante et aux ressources de biogaz disponibles. L'électrification coûte 52% moins cher que la transition au gaz renouvelable lorsque la demande

de chaleur est faible; la transition au gaz renouvelable est 35% moins coûteuse lorsque la disponibilité du biogaz comprend la gazéification du bois.

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List of symbols and abbreviations

Alberta
British Columbia Balancing Authority
British Columbia
Electrification pathway
Giga Watt
Open Source Energy System Model
Peta Joule
Renewable gas pathway
Terra Watt Hours
United States of America

1. Introduction

Mitigating climate change and limiting global warming to below 2 °C by 2100 will require reducing global greenhouse gas emissions to net-zero by mid-century. The Canadian province of British Columbia (BC) has committed to reducing its annual emissions from 2007-levels by at least 80% by 2050. Achieving these targets necessitates the elimination of fossil fuel combustion as an energy source.

Replacing fossil fuels with low-carbon electricity has been identified as among the lowest-cost strategies to mitigating climate change (Trottier Energy Futures Project, 2016). BC generates 98% of its electricity from renewable sources; hydro power contributes the largest share at 91%, biomass and wind provide another 6% and 1%, respectively (Canada Energy Regulator, 2021). This low-carbon electricity offers immediate emission reduction potential via electrification, but the available energy and power generation capacity cannot replace the vast quantity of fossil fuel consumed in all other sectors. Operating constraints limit the share of flexibly dispatchable hydroelectric energy to about one third of annual supply. Constraints include minimum water discharge rates, flood control, and the large snowmelt-driven water inflows that occur in early summer when electricity demand is low (BC Hydro, 2017a). Electrification of the heating sector and transportation sectors would increase winter peak electricity demand beyond the province's load-carrying capability of approximately 13 GW and require additional dispatchable generation capacity (Palmer-Wilson, 2020).

In the residential and commercial building sectors of British Columbia, natural gas provided 68% of space and water heating in 2016 (Natural Resources Canada, 2020). Replacing natural gas with biogas or electrolytic hydrogen offers an alternative to direct electrification and does not increase winter-peak electricity demand. Power-to-gas technologies facilitate use of low-cost gas storage capacity to indirectly store electricity from variable renewable sources, reducing electricity storage requirements, retaining gas infrastructure to avoid stranded assets, and increasing resilience to energy demand and supply variability.

This report describes the investigation of substituting natural gas in the building heating sector of the Metro Vancouver Regional District in British Columbia, Canada. Two distinct transition

pathways compare electrification and renewable gas alternatives. A combined electricity and gas system model reveals system costs, emission reductions, and electricity and gas production and storage capacity requirements. Along each transition pathway, three scenarios vary energy demand and renewable energy resource availability to delineate probable upper and lower energy system bounds for a range of potential futures. The description in this report discusses available data and their limitations, the system model development and its accessibility, the scenario assumptions and their impact on modelling results, and concludes with policy implications and recommendations for future research. The following questions guide the investigation:

1) What are the end-use energy demands for space heat, water heat and electricity in Metro Vancouver, and what are their temporal profiles?

2) How much additional energy production and storage capacity must be installed to meet those energy demands?

3) To what extent can fossil fuel substitution reduce Metro Vancouver's heating sector emissions?

4) What are the energy system costs of fossil fuel substitution?

2. Data availability

2.1. Electricity demand and generation capacity

British Columbia's hydropower-dominated electricity system produces surplus energy and can, potentially, accommodate some electrification of fossil fuel sectors. However, publicly available electricity system data lacks clear delineation of system boundaries and data collection procedures. This lack of documentation introduces uncertainty when comparing data across different sources to estimate the electric energy and capacity available for fuel substitution.

Comparison of hourly electricity demand, cross-border trade, and load-carrying capability using public data exemplifies this uncertainty. In its role as Balancing Authority (BA), BC Hydro controls real-time electric load and generation on British Columbia's integrated transmission system. In

this role, BC Hydro publishes "telemetered load" (BC Balancing Authority, 2021). Due to lack of documentation, it is unclear whether the data includes a) transmission losses, b) trade with Washington and Alberta, and c) behind-the-fence prosumers such as Rio Tinto Alcan. In its role as an electricity provider, BC Hydro supplies most, but not all electricity consumers connected to the integrated transmission system. Figure 1 shows that the BA's all-time peak hourly load between 2007 and 2018 approached BC Hydro's 2018 load carrying capability. That figure suggests that British Columbia's installed electricity generation capacity is constrained in peak demand hours with little surplus to accommodate additional winter peak load resulting from electrified heating. However, BA loads are likely not equivalent to loads "carried" exclusively by BC Hydro in its electricity supplier role. British Columbia's electricity system may be able to accommodate a larger additional peak load than this analysis suggests.

Additionally, the uncertainty regarding electricity trade affects this analysis of available energy. The annual sum of telemetered load differs from the sum of electricity generation published by the Canada Energy Regulator (Canada Energy Regulator, 2021), and also differs from the sum of electricity generation published by BC Hydro and Fortis BC, the two largest utilities in British Columbia.



Figure 1. Comparison of electric load, cross-border trade, and load-carrying capability in British Columbia highlights the capacity constraint in winter peak-demand periods. The red straight line shows BC Hydro's 2018 Effective Load Carrying Capability of 11,315 MW (BC Hydro, 2016, Ch. 3, Table 3-9). The green line shows all-time peak load between 2007 and 2018 as recorded by the Balancing Authority's "Telemetred Load" (BC Balancing Authority, 2021). Boxplots of telemetered load in yellow and electricity net import/export in blue (BC Hydro, 2021) show the variability of weekly means between 2007 and 2018. Imports/exports show the sum of flows across BC-US and BC-AB tie lines.

2.2. Space and water heat demand data

In British Columbia, the natural gas system delivers more energy and power to buildings than the electricity system. Modelling the transition from fossil fuels to renewable energy sources requires detailed energy demand and supply data. To investigate the impacts of fuel substitution on the electrical system, fuel consumption data would ideally be available at high temporal and spatial resolution, and distinguish between types of consumers. Unfortunately, high temporal resolution natural gas consumption data is not available in British Columbia. Most natural gas consumed by

residential, commercial, and institutional customers is metered for billing proposes in monthly intervals. Only select industrial consumers are metred at higher frequencies.

Two sources provide fuel consumption data at annual resolution. First, the Comprehensive Energy Use Database contains sector-specific data for each of Canada's provinces and territories (Natural Resources Canada, 2020). In this database, detailed historic records for residential, commercial, industrial, agricultural, and transportation sectors span 2000 to 2018. Data includes secondary energy consumption by fuel type and end-use, greenhouse gas emissions, and technology efficiencies. Second, the Community and Emissions Data Inventory provides municipal and utility-specific data for British Columbia between 2007 and 2017 (Ministry of Environment and Climate Change Strategy, 2021). This inventory contains historic records that distinguish between several fuel types and 1) residential and 2) commercial, and small and medium industrial consumers.

The lack of high temporal resolution data, and the aggregation of commercial and industrial consumers at the municipal level are barriers to investigating the electricity system's ability to accommodate electrification of natural gas consuming services. Estimating additional demand during peak demand events is critical to quantifying necessary but high-cost expansion of dispatchable and low-carbon generation capacity. To overcome the limited data availability, this study derives residential hourly heat demand from proprietary electricity consumption records provided by BC Hydro, and applies bottom-up building model data to derive hourly heat demand for commercial consumers. Improving data availability for British Columbia would reduce the uncertainty introduced by those estimation techniques.

3. Methods

The study presented in this report cost-optimizes a combined electricity and gas system model of the Metro Vancouver Regional District in British Columbia, Canada. In two distinct pathways, renewable gas or electricity substitute for natural gas that serves the Metro Vancouver residential and commercial building sectors. Along each pathway, three scenarios capture a range of energy demand and renewable energy resource availability. These scenarios delineate

probable upper and lower bounds of overall system costs, emission reductions, and electricity and gas production and storage capacity requirements.

Energy demands include space heat, water heat, and net electricity that excludes space and water heating. To overcome limited data availability, annual end-use energy demands are calculated from historic secondary energy consumption records. Next, hourly demands are constructed by estimating normalized profiles and scaling these profiles to match annual demands (Section 3.3). Residential profiles are derived from proprietary electricity consumption data recorded at the household level. Commercial and institutional profiles are derived from building models. Correlating temperature records and space heat demand produces a profile for low-temperature conditions (Section 3.4). The resulting hourly data enables the investigation of supplying demand with variable renewables like wind and solar power, and related storage requirements.

3.1. Energy system model

This study applies the Open Source Energy System Model OSeMOSYS (Howells et al., 2011) to optimize the energy system transition of Metro Vancouver. This linear programming framework expands and dispatches energy production and storage capacities to supply energy demands while minimizing total annualized costs (Figure 2). The model determines the necessary capacities for natural gas substitution rates from 0 to 100% for a one-year period with hourly resolution. To limit the computational complexity of hourly time steps, the substitution occurs "overnight" at the beginning of the modelling period. No long-term evolution occurs because the model separately optimizes the energy system for each substitution rate. In the electrification pathway, air-source heat pumps and electric resistance water heaters exogenously replace natural gas via exogenously mandated renewable gas consumption shares. Iterating over the same one-year model period with varying electrification and renewable gas shares reveals energy system expansion trends.

Energy demands include water heat, space heat, and net electricity that serves non-heating loads. Air-source heat pumps and baseboard resistance heaters consume electricity, and furnaces consume gas to provide space heat. Electric and gas water heaters provide hot water.

The model uses existing hydro electricity and natural gas production to supply demands at the zero substitution rate. As necessary to meet demand at higher substitution rates, the model can choose to expand wind and solar electricity generation, biogas production, electricity and gas storage, and hydrogen production via electrolysis. This substitution reduces greenhouse gas emissions endogenously.



Figure 2. Energy system model used to investigate electrification and renewable gas pathways for Metro Vancouver. In the electrification pathway furnaces and gas water heaters are replaced by electric heat pumps and electric water heaters. In the renewable gas pathway, natural gas is replaced by biogas and electrolyzed hydrogen.

3.2. Model modifications

The model used in this study is based on the linear programming model OSeMOSYS (Howells et al., 2011). This model is well suited to investigate supply-side capacity expansion and dispatch. For the investigation described in this report the OSeMOSYS model is modified in in two ways.

First, an added *simultaneity* constraint allows simultaneous dispatch of more than one heating technology. This modification ensures that each heating technology provides heat in every hour of the year in accordance with its market share. The modification prevents a single technology

from providing all heat demand. A building that uses gas heating cannot provide heat to an electrically heated building when unavailable wind and solar power limits electricity supply.

Second, the storage module contained in the original OSeMOSYS is simplified to reduce computational complexity. The original code distinguishes between charging and discharging of storage technologies by two separate modes of operation. These two modes increase the solution space of the optimization in comparison to single mode optimization. The altered code removes additional modes of operation by allowing storage technologies to operate in reverse.

3.3. Energy demands

The space heat, water heat, and net electricity demands shown in Figure 3 are each constructed from an annual demand and a normalized profile. The total annual space and water heat demands are population-scaled from provincial secondary energy consumption records for the year 2016 (Natural Resources Canada, 2020). Space heat and water heat include natural gas and electricity consumed in the residential and commercial sectors. Annual electricity demand is based on the BC Hydro fiscal 2016 total electricity supply (BC Hydro, 2016). Net electricity excludes electric heating. Space heater efficiencies (Natural Resources Canada, 2020) and water heater efficiencies (NRCan, 2012) are used to estimate end-use energy demands from the available secondary energy consumption data.



Figure 3. Estimated hourly end-use energy demands for Metro Vancouver are the product of annual secondary energy demand records, heater efficiencies, and normalized hourly demand profiles.

The energy demand profiles determine the fraction of annual energy demand that the model must provide in each hour of the year. The commercial space and water heat demand profiles

are based on 15 commercial reference building models that represent ~ 70% of the commercial building stock in the United States of America (NREL, 2011). The residential water heat demand profile is based on data provided by Ontario's Independent Electricity System Operator (IESO, 2019). The residential space heat demand profile is derived from proprietary residential electricity demand data provided by the utility BC Hydro, as described in Palmer-Wilson (2020). The net electricity demand profile is the difference between the provincial electricity demand profile (BC Balancing Authority, 2021) and the space and water heat demands served by electricity.

3.4. Space heat demand under low temperature conditions

Based on 2016 residential demand and typical mean year commercial demand, the estimated hourly end-use space heat energy demand in Metro Vancouver peaks at 5.9 GW. That demand may underestimate the peak demand under low temperature conditions. Personal correspondence between the authors of this report and FortisBC Inc. revealed that natural gas delivery in British Columbia reached ~20 GW above baseload during a minimum temperature weather event in 2020.

To quantify energy system requirements for low-temperature demand peaks, a regression analysis between space heat demand and ambient temperature was performed. Between 1995 and 2019, the Pitt Meadows Climate Station recorded the lowest temperature of -16 °C in 1996. The 3197 heating degree days in that year are the third highest on record. For comparison, the lowest temperature in 2016 was -12.8 °C with 2568 heating degree days.

To hind cast a low-temperature demand profile, a second-degree polynomial equation was fit to minimize square errors between hourly end-use space heat demand and ambient temperature for temperatures below the chosen heating degree day threshold of 18 °C (Figure 4). For the residential sector, the equation was fitted directly onto the temperature data. For the commercial sector, the equation was fitted onto the 90th percentiles of 20 temperature bins of equal width to better capture peak space heat demand during low temperature events. Next, the residential and commercial equations of best fit each hind cast respective hourly space heat demand profiles for all temperature profiles recorded between 1995 and 2019 using the hourly

ambient temperature records for the Pitt Meadows Climate Station. The sum of the resulting demand profiles peak at 12 GW for the temperature profile recorded in 1996.



Figure 4. End-use space heat demand versus temperature in the residential and commercial sectors. The red curve shows the second-degree polynomial equation of best fit. The residential equation is fitted directly onto the temperature data and results in a Coefficient of Determination $R^2 = 0.84$. The commercial equation is fitted onto the 90th percentiles (black dots in right graph) of 20 temperature bins of equal width to better capture peak space heat demand during low temperature events.

3.5. Energy production

Hydro power generation capacity (12.9 GW) and annually available energy (60 TWh) are based on the BC Hydro Load-Resource Balance for fiscal year 2015 (BC Hydro, 2013, Tables 2 - 3). Available energy and power are population-scaled Metro Vancouver. Hydro power capacity is fixed. The available energy is dispatched on a partially flexible, partially pre-determined profile (Figure 5) to simplify the complex operating constraints observed by British Columbia's large hydro and run-of-river power stations. These constraints include snowmelt-driven water inflows, minimum water discharge rates, or flood control. This study estimates that approximately 41 TWh are dispatched to meet operating constraints; approximately 19 TWh are dispatchable at any time of the year (BC Hydro, 2017b). The cost and emissions of hydroelectric energy are 60 \$/MWh and 29.9 g_{CO2_eq} /kWh (Government of British Columbia, 2019).



Figure 5. Estimated monthly minimum capacity factors define the profile shape of ~ 41 TWh generated by British Columbia's hydroelectric power stations on a pre-determined schedule (BC Hydro, 2017). Generation peaks in June and July when snowmelt-freshet inflows dominate.

The model installs wind power capacity at scenario-dependant costs between 1219 and 2395 \$/kW. The exogenous wind generation profile is based on the hourly mean capacity factor of 30 potential sites located in southern, central, coastal, and eastern British Columbia (GE Energy Consulting, 2016). The annual mean capacity factor is 33.2%.

The model chooses to install solar power capacity at scenario-dependant costs between 669 and 2021 \$/kW. The exogenous solar generation profile is based single-axis tracking potential in Vancouver and provided by NREL's PV Watts (National Renewable Energy Laboratory, 2013). The annual mean capacity factor is 24.3%.

Gas production includes natural gas, biogas, and hydrogen produced from electrolysis. In this study, biogas and hydrogen substitute natural gas on an energy-equivalent basis. Natural gas costs 1.19 GJ (U.S. Energy Information Administration, 2020) and emits 50.3 g_{CO2}/MJ (U.S. Energy Information Administration, 2011). FortisBC plans to procure 30 GJ of biogas that emit 11 g_{CO2}/MJ to meet renewable gas and emission reduction targets by 2030. Costs of biogas were estimated at 23 GJ by the authors. Specific costs are confidential, but FortisBC confirmed that this estimate reasonably aligns with their portfolio average. Beyond the 30 GJ of biogas, the energy system model can choose to produce hydrogen by installing electrolyzer capacity at a scenario-dependant cost of 1400 W (ZEN, 2019) or 500 W (Thema et al., 2019) and an assumed efficiency of 78%.

3.6. Energy storage

Electricity and gas storage technologies provide flexibility to balance supply and demand. Storage technologies can store energy up to their installed energy capacity. Storage technologies can provide power to supply demand, or demand power to increase stored energy, up to the installed power and energy capacities, respectively. The model determines energy and power capacities independently of each other.

The model can choose to install electricity and gas storage technologies. Electricity storage has a round-trip efficiency of 86%. Installation costs are scenario dependant to reflect 2030 or 2050 battery storage as forecast by Schmidt et al. (2019). Gas storage capital costs (1 \$/kW and 0.1 \$/kWh) are consistently low across all scenarios, with assumed operating costs being nil. Gas storage has an assumed round-trip efficiency of 100%.

3.7. Scenarios

Three scenarios investigate energy system costs and capacity requirements across a range of possible futures. Technology costs, technology performance, energy demand, or renewable energy supply varies between each scenario. Table 1 summarizes the defining variation of each scenario.

- The *Reference* scenario applies 2030 lithium-ion battery storage costs, and present wind and solar costs determined by the latest resource options report performed by BC Hydro. FortisBC's provincial biogas target of 30 PJ is scaled to Metro Vancouver by population. The space heat demand is based on historic temperature correlation and hind cast for the 1996 temperature profile.
- The *MuchBiogas* scenario applies a large availability of biogas resources. The 93 PJ include estimated wood gasification supplies in British Columbia.
- The *LowHeatDemand* scenario applies 2016 space heat demand data. That data has a lower peak and lower overall energy demand than the hind cast 1996 demand applied in all other scenarios.

Scenario	Description	Rationale
Reference	a) 2030 Li-Ion battery cost	a) (Schmidt et al., 2019)
	b) BC Hydro Wind/Solar cost	b) (BC Hydro, 2020)
	c) Biogas target 2030 (30 PJ x 53%)	c) Personal
	d) 1996 temperature profile (high heat	correspondence with
	demand)	FortisBC Inc.
		d) Section 3.4
MuchBiogas	High biogas availability, including wood	(Hallbar Consulting, 2017)
	gasification (93.6 PJ x 53%)	
LowHeatDemand	2016 temperature profile (low heat demand)	Section 3.3

Table 1. Three scenarios determine low-carbon energy system costs and capacity requirements for a range of future energy demand, and renewable energy resource potentials.

4. Results

4.1. Greenhouse gas emissions

In both pathways, substituting natural gas with electricity or renewable gas reduces greenhouse gas emissions by approximately 80%. That reduction aligns with British Columbia's 2050 target, but the model includes only a fraction of overall emission sources. The 80% reduction includes all electricity generation, and the share of natural gas combusted for space and water heating in Metro Vancouver's residential, commercial and institutional building sectors.

Figure 6 shows emission reductions in the *Reference* scenario as natural gas substitution rates increase from 0 to 100% in the electrification pathway (Elec) on the left, and the renewable gas pathway (RNG) on the right. The whiskers delineate the range of emissions observed across all scenarios. At a natural gas substitution rate of 100%, the remaining emissions result from hydro power and, in the renewable gas pathway, from biogas. The *MuchBiogas* scenario retains the largest emissions (top whiskers) because the larger biogas resource availability enables larger emissions. The *LowHeatDemand* scenario retains the lowest emissions (bottom whiskers) because lower overall energy production leads to lower emissions.



Figure 6. Reference scenario greenhouse gas emissions from electricity generation and gas combustion in Metro Vancouver's building heating sector. Horizontal axes show natural gas substitution rates ranging from 0% to 100% in 10% increments. Whiskers denote emissions observed across all scenarios in the electrification pathway (Elec) on the left, and in the renewable gas pathway (RNG) on the right.

4.1. Electricity generation and storage capacity

Figure 7 shows the energy system expansion in the *Reference* scenario. Electricity (left column) or renewable gas (right column) gradually replace natural gas in 10% increments. Wind and solar supplement hydro electricity generation (top row) in both pathways. The installed electricity generation capacity (center row) in the electrification pathway exceeds installation in the renewable gas pathway. That larger capacity installation is driven by a peak space heat demand event during a five-day cold period in February, and leads to large surplus electricity generation in the remaining year. The energy storage capacity (bottom row) reaches 80 GWh of electric, and ~1000 GWh of gas storage capacity.



Figure 7. Reference scenario energy system transition in the electrification (Elec) and renewable gas (RNG) pathways. Horizontal axes show natural gas substitution rates ranging from 0% to 100%. The top row shows electricity generation and potential surplus for the one-year modelling period. The center row shows installed electric power generation capacities. The bottom row shows electric energy storage capacity on the left, and gas storage energy capacity on the right. Gas storage capacity reaches ~ 1000 GWh; the axis range highlights the electric energy storage capacity because gas storage is effectively unconstrained in British Columbia. Error bars show minimum and maximum energy storage capacities observed across all scenarios.

Scenario analysis reveals that energy storage capacity requirements and resulting total system costs are sensitive to biogas supply and energy demand. The error bars in Figure 7 show minimum and maximum energy storage capacities observed across all scenarios. The Reference scenario results in the largest electric energy storage capacity of 80 GWh. The *LowHeatDemand* scenario requires only 4 GWh of electric energy storage capacity.

4.2. Pathway costs

The large range of electric storage capacity installation leads to significant system cost differences between the electrification and the renewable gas pathways. Either pathway can result in lower overall costs, but the range of costs is more narrow in the renewable gas pathway. The Reference scenario reveals that peak electricity demand that exceeds present-day dispatchable generation capacity is the largest cost driver in the electrification pathway. The *MuchBiogas* scenario reveals that limited biogas supply is the largest cost driver in the renewable gas pathway because higher-cost hydrogen production requires expansion of electrolyzers, additional electricity generation capacity, and gas storage.

The cost differences between electrification and renewable gas pathways range from -52% to +35% across all sensitivity scenarios (Figure 8). The electrification pathway is most cost-favourable (-52%) in the *LowHeatDemand* scenario where electricity demand peaks at 5.9 GW, as opposed to 12.3 GW in the Reference scenario. The renewable gas pathway is most cost-favourable (+35%) in the *MuchBiogas* scenario.



Figure 8. Percentage cost difference between electrification and renewable gas pathways at 100% natural gas substitution across all scenarios.

5. Discussion

5.1. Policy implications

The electrification and the renewable gas pathway both reduce emissions by ~80%, but costs are sensitive to energy demand and biogas supply. In the electrification pathway, total system costs increase significantly when peak electricity demand exceeds the dispatchable electricity generation capacity. New renewable and dispatchable generation capacity must supply any

electricity demand that exceeds present load-carrying capability. In British Columbia, dispatchable generation is limited to large hydro power stations, and to a smaller extent biomass and natural gas fired power stations that are not included in this study. The high cost of meeting peak electricity demand with storage technologies warrants support to develop and deploy renewable dispatchable generation technology like geothermal power stations, or expanding the capacity of existing hydroelectric dams. Conversely, the high value of avoiding an increase in peak electricity demand warrants support for building-efficiency improvements, heat-pump adoption, and demand side measures.

Relying on storage to provide electricity during extended peak demand events may not be feasible. The 80 GWh of electric storage capacity observed in the reference scenario is equivalent to ~ 8 pumped storage facilities of typical size. For comparison, the existing Aitken Creek gas storage facility in northeastern BC can store 80,000 GWh of natural gas. Installing 8 pumped storage facilities to decarbonize a relatively small economic segment (residential and commercial heating in Metro Vancouver) does not appear feasible in light of environmental impacts and public opposition these facilities face. Further research is required to identify economic segments where electrification provides the best cost-benefit.

5.2. The Open Source Energy System Model OSeMOSYS

The Open Source Energy System Model applied in this study is developed and maintained at the Swedish Royal Institute of Technology KTH. OSeMOSYS is available in the GAMS, MATHPROG, or Python programming languages (GitHub, 2021). An active community of energy specialists provide support for new and experienced users to facilitate adoption (Google Groups, 2021).

OSeMOSYS has been used to investigate a wide variety of energy transitions because the open source code is adaptable to a wide range of regional scales and energy systems. More than 60 publications study regions across four continents (osemosys.org, 2021). Examples include residential building decarbonization at municipal scale (Leibowicz et al., 2018), inter-provincial electricity transmission expansion (English et al., 2017), and game-theory application to international electricity trade (de Moura et al., 2018). The user can define different energy demands, production, and storage technologies. In this study, the model must satisfy Metro

Vancouver's electricity and gas demands by optimizing several electricity and gas production and storage technologies. The model is ideal to represent a custom subsection of the energy system, and provides opportunity to investigate the interactivity of the gas and electricity system.

OSeMOSYS provides flexible implementation of temporal resolution to control computational complexity. For long-term planning, variable-length representative time slices enable multi-decadal capacity expansion to avoid computationally expensive higher-resolution time steps. Without requiring modifications to the model code, the investigation described in this report applies hourly time steps that provide detailed analysis of balancing demand with variable renewable energy sources. This temporal detail is crucial to comparing the infrastructure requirements of electrification and renewable gas pathways in British Columbia because 1) fossil fuel substitution will increase low-carbon electricity demand, 2) British Columbia commits to a minimum renewable electricity share of 93%, and 3) variable wind and solar power are the most abundant renewable energy sources.

The integration of the OSeMOSYS energy system model and its derivatives would benefit the national modelling platform. Making all Canadian energy system models available in a single national platform increases the potential of that platform to become the predominant repository.

5.1. Model and data availability

This report's energy system model, parameter inputs, and resulting output files are available for download via the GitHub repository located at:

https://github.com/ResearchAtPlay/MetroVanRNG

Energy demand and supply data are taken from publicly available sources. The model and parameter files are human-readable. A third-party modeller can solve the optimization problem and reproduce the results presented in this report using the freely available open source GNU Linear Programming Kit GLPK (Makhorin, 2000). However, the published repository does not allow recreating of the entire workflow from raw public data to optimization results. Model development is an iterative process with prototypical workflow design. The files in the published repository are a subset of the larger workflow. This workflow incudes: 1. Retrieving, cleaning, and formatting several energy supply and demand datasets using the Excel software package and python scripts.

2. Processing energy supply and demand datasets to create scenario-specific data using the Excel software package and python scripts.

3. Compiling scenario-specific datasets into comprehensive model parameter files using python scripts.

4. Executing the optimization to solve the computational problem defined in the model and parameter files. This step is performed on a high-performance computer cluster using layered python and bash scripts that interface Windows and Linux operating systems.

5. Retrieving and processing the optimization results to produce succinct result tables and visualizations using python scripts.

The complexity of this workflow design and the dependency on a range of software and hardware environments makes recreation of the entire workflow challenging. Even if all scripts and data are publicly available, a third party modeller would need to adapt these scripts to their own computing environment and matching folder structure. New modelling tools like the Spine Toolbox are in development to solve the workflow design problem and enable more complete model, data, and workflow sharing (spine-model.org, 2021).

5.2. Model usability for policy design

Achieving net-zero emissions by 2050 – only 29 years from the writing of this report – requires 1) vast low-carbon infrastructure expansion to eliminate fossil fuel combustion via fuel substitution, 2) reduce energy demand through energy efficiency measures, and 3) create greenhouse gas sinks to balance emissions from difficult-to-decarbonize sectors. Public support for this transition is crucial to avoid delays in mitigating the global climate change. Results from this model can help quantify those infrastructure requirements and then transparently communicate the global scale and unprecedented pace of the low-carbon energy transition.

Cost-effective policy design can help expedite the emission reductions. Scenario analysis captures uncertainties regarding cost forecasts, energy demands, and renewable energy availability.

Comparison of the range of total costs for renewable gas and electrification pathways reveals that the range of costs is more narrow in the renewable gas pathway. Considering this uncertainty in energy policy design may mitigate the risk of incurring excessive costs.

5.3. Future work

The investigation described in this report revealed possible emission reductions of ~ 80% in the combined building heating and electricity sector for both pathways. The relatively small but still significant greenhouse gases emitted by hydropower and biogas will ultimately need to be eliminated. Negative emission services like direct air capture with carbon sequestration may be necessary to mitigate the global climate change. Additional study is required to understand the overall costs and energy system impacts of integrating such negative emission technologies.

This report's investigation is limited to net electricity demand, and space and water heat demand. To better understand the energy system impacts of electrifying several economic sectors simultaneously, and to determine which sectors the existing electricity system can best accommodate, fuel substitution in other sectors need to be integrated. The "overnight" substitution of natural gas in this study does not include future changes in energy demand. A gradual transition of the energy system from a present state to a future state could account for efficiency measures, economic development, or population growth.

Further research is required to assess operational feasibility and resilience of the energy system capacities determined in this report. Operational feasibility means ensuring that the energy system provides sufficient dispatchable capacity, flexibility and energy to meet all demands. Investigating snapshots of the energy system using high temporal and spatial resolution will reveal resilience under varying energy demand and supply scenarios.

Demand side variations may include:

- varying penetrations of distributed generation technologies that reduce net load, e.g. rooftop photovoltaics
- weather and climate variability that impact building heating and cooling demands
- transportation demand profile dynamics

Supply-side variation may include:

- low-water inflow to the hydroelectric dams
- extended time periods without wind or solar availability

Linking the results reported here with the production cost model SILVER (McPherson and Karney, 2017) lends itself to investigating these variations. SILVER combines scenario planning, network-constrained dispatch, unit commitment, and power flow analyses frameworks, and is presently being adapted to include the cascaded hydroelectric system of British Columbia. Combining the application of OSeMOSYS and SILVER will reveal comprehensive insight into feasible emission reduction pathways for British Columbia.

5.4. Data availability constraints

Data availability determines the ability to design decarbonization research. The data available for British Columbia presents a barrier to improve investigations of uncertainty regarding the balancing of energy demand and supply, as described in Section 2. Matching supply and demand is a stochastic process. Ideally, variable renewable energy production data at high temporal and spatial resolution would be available for multiple years across Canada. Modelling stochasticity would improve uncertainty estimates.

This study focuses on the largest population center, Metro Vancouver Regional District, rather than all of British Columbia because of limited demand data availability. Since Metro Vancouver houses 53% of BC's population and plans to achieve carbon neutrality by the same year as the province, eliminating fossil fuel combustion in Metro Vancouver is a significant step towards overall emission reductions.

6. Conclusion

This report investigates greenhouse gas emission reduction options in the building heating sector of Metro Vancouver, British Columbia. Two transition pathways compare substitution of fossil fuels with electricity or gas produced from renewable sources. An energy system model determines energy production and storage capacities able to supply space heat, water heat, and electricity for a one-year period. The hourly resolution of this model enables investigation of supplying those energy demands with variable wind and solar power.

The existing low-carbon electricity system in British Columbia can substitute some fossil fuels at relatively low cost, but the available energy and power capacities limit this substitution. Electrification of large energy-consuming sectors result in additional electricity storage infrastructure requirements that lead to high overall costs. The completed study shows that electricity or renewable gas substitution of fossil fuels can both reduce greenhouse gas emissions, but costs and capacity requirements of either pathway are sensitive to energy demand and available resources. Peak electricity demand is the largest cost driver in the electrification pathway – this finding shows the value of using both electrification and renewable gas transitions in combination. The overall goal of quantifying energy system impacts of both pathways is achieved by analyzing a range of scenarios. This analysis results in upper and lower bounds of possible pathway trajectories.

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