Impacts of Curtailment Costs on Optimal Generation and Storage Capacity

by

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B.Eng., Universidad Autónoma de Nuevo León, 2019

A Thesis Submitted in Partial Fulfillment of the
Requirements for the Degree of

MASTER OF APPLIED SCIENCE

in the Department of Mechanical Engineering

University of Victoria

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ABSTRACT

This study examines the effects of curtailment costs on cost-minimized energy capacity for Metro Vancouver, focusing on electrification and Renewable Gas (RG) pathways. Using Calliope, we assess the impact of curtailment costs on storage capacity, renewable generation, and system costs. Results show that curtailment costs significantly affect the electrification pathway, driving increased battery storage activity and selective deployment of renewable generation to limit curtailment. In contrast, the RG pathway adjusts only gas storage capacity in response to curtailment costs, relying solely on wind technology as its Variable Renewable Energy source without the need of an electric storage. These findings highlight the importance of tailored curtailment cost strategies for efficient renewable integration, enhancing resilience and cost-effectiveness across energy transition pathways.

Contents

List of Tables

List of Figures

List of Abbreviations

Abbreviations

BC	British Columbia
CAISO	California Independent System Operator
CO_2	Carbon Dioxide
CSV	Comma-separated values
ERCOT	Electric Reliability Council of Texas
GHG	Greenhouse Gas
LCOE	Levelized Cost of Energy
O&M	Operation and Maintenance
OSeMOSYS	Open Source Energy Modelling System
RG	Renewable Gas
VRE	Variable Renewable Energy

Units

GW	Gigawatt
GWh	Gigawatt-hour
kW	Kilowatt
kWh	Kilowatt-hour
MW	Megawatt
MWh	Megawatt-hour
TWh	Terawatt-hour

ACKNOWLEDGMENTS

This research was partially funded by Fortis BC, whose support has been instrumental in allowing the progress and completion of this work. I greatly appreciate their contribution to the advancement of research in this field.

First, I would like to extend my deepest gratitude to my supervisor, Dr. Andrew Rowe. From the first response to my email that I received three years ago, he has provided unwavering support, insightful feedback, and guidance throughout my research journey. His mentorship has been invaluable in shaping both my academic growth and my professional skills, and I am profoundly thankful for his encouragement and expertise.

I am also grateful to my co-supervisor Peter Wild, my colleagues and friends in the AMRLab team, and IESVic, whose camaraderie and support enriched my experience. Our collaborative discussions and shared challenges provided strength and invaluable learning opportunities that have greatly contributed to this journey.

To my family, I cannot express enough appreciation for your constant belief in me. Your love, understanding and sacrifices have provided the foundation that allowed me to pursue my academic aspirations and kept me grounded throughout.

Finally, to my partner, Cinthia Serrato, your patience, support, and unwavering encouragement have been my rock throughout this journey. Your belief in my work and your constant presence have kept me motivated, and I am deeply grateful for your presence at every step of the way.

DEDICATION

To my loving parents, Gloria Ibarra and Antonio Herrera, who always supported and encouraged me in my decision to study abroad; to my siblings Ana and Isaías, whose achievements inspire me to keep improving; to my friends in Mexico and the new ones I've found while conducting this research—especially Ariel Gallegos, Luis Tamez, and Jair Licea—who have always been a source of encouragement and connection throughout this journey; and to my amazing fiancée, Cinthia Serrato, who shared in this journey, and whose support and encouragement have been my strength.

I could not have come this far without each of you. I am forever grateful.

Chapter 1

Introduction

As Canada and other nations aim to achieve net-zero carbon emissions in alignment with the Paris Agreement [1], renewable energy sources play a vital role in the pathway to sustainability. This global shift toward decarbonization is heavily reliant on Variable Renewable Energy (VRE) technologies such as wind and solar, which help reduce greenhouse gas emissions, playing a critical role in mitigating climate change [2, 3, 4, 5, 6].

Once installed, wind and solar technologies have the economic advantage of low operating costs [7]. Over time, advancements have further driven down costs [8], making these sources increasingly competitive with traditional energy sources such as coal and natural gas. However, large-scale deployment of VRE presents unique challenges, notably the need to balance fluctuations in supply and demand [9]. Curtailment—when VRE output is reduced due to oversupply, grid limitations, or mismatches between energy supply and demand—has emerged as a significant issue in regions rapidly expanding their renewable energy infrastructure [10, 11, 12, 13].

Curtailment is particularly noticeable in regions like California and Texas, where renewable energy deployment is high. For example, California has seen rising levels of curtailment, especially in spring when solar production peaks, but electricity demand is low. The California Independent System Operator (CAISO) has reported record curtailment in recent years as a result of overgeneration, grid limitations, and insufficient storage [14]. In Texas, where wind energy plays an important role, curtailment often occurs during periods of high wind generation and low demand. The Electric Reliability Council of Texas (ERCOT) has also reported major curtailment events, highlighting challenges in fully utilizing wind resources within existing grid infrastructure [15]. Despite these limitations, both states continue to expand their renewable capacities [16, 17].

Without significant grid upgrades or storage solutions, curtailment issues are expected to intensify as more renewable projects come online. The impact of curtailment on energy systems is largely determined by grid flexibility and storage capacity [18]. In British Columbia, Canada (BC), Palmer-Wilson et al. demonstrated that achieving provincial electrification goals, such as reducing natural gas usage for building heating, requires substantial increases in wind and solar capacity, alongside energy storage [19]. Their findings highlight the need to integrate storage systems to balance supply and demand effectively, especially during peak generation periods.

Alongside electricity storage, renewable gas technologies such as hydrogen provide an alternative method for storing surplus renewable energy. These technologies also help decarbonization in sectors less suitable for direct electrification, such as heavy industry and heating [20]. The British Columbia government's 2050 roadmap highlights these renewable gas technologies as part of the transition to net-zero emissions by mid-century [21]. Consequently, energy storage is essential in managing the variability of renewable sources like solar, wind, and hydro, ensuring the resilience of BC's energy system [9, 22].

Curtailment poses several challenges for energy system planning and operations. When energy production exceeds demand or grid capacity, the resulting surplus must either be curtailed or stored, leading to inefficiencies and potential economic losses. In the context of capacity expansion planning, curtailment affects decisions related to the sizing and deployment of VRE technologies and energy storage systems. High levels of curtailment can discourage investment in renewables, as the value of excess energy goes unrealized. Moreover, ”take-or-pay” agreements—where energy producers are compensated regardless of whether their output is utilized—can exacerbate these challenges, imposing additional costs on system operators and end users [23].

To investigate curtailment's role in energy system planning, this study uses Calliope, an open-source energy system modelling tool [24]. This model enables simultaneous storage and curtailment optimization, providing a unified framework to evaluate different scenarios focused on the 100% electrification and RG pathways in Metro Vancouver. Building on the work of Palmer-Wilson et al. [19], this research introduces various levels of curtailment costs and examines their effects on storage requirements and energy system outputs. By exploring the implications of curtailment in this region, the study addresses an aspect that has not been fully addressed in previous analyses.

Long-term energy planning requires determining the optimal storage sizes and technologies to meet BC's projected energy demand. Given the variability of renewable energy production, an accurate representation of energy balance within the system is vital for assessing the potential benefits and limitations of storage solutions, which can shape future investment and policy decisions [25]. Effective energy storage strategies are particularly necessary to handle excess generation from renewables and store them for periods of low production.

The primary aim of this thesis is to evaluate the impacts of curtailment cost on optimal mature infrastructure and optimize storage solutions based on projected demand in Metro Vancouver using the Calliope framework [24]. This research investigates different storage technologies and examines the interactions between electrification and renewable gas pathways, contributing to a comprehensive approach to meeting British Columbia's future energy needs.

This study focuses on optimizing storage capacities, as well as the capacities of VRE technologies and electrolyzers (where applicable) while evaluating the role of renewable gas in British Columbia's energy system. To understand the effects of curtailment on energy outputs and storage requirements, various curtailment levels—from 0 to 0.1 \$/kWh—are applied to both wind and solar technologies. Incorporating these curtailment scenarios is essential to assess the lost value of energy that is available but not utilized, often due to grid limitations or mismatches in supply and demand.

The following research questions guide this thesis: What is the optimal storage size needed when considering curtailment to meet energy demands in Metro Vancouver? How do different storage technologies, such as batteries and hydrogen, perform across different curtailment cost scenarios, and how do electrification and renewable gas pathways influence storage requirements? This study addresses these questions by analyzing the impact of curtailment costs in overall system costs, energy outputs, and storage needs in Metro Vancouver's energy model.

The thesis is structured as follows: Chapter 2 reviews the relevant literature, providing essential background for this study. Chapter 3 outlines the methodology, detailing the setup and scenario design within the model, including the integration of storage options, curtailment costs, and energy pathways. Chapter 4 presents the simulation results, focusing on how curtailment costs affect model outcomes. Finally, Chapter 5 discusses key findings and their implications for energy system planning, concluding with recommendations for future research.

Chapter 2

Background

This chapter reviews existing research on renewable energy integration, energy storage technologies, and optimization frameworks, with a focus on modeling approaches for managing variable renewable energy curtailment.

2.1 Variable Renewable Energy and Curtailment

In Canada, renewable energy sources accounted for 16.9% of total primary energy supply in 2015 [26]. By 2022, the country produced 639 terawatt hours of electricity, with renewable sources accounting for 70% and non-GHG emitting sources comprising 82%, including solar, hydro, wind, and nuclear power [27]. However, the intermittent nature of renewable energy sources has raised concerns about their integration into the power system [26]. The market is poised for exponential growth due to the adoption of electric vehicles, hydrogen production, and industrial electrification [28].

Large-scale deployment of VRE technologies presents unique challenges, notably the need to balance fluctuations in supply and demand [9]. Curtailment—when VRE output is reduced due to oversupply, grid limitations, or mismatches between energy supply and demand—has emerged as a significant issue in regions rapidly expanding their renewable energy infrastructure [10, 11, 12, 13].

Curtailment is particularly noticeable in regions like California and Texas, where renewable energy deployment is high. For example, California has seen rising levels of curtailment, especially in spring when solar production peaks but electricity demand is low. The California Independent System Operator (CAISO) has reported record curtailment in recent years due to overgeneration, grid limitations, and insufficient storage [14]. In Texas, where wind energy plays a significant role, curtailment often occurs during periods of high wind generation and low demand. The Electric Reliability Council of Texas (ERCOT) has also reported major curtailment events, highlighting challenges in fully utilizing wind resources within existing grid infrastructure [15]. Despite these limitations, both states continue to expand their renewable capacities [16, 17].

2.2 Energy Storage Technologies

Energy storage technologies are expected to play a crucial role in grid balancing and integrating renewable energy sources, as well as addressing their intermittency challenges [29, 30, 31, 32, 33]. Storage technologies enable functions such as load leveling, peak shaving, frequency regulation, damping of energy oscillations, and improvement of power quality and reliability [34, 35, 36]. These systems are important for mitigating the effects of renewable intermittency, which can impact stability, voltage regulation, and overall power quality [26].

2.2.1 Electric Energy Storage: Pumped Hydro

One of the most established electric energy storage technologies is pumped hydro, which accounts for over 96% of global energy storage capacity [37]. BC Hydro has previously assessed the feasibility of pumped hydro storage in British Columbia, identifying nearly 200 potential sites in the Lower Mainland and Vancouver as viable options for storing renewable-produced electricity [38]. For this study, pumped hydro will be used to model electric storage; however, future work could explore the use of chemical batteries, which have already seen deployment in the province [39, 40].

2.2.2 Renewable Gas Technologies: Gas Cavern Storage

Alternatively, gas caverns provide seasonal storage, useful for balancing renewable variability. In BC, potential methane reservoirs, such as the Lower Cretaceous Buckinghorse Formation, have been identified [41]. Power-to-gas storage can convert excess electricity to hydrogen and natural gas, providing flexibility in integrated energy systems [42]. Gases like hydrogen can also be stored in underground salt caverns, enabling large-scale, long-term storage [43, 44, 45]. Salt caverns are particularly valuable for renewable energy integration, as they provide flexible grid-balancing capabilities [46]. For example, in China, the aim is to develop 300 million m^3 of underground salt caverns by 2030, contributing to reducing CO_2 emissions through various storage applications, including compressed air, natural gas, hydrogen, and carbon dioxide storage [47].

McPherson et al. [48] highlight the potential for hydrogen production and storage as a flexible mechanism for managing excess electricity in decarbonized grids. Their work demonstrates that pairing energy storage technologies with hydrogen systems can significantly reduce curtailment while improving grid flexibility.

For this study, electricity can be converted into hydrogen, and renewable gas can be stored in salt caverns, presenting an alternative to conventional batteries for the RG pathway.

2.3 Optimization Frameworks for Energy Systems

To evaluate these storage options in a unified framework, this study employs Calliope, an open-source energy system modeling tool designed for spatially and temporally explicit analysis [24]. Calliope's flexibility in integrating both electric and gas storage technologies within a single optimization framework makes it ideal for examining complex renewable energy systems in British Columbia. Previous studies have utilized Calliope to model energy storage solutions across diverse geographic regions [49, 50, 51, 52, 53, 54, 55, 56, 57, 58], underscoring its effectiveness in balancing renewable energy with storage at various scales. However, no other Calliope studies have specifically examined curtailment costs to date. This study uses Calliope for spatial optimization of renewable deployment, focusing on storage size and curtailment costs.

2.4 Curtailment Costs and System Planning

While energy storage technologies offer numerous benefits, each option involves trade-offs concerning efficiency, capacity, environmental impact, and cost-effectiveness [59, 60]. One significant economic consideration is curtailment cost—the cost encountered when excess renewable energy must be curtailed, or "turned off," if a power system does not have enough operational flexibility [11, 61]. As renewables have low variable operational costs, high curtailment costs can reduce the economic viability of renewable energy systems and place added financial strain on storage solutions [62, 63], particularly in regions aiming for aggressive renewable integration, such as California [14, 61, 64, 65, 66].

Curtailment poses several challenges for energy system planning and operations. When energy production exceeds demand or grid capacity, the resulting surplus must either be curtailed or stored, leading to inefficiencies and potential economic losses. In the context of capacity expansion planning, curtailment affects decisions related to the sizing and deployment of VRE technologies and energy storage systems. High levels of curtailment can discourage investment in renewables, as the value of excess energy goes unrealized.

Niet et al. [67] emphasize that curtailment costs have profound implications for the economic feasibility of decarbonization pathways. Their analysis highlights how pricing curtailment appropriately can improve decision-making regarding storage deployment and renewable expansion. Their findings align with this study's approach of incorporating curtailment cost sensitivity into modeling, as it directly impacts system-wide optimization.

This study builds upon the work made by Palmer-Wilson et al. [19], by explicitly evaluating curtailment cost sensitivity and its influence on both electrification and renewable gas pathways for Metro Vancouver. By incorporating these costs into energy models, it becomes possible to evaluate the economic trade-offs between storage investment and renewable curtailment, helping to identify the most cost-effective strategies for grid stability and decarbonization.

The BC government's 2050 decarbonization roadmap emphasizes a need for increased renewable energy integration and effective storage solutions to manage the growing demand [21]. This roadmap, combined with a focus on electrifying sectors such as building heating in British Columbia [19, 68, 69], underlines the role of storage in mitigating curtailment and optimizing renewable deployment within an expanded energy framework. All scenarios in this study are designed to achieve low-emission pathways, reflecting the overarching goal of decarbonization.

Grounded in optimization and energy balancing theories [24, 70, 71], this study's modeling approach supports cost-effective, reliable integration of VRE and storage. By including curtailment costs, this study addresses previously underexplored economic implications of renewable curtailment, enhancing understanding of optimal resource allocation for decarbonization.

Finally, this research situates itself within the broader goal of integrating renewables and storage to achieve carbon reduction targets [1], emphasizing the role of curtailment in system-wide optimization. As curtailment costs directly influence the viability of storage solutions, their inclusion in energy models helps refine strategies for achieving optimal resource allocation and decarbonization. Together, these theoretical frameworks form a foundation for the methodology detailed in the following chapter.

Chapter 3

Methodology

3.1 Introduction

This study models the energy storage needs for Vancouver, BC, utilizing Calliope due to its flexibility in handling diverse geographic and temporal configurations. Capacity expansion models simulate generation and transmission investments based on assumptions about demand, fuel prices, technology costs, performance, and policy constraints [72]. Calliope, chosen over alternatives like the Open Source Energy Modelling System (OSeMOSYS) [73], balances technology and resource constraints [24], making it ideal for exploring optimized storage capacities for Vancouver's energy future.

Calliope's short-term optimization capabilities adapt to scenarios involving dynamic changes, such as those seen with VRE sources. This flexibility allows for a dual optimization approach, advantageous when modeling storage solutions over varied temporal and geographical scales. Because of this, combined with the ease of use of the package and good documentation, Calliope was selected as the modeling tool for this research.

Calliope's ability to optimize over short-term windows, comparable to the SILVER model [74] makes it particularly well-suited to the temporal and geographical intricacies of energy storage. This dual optimization technique, which allows the system to be fine-tuned before running more complex scenarios, is crucial for finding the ideal storage capacity required to fulfill future energy demand in British Columbia. Figure 3.1 depicts Calliope's two main modes of operation: planning and operational. The planning mode is intended to determine the optimal capacities of various tech-

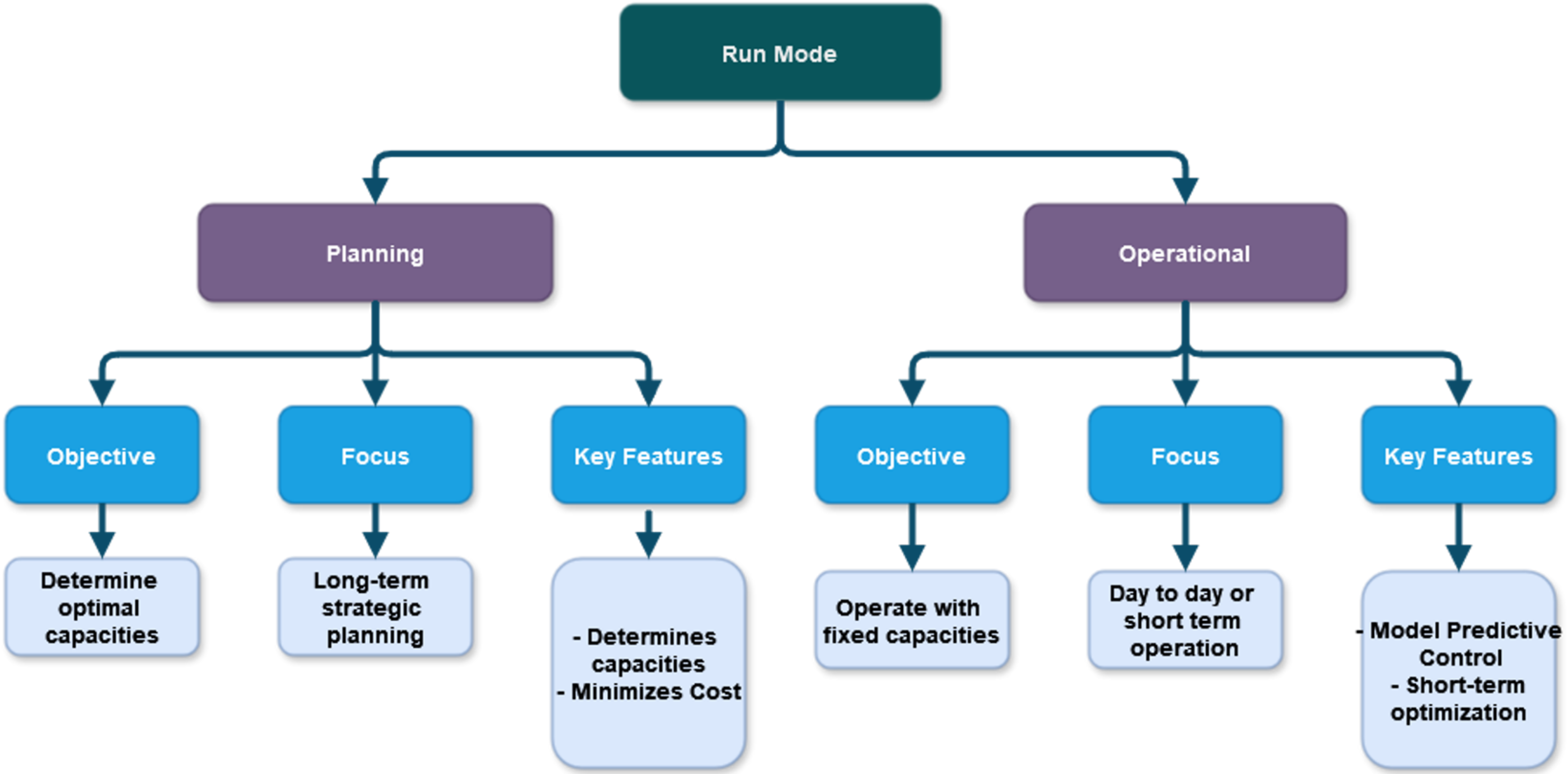

Figure 3.1: Schematic describing the two main modes available in Calliope and its key features.

nologies over a long-time horizon, whereas the operational mode simulates how the energy system will function in real-time with those fixed capacities. This dual modeling framework is especially useful for discussing both the strategic (long-term) and practical (short-term) aspects of energy storage solutions.

While this study focuses on Metro Vancouver, BC as the primary region for analyzing storage solutions and energy demand, the methodologies and findings are intended to contribute toward a broader application across British Columbia in future research thanks to the package's flexibility in integrating multiple energy pathways, ease of modifying regional parameters, and scalability to larger geographic areas.

The following sections describe how Calliope was used to simulate Vancouver's energy and storage requirements while considering curtailment, using the framework established by Pfenninger et al. [24] and using the instructions for version 0.6.10 [70].

3.2 Framework and Tools

3.2.1 Calliope Framework

This study's Calliope model was developed using four primary YAML configuration files—*'model.yaml', 'scenarios.yaml', 'technologies.yaml', and 'locations.yaml'*—to capture all relevant parameters, pathways, technologies, and spatial configurations. The "model" file sets the foundational parameters, such as temporal resolution and overall system constraints, while "scenarios" specifies alternative modeling pathways, including the curtailment cost scenarios for wind and solar ranging from 0 to 0.1 \$/kWh. In the "technologies" file, energy technologies are detailed by type and locations.yaml maps the geographical deployment of these technologies and demand across the region. The final configuration of these files for this research can be seen in Appendix A.1.1 - A.1.4.

In Calliope, technologies serve as essential components that build the model's energy system, classified into supply, storage, conversion, and demand categories [24]. Each of these categories plays a unique role in the model setup for this research:

- Supply Technologies: The model includes energy sources like solar panels, wind turbines, hydropower, and renewable gas plants. These sources are characterized by their capacity, efficiency, and cost parameters.

- Storage Technologies: Energy storage allows the system to capture surplus supply during low-demand periods and release it during high-demand times, enhancing overall system efficiency. Storage models include parameters like efficiency and capacity for technologies such as pumped hydro storage and salt-cavern gas storage.

- Conversion Technologies: Conversion enables the transition from one energy type to another, as with the model's simplified electrolyzer that converts electricity to hydrogen. This ensures the connection from the electricity network to the RNG pathway.
- Demand Technologies: Demand represents the energy requirements of end users. Demand profiles are based on Palmer-Wilson's projections [19], while the model's curtailment costs are treated as an additional "demand" with a cost integrated through Operation and Maintenance (O&M) cost values in "scenarios.yaml".

These technologies are assigned a location in the "locations.yaml" file. Defined by geographic coordinates, these locations represent specific areas where technologies are deployed. While transmission links in Calliope model energy flows between locations, this study uses them only for representational purposes, omitting specific costs or losses.

3.2.2 Other Tools and Software

The modeling environment is based on a Windows system, managed through Anaconda with Mamba to handle Calliope dependencies. Following Calliope's installation, Jupyter Notebook was the primary interface for scenario configuration and execution, allowing for real-time testing and iterative development. Each scenario, defined within the YAML files, ensured consistency across runs by loading a uniform set of inputs and constraints.

To execute the scenarios, the IBM CPLEX solver was employed [75] for its efficiency in handling cost optimization and the various constraints specified in the model. Each simulation considered the capacity, spatial placement, and operational constraints of the technologies involved, providing cost-optimized results across the defined scenarios.

3.3 Model Development

3.3.1 Data Collection and Preparation

This study utilizes the demand profiles found in previous literature [19] for the 100% electrification and 100% RG pathways. Hourly profiles of heat and electric demand, provided in megawatts (MW), were formatted as CSV files to meet Calliope's input requirements. Capacity factors for Variable Renewable Energy (VRE) sources, including wind and solar, as well as hydropower, were also derived from these previous datasets [76, 77, 78]. Additionally, renewable energy potential data were obtained from Palmer-Wilson's baseline assumptions [19] which were sourced from region-specific repositories.

The data inputs for this study's technologies are categorized into four key categories:

- **Supply:** Hydropower (must-take and flexible), Wind, and Solar technologies with hourly capacity factors.
- **Demand:** Electrical and heat demand, provided as hourly profiles in GW.
- **Storage:** Electric and Gas storage technologies able to reserve energy.
- **Conversion:** Electrolyzer to convert from electric energy to hydrogen in the RG pathway.

The capacity factors for VRE sources reflect Metro Vancouver's seasonal patterns (See Appendix Figure A.5), while hydropower is modeled as two distinct resources: must-take and flexible hydro, each defined as separate technology inputs within Calliope. Flexible hydro is further constrained by regulatory and environmental limitations.

Efficiency values play a pivotal role in modeling accurate energy flows. Table 3.1 outlines the efficiencies used in this study. Table 3.2 provides cost values in \$/kW or \$/kWh, depending on the technology parameter. The higher values from Palmer-Wilson's range were selected to represent a conservative assumption, accounting for uncertainties in future cost projections. Lastly, Table 3.3 lists capital investment costs, technology lifetimes, and interest rate assumptions. Unless specified otherwise, an interest rate of 10% is used. Any value not explicitly included in these tables was considered zero for cost parameters or 100% for efficiencies.

Table 3.1: Efficiencies used in the Calliope model by technology.

Technology	**Efficiency (%)**	**Source**
Electrolyzer	78	Palmer-Wilson [19]
Electric Storage (Validation Only)	86 (round-trip)	Palmer-Wilson [19]

To ensure compatibility with Calliope's requirements, data preprocessing steps included cleaning, reformatting, and aligning datasets with consistent units. This process set the foundation for the modeling scenarios explored in later sections.

3.3.2 Model Design

The model was developed with cost optimization as the primary objective function, focusing on minimizing system-wide costs while considering storage technologies. To align costs accurately, operational and maintenance (O&M) expenses were attributed to the transmission infrastructure rather than the storage technology itself. Additionally, Calliope's modeling constraint of a single efficiency parameter for both charging and discharging required data adjustments. For instance, storage technologies with a target round-trip efficiency of 86% were modeled with an efficiency of 92.7% for charging and discharging to approximate the desired performance. This adjustment is relevant to the Validation section (found further in Chapter 3.4). In contrast, model runs incorporating curtailment costs assumed a simplified 100% efficiency for storage technologies to reduce computational time.

Curtailment was modeled as a demand technology, without requiring resource matching, by setting the ”force_resource” constraint to ”false.” This was achieved by introducing a high unmet demand value (1000 GW every hour), ensuring that curtailment could occur when system resources were unavailable. Curtailment costs, defined as O&M expenses, were scenario-specific and ranged between 0 and 0.1 $/kWh.

Scenarios

This study models two main scenarios: the Electrification Pathway and the Renewable Gas (RG) Pathway. Figure 3.2 illustrates the Electrification Pathway, while Figure 3.3 outlines the RG Pathway. These block diagrams highlight the differences in energy infrastructure and technologies, such as electric storage and hydrogen storage in the RG Pathway, which are critical to the unique design and operation of each scenario.

Table 3.2: Costs implemented in this study by technology.

Technology	**Parameter**	**Value Used**	**Units**	**Source**	**Comment**
Solar Power	Energy capacity	2021	$/kW*cap*	Palmer-Wilson [19]	Using higher value from Palmer-Wilson's range.
Wind Power	Energy capacity	2395	$/kW*cap*	Palmer-Wilson [19]	Using higher value from Palmer-Wilson's range.
Hydro Power	O&M	0.0006	$/kWh	Trottier [79]	Added to both must-take and flexible hydro.
Electric Storage	Rated Power	156	$/kW	Palmer-Wilson [19, 80]	Projection for 2030.
Electric Storage	Energy capacity	184	$/kWh	Trottier, Palmer-Wilson [19, 80]	Projection for 2030.
Transmission to Battery	O%M	0.0023	$/kWh	Dolter [79, 81]	Data for pumped hydro in Canada.
Renewable Gas	O&M	0.083	$/kWh	Palmer-Wilson [19]	
Electrolyzer	Energy capacity	1400	$/kW*cap*	Palmer-Wilson [19, 80]	
Gas Storage	O&M	0.0012	$/kWh	Reuss [43]	
Gas Storage	Energy capacity	0.61	$/kWh	Sunny [43, 44, 45]	Average value is taken from Table 4. Consistent with other studies.
Electrolyzer (Low-end cost)	Energy capacity	500	$/kW*cap*	Thema [82, 19]	Used only for low cost electrolyzer scenario.
Gas Storage	Energy capacity	0.158	$/kWh	Frischmuth [45]	Table 2. Used for retrofitting gas cavern scenario.

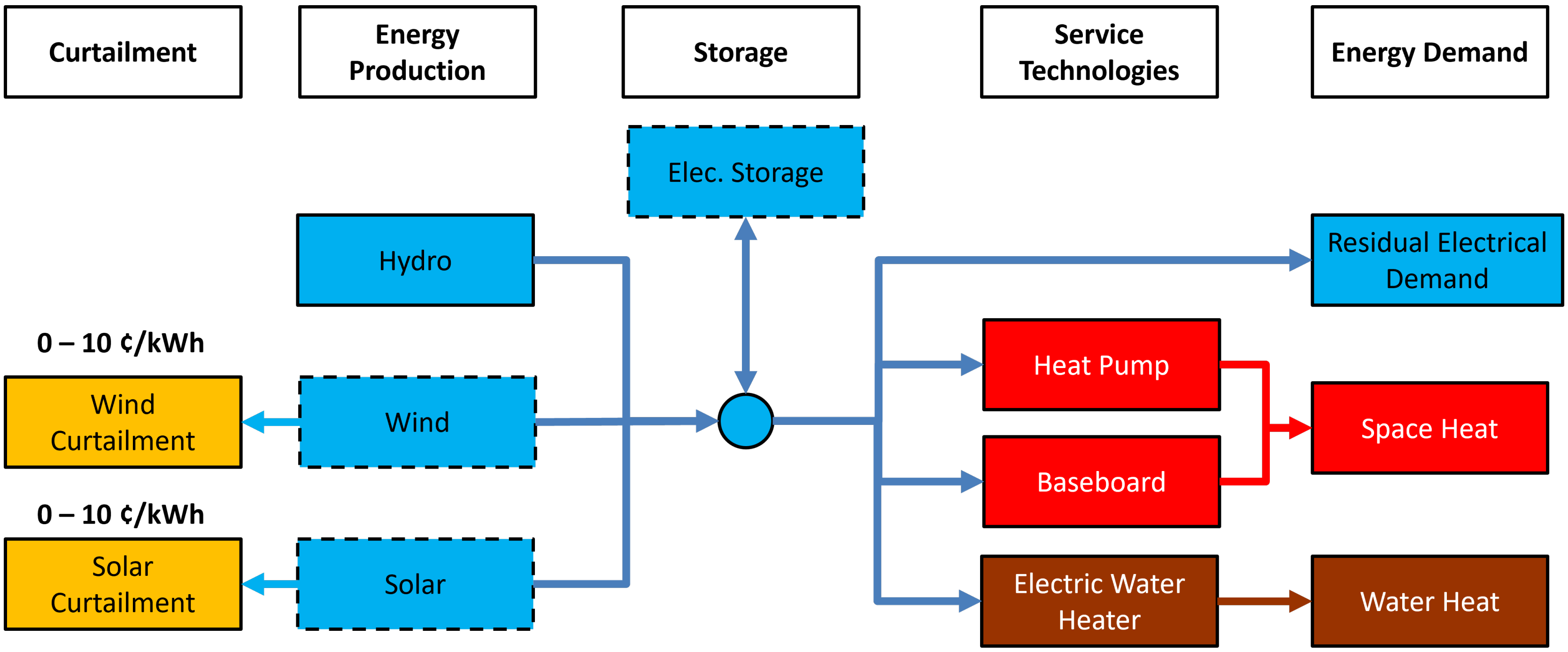

Figure 3.2: Diagram representing the 100% electrification pathway scenario describing the different technologies used to fulfill the specified demand. The dotted-line boxes indicate technologies optimized by the model.

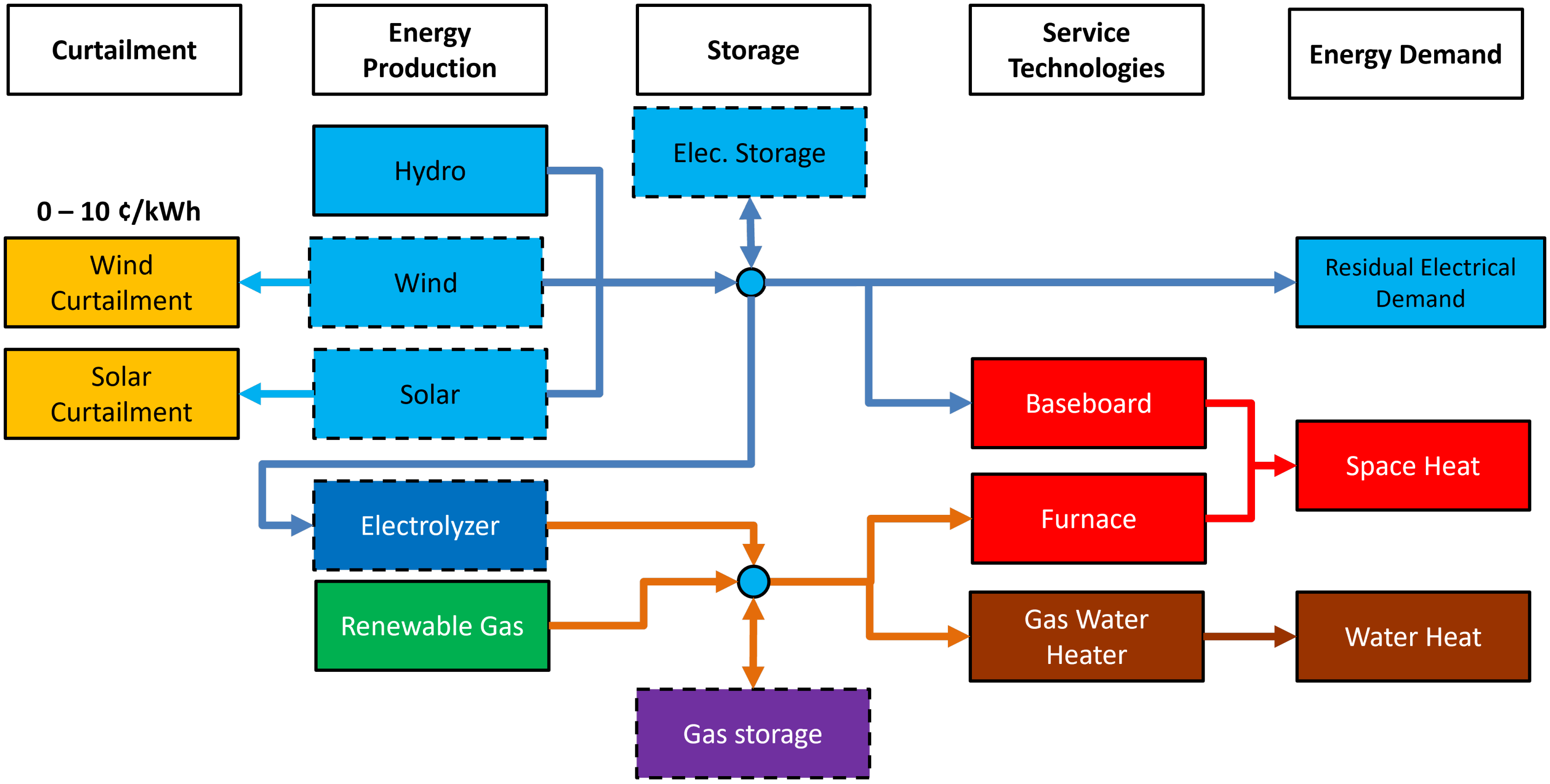

Figure 3.3: Diagram representing the 100% RG pathway scenario describing the different technologies used to fulfill the specified demand. The dotted-line boxes indicate technologies optimized by the model.

Table 3.3: Lifetime and interest rate values for technologies that considered installation costs in the model.

Technology	**Lifetime (years)**	**Discount Rate (%)**	**Source**
Solar Power	30	10	Lombardi [83]
Wind Power	20	10	Lombardi [83]
Electric Storage	50	10	Lombardi [83, 80]
Renewable Gas	20	10	Lombardi [83]
Electrolyzer	18	10	Lombardi [83]
Gas Storage	30	10	Reuss [43], Frischmuth [45]

In both scenarios, service technologies—such as heat pumps, baseboards, and water heaters—are not explicitly modeled. Instead, their collective energy demand is aggregated into a single demand node in the model. This aggregation simplifies the modeling process without compromising accuracy, as the total energy demand is derived from detailed projections. By consolidating service technologies into a unified demand node, the model achieves a balance between computational efficiency and the fidelity of demand representation.

For the RG Pathway, hydrogen storage is modeled using salt-gas caverns, a well-established approach for large-scale hydrogen storage that reflects real-world practices. To streamline the modeling configuration, the term ”biogas” is used in Calliope to represent both renewable methane and hydrogen, ensuring consistency in terminology across the model.

Figure 3.4 illustrates the base RG and Electrification Pathways alongside two additional scenarios, which have been introduced to assess the sensitivity of the system to varying cost assumptions. The first new scenario examines retrofitting costs for gas storage infrastructure, which reduces costs to 35% of the base case, highlighting the potential savings from repurposing existing facilities. The second scenario combines these retrofitting costs with reduced electrolyzer capital costs, which lowers capital investment to 26% of the base electrolyzer, reflecting the impact of more affordable electrolysis technology (see Table 3.4).

In the Electrification Pathway, electric storage is represented by pumped hydro storage, a technology particularly suited to British Columbia’s geographic and energy

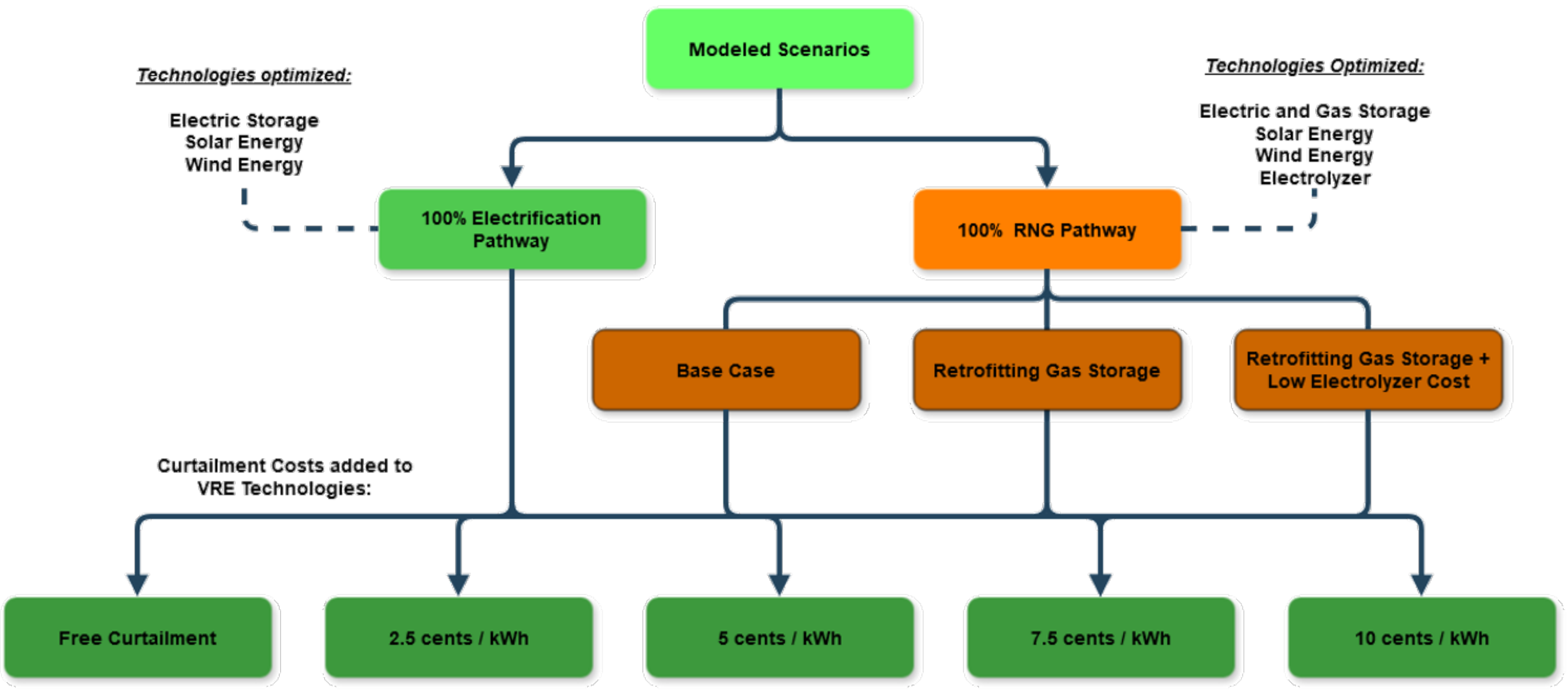

Figure 3.4: Diagram representing the different scenarios to be modelled in this study.

Table 3.4: Capital costs considered in this study for the RG Pathway scenarios modeled.

RG Scenarios	**Gas Storage Capacity Cost ($/kWh)**	**Electrolyzer Capacity Cost ($/kWh)**
1. Base Case	0.61	1400
2. Retrofitting gas storage	0.16	1400
3. Retrofitting gas storage + low electrolyzer cost	0.16	500

landscape due to the province's significant experience with hydroelectric systems.

3.3.3 Assumptions

For this study, transmission losses were excluded from the model, and the efficiency of electric and gas cavern storage technologies was assumed to be 100% in curtailment cost scenarios to reduce solution times. This simplification expedites model computation but may affect the model's alignment with real-world constraints.

The impact of this simplification is shown in Figure 3.5. By holding the capacities of all other technologies constant, the storage capacity increases to account for charging and discharging efficiencies. As a result, the assumption of no inefficiencies in the storage systems is expected to lead to an undersized pumped hydro or salt cavern capacity.

This model uses cost data from a defined set of parameters, balancing accuracy with simplicity to avoid over-specifying the system. It's important to note that the demand data was sourced without re-evaluation or updates, maintaining limitations such as not considering energy trading and the exclusion of emerging sectors like data centers. Increasing the spatial resolution of the model could reduce uncertainty around infrastructure adaptation costs and provide more granular insights into the regional impact.

3.4 Simulation Process

3.4.1 Validation

The new Calliope model was validated by comparing results with Palmer-Wilson's study, while using the same parameters such as setting the solar and wind capacities to the optimal levels identified in that research. For the validation runs, electric storage efficiency was approximated to 86%, matching the previous study's round-trip efficiency, though implemented slightly differently due to Calliope's configuration requirements. While the Palmer-Wilson study had separate charging (100%) and discharging (86%) efficiencies, Calliope applies the same efficiency rate for both processes, which may introduce minor differences in output between this model and the original made with the OSeMOSYS framework. Additionally, Palmer-Wilson's model relied on very low values to simulate zero-cost parameters, while this model now directly assigns values of zero, enhancing accuracy and consistency in configuration.

These validation runs concentrated on optimizing storage for the reference scenario with 100% electrification pathway, and then comparing the resulting data. These results will be further discussed in Chapter 4.2.

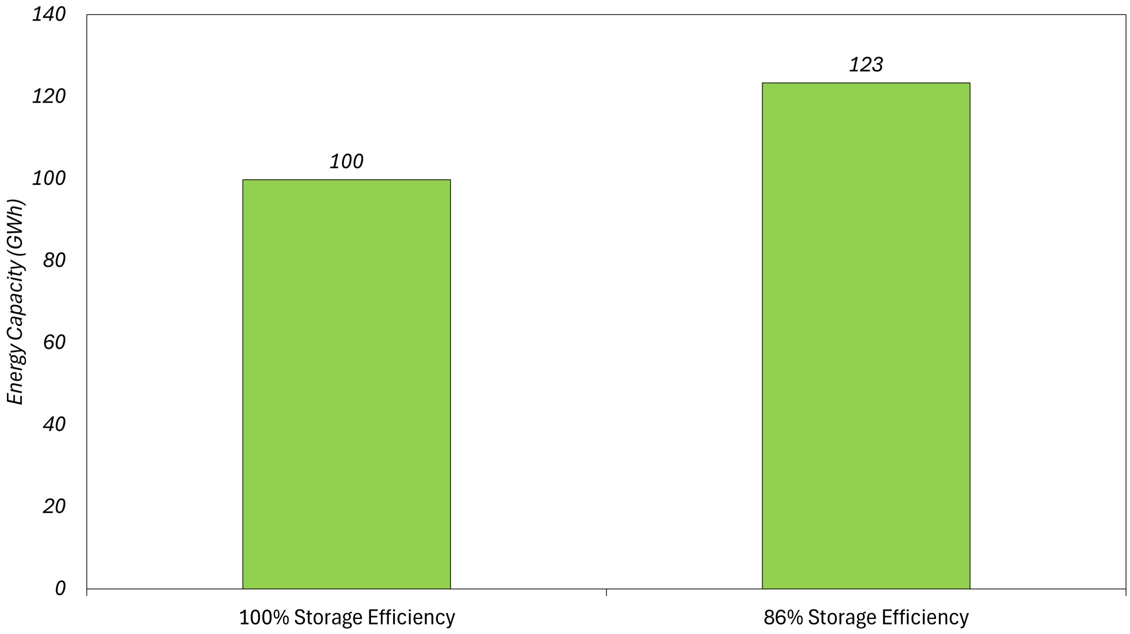

Figure 3.5: Comparison of electrical storage energy capacity sizing without curtailment cost depending on round-trip efficiency.

The alignment in storage and curtailment values was deemed sufficiently accurate for continuing with Calliope. With this validated configuration, curtailment technologies and associated costs were added to the model to proceed with further scenario testing in this study.

3.4.2 Simulation Setup

The curtailment cost scenarios were implemented to explore the economic and operational implications of varying costs on system performance and VRE utilization. By adjusting these costs, the model captures the financial trade-offs between maintaining higher VRE capacity and allowing for energy curtailment when it isn't economically viable to store or use all generated energy. For example, higher curtailment costs encourage the system to avoid waste, optimizing the balance between supply and demand to preserve renewable energy, while lower costs indicate a more lenient approach where some waste may be acceptable. This approach is also highly relevant in policy discussions where incentives for renewable energy utilization vary, reflecting potential scenarios in which policy might drive energy systems toward maximum renewable energy usage with minimal curtailment.

The decision to vary curtailment costs incrementally, in steps of 0.025 $/kWh, ensures that the model captures the impacts of cost changes on curtailment without overwhelming computation time or overcomplicating the analysis. This step size allows for a detailed sensitivity analysis of curtailment costs while keeping the results convenient for interpretation. Ranging from 0 to 0.1 $/kWh, the curtailment costs were selected to provide insight into the effects of both negligible and substantial curtailment costs on storage and VRE optimization, supporting an analysis of possible cost scenarios.

This cost sensitivity is needed for determining the economic feasibility of different storage technologies within a high-renewable environment, offering valuable insight into which storage solutions remain cost-effective as curtailment costs fluctuate. The scenarios also have implications for carbon emissions, as higher curtailment costs could promote reliance on renewable energy stored for later use, potentially decreasing dependency on backup non-renewable energy sources.

In practice, these scenarios were executed by adjusting the curtailment costs directly in the "scenarios.yaml" file, as shown in Appendix A.1.2. Each scenario was created by manually changing the curtailment costs for wind and solar in increments of 2.5 cents per kWh, from 0 to 0.1 \$/kWh. For each adjusted cost, results were saved in CSV files for later data processing and analysis. This setup allowed for consistent and accurate comparison across scenarios.

3.5 Evaluation and Analysis

3.5.1 Performance Metrics

The selected metrics—installed VRE capacity, curtailed energy, storage size, and Levelized Cost of Energy (LCOE)—each provide essential insights into system performance and cost-effectiveness under varying curtailment cost scenarios. Installed VRE capacity highlights the extent to which renewable sources like solar and wind contribute to meeting energy demand, offering a direct measure of the investment in VRE needed to satisfy system requirements under each scenario. Curtailed energy, the energy that is available but not utilized, reflects the efficiency and flexibility of the system to manage excess generation. High levels of curtailment may indicate a mismatch between VRE capacity and storage, underscoring the need for optimal storage solutions to minimize wasted resources.

Storage size is crucial for understanding the role of energy storage in balancing supply and demand, particularly during periods of high VRE output and low demand. By adjusting storage capacities, the study gauges how storage requirements fluctuate with different curtailment cost levels, providing a clear picture of the infrastructure needed to support both Electrification and RG pathways effectively. Lastly, LCOE serves as a comprehensive cost metric, capturing the overall expense associated with each pathway under each scenario. Tracking LCOE changes with varying curtailment costs helps quantify the economic impact of curtailment decisions, informing cost-efficient energy transition strategies.

3.6 Summary of Methodology

The methodology in this study establishes a framework for evaluating renewable energy integration in Metro Vancouver, British Columbia, examining the effects of curtailment costs on energy storage and system efficiency in both Electrification and Renewable Gas pathways. To build this model, Calliope was selected as the energy modeling tool. Model parameters, technologies, and pathways were adapted to suit

BC's energy profile, with solar and wind capacities set according to optimal values identified in previous studies.

The study considered storage solutions suited to each pathway, with hydrogen stored in salt-gas caverns for the RG pathway and pumped hydro storage applied to the Electrification pathway, reflecting BC's potential infrastructure. This configuration ensured that storage solutions were not only theoretically sound but also regionally practical. Validation was performed by replicating known outcomes from previous studies under the new model framework, allowing the comparison of model performance and consistency in storage and generation outputs.

To examine the impact of Variable Renewable Energy (VRE) curtailment costs, several scenarios were run with curtailment costs for wind and solar energy varying from 0 to 0.1 $/kWh. Metrics including the installed VRE capacity, curtailed energy, storage sizing, and Levelized Cost of Energy (LCOE) were tracked across scenarios to evaluate how cost signals impact energy system configurations in the Electrification and RG pathways. In the following chapters, these scenarios and results are analyzed in detail to provide insights into the system's response to curtailment incentives, informing both optimal storage sizing and VRE investment strategies.

Chapter 4

Results

4.1 Overview

This chapter presents the results from the Calliope model runs. To clarify the terminology used in the figures presented in this section, we define three key terms: *potential energy, delivered energy*, and *curtailed energy.* In this study, potential energy refers to the total possible energy that VRE sources can generate, accounting for both the hourly capacity factor and the overall installed capacity. Delivered energy is the amount of energy that meets demand or is stored for later use by using the electric storage facilities installed. Lastly, curtailed energy refers to the energy that is available but not utilized by the system.

This section includes the model validation, the main findings for both the electric and renewable gas pathways and a summary of the results. Comparisons between the two pathways will be explored in Chapter 5.

4.2 Model Validation

To validate the model, we replicated Palmer-Wilson's 100% electrification reference case while optimizing only for storage sizing, keeping all other data inputs and parameters consistent. The validation results are presented in Figures 4.1 and 4.2 and demonstrate alignment between the models with minor deviations.

Figure 4.1 compares the storage capacity results between the Calliope model and the original data. The energy capacity is shown on the primary y-axis, while the rated power capacity is on the secondary y-axis. The results exhibit strong agreement,

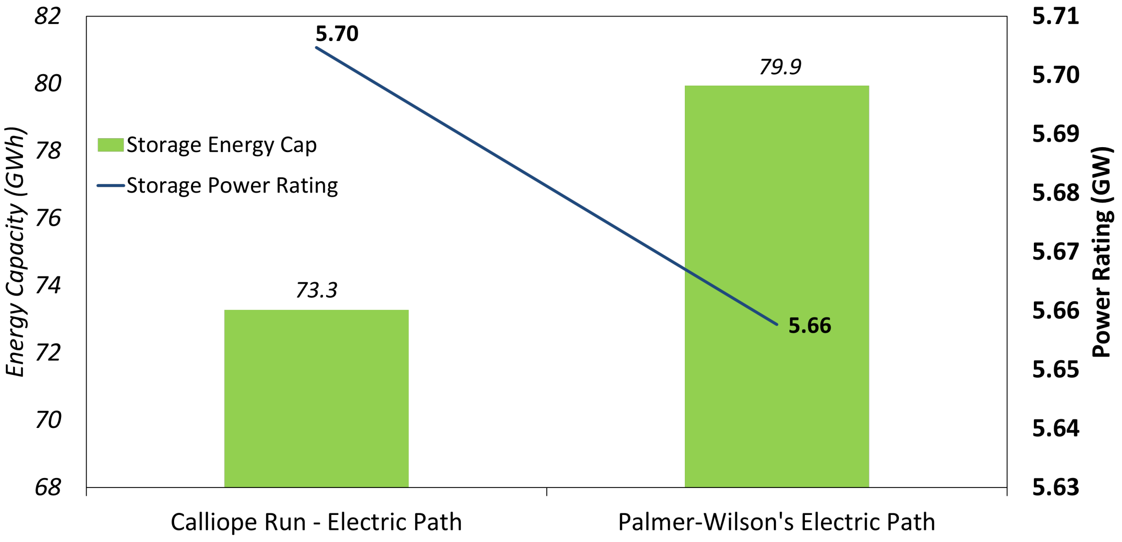

Figure 4.1: Comparison for validation between Palmer-Wilson's results for storage sizing and this study's results.

with differences under 10% indicating that Calliope accurately captures the storage requirements of the system.

Figure 4.2 highlights total VRE generation for solar (left) and wind (right). While the allocation of curtailment between wind and solar varies between the models, the total VRE curtailed is consistent at approximately 30 TWh. This demonstrates that both models produce similar energy outputs despite differences in internal allocation mechanisms.

Minor discrepancies can be attributed to differences in how each model handles certain parameters. For instance:

- **Efficiency Approximation**: Calliope applies a single round-trip efficiency setting, which was approximated at 92.7% for charging and discharging, whereas Palmer-Wilson's data specifies charging efficiency at 100% and discharging at 86%.

- **Handling of Zero Values**: To address instances where OSeMOSYS uses near-zero values instead of true zeroes, the Calliope model was configured to handle absolute zero values where appropriate.

- **Optimization Differences**:Both Calliope and OSeMOSYS are cost-optimization tools implemented in Python, but slight variations in their algorithms can lead to differences in the final solution or allocation of resources.

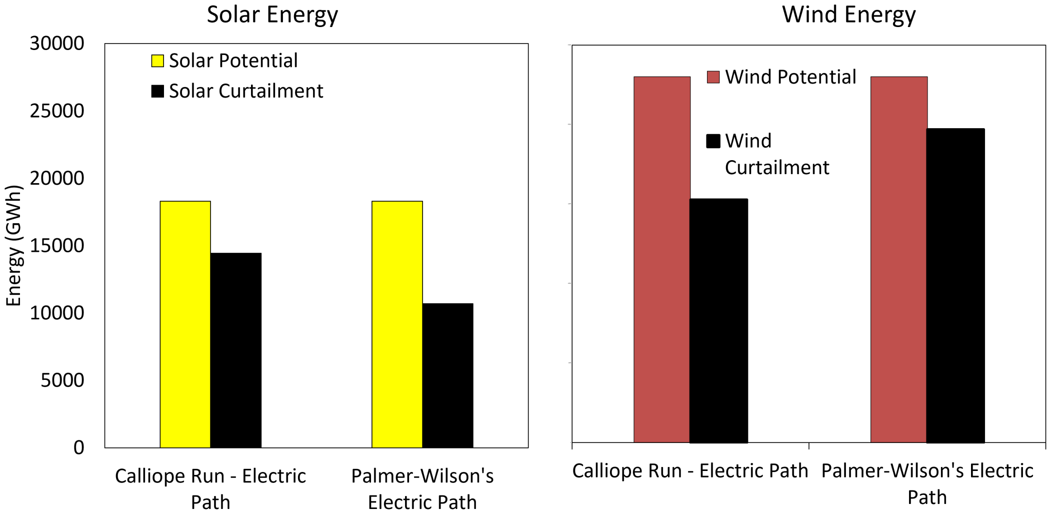

Figure 4.2: Comparison between Palmer-Wilson's results for VRE annual and curtailed energy depending on technology curtailment by technology.

To enhance clarity, Table 4.1 summarizes the key comparison metrics between the two models, providing a high-level view of the validation process. Overall, the results validate Calliope for the subsequent analysis presented in this study.

Table 4.1: Key comparison metrics for validation of the model.

Metric	**Palmer-Wilson**	**Calliope**	**Difference**
Energy Storage Capacity (GWh)	80	73	8.2%
Rated Power Capacity (GW)	5.7	5.7	0.7%
Total VRE Curtailment (TWh)	30	29	2.3%
Charging Efficiency (%)	100	92.7	–
Discharging Efficiency (%)	86	92.7	–

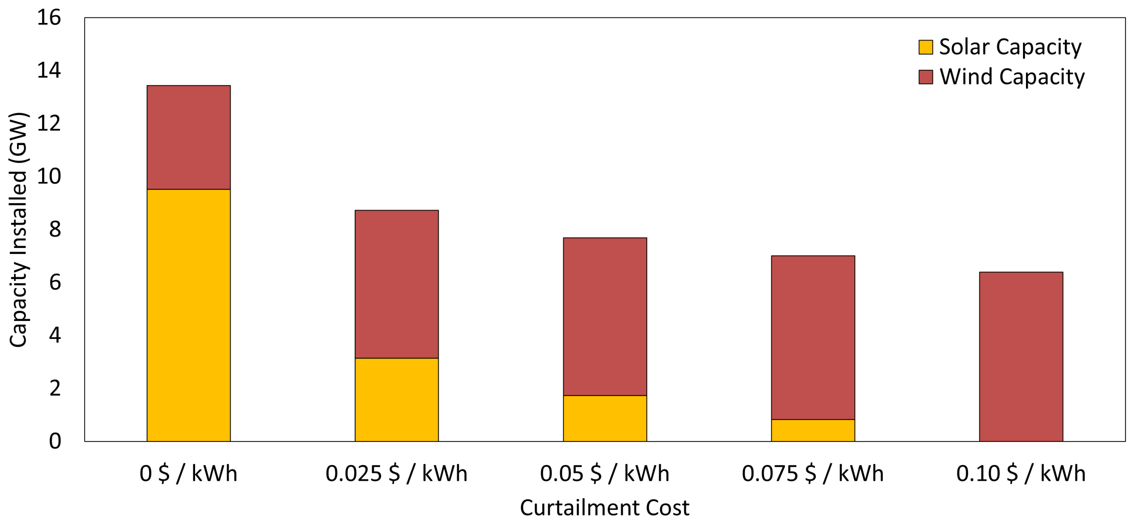

Figure 4.3: Results for installed capacities of variable renewable energy for the electrification scenario with different curtailment costs.

4.3 Pathway-Specific Results

This section presents the results for two decarbonization pathways modeled for Metro Vancouver: 100% Electrification and 100% Renewable Gas (RG). The focus is on how these pathways respond to curtailment costs ranging from 0 to 10 cents per kWh. Metrics such as installed Variable Renewable Energy VRE capacity, the balance of curtailed and delivered energy, storage requirements, and the Levelized Cost of Energy (LCOE) are analyzed.

4.3.1 Electrification Pathway Results

In the electrification pathway, as curtailment costs increase, the model adjusts capacity size to more efficiently balance energy generation with system demand. Figure 4.3 demonstrates this behavior, where higher curtailment costs lead to reduced solar capacity in favor of increased wind capacity. Although solar energy generally incurs lower costs (see Tables 3.2 and 3.3), wind energy's higher annual capacity factor in BC (Appendix Figure A.5) [77, 78] makes it a better choice under higher curtailment cost conditions. Winter demand, driven by heating requirements, aligns with the higher wind energy supply observed in British Columbia, as shown in Figure A.5.

Looking forward, cooling demands could increase significantly during the summer months due to climate change or shifts in building energy needs. This change might

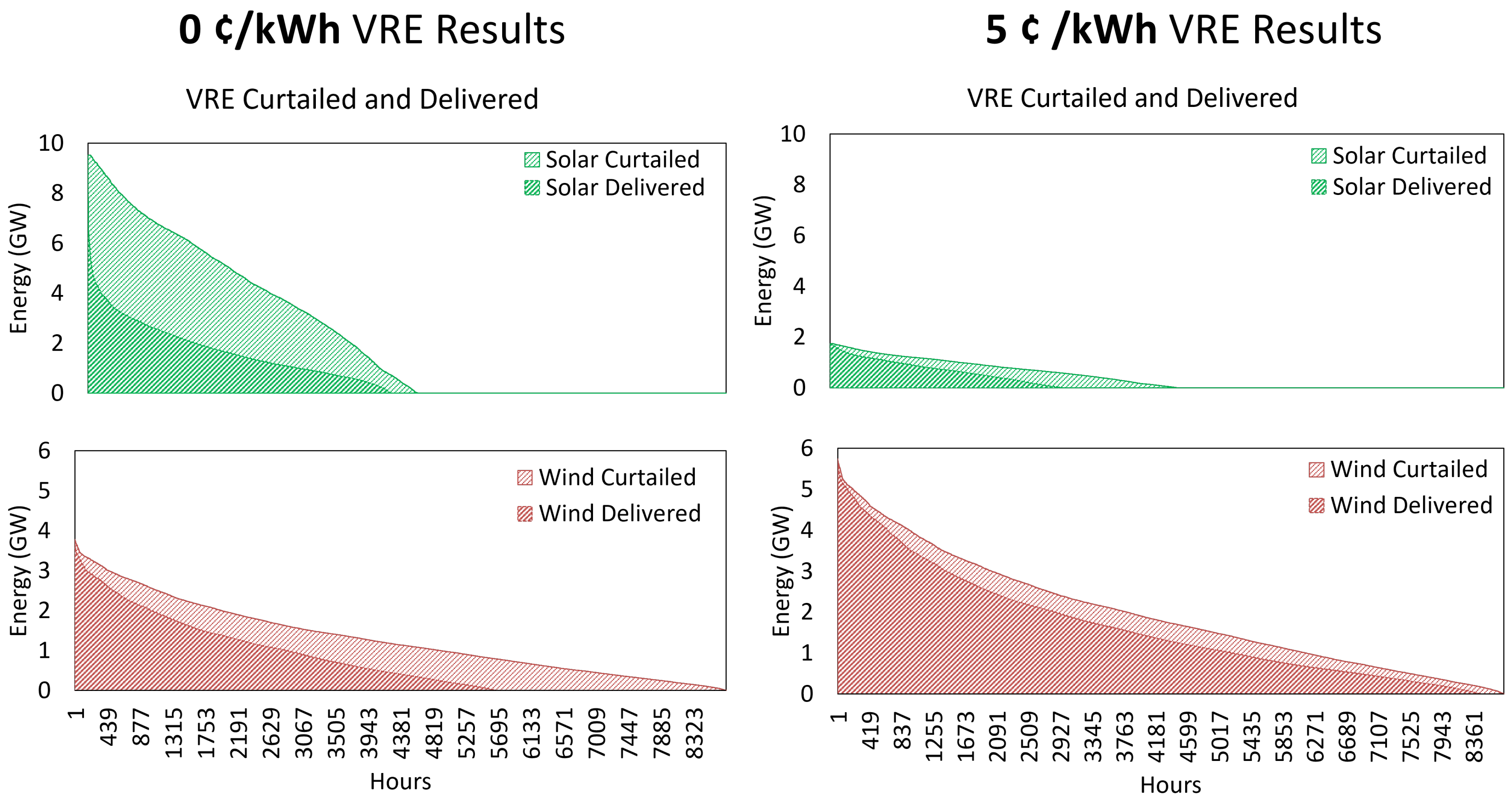

Figure 4.4: Variable renewable energy curtailment for the electrification scenario with free curtailment and a curtailment cost of 0.05 $/kWh.

result in a more balanced seasonal demand profile, potentially altering the optimal mix of solar and wind capacity in the region. Consequently, these dynamics should be revisited in future studies to account for evolving demand patterns and their impact on system design.

Figure 4.4 examines the balance between curtailed and delivered energy for VRE technologies. Without curtailment costs, the model curtails a significant proportion of available energy, particularly solar. In the free-curtailment scenario, approximately two-thirds of the total solar energy potential is curtailed. When curtailment costs are applied (e.g., 5 cents per kWh), the model prioritizes energy delivery, significantly reducing curtailment. This is evident in the reduced size of the lightly shaded areas in Figure 4.4. For wind energy, curtailment also decreases but to a lesser extent due to wind's higher capacity factor and lower generation variability compared to solar. Figure A.1 in the Appendix provides additional information, with potential and curtailed energy represented for each curtailment scenario.

The reduction in VRE curtailment when costs are applied raises the question of where the capacity comes from to meet demand as overall VRE capacity decreases. In this scenario, the model compensates by increasing reliance on energy storage systems and utilizing stored energy more effectively, as discussed next.

The energy not curtailed is either delivered directly or stored for later use. Figure 4.5 illustrates the changes in electric storage capacity and power rating across different curtailment cost scenarios. As curtailment costs rise, storage energy capacity nearly doubles, suggesting that the model increasingly relies on energy storage to balance supply and demand. Interestingly, the rated power of the storage system decreases slightly (over 1 GW reduction), reflecting less frequent charging and discharging activity. This highlights a shift towards optimizing the use of storage capacity rather than increasing its output power.

Finally, Figure 4.6 presents the increase in the LCOE as curtailment costs rise. The overall system cost can increase by approximately one-third, depending on the curtailment cost applied, with the electrification pathway experiencing the greatest sensitivity to these cost adjustments. This increase emphasizes the influence of curtailment costs on overall economic feasibility in the electrification pathway.

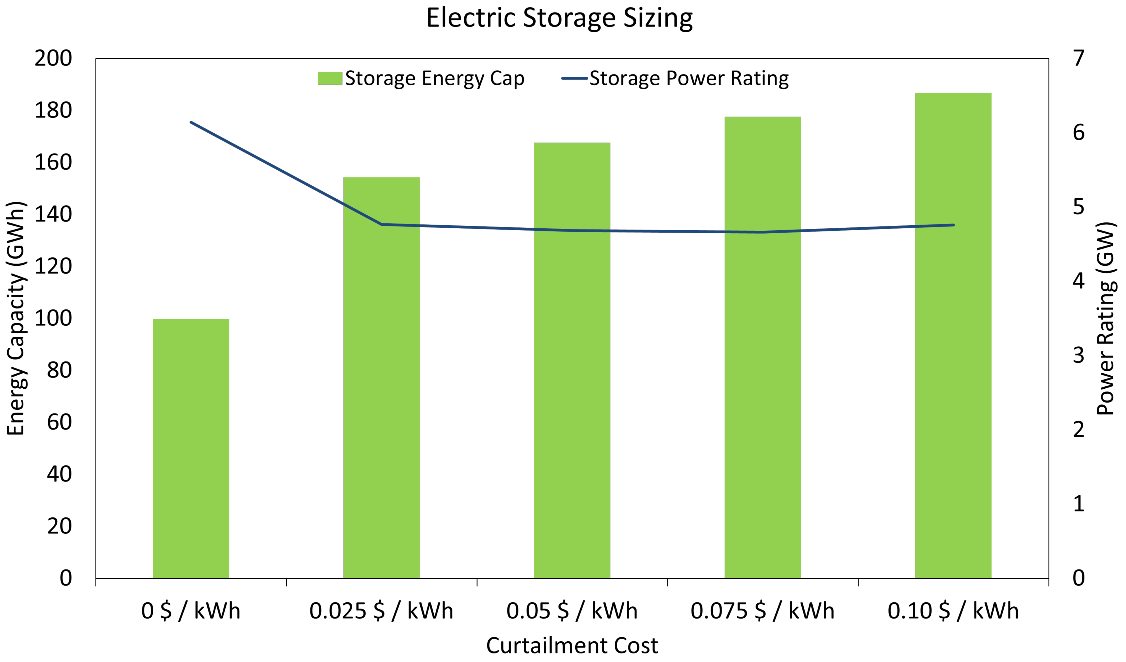

Figure 4.5: Installed electric storage size in capacity and rated power for the electrification pathway varying curtailment costs between 0 to 10 cents per kWh.

4.3.2 RG Pathway Results

The RG pathway integrates additional technologies, including electrolyzers and gas storage, to enhance system performance and flexibility. Unlike the Electrification Pathway, this pathway does not optimize to install pumped hydro storage in any of the analyzed scenarios. Instead, surplus energy from VRE sources is managed through electrolysis, which produces hydrogen for storage and later use. Building heating demands are met by newly integrated service technologies, as depicted in Figure 3.3. However, these technologies are not explicitly modeled in Calliope; instead, their aggregated energy demand is represented as a single demand node for simplicity and computational efficiency.

In contrast to the electrification pathway, the addition of a curtailment cost has minimal impact on installed capacities. For example, the model consistently installs 3.1 GW of wind capacity across all scenarios and excludes solar energy entirely, regardless of the curtailment cost applied. Similarly, LCOE remains steady at approximately 163 $/MWh (Appendix, Figure A.3) and curtailed energy levels (Appendix, Figure A.4) show little variation as curtailment costs increase. These findings highlight the relative stability of the RG pathway under varying curtailment cost scenarios, driven

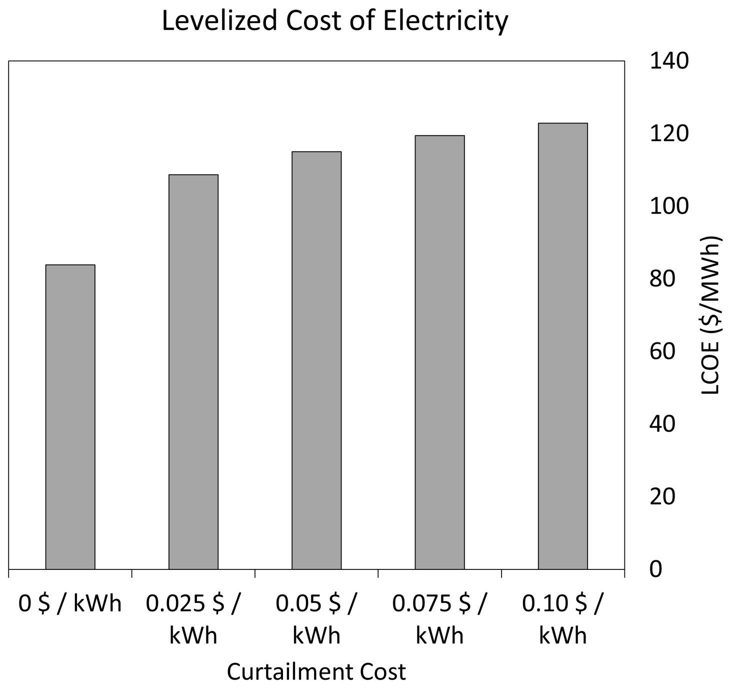

Figure 4.6: Difference in levelized cost of energy for the Metro Vancouver model varying curtailment costs between 0 and 10 cents per kWh.

primarily by the lower cost of gas storage compared to electric storage.

Gas storage sizing, however, does exhibit sensitivity to curtailment costs. Figure 4.7 illustrates the size of gas cavern storage decreasing from approximately 1450 GWh to around 1100 GWh as curtailment costs rise. This reduction in storage size is accompanied by an increase in electrolyzer capacity, as shown in Figure 4.8. Specifically, electrolyzer capacity increases from 1.3 GW to 1.4 GW, allowing the system to produce and deliver more hydrogen gas directly to meet heating demand, reducing reliance on large storage volumes. While these adjustments are less pronounced than those observed in the electrification pathway, they indicate that the RG pathway still responds to curtailment costs, albeit to a smaller degree.

Retrofitting and Reduced Electrolyzer Costs

Further sensitivity analyses were conducted to examine the effects of retrofitting gas storage and reduced electrolyzer costs on the RG pathway. These scenarios assess the impact of lower infrastructure costs on system performance and capacity requirements.

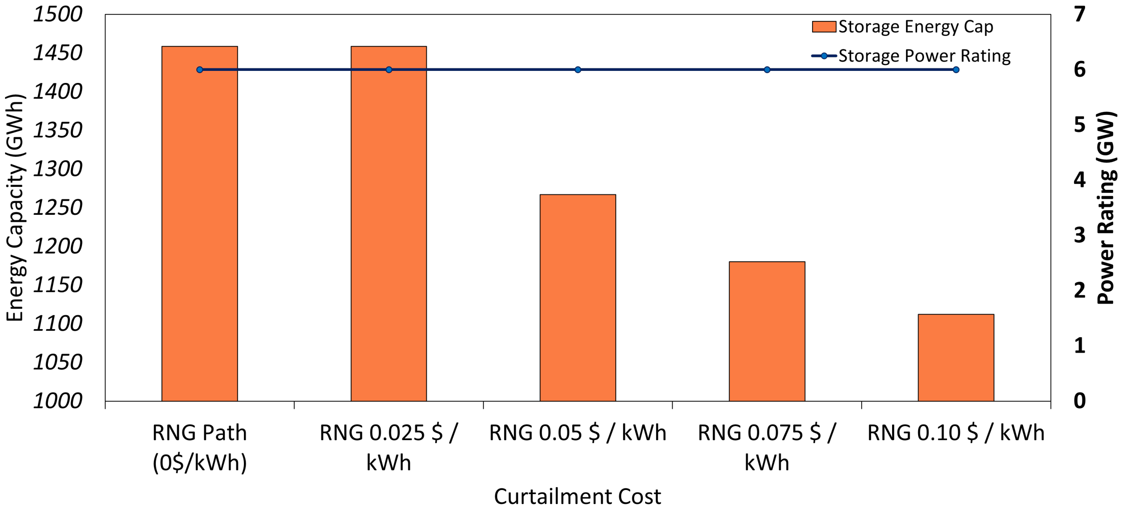

Figure 4.7: Installed gas storage size in capacity and rated power for the RG pathway varying curtailment costs between 0 and 10 cents per kWh.

Under the retrofitting scenario, where the cost of gas storage is reduced, the model installs larger gas storage energy capacity—ranging from 2095 to 1660 GWh depending on the curtailment cost—compared to the baseline scenario. Despite this adjustment, the system retains the same behavior described previously, with minimal changes in installed VRE capacities and a consistent reliance on wind energy. This underscores the system's preference for optimizing hydrogen production and storage rather than altering the generation mix.

When reduced electrolyzer costs are introduced on top of the retrofitting scenario, the system increases electrolyzer capacity slightly—ranging from 1.37 to 1.46 GW—enhancing its ability to produce hydrogen at a lower cost. Interestingly, gas storage capacity decreases relative to the other scenarios, ranging from 1165 to 997 GWh. Despite these adjustments, the overall system configuration remains largely consistent with the baseline, suggesting that the RG pathway's stability persists even under improved cost assumptions.

These findings reaffirm the RG pathway's stability and its ability to adapt to economic shifts without substantial changes in overall system design or operation. While cost reductions improve efficiency and reduce system costs, the pathway's reliance on hydrogen storage and wind generation remains a defining characteristic.

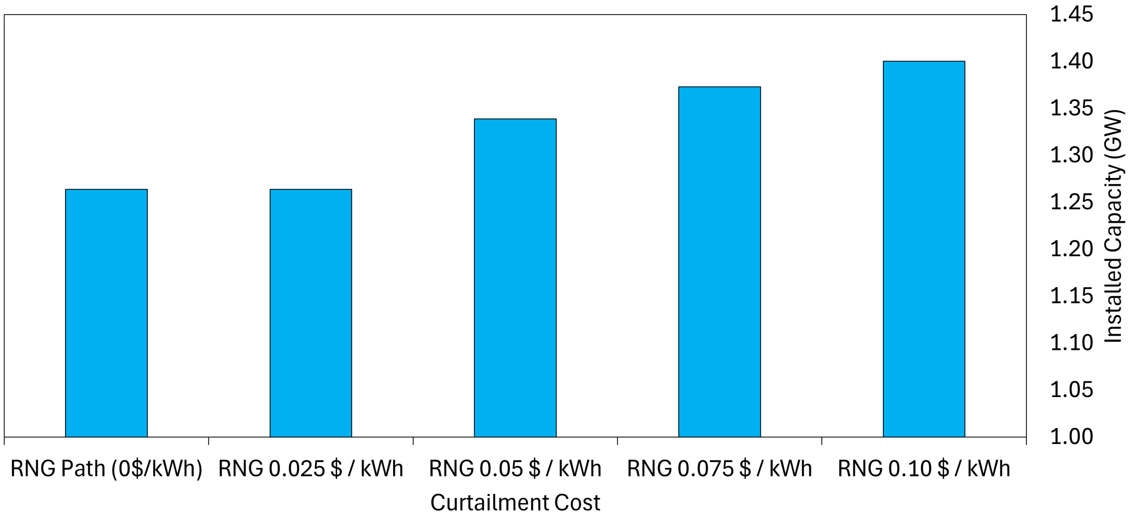

Figure 4.8: Installed electrolyzer capacity for the RG pathway varying curtailment costs between 0 and 10 cents per kWh.

4.4 Summary of Results

The results demonstrate that curtailment costs significantly influence system design choices, storage capacities, and economic outcomes, particularly in the electrification pathway. When curtailment costs are applied, the electrification pathway responds by adjusting VRE capacities and increasing electric storage size, underscoring the pathway's high sensitivity to these costs. This response ultimately leads to a higher LCOE as curtailment costs rise, with nearly a third of total system costs attributed to these adjustments.

In contrast to the electrification pathway, the RG pathway shows a less pronounced overall response to curtailment costs, primarily due to the flexibility offered by gas storage and electrolysis. The comparatively low cost of gas storage, coupled with the model's shift towards using an expanded electrolyzer to manage excess VRE energy, allows the system to maintain relatively stable levels of curtailment across scenarios. The LCOE for the different RG pathway scenarios exhibit only modest increases as curtailment costs rise, reinforcing its resilience in this respect, though the capacity changes indicate that this pathway still requires careful consideration of storage sizing.

Overall, the findings underscore that while both pathways offer viable routes to decarbonization, their sensitivity to curtailment costs differs. The electrification pathway is more responsive, with notable impacts on storage requirements and system costs, whereas the different scenarios in the RG pathway demonstrates steadier performance under similar conditions. These results highlight the importance of accounting for curtailment costs in pathway selection, particularly when seeking to balance cost-effective energy storage with supply reliability in decarbonization efforts.

Chapter 5

Discussion

5.1 Interpretation of Results

This section delves into the implications of findings from both electrification and RG pathways, particularly how curtailment costs shape system design, storage optimization, and economics. Accurate interpretation of model results is essential here for drawing insights and directing system design decisions.

Table 5.1 summarizes the key differences between the electrification and RG pathways in terms of installed capacities, storage types, sensitivity to curtailment costs, and overall system dynamics. While the electrification pathway relies on variable renewable energy and battery storage, the RG pathway employs wind energy coupled with gas storage and electrolyzers to meet demand. This comparative overview highlights how distinct technological and economic trade-offs emerge from the two approaches, emphasizing the significance of curtailment costs in influencing design priorities.

In the electrification pathway, rising curtailment costs make energy storage more economical than curtailing surplus energy, significantly influencing the levelized cost of energy (LCOE). This underscores the critical role of storage in minimizing energy losses and maintaining the feasibility of renewable-heavy systems by reducing costs and optimizing asset utilization.

Figure 5.1 illustrates the total LCOE for the RG and Electrification pathways under varying scenarios, including retrofitting costs and reduced electrolyzer prices. The baseline LCOE for the RG pathway remains unaffected by curtailment costs due to limited reliance on curtailment-sensitive technologies. However, reduced electrolyzer

Table 5.1: General behavior and comparison of results for the electrification and RG pathways when applying curtailment costs (0 to 10 cents per kWh).

Category	**Electrification Pathway**	**RG Pathway**
Installed VRE Capacity	Highly variable with curtailment costs: more solar at low costs, more wind at high costs; total VRE capacity decreases by approximately 50% at high curtailment costs.	Fixed: 3.1 GW of wind; no solar across all curtailment cost scenarios.
Storage Type	Electrical storage only, with capacity nearly doubling at higher curtailment costs.	Gas storage caverns only; capacity decreases as curtailment costs increase.
Electrolyzer Capacity	Not applicable.	Increases slightly with curtailment costs.
Energy Curtailment	Reduced as curtailment costs increase, with a shift from curtailed energy to delivered/stored energy.	Minimal change in curtailed energy regardless of curtailment costs.
LCOE	Increases with curtailment costs (up to approximately 33% higher).	Stable at approximately 163 $/MWh across all curailment costs in the base case scenario. Reduces when considering cheaper electrolyzer or retro-fitted gas storage
Curtailment Sensitivity	Capacity sizing and system design adjust significantly to curtailment costs.	System design remains relatively stable across curtailment scenarios, but is sensitive to infrastructure cost assumptions.
Main Technologies	Relies on hydro, VRE and battery storage to meet demand.	Relies on hydro, wind, gas storage, and electrolyzers to produce hydrogen for residual electric and heating demand.

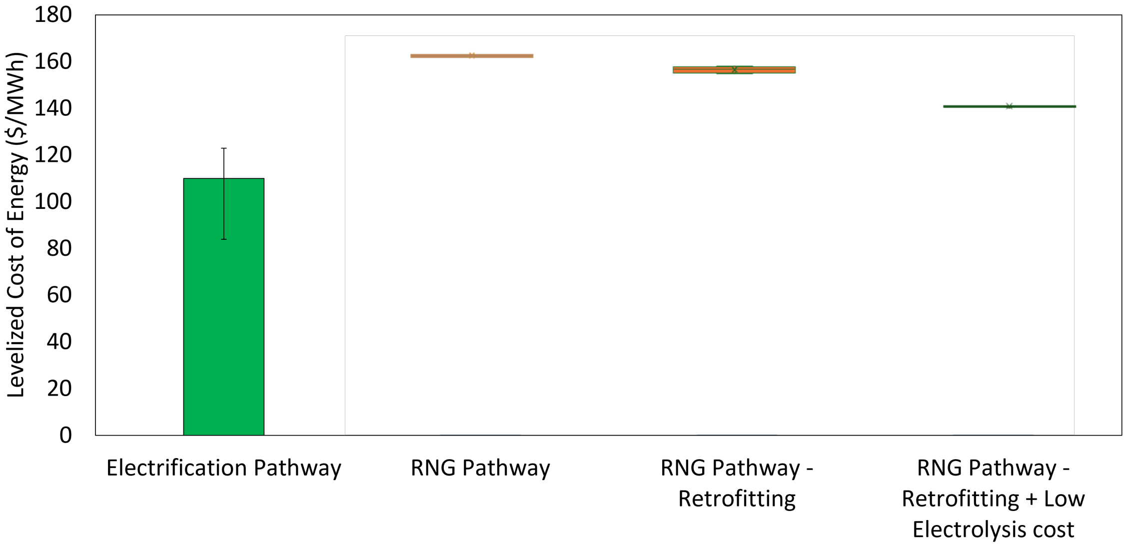

Figure 5.1: Total LCOE results for RG and Electrification Pathways considering curtailment costs between 0 and 10 cents per kWh. Retrofitting and low electrolysis cost scenarios included for the RG pathway.

costs lower the RG pathway's LCOE, emphasizing the importance of cost reductions in hydrogen production for enhancing its economic viability.

Curtailment costs especially affect the installed capacities of variable renewable energy sources in the Electrification Pathway (see Figures 4.3 and 5.2). Higher curtailment costs drive the model to prioritize efficient, cost-effective technologies, selectively deploying renewable capacity. Figure 5.2 highlights the total VRE capacity installed across the RG and Electrification pathways as curtailment costs increase. While the RG pathway exhibits consistent capacity requirements, the Electrification Pathway optimizes VRE capacity by scaling down installations in response to rising curtailment costs, underscoring the system's economic trade-offs. This approach ensures that installed capacity aligns with economic considerations, avoiding excess infrastructure while meeting demand efficiently.

The impact of curtailment costs also extends to electric battery storage sizing and behavior. With higher curtailment costs, storage units cycle more intensively, as storing surplus energy becomes preferable to wasting it (Appendix Figure A.2). This increased storage utilization in the electrification pathway underscores the importance of flexible storage operations for systems facing high curtailment sensitivity.

The shift in storage requirements across curtailment scenarios is approximately 86 GWh. To contextualize, this difference is equivalent to the battery capacity of

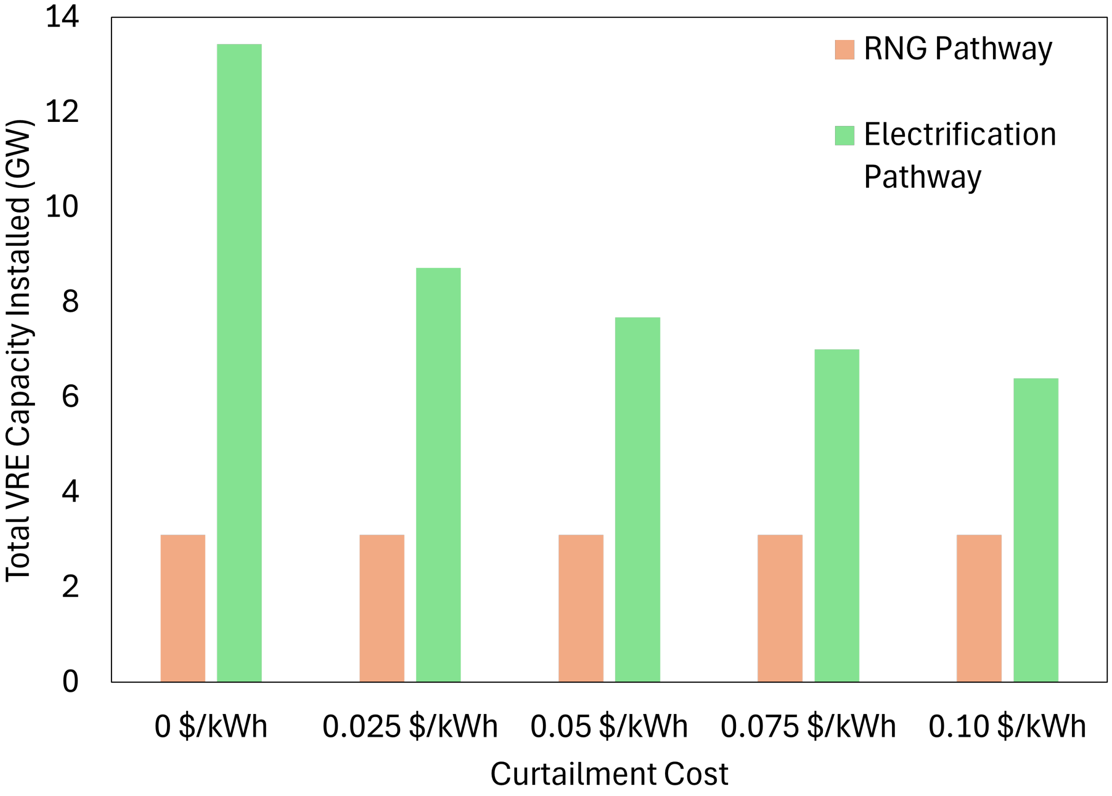

Figure 5.2: Total VRE Capacity Installed for RG and Electrification Pathways considering curtailment costs between 0 and 10 cents per kWh.

around 1.1 million Tesla Model 3 Performance vehicles, each with a 78 kWh battery [84]. This comparison equates to about 60% of all electric vehicles sold by Tesla in 2023, their best sales year to date [85]. Such a visualization emphasizes the scale of additional capacity needed to manage curtailment within Metro Vancouver's energy system. It illustrates how even modest curtailment costs can dramatically alter system requirements, potentially driving up investment in storage infrastructure to absorb excess renewable generation.

On the other hand, the RG pathway shows comparatively limited change in overall system dynamics in response to curtailment costs, largely due to the lower cost of gas storage considered in this study (Tables 3.2 and 3.3). However, sensitivity to infrastructure assumptions, such as retrofitting costs or electrolyzer prices, reveals opportunities for optimizing the pathway further. For example, the retrofitting scenario reduces costs marginally, while the low electrolyzer cost scenario shows a higher LCOE reduction.

An interesting aspect of the RG pathway is the absence of solar energy installation, attributed to Solar's lower capacity factor relative to wind in this region. The installation decisions remain unchanged with the inclusion of curtailment costs, further reinforcing the cost stability of the RG approach. Additionally, while the study applies an average cost for salt-cavern gas storage, future research could explore cost variability based on factors like storage pressure. This could reveal opportunities for further optimization within the RG pathway, though this study's results support the cost-effectiveness and scalability of gas-based storage for managing renewable energy surplus.

Incorporating curtailment costs into the model reduces the amount of energy curtailed by the system, reflecting a more realistic and financially grounded approach to energy planning. This addition provides a more accurate representation of real-world conditions, as curtailment is seldom cost-free in practice. By accounting for the economic impact of excess generation, decision-makers can better assess the true value of storage investments and avoid overestimating the cost-efficiency of VRE deployment without storage.

Including curtailment costs enhances system representation by revealing the comparative resilience of the RG pathway alongside the increased storage demand seen in the electrification pathway. This insight is valuable for policymakers and planners aiming to maximize the economic efficiency and effectiveness of renewable energy investments, as it highlights the trade-offs between capacity stability and flexibility within each pathway.

5.2 Comparison with Previous Studies

The role of energy storage in reducing curtailment and managing variability in renewable energy systems has been widely documented. Studies such as those by McPherson et al. [48] emphasize the flexibility offered by hydrogen production and storage in decarbonized grids. Similarly, research by Niet et al. [67] highlights how appropriately pricing curtailment can guide decisions around storage deployment and renewable capacity expansion. By building on these findings, this study adds depth to existing literature by directly quantifying the influence of curtailment costs on energy system design in both electrification and RG pathways.

A significant divergence from prior studies is the explicit inclusion of curtailment costs in the modeling process. Much of the existing literature, including studies that focus on renewable integration and storage, either assumes curtailment is cost-free or omits it altogether [11, 61]. This assumption can lead to overly optimistic projections of renewable energy capacity and an underestimation of storage requirements. For instance, models that treat curtailment as negligible may prioritize renewable expansion without adequately addressing the economic inefficiencies tied to surplus generation. In contrast, the results from this study demonstrate how curtailment costs incentivize more balanced system designs. The inclusion of curtailment costs in this work led to a reduction in curtailed energy, more efficient use of VRE, and higher reliance on energy storage to manage surplus.

Furthermore, by evaluating curtailment costs within two distinct decarbonization pathways, this study highlights the differentiated impact on system design. For instance, while the electrification pathway requires significant battery storage to mitigate curtailment, the RG pathway leverages salt cavern storage for hydrogen and renewable gas. These technologies provide large-scale, low-cost storage options, aligning with findings by McPherson et al. [48], which emphasize the utility of hydrogen systems in reducing curtailment. Our results also corroborate studies such as those by Henriot [63] and Bird et al. [62], which underscore the economic implications of curtailment on renewable-heavy systems, further validating the methodology employed here.

The effect of curtailment costs on system planning is particularly pronounced in the electrification pathway. Higher curtailment costs drive the adoption of efficient storage systems, which cycle more frequently to capture surplus energy, as seen in the increased reliance on battery systems. This aligns with previous research showing that higher storage utilization can reduce overall system costs by minimizing energy losses [67]. However, unlike other studies that focus exclusively on short-term storage technologies, this work also integrates long-term storage in the RG pathway. The use of salt caverns for hydrogen and renewable gas demonstrates how leveraging geological resources can offer cost-effective solutions for seasonal energy storage, a finding consistent with prior work on underground storage solutions [59].

In comparison to Palmer-Wilson et al. [19], this work provides an enhanced understanding of the sensitivity of system configurations to curtailment costs. While their study primarily focuses on evaluating cost and capacity trade-offs, this analysis explicitly demonstrates how curtailment costs shape storage deployment and renewable integration strategies. By examining both pathways under varying curtailment scenarios, this study builds upon their findings to offer practical insights for policymakers and system planners. The results highlight how curtailment cost inclusion leads to economically grounded decisions, ensuring that resources are neither overbuilt nor underutilized.

Lastly, this work underscores the importance of pricing curtailment costs in achieving decarbonization goals. As Niet et al. [67] argue, pricing curtailment appropriately encourages investment in storage infrastructure and helps balance system flexibility with capacity stability. By aligning with these principles, this study contributes to the growing body of literature advocating for the integration of economic considerations, such as curtailment and storage costs, into renewable energy planning. This approach provides a better representation of the trade-offs involved in transitioning to low-carbon energy systems, making it especially relevant for regions like Metro Vancouver that aim to balance aggressive decarbonization with cost-effectiveness.

5.3 Limitations and Future Work

5.3.1 Study Limitations

Expanding this model from Metro Vancouver to encompass all British Columbia, with multiple nodes and geographic-specific data, would allow Calliope's spatial optimization capabilities to enrich provincial modeling. Such an approach aligns with studies like Lomardi's research on Italy [83], adding regional insights for broader applicability.

Additionally, the demand profiles and capacity factors taken from previous studies [19] and were not updated, retaining its data limitations. Similarly, the renewable gas supply technology was assumed to have fixed supply and costs across all scenarios, which simplifies its role in the system but does not account for potential variations in production costs, supply availability, or regional scalability. Future research could enhance result accuracy by updating these variables and integrating multiple weather years to assess climate resilience.

Further exploration of renewable gas demand variability or new technologies such as hydrogen pyrolysis could refine the system's adaptability to specific conditions. Expanding the model to assess the viability of novel technologies by regional factors could offer more insights into localized implementation.

5.3.2 Future Research

Future research is planned to expand the model from Metro Vancouver to consider the whole province of British Columbia divided into different regions and taking advantage of Calliope's geographic decision-making abilities (making a study more similar to Lomardi's research for Italy [83]). By assigning a location with coordinates and multiple nodes instead of one, we expect to gain a better understanding of the modelling of the province.

This study did not consider imports or exports that can happen between BC and its neighbors Alberta and Washington state. Further studies can incorporate these fluctuations into the model as they can have an effect when inter-regional transmission is considered.

The data used on this research focuses on specific weather years to create demand profiles for residual electricity and building heating. By integrating diverse weather years, we can evaluate the results and increase model robustness across varying climate conditions.

Changing the renewable gas demand to analyze the effect of multiple different productions for this technology is another viable further research for this study. Likewise, by integrating new technologies into the system, such as hydrogen production via pyrolysis, we can analyze the viability of this technology depending on the region-specific characteristics, and, in an expanded model for the province, analyze the viability of implementation.

Chapter 6

Conclusions

6.1 Summary of Findings

This study examines how curtailment costs influence energy system configurations for Metro Vancouver's energy transition, comparing Electrification and RG pathways. Curtailment costs emerge as a critical driver of system design, particularly in the Electrification pathway, where they influence renewable capacity and battery storage deployment. By incentivizing surplus energy storage over curtailment, these costs reduce energy waste and improve cost-effectiveness. The RG pathway, in contrast, relies on flexible gas storage to adapt to curtailment costs, maintaining stable levelized costs of energy (LCOE) and showcasing its inherent economic resilience. These findings reveal the distinct trade-offs in system configurations, underscoring the importance of aligning technology choices with pathway-specific strengths and cost sensitivities.

6.2 Contributions to the Field

This research advances energy systems modeling by integrating curtailment costs into pathway optimization, offering a comparative analysis of Electrification and RG strategies tailored to Metro Vancouver. By bridging the gap between theoretical modeling and practical system design, this study highlights the economic and operational implications of curtailment costs, demonstrating their impact on storage, generation, and renewable integration. These findings provide valuable insights for policymakers and modelers seeking to balance cost efficiency, renewable utilization, and system cost in the energy transition.

6.3 Recommendations

To optimize energy systems, policymakers should consider curtailment pricing policies tailored to pathway strengths. For Electrification, investing in cost-effective battery storage enhances stability and affordability by reducing reliance on curtailment. For RG, flexible gas storage provides an alternative to electric storage, ensuring stability without additional infrastructure costs. Differentiated pricing structures can help align system configurations with demand needs, maximize renewable integration, and promote cost-effective decarbonization strategies.

6.4 Final Thoughts

This study underscores the importance of integrating curtailment costs into energy system planning, demonstrating their role in shaping renewable utilization, storage strategies, and system costs. By highlighting the trade-offs between Electrification and RG pathways, the findings offer a framework for designing resilient, cost-sensitive energy systems. As the global energy transition accelerates, these insights provide a foundation for future research to explore region-specific strategies, optimize renewable investments, and support sustainable energy development.

Appendix A

Additional Information

A.1 Yaml Files

A.1.1 model.yaml

```yaml
import:  # Import other files from paths relative to this file, or absolute paths
    - 'model_config\techs.yaml'  # This file specifies the model's technologies
    - 'model_config\locations.yaml'  # This file specifies the model's locations
    - 'scenarios.yaml'  # Scenario and override group definitions

# Model configuration: all settings that affect the built model
model:
    name: Vancouver Model

    # What version of Calliope this model is intended for
    calliope_version: 0.6.10

    # Time series data path - can either be a path relative to this file, or an absolute path
    timeseries_data_path: 'timeseries_data'

    subset_time: ['2013-01-01', '2013-12-31']  # Subset of timesteps
```

```

 # Run configuration: all settings that affect how the built model is run
run:
    solver: cplex

    ensure_feasibility: true  # Switches on the "unmet demand" constraint

    bigM: 5e4  # Sets the scale of unmet demand, which cannot be too high, otherwise the optimisation will not converge

    zero_threshold: 1e-6  # Any value coming out of the backend that is smaller than this (due to floating point errors, probably) will be set to zero

    mode: plan  # Choices: plan, operate

    objective_options.cost_class: {monetary: 1}

group_constraints:
    maximum_hydro_prod:                 # Maximum possible production of hydro   https://calliope.readthedocs.io/en/stable/user/advanced_constraints.html
        techs: ['hydro']
        locs: ['hydro-power']
        carrier_prod_max:
            electric_power: 10168 #GWh
```

A.1.2 scenarios.yaml

```
# Scenarios are optional, named combinations of overrides
##
scenarios:
    RNG-pathway: ['RNG_pathway']
    RNG-defined-storage: ['RNG_pathway','defined_storage']
    curtailment-cost: ['curtailmentcostchange']
```

```
    no-curtailment: ['no_curtailment']
    no-forced-vre: ['unforced_vre']
    RNG-curtailment-cost: ['RNG_pathway','curtailmentcostchange']
##
# Overrides are the building blocks from which scenarios can be defined
##

overrides:
    curtailmentcostchange:
        techs.demand-solar-curtailment.costs.monetary.om_con: 0.0 # $ / kWh
        techs.demand-wind-curtailment.costs.monetary.om_con: 0.0 # $ / kWh
        model.name: 0.0 $/kWh Curtailment Cost


    RNG_pathway:
     # Palmer-Wilson values:
        #techs.wind.constraints.energy_cap_equals: 8.9 #GW
        #techs.solar.constraints.energy_cap_equals: 0.4 #GW

        techs:
            gasdemand:
                essentials:
                    name: 'Gas demand'
                    color: 'red'
                    parent: demand
                    carrier: biogas

        locations:
            gas_demand:
                techs:
                    gasdemand:
                        constraints:
                            resource: file=demand-8760.csv:demand-3 # GWh demand
```

```

            gas_storage:
                techs:
                    gasstorage:

            biogas:
                techs:
                    biogas:

            electrolyzer:
                techs:
                    electrolyzer:

            electrolyzer.coordinates: {lat: 49.2794229822966, lon: -123.0601400081442}
            gas_demand.coordinates: {lat: 49.240671165704114, lon: -123.11223203743818}
            biogas.coordinates: {lat: 49.21998930539962, lon: -123.0601400081442}
            gas_storage.coordinates: {lat: 49.199286171518744, lon: -123.11223203743818}

            demand:
                techs:
                    demand_power:
                        constraints:
                            resource: file=demand-8760.csv:demand-2 # GWh demand

        links:
            biogas,gas_demand:
                techs:
                    free_transmission3:
                        constraints:
                            one_way: True
            demand,electrolyzer:
                techs:
```

```
                    free_transmission:
            electrolyzer,gas_demand:
                techs:
                    free_transmission3:
                        constraints:
                            one_way: True
            gas_demand,gas_storage:
                techs:
                    free_transmission4:


    defined_storage:
        techs.storage1.constraints.energy_cap_equals: 5.7 #GW
        techs.storage1.constraints.storage_cap_equals: 79.9 #GWh

    no_curtailment:
        techs.demand-solar-curtailment.exists: False
        techs.demand-wind-curtailment.exists: False
        locations.curtailment1.exists: False
        locations.curtailment2.exists: False

    unforced_vre:
        techs.wind.constraints.force_resource: False
        techs.solar.constraints.force_resource: False
        techs.demand-solar-curtailment.exists: False
        techs.demand-wind-curtailment.exists: False
        locations.curtailment2.exists: False
        locations.curtailment1.exists: False
```

A.1.3 techs.yaml

```
techs:
    # Must specify constraints.lifetime and costs.monetary.interest_rate when specifying fixed `monetary` costs for `solar` & 'wind'.
    # Set lifetime to 1 and interest rate to 0 if you do not want them to have an effect
```

```

    # csp-start
    solar:
        essentials:
            name: 'Solar power'
            color: 'yellow'
            parent: supply
            carrier_out: electric_power
        constraints:
            resource: file=solar-resource-8760.csv
            resource_unit: energy_per_cap
            force_resource: True
            energy_eff: 1
            #energy_cap_equals: 8.6 #GW
            lifetime: 30   # From Lombardi
        costs:
            monetary:
                interest_rate: 0.1   # From Lombardi
                energy_cap: 2021 # 2021
                om_prod: 0
    # csp-end

    # wind-start
    wind:
        essentials:
            name: 'Wind Power'
            color: 'orange'
            parent: supply
            carrier_out: electric_power
        constraints:
            resource: file=wind-resource-8760.csv
            resource_unit: energy_per_cap
            force_resource: True
            energy_eff: 1
            #energy_cap_equals: 7.9 #GW
            lifetime: 20   # From Lombardi
        costs:
```

```
            monetary:
                interest_rate: 0.1   # From Lombardi
                energy_cap: 2395 #2395
                om_prod: 0
    # wind-end

    # hydro start
    hydro:
         essentials:
             name: 'Hydroelectric power - flex'
             color: 'lightskyblue'
             parent: supply_plus
             carrier_out: electric_power
         constraints:
             resource: file=hydro-reservoirs-8760.csv
             energy_cap_equals: 6.065  # GW
             resource_unit: energy_per_cap
             force_resource: False
             resource_eff: 1
             lifetime: 1
         costs:
             monetary:
                 interest_rate: 0
                 #energy_cap: 10  # M$/GW 100
                 om_prod: 0.0006 # M$/GW  from Trottier table 17

    hydro_mt:
        essentials:
            name: 'Hydroelectric power - Must Take'
            color: 'blue'
            parent: supply_plus
            carrier_out: electric_power
        constraints:
            resource: file=hydro-reservoirs-8760.csv
            force_resource: True            # Tells the model to force the use of this technology (no fraction - all in).
```

```
            #energy_cap_min_use: 1           # Fraction of minimum production. More info here: https://calliope.readthedocs.io/en/stable/user/config_defaults.html
            energy_cap_equals: 6.852  # GW
            resource_unit: energy_per_cap
            resource_eff: 1
            lifetime: 1
        costs:
            monetary:
                interest_rate: 0
                energy_cap: 0  # €/kW
                om_prod: 0.0006 # $/kW

    # battery-start
    storage1:
        essentials:
            name: 'Battery storage'
            color: 'seagreen'
            parent: storage
            carrier: electric_power
        constraints:
            energy_cap_max: inf  # GW
            storage_cap_max: inf
            energy_eff: 1.0 # for a 0.86 round trip efficiency, use 0.9274 --- 0.9274^2=0.86
            storage_loss: 0  # No loss over time assumed
            lifetime: 50   # From Lombardi
            force_asynchronous_prod_con: True
        costs:
            monetary:
                interest_rate: 0.1   # From Lombardi
                storage_cap: 184  # M$ per GWh for energy capacity ---- other source: Lithium ion utility system investment cost tab in storage ninja: 65 USD /kWh in 2050 - 88 CAD
                energy_cap: 156      # Power capacity M$ / GW
```

```


    # battery-end

    # demand-start
    demand_power:
        essentials:
            name: 'Power demand'
            color: '#072486'
            parent: demand
            carrier: electric_power
    # demand-end

    # transmission-start

    free_transmission:
        essentials:
            name: 'Local power transmission'
            color: 'black'
            parent: transmission
            carrier: electric_power
        constraints:
            energy_cap_max: inf
            energy_eff: 1
        costs:
            monetary:
                om_prod: 0

    free_transmission2:
        essentials:
            name: 'Transmission to battery'
            color: 'seagreen'
            parent: transmission
            carrier: electric_power
        constraints:
            energy_cap_max: inf
            energy_eff: 1
```

```
            costs:
                monetary:
                    om_prod: 0.0023 # $/kWh carrier production cost: Dalton paper and then table 18 from Trottier Energy Future Projects 0.0023

    # transmission-end

    demand-solar-curtailment:
        essentials:
            name: 'Solar Curtailment'
            color: 'red'
            parent: demand
            carrier: electric_power
        costs:
            monetary:
                om_con: 0.005 #$/kWh


    demand-wind-curtailment:
        essentials:
            name: 'Wind Curtailment'
            color: 'red'
            parent: demand
            carrier: electric_power
        costs:
            monetary:
                om_con: 0.005 #$/kWh


## RNG Pathway
    biogas:
        essentials:
            name: 'biogas'
            color: 'green'
            parent: supply
            carrier_out: biogas
```

```
        constraints:
            resource: 0.5074  # hourly GW available
            resource_unit: energy
            force_resource: True
            energy_eff: 1
            lifetime: 20  # From Lombardi
        costs:
            monetary:
                interest_rate: 0.1  # From Lombardi
                energy_cap: 0
                om_prod: 0.083

    gasstorage:
        essentials:
            name: 'Gas storage'
            color: 'seagreen'
            parent: storage
            carrier: biogas
        constraints:
            energy_cap_max: inf  # GW
            storage_cap_max: inf
            energy_eff: 1.0
            storage_loss: 0  # No loss over time assumed
            lifetime: 30  # From REUSS table 3
            # storage_initial: 0
            force_asynchronous_prod_con: True
        costs:
            monetary:
                interest_rate: 0.06  # From Firschmouth
                storage_cap: 0.61  # $/kwh. Based on Table 4 (Sunny 2020)
                om_prod: 0.0012   # $/kwh. Based on table 1 (Reuss 2019)


    electrolyzer:
        essentials:
```

```
            name: 'electrolyzer'
            color: '#8E2999'
            parent: conversion
            carrier_out: biogas
            carrier_in: electric_power
        constraints:
            #energy_cap_equals: 4.5 #GW
            energy_eff: 0.78  #0.78
            lifetime: 18   # From Lombardi
        costs:
            monetary:
                interest_rate: 0.1   # From Lombardi
                energy_cap: 1400 # M$ / GW


    free_transmission3:
        essentials:
            name: 'Gas transmission'
            color: 'black'
            parent: transmission
            carrier: biogas
        constraints:
            energy_cap_max: inf
            energy_eff: 1
        costs:
            monetary:
                om_prod: 0

    free_transmission4:
        essentials:
            name: 'Gas transmission to battery'
            color: 'seagreen'
            parent: transmission
            carrier: biogas
        constraints:
            energy_cap_max: inf
            energy_eff: 1
```

```
        costs:
            monetary:
                om_prod: 0
```

A.1.4 locations.yaml

```
locations:
    demand:
        techs:
            demand_power:
                constraints:
                    resource: file=demand-8760.csv:demand # GWh demand
    battery:
        techs:
            storage1:
    hydro-mt:
        techs:
            hydro_mt:
    solar-power:
        techs:
            solar:
    hydro-power:
        techs:
            hydro:
    wind-power:
        techs:
            wind:
    curtailment1:
        techs:
            demand-solar-curtailment:
                constraints:
                    resource: -1e4
                    force_resource: False
    curtailment2:
        techs:
            demand-wind-curtailment:
```

```
                constraints:
                    resource: -1e4
                    force_resource: False

    solar-power.coordinates: {lat: 49.259729573200865, lon: -123.17541566317882}
    wind-power.coordinates: {lat: 49.263370770792065, lon: -122.98982898187695}
    curtailment1.coordinates: {lat: 49.25702622341958, lon: -123.20493168776198}
    curtailment2.coordinates: {lat: 49.263824292942914, lon: -122.94418926637398}
    demand.coordinates: {lat: 49.240671165704114, lon: -123.11223203743818}
    battery.coordinates: {lat: 49.2794229822966, lon: -123.1242254988558}
    hydro-power.coordinates: {lat: 49.19425173510429, lon: -123.13763555787591}
    hydro-mt.coordinates: {lat: 49.200735988529, lon: -123.08267851864403}

##
# TRANSMISSION CAPACITIES
##

links:
    solar-power,demand:
        techs:
            free_transmission:
                constraints:
                    one_way: True
    hydro-power,demand:
        techs:
            free_transmission:
                constraints:
                    one_way: True
    hydro-mt,demand:
```

```
        techs:
            free_transmission:
                constraints:
                    one_way: True
    wind-power,demand:
        techs:
            free_transmission:
                constraints:
                    one_way: True
    hydro-ror,demand:
        techs:
            free_transmission:
                constraints:
                    one_way: True
    biomass-power,demand:
        techs:
            free_transmission:
                constraints:
                    one_way: True
    demand,battery:
        techs:
            free_transmission2:

    solar-power,curtailment1:
        techs:
            free_transmission:
                constraints:
                    one_way: True
    wind-power,curtailment2:
        techs:
            free_transmission:
                constraints:
                    one_way: True

    # links-end
```

A.2 Extra Pathway-Specific Figures

A.2.1 Electrification Pathway

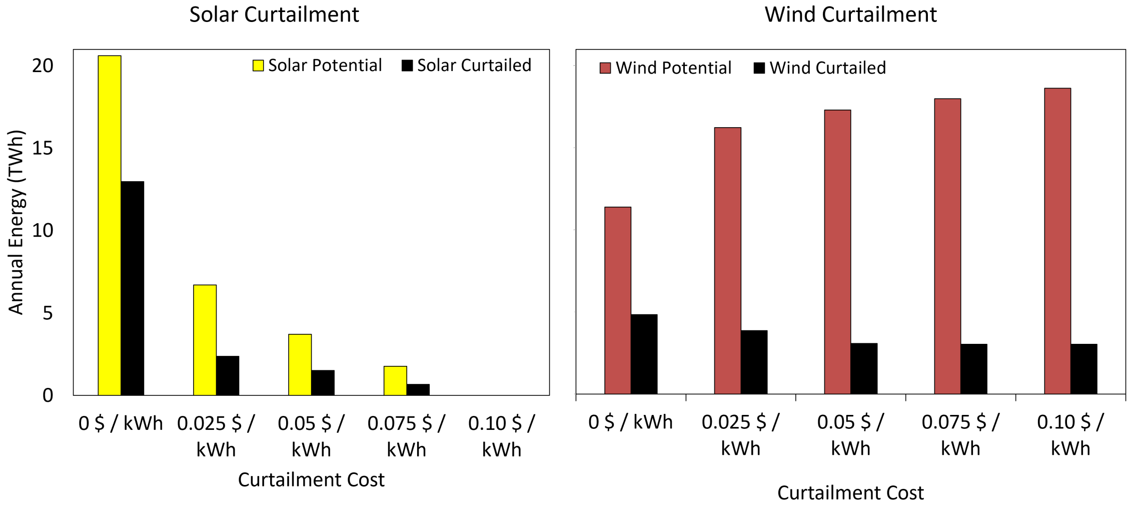

Figure A.1: Annual and curtailed VRE energy by technology for the electrification pathway varying curtailment costs.

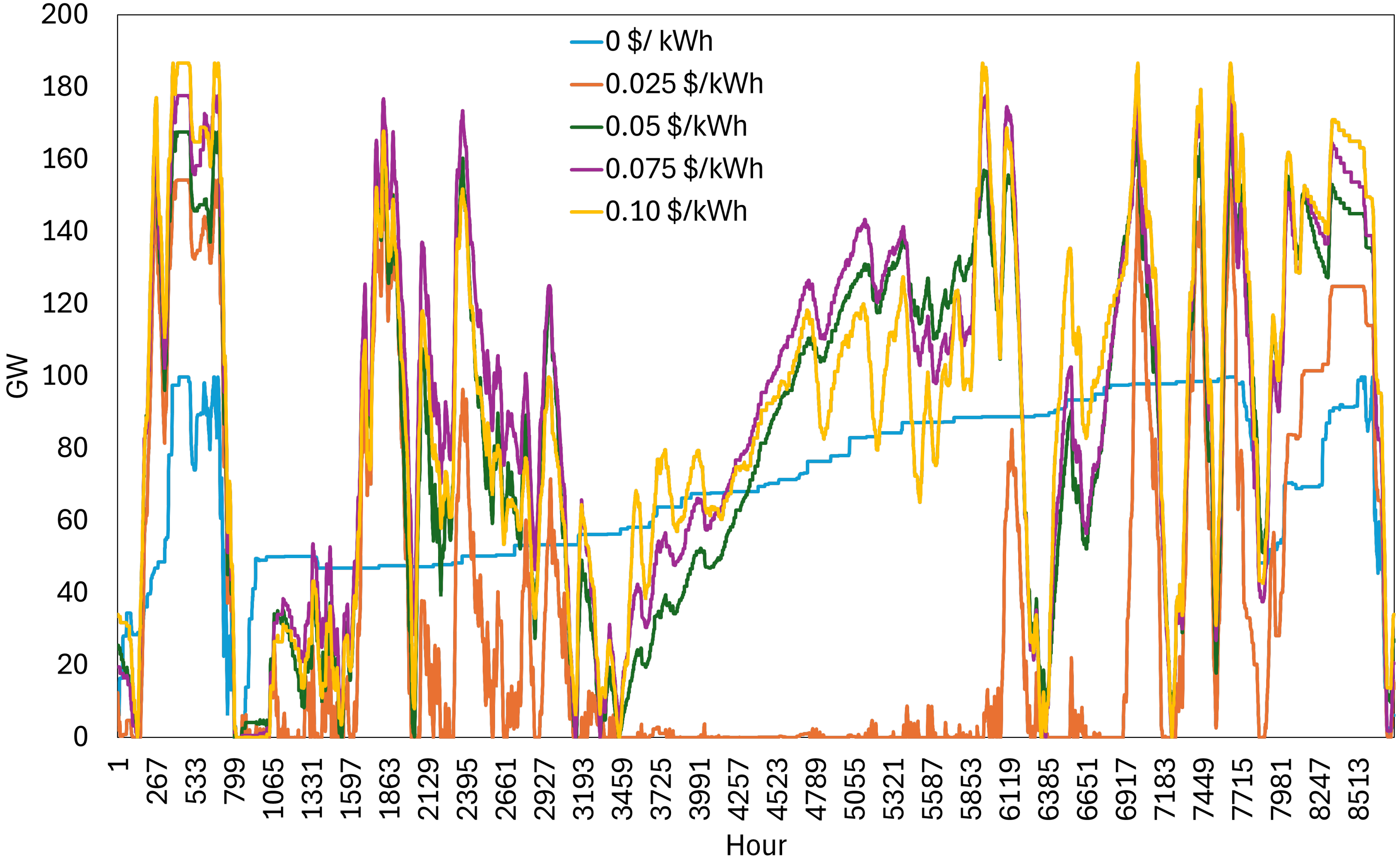

Figure A.2: Yearly electric storage operation profile varying curtailment costs.

A.2.2 RG Pathway

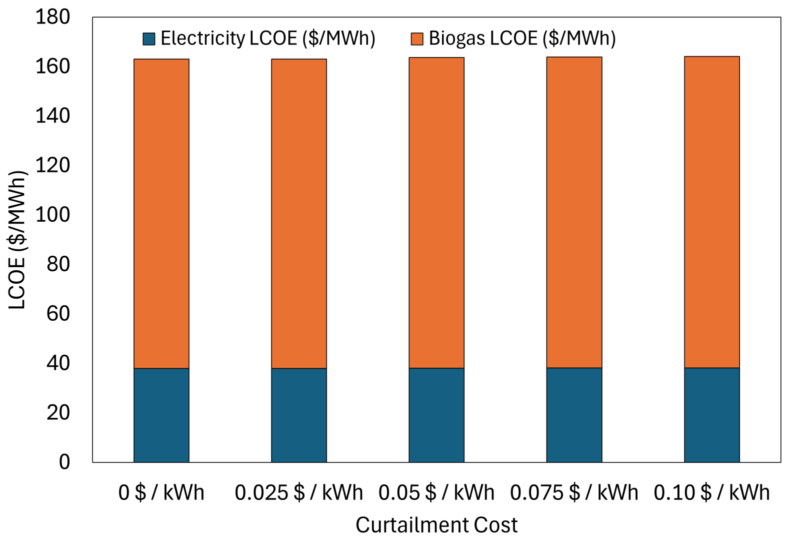

Figure A.3: Levelized Cost of Energy for each curtailment cost studied for the RG pathway.

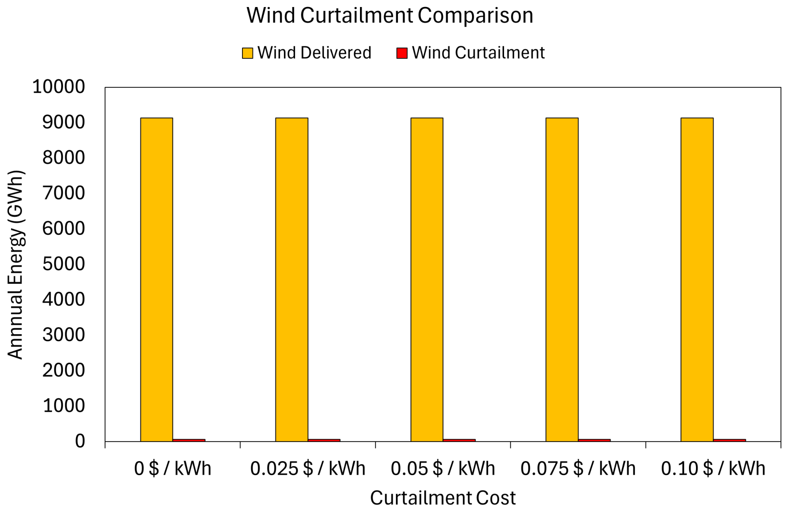

Figure A.4: VRE annual energy and curtailment (wind only) for the RG pathway varying curtailment costs.

A.2.3 Input Data

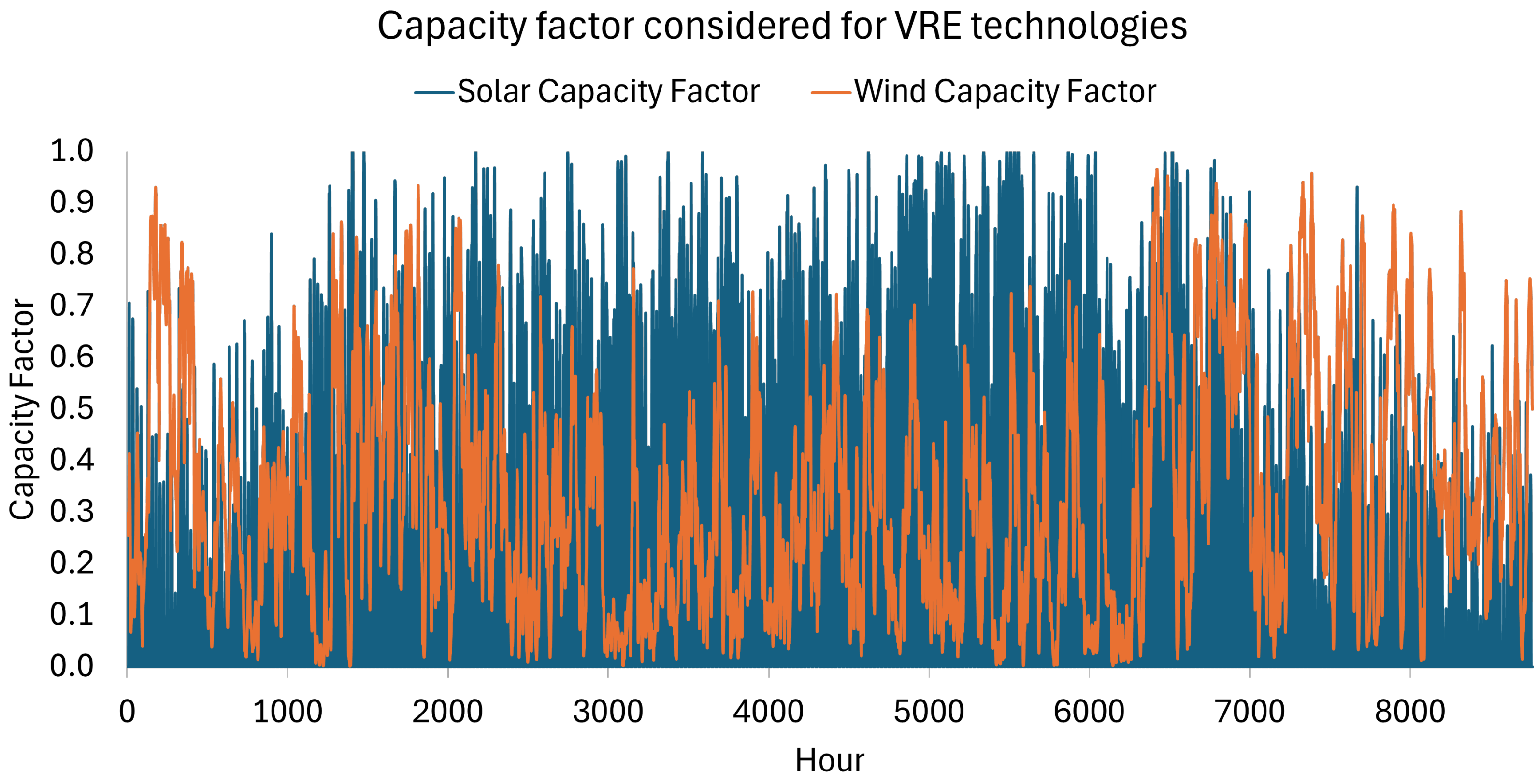

Figure A.5: Hourly capacity factor profiles considered for VRE technologies in BC.

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