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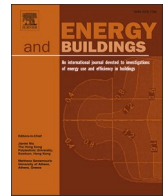
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# A meta-analysis of the schematic design process of deep retrofit projects

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## ABSTRACT

Deep retrofits of the existing building stock will be necessary to meet global emissions reductions targets. One building archetype, low-rise MURBs have been neglected in terms of research and funding for deep retrofits. A meta-analysis was conducted that compares and contrasts the schematic design approach taken for six such buildings in British Columbia which are scheduled to undergo deep retrofits with the goal of reducing GHG emissions by 80%. The analysis showed that design teams had converged toward common solutions for each building while achieving the GHG reduction target. The recommended measures include electrification of space and domestic hot water heating, adding insulation through overcladding, air sealing, ventilators for each unit, and double pane windows. A life cycle cost analysis showed that the economic viability of deep retrofits were dependent on energy price forecasts, capital cost reductions through market forces and transformation, or incentives cover the non-monetizable co-benefits of deep retrofits such as improved resiliency to climate-change or reducing overheating and air quality risks. The meta-analysis can help to streamline the early-stage and schematic design process for such buildings, which is critical to increasing the retrofit rate. This process could be replicated for other building types and construction archetypes.

## 1. Introduction

The majority of the existing residential building stock will need to be retrofitted to meet ambitious greenhouse gas emission reduction targets being set by federal and provincial governments in Canada. To meet the targets being set for the building sector, an estimated 3 to 5% of the existing residential building stock will need to be retrofitted every year [1–3]. Presently, the retrofit rates are less than 1%/year for low-rise residential buildings in Canada and in Europe, far below what is required [2,4]. To meet the sector's greenhouse gas emissions targets on time, this retrofit rate will need to increase significantly. It is imperative that we understand what the barriers are to implementing deep retrofits and improve communication regarding the benefits and opportunities of deep retrofits. This will lead to new policies being implemented, and technological and logistical solutions being found that will allow deep retrofits of residential buildings to happen at the required speed and scale.

The Canadian deep retrofit industry needs to expand greatly if Canada's building sector is to achieve this increased retrofit rate. As this industry is in its relative infancy, there isn't the established

infrastructure and knowledge base among the architecture, engineering, and construction (AEC) field, or financial mechanisms to execute deep energy retrofits to their fullest potential. To accelerate the adoption of effective deep retrofits across Canada, our knowledge base needs to expand and coalesce. Demonstrating an extensive and informative track record of successful deep retrofits projects is an important step in acquiring the necessary political and capital buy-in to transform Canada's existing residential sector into one that embraces low carbon designs. This can be accomplished through the sharing of performance data, life cycle cost analyses, and other lessons learned from the implementation of deep retrofits across Canada's many diverse climate regions. The lessons learned from these deep retrofits come in several forms and throughout the project life cycle – from financing, planning, design, construction to commissioning.

A meta-analysis was performed on the schematic design of six low-rise multi-unit residential buildings (MURBs) located in the Canadian province of British Columbia that are scheduled to begin construction of deep retrofits in 2023 and 2024. The data collected as part of this study supplements a relative lack of technical, performance, and costing data on deep retrofits of low-rise MURBs in Canada. The meta-analysis

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discusses the technical solutions and predicted performance of the proposed retrofits, as well as their economic viability through a life-cycle cost analysis of these retrofits. By comparing the findings from each schematic design, we will highlight the commonalities and differences between designs, and areas where efficiencies can be made to streamline the delivery of deep retrofits, specifically the preliminary design stages. The similar nature of the six buildings being studied means the lessons learned from this *meta*-analysis are transferable to other low-rise MURBs. This will improve the scalability of deep retrofit adoption, where the capacity or budget for undertaking individual schematic design processes on multiple buildings is limited. This in turn will help accelerate our ability to deliver deep retrofits at the speed and scale required to meet greenhouse gas emission objectives.

## 2. Literature review

The provincial government of British Columbia (B.C.), Canada has established a 2030 greenhouse gas (GHG) reduction target for buildings and communities between 59 and 64 % relative to 2007 emissions levels [5]. There has been mixed progress made in the British Columbia residential sector's energy consumption and GHG emissions relative to 2007. In 2020, the residential building sector's total energy consumption and GHG emissions had increased 13 % and 6 % respectively since 2007, when normalized by heating degree days (driven by population growth), but energy consumption and GHG emissions per floor area had decreased by 11 % and 16 % respectively [6]. A significant proportion of B.C. homes use fossil fuels (gas, oil, wood) for space heating and hot water heating. 50 % of B.C. residences rely entirely on fossil fuels for space heating with another 7 % having a dual fossil fuel/electric system. 58 % of residences rely on fossil fuels for water heating [6].

In 2021, British Columbia generated 94 % of its electricity through hydro. The carbon intensity of the province's grid is low at 15 g CO<sub>2</sub>e/kWh of electricity consumed [7]. This allows for a relatively straightforward pathway to achieve ambitious decarbonization goals through fuel switching compared to several other Canadian provinces with higher grid intensities. As part of the British Columbia government's GHG mandate, it was anticipated that heat pumps for space and water heating systems would need to be installed in a minimum of 10 % of residential buildings by 2030 (currently it is just 3.6 %) [5].

### 2.1. Deep retrofits

Deep retrofits will make a significant contribution in meeting the residential sector's GHG targets. We use the term 'deep retrofit' instead of 'deep energy retrofits' to avoid the connotation that these retrofits only deliver energy efficiency improvements, but also offer chances to improve emissions, indoor environmental quality (IEQ), accessibility, and resilience among other things. A deep retrofit is defined as a minimum 50 % reduction in site energy use intensity with corresponding improvements in indoor environmental quality and comfort [8]. A deep retrofit often tackles multiple building systems simultaneously such as building envelope, heating, ventilation and air conditioning (HVAC), domestic hot water (DHW), lighting, etc. Recently, (as with this project) the focus has shifted to meeting carbon emission reduction targets and not just energy reduction targets.

The focus of this paper is on retrofitting low-rise MURBs (defined as 4 storeys or less). MURBs make up a significant proportion of the building stock in Canada. There are an estimated 70,000 low rise apartment buildings and 10,000 high rise apartment buildings, with approximately 31 % of Canadians living in such a building [2]. Retrofits of this archetype have received less attention in the academic literature than that of high-rise MURBs and other archetypes. For example, in a *meta*-analysis of energy consumption of Toronto MURBs only 6 of 108 buildings were low-rise [9] despite low-rise buildings being more numerous. This is possibly due to economies of scale in retrofitting larger buildings over smaller ones. Existing low-rise MURBs require

equal attention, investment, and research to that of existing high-rises and single-family homes if the building sector's emissions targets are to be met. Keeping our existing, aging MURBs economically viable is also critical considering many Canadian cities are facing a severe affordable housing shortage [10–12].

Canada lacks a thorough database which tracks building performance, and upgrades for MURBs. The EnerGuide database collects data through home energy audits, but this system is voluntary and is primarily used for single-family homes [13]. From the EnerGuide database, only 0.7 % percent of single and detached homes were retrofitted in 2019–2020. No equivalent rate data exists for the MURB building stock.

Relative to Europe, performance and technical information regarding deep retrofits of low-rise MURBs in Canada is scarce and highly fragmented with few case studies presented in peer-reviewed publications. A study performed on five low to mid-rise social housing buildings built from the 1950s to the 1980s identified effective strategies for reducing greenhouse gas emissions and the barriers toward implementing these strategies [14]. The report identified fuel switching to air-source heat pumps (ASHP), envelope upgrades, and ventilation system upgrades (heat recovery ventilators), and the separation of heating and cooling from ventilation) as the most effective retrofitting strategies for reducing GHG emissions. While not recommended, the integration of passive strategies to reduce solar gains and the addition of photovoltaics were considered. The average estimated GHG reduction for the buildings in this analysis was 39 %. Some of these buildings have since been retrofitted but post-construction performance data is unavailable. Other North American case studies of this archetype include [15–17].

An international review of 26 deep retrofit case studies contained just 7 residential buildings, all located in Europe. These buildings demonstrated energy savings ranging from 51 % to 88 % when renewable solar systems were not implemented and 72 % to 94 % when they were. The mean annual energy consumption of the 7 buildings was approximately 300 kWh/m<sup>2</sup> before the retrofit and 80 kWh/m<sup>2</sup> after. The common retrofit strategies for residential buildings in this study included adding wall, roof, and floor insulation, upgrading windows and doors, mechanical ventilation with heat recovery, and upgrading the heating/cooling system [18]. The Mustbe0 project has recently completed retrofits of 11 residential and school buildings in France, Germany, Netherlands and the UK [19].

### 2.2. Economics

Several non-technical barriers to deep retrofits have been identified. The foremost barriers are economic, but others exist at the regulatory, social, and industrial levels [20–21]. The low cost of energy (relative to other nations) means that Canadian home and building owners are less incentivized to consider energy efficiency measures based purely on economic payback periods. Building owners will not consider measures if the measures have a payback period > 10 years, and many will only consider measures if the payback period is < 5 years [22]. A 2021 study showed that deep carbon retrofits of low-rise MURBs in various Canadian cities did not provide attractive rates of return [23]. For the math to make sense to building owners, either a modified approach to life cycle costing needs to be used, or subsidies are required to overcome the high payback periods (or in several instances, no payback period at all).

In their 2020 report, The Atmospheric Fund describe alternate approaches to make business cases for deep retrofits based on their experiences of retrofitting five high-rise MURBs [22]. They recommend analyses consider the avoided capital improvement and maintenance costs doing the status quo, extra revenue from rental income, and reduced insurance premiums to help make a stronger business case for deep retrofits. Other economic barriers identified in this report include access to loans and a lack of confidence that predicted savings will be achieved. Azcarate-Aguerre et al [24] proposed adopting a Total Value of Ownership (TVO) financial model which recommends internalizing

and monetizing improved productivity and property values to strengthen the case for deep retrofits.

For operators of low-income and social housing the business case for retrofits can be especially difficult to make with tight budgets and limited human resources at their disposal. These operators have limited access to sufficient financing and may have limitations on the amount they can raise rent to recuperate their investment (pricing their residents out of the market). This is unfortunate because retrofitting these buildings presents an excellent opportunity for savings and to reduce socioeconomic inequalities. These buildings tend to be older buildings which are in poorer condition, have less efficient mechanical systems and appliances, and therefore offer greater scope for savings [25]. Residents of these buildings spend a higher percentage of their income on energy bills and experience greater energy burden [26–28]. As a result, incentives and subsidies are important to push deep retrofits over the finish line for low-income and social housing MURBs.

The cost of a deep retrofit is dependant on several factors including the target savings objective, degree of intervention, condition of the existing building, and climate. Estimates for deep retrofits in Canadian MURBs span from \$28–58 K per unit. [2–3]. Concerningly, a 2014 analysis of deep retrofits performed on US homes found only a weak positive correlation between project cost and measured energy cost savings [29]. The poor correlation affirms a common barrier of deep retrofits – uncertainty that they will produce the cost savings required to justify the payback period.

To meet national climate change objectives, it has been estimated that \$277 billion CAD of investment is required by 2040 just for the residential building stock, with \$1.9 billion/year of that investment for British Columbia alone [3]. Currently enacted initiatives for residential retrofits from the federal and provincial governments provide only a small fraction of the investment needed [30–36]. Many incentive programs are limited in the amount of funds which can be distributed, have short windows of availability, place limits on eligibility, or are only available to be claimed post-construction. The incentives vary in size and structure – from small amounts to perform energy audits, fixed grants for the whole building (for example, \$200 k for CleanBC Social Housing Incentive Program), or repayable/forgivable loans on a per unit basis (for example, up to \$170 k/unit from Canada Mortgage and Housing Corporation’s (CMHC) Canada Greener Affordable Housing Retrofit Funding program). This funding ecosystem can be difficult to navigate, and costly in time and resources to prepare applications.

A stronger case can be made for deep retrofits if the economic co-benefits are considered. This includes increased tax revenues and employment, improved health and well-being of residents reducing healthcare costs, and reduced cost of climate adaptation and recovery from major climate events [3,37–38]. These benefits are shared by the wider public and are not easily monetizable by building owners or investors [22].

### 2.3. Indoor environmental quality

For owners of rental buildings, economics is often the dominant factor in the decision whether to proceed with a deep retrofit or not. The co-benefits often get outweighed by economic realities, though these attitudes are beginning to change. Studies of IEQ in MURBs have highlighted concerns with thermal comfort and IEQ in MURBs with vulnerable populations [39–40]. Deep retrofits offer an excellent opportunity to address these IEQ shortcomings via envelope and mechanical system interventions.

Overheating has especially become a concern for social housing in British Columbia as a result of the unprecedented heat dome event in 2021 which caused dangerous temperatures exceeding 40 °C in the province. 619 deaths were attributed to this event with 62 deaths occurring in social and supportive housing sites [41–42]. This risk is compounded by the fact a large proportion of existing residential buildings do not have air conditioning. Only 32 % of British Columbians

have air conditioning in their homes. Among heat-vulnerable populations, this figure is slightly lower [43]. Canadian residences have historically been designed to retain heat in winter, with minimal considerations for cooling. Characteristics of Canadian MURBs which contribute to overheating include lightweight wood frame construction, high insulation levels, inadequate mechanical and cross ventilation, stack effect, and unshaded windows [44].

The aftermath of the heat dome and the lack of cooling in British Columbia’s residential buildings has led to calls to mandate improved resiliency to extreme heat events for residential buildings in the region. As a result, the City of Vancouver has proposed a building by-law which effectively mandates cooling systems be installed in all new builds falling under Part 3 of the building code (floor area > 600 m<sup>2</sup>) by 2025. The City of Vancouver also approved a by-law in 2022 mandating that passively cooled spaces do not exceed the 80 % acceptability limits defined in American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) 55 for no more than 20 h per year, in spaces containing seniors housing, shelter or supportive housing, daycares, schools, or healthcare facilities [45–46]. For all other spaces the limit is 200 h per year. These by-laws will make the analysis and mitigation of overheating risk an essential objective of all deep retrofits.

Poor indoor air quality (IAQ) can lead to discomfort and respiratory health issues for residents. Contaminants of concern include high concentrations of CO<sub>2</sub>, volatile organic compounds (VOC), humidity (leading to risk of mould growth) and particulate matter (PM<sub>2.5</sub>). It is common for older MURBs to have insufficient mechanical ventilation to exhaust these contaminants. They rely on a combination of bathroom and kitchen exhaust fans, natural ventilation, an air leaky envelope.

Air sealing the building envelope can have negative consequences on IAQ if there is no mechanical ventilation as the flow rate of incoming dilution air is reduced. As a result, there have been documented concerns about whether IAQ worsens after a deep retrofit with some undergoing pre – and post-retrofit monitoring. [47–50]. General conclusions were that concentrations remained within acceptable levels, though there were some increases in species concentration that residents may perceive as worsening the air quality. New ventilation systems such as distributed heat or energy recovery ventilators (HRV/ERV) should be considered as part of a deep retrofit. In British Columbia, an additional IAQ concern is the recurring threat of particulate matter from wildfire smoke. The frequency and intensity of wildfire smoke events have increased because of climate change, culminating in a record wildfire season in 2023 [51]. In buildings which rely on natural ventilation and infiltration, air enters unfiltered and particulate matter can accumulate, which can be hazardous for residents with respiratory health issues. Few studies have examined the pre – and post-retrofit susceptibility to wildfire smoke in MURBs.

### 2.4. Business models

To address the economic and informational barriers to deep retrofits, there has been a push by industry proponents to pursue market transformation through a more coordinated, mission-oriented innovation policy for deep retrofitting residential buildings. This type of policy brings in a broad spectrum of stakeholders to deliver on the goal (accelerating retrofit adoption) and be defined not only in terms of technical achievement, but socioeconomic indicators too [52]. The most commonly cited example of a successful mission-oriented approach for retrofits is Energiesprong, a proven successful program in the Netherlands which has transformed the country’s construction industry. The program began focusing on the social housing sector with a different philosophy to project delivery and resulted in a shift in business model [53]. Traditionally, the business model in Canada (as was the same in the Netherlands) is the ‘atomized’ model [54]. This model requires home or building owners to ‘go-it-alone’ and arrange interventions one-at-a-time from different contractors. The average building owner may not have the knowledge, experience, or contacts to make optimal

decisions. Retrofits requiring multiple interventions are not undertaken in a coordinated, holistic manner and opportunities are lost for increased synergy and efficiency. Under this business model the customer bears the financial risk and uncertainty.

It has been recommended for the industry to push toward a ‘one-stop shop’ or ‘managed energy services agreement’ (MESA) business model [54]. These business models provide a more holistic approach toward deep retrofits covering design, build, and in the case of MESAs, the operating phases. Under the MESA financial model, retrofit providers assume more of the financial risk and uncertainty. A result of this business model has been an increased demand for ready-made retrofit solutions which in turn acts an incubator for innovation and efficiency throughout the supply chain (eg. pre-fabrication) [55].

Absent a coordinated national policy, several small Canadian organizations have adopted mission-oriented principles into their projects [56–57], *Reframed* [58–59]. The New York State Energy Research and Development Authority (NYSERDA) commissioned a study to evaluate if Energiesprong principles could be adopted for their housing retrofits need [60]. They concluded that the technology is transferable to the North American context, but adaptations will be needed to accommodate local construction practices.

### 2.5. Summary

In summary, there is a lack of published information on deep retrofits in low-rise Canadian MURBs. Some performance data and technical solutions have been reported in literature, but some key analysis such as life-cycle cost analysis (LCCA), overheating risk analyses, and a commentary on the design solutions which were explored and rejected is often omitted. The six schematic designs in this *meta*-analysis offer an opportunity to contribute insights into the literature about the technical solutions being proposed, their projected energy, emissions and cost savings, and their economic viability. The *meta*-analysis will also permit qualitative assessment of convergences and disagreements between design solutions, limitations in the deep retrofit business model, and areas where the project delivery of retrofits can be streamlined.

An overview of the schematic design process used for each building, a quantitative and qualitative description of the six buildings in their existing state, and the energy modelling procedures used to predict the net energy savings is provided in Section 3. The results of the schematic design including, calibrated energy models, proposed bundles, and projected savings are provided in Section 4. The results of the life cycle cost analysis and overheating risk study are presented in Section 5.

## 3. Methodology

This study examines the schematic design process for six low-rise multi-unit residential buildings (MURBs) located in British Columbia,

Canada, which will undergo deep energy retrofits beginning in 2023 and 2024. The six buildings are part of the Reframed Labs project which is a collaboration between the Pembina Institute, BC Housing, Metro Vancouver Housing Corporation, and the BC Non-profit Housing Association.

### 3.1. Overview of schematic design process

In 2022, seven consulting teams were chosen to create a schematic design proposal for one of the six buildings under an Integrated Design Process framework (the Manor House had two proposals submitted, one using gas systems and one fully electric). An overview of the process is illustrated in Fig. 1. Per the contract, each team developed and modelled five different retrofit bundle options for each building. Each team was required to report the TEUI (Total Energy Use Intensity), TEDI (Thermal Energy Demand Intensity), (GHGI) Greenhouse Gas Intensity, estimated annual energy costs, and Net Present Value (NPV) for the existing baseline condition and each of the five bundles. From the model results, a recommended bundle was selected based on a multi-objective criteria which included energy and carbon emissions savings, climate adaptation & resilience, occupant comfort and well-being, and NPV. More details about the bundles and selection criteria are given in Section 3.2. The recommended bundle would then form the basis for design development. Construction began in late 2023 for some buildings whereas others are scheduled to begin in late 2024. Teams were also required to submit additional secondary modelling studies with their reports which included an overheating risk analysis, and embodied carbon study.

The design briefs also included other objectives including minimizing disruption to residents during construction, improving structural performance under seismic loads, and improving accessibility. While these were important objectives for some buildings, they did not have a significant influence on the selection of retrofit bundles from an energy and emissions standpoint.

### 3.2. Schematic design bundles

Teams were required to develop design bundles based on their calibrated energy model. This model was referred to as ‘Baseline A’ and was used as a benchmark to compare the proposed retrofit design’s energy consumption and GHG emissions to the existing building. Teams were then required to design and model five different retrofit bundles as follows:

- **Baseline A:** Existing building
- **Baseline B:** “Business-as-usual” – replace equipment at end-of-service-life in the next 5 years to current code standards.

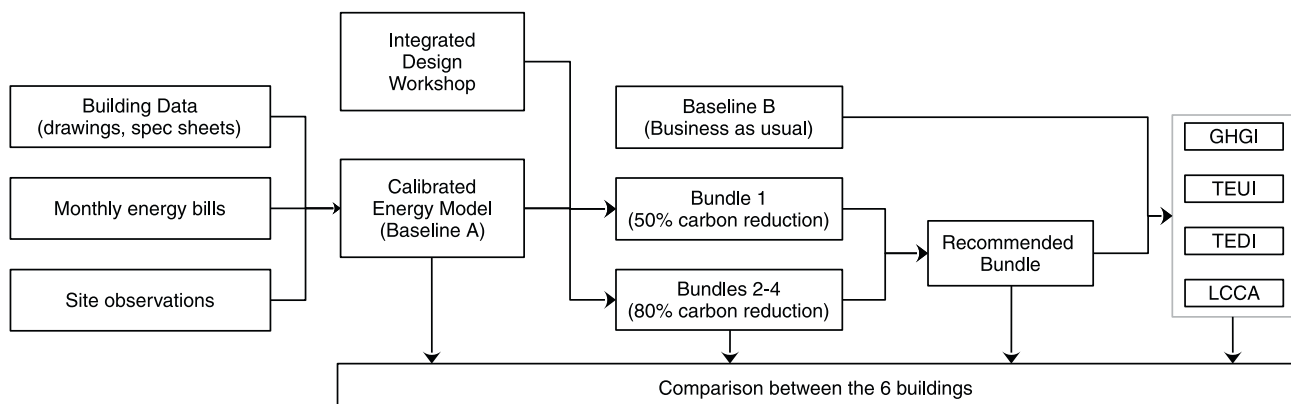


Fig. 1. Flow chart illustrating the schematic design process and outputs for each design team.

- **Bundle 1:** 50 % operational GHG emission reduction compared to Baseline A and a 30 % operational GHG emission reduction compared to Baseline B.
- **Bundle 2 – 4:** 80 % operational GHG emission reduction from the Baseline A.

While the target for bundles 2–4 was the same, teams were encouraged to arrive at those targets using different paths and design philosophies. Examples of different paths included using market-ready vs. innovative technologies, using a gas-powered heat pump (eg. Bundle 4 Dany Guincher and Crown Manor), or a focus on building envelope improvements. Bundles were to balance performance improvements with other Reframed Labs objectives: GHG emissions and energy, adaptation and resilience, indoor environmental quality, project goals, and financial/other goals. A decision matrix was used to objectively score the bundles with the highest score serving as the basis to proceed to design development and then onto construction.

### 3.3. The buildings

Details of the six buildings are shown in Table 1. The buildings were constructed between 1963 and 1994. They range from 2 to 4 stories in height, have between 11 and 52 units, and floor areas between 558 m<sup>2</sup>

and 3,865 m<sup>2</sup>. The six buildings are located in ASHRAE Climate Zones 4 (Victoria and the Metro Vancouver Regional Districts) and Climate Zone 5 (Kamloops). Both Victoria and Vancouver have coastal climates characterized by mild winters ( $T_{design} = -4$  to  $-8$  °C) and temperate summers ( $T_{design} = 24$  to  $29$  °) with between 2650 and 2910 heating degree-days (HDD). Kamloops is located further away from the Pacific coastline in the British Columbia interior and has harsher winters and hotter peak summer temperatures ( $T_{design} = -17$  °C and  $33$  °C) and 3400 HDD [61]. A warming climate is a significant concern in the region. Under the shared socioeconomic pathway (SSP) 2.6–4.5 scenario peak temperatures are expected to increase by between 2.6 and 2.9 °C and cooling degree days (CDD) by 98 and 179 [62–63].

The buildings are of similar lightweight wood or steel-stud construction with batt insulation between studs or rafters. The original windows and patio doors were single-pane, although some have been upgraded to double-pane. Envelopes have poor thermal resistance and are of the concealed barrier type with combinations of wood, stucco, and masonry cladding. All buildings except Crossroads Inn have balconies. Space heating is provided by gas-fired boilers that feed hydronic baseboards. Le Chateau has supplemental gas fireplaces which some residents continue to use. There are no centralized mechanical cooling systems installed in any of the buildings, although some tenants have portable or in-window A/C units. In-unit ventilation is accomplished via

**Table 1**  
Overview of the six case study buildings and their current envelope, mechanical system, and lighting systems as observed by design teams.

	Medewiwin	Dany Guincher	Crossroads Inn	Manor House	Le Chateau	Crown Manor
City	Victoria	Vancouver	Kamloops	North Vancouver	Coquitlam	New Westminster
Year Built	1963 (2002 addition)	1972	1994	1972	1976	1964
Stories	2–3	3	4	3	3	3
Units	26	11	52	50	24	28
Residents	26–50	11–15	50–75	50–80	24–48	28–60
Floor Area [m <sup>2</sup> ]	1,347	558	1,474	3,865	2,356	2,468
Window-to-Wall Ratio	19 %	16 %	11 %	13 %	15 %	25 %
Wall Effective R-Value [m <sup>2</sup> ·K/W]	Original: 0.84 Addition: 2.25	1.97	1.06	Team 1 (Gas): 1.07 Team 2 (Elec): 0.99	1.48	1.06
Roof Effective R-Value [m <sup>2</sup> ·K/W]	Original: 1.32 Addition: 2.89	2.47	2.82	Team 1 (Gas): 1.80 Team 2 (Elec): 2.20	4.40	2.64
Glazing U-value [W/m <sup>2</sup> ·K]	Original: Single pane 4.30 Addition: Double pane 2.07	Single pane 6.13	Units: Double pane 3.41 Stairways: Single pane 6.02,	Team 1 (Gas): Single pane 6.70 Team 2 (Elec): Single pane 6.02	Single pane 6.98	Single/double pane 3.41
Glazing SHGC	Original: 0.70 Addition: 0.35	0.80	0.70 – 0.84	0.80	0.80	0.5
Heating Boiler Efficiency	83 %	83 %	92 %	Team 1 (Gas): 82 % Team 2 (Elec): 80 %	80 %	87 %
DHW Boiler Efficiency	80 %	65 %	80 %	Team 1 (Gas): 95 % Team 2 (Elec): 96 %	80 %	82 %
Corridor Ventilation	AHU	None	AHU	AHU	MUA	None
Lighting	Fluorescent & LED	Fluorescent & LED	Incandescent & fluorescent	Incandescent & fluorescent	Incandescent & fluorescent	Incandescent & fluorescent
Main Electrical Service	600A, 120/240 V	60A, 120/240 V	400A, 600/347 V	400A, 120/208 V	400A, 120/208 V	400A, 120/240 V
Infiltration Rate [L/s/m <sup>2</sup> @ 5 Pa]	0.48	0.45	0.38	0.5	1.06	0.5
Heating Setpoints [Night/Day]	22 °C (Constant)	18 °C/22 °C	20 °C/22 °C	20 °C/22 °C	20 °C/22 °C	22 °C (Constant)
Lighting Power Density [W/m <sup>2</sup> ]	5.0	1.65	5.0	Team 1 (Gas): 5.0 Team 2 (Elec): 3.6	5.0	5.5
Peak Plug Load [W/m <sup>2</sup> ]	5.0	5.0	5.0	Team 1 (Gas): 5.0 Team 2 (Elec): 4.41	6.0	3.7
DHW Consumption [L/s/person]	0.0016	0.00237	0.0016	Team 1 (Gas): 0.0016 Team 2 (Elec): 0.00239	0.00432	0.0016

bathroom fans and/or infiltration. Most of the buildings have rooftop air handling units (AHU) or make-up air units (MAU) to provide ventilation to corridors and common areas which may reach the units through corridor pressurization. The performance of corridor pressurization systems have been measured, and often do not provide adequate ventilation into the units [64]. In a pre-retrofit survey, residents had indicated poor thermal comfort and indoor air quality. The results prompted a greater emphasis on reducing overheating risk and improving ventilation in the schematic designs. Domestic hot water (DHW) heating is provided by gas boilers. Many of the building's major components (mechanical systems and cladding in particular) have reached or are approaching the end of their expected lifespan. The urgent need to replace end-of-life components was a contributing factor in the decision to pursue a deep retrofit now.

None of the buildings have performed air infiltration testing. Infiltration rates in Table 1 are estimates, and are generally double the minimum value recommended by the City of Vancouver guidelines. This is a reasonable assumption because of the buildings' age, construction methods, and the number of patio doors and operable windows. The Le Chateau building has an assumed infiltration rate more than double the other buildings, which is partly caused by chimneys for the gas fireplaces. Peak DHW flow was increased in some buildings from the base value of 0.0016 L/s/person based on analysis of gas utility data during summer months.

### 3.4. Building energy models

All teams created energy models of the buildings in their existing state to serve as a baseline. The teams had access to at least 12 months of electrical and gas utility bills, architectural and mechanical system drawings, building condition assessment reports and site access from which to create and calibrate their models. Of the seven design teams, three used EnergyPlus, three IES-VE, and one eQUEST as their simulation engine. Teams followed the ASHRAE 14 Guideline for calibration using monthly data, which considers a model to be calibrated if the absolute value of the NMBE (normalized mean bias error) is less than 5% and the CVMSE (coefficient of variation of the root mean square error) is less than 15% [65]. Actual meteorological years were gathered for energy model calibration, while CWEC (Canadian Weather Year for Energy Calculation) files, were used for the design bundles.

For the bundles' model inputs, teams were directed to use the ASHRAE Handbook – Fundamentals and the Vancouver Energy Modelling Guidelines v.2.0 for default values if information on the existing building was unavailable [66]. The Vancouver Energy Modelling Guidelines v.2.0 were used for the following inputs:

- Thermal resistance of envelope components calculated in accordance with the Building Envelope Thermal Bridging Guide [67].
- Infiltration modelled at a fixed rate at operating pressure (5 Pa).
- Peak hourly DHW flow of 0.0016 L/s/person with reductions permitted. Cold water inlet temperature of 5°C.
- Default plug and lighting loads of 5 W/m<sup>2</sup> with reductions permitted if using ENERGY STAR appliances or a complete unit lighting design is provided.
- Schedules and temperature setpoints in accordance with the National Energy Code for Buildings [68].
- Natural gas fireplace have at minimum a capacity of 10 kW and runs 2 h per week.

The model inputs for the calibrated energy models of the existing buildings varied slightly from the guidelines based on site observations, and calibration to the historical utility data (DHW load per person). Table 1 shows the assumptions used for each building's baseline model.

## 4. Results

### 4.1. Existing building performance

Each team was required to report the TEUI (Total Energy Use Intensity), TEDI (Thermal Energy Demand Intensity), GHGI (Greenhouse Gas Intensity), fuel consumption and, estimated annual energy costs (Table 2). Emission factors of 0.011 kgCO<sub>2</sub>e/kWh for electricity and 0.185 kgCO<sub>2</sub>e/kWh for gas were used from the City of Vancouver Energy Modelling Guidelines. The Crossroads Inn team used different emission factors of 0.0401 kgCO<sub>2</sub>e/kWh for electricity and 0.179 kgCO<sub>2</sub>e/kWh for gas. Teams assumed a range of fuel prices, based on historical rates for their building. Gas prices ranging from \$11.01/GJ to \$14.30/GJ and electricity prices ranging from \$0.1096/kWh and \$0.1474/kWh were used. Fig. 2 contains a breakdown of energy end-uses for each building.

The highest consuming building is Medewiwin. It is an outlier in terms of TEDI with 57.5% more thermal demand than the second-highest building (Crossroads Inn) despite being in the most favourable climate in terms of heating-degree-days. This is not entirely surprising because it has one of the poorest building envelopes alongside the Crossroads Inn. A large percentage of its TEUI (33.2%) came from an inefficient MAU serving corridor spaces. The high thermal demand also contributes to it having the highest natural gas consumption, GHGI and space heating load. The second highest consumption building is the Crossroads Inn. It has the second highest TEDI and TEUI. It is located in the harshest climate of the six buildings which contributes to the higher thermal demand. Its higher TEUI is bolstered by higher cooling, fan, pump and elevator end-usages than the other buildings.

An interesting observation is the differences in modelled base loads (DHW, plug, lighting) between the six buildings. Most buildings had similar lighting and plug loads apart from Dany Guincher and Le Chateau. As noted in Table 1, some of the buildings still rely on incandescent bulbs, while some have converted to more efficient compact fluorescent and LED lamps. This is an obvious target for energy and operational costs reduction with up to 10 to 20 kWh/m<sup>2</sup>/a of annual savings easily achievable. Le Chateau had the highest lighting and plug loads (56.1 kWh/m<sup>2</sup>/a) of the six buildings by a significant margin. These were adjusted as a result of calibration. Dany Guincher has the lowest lighting and plug loads partly because the building is underlit, which was addressed in schematic design.

Domestic hot water EUJ differs by a factor of 2.4 between the lowest (42 kWh/m<sup>2</sup>/a) and highest building (100.8 kWh/m<sup>2</sup>/a). Hot water usage higher than the default rate was found in the Manor House and Le Chateau through calibration of gas utility bills in summer. The lowest DHW usage was in the Crown Manor, partly because the minimum permitted flow rate was used (0.0016 L/s/person) and the building has the lowest occupant density.

### 4.2. Schematic design

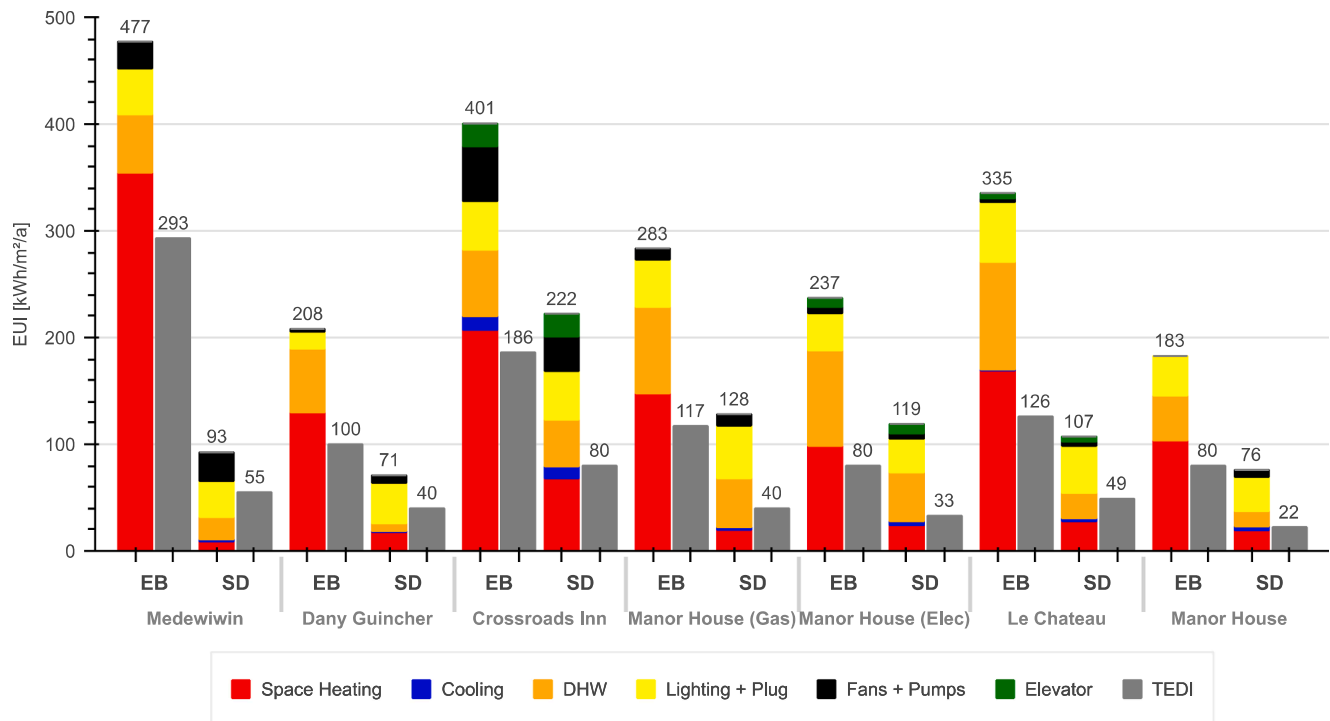
Teams explored various design strategies to achieve each bundle's GHG reduction targets and meet the Reframed design objectives. Improvements to mechanical systems, building envelope, and domestic hot water were all necessary for teams to attain GHG emission reductions of 80% or greater. Fig. 3 shows what systems were recommended for each bundle and how the choice of systems progressed with more stringent targets.

#### 4.2.1. Mechanical systems

The 50% GHG emission reductions as required for design bundle 1, can be achieved with high-efficiency gas boilers, in tandem with building envelope upgrades. This allows for the re-use of the existing heating infrastructure in the building. However, to reach the 80% GHG emission reduction target set for retrofit bundles 2–4, gas boilers were commonly replaced with heat pumps as shown in Fig. 3. Two design teams explored alternatives to heat pumps in their bundles 2–4 – a high

**Table 2**  
Modelled performance of the existing building.

	Medewiwin	Dany Guincher	Crossroads Inn	Manor House (Gas)	Manor House (Elec)	Le Chateau	Crown Manor
TEUI (kWh/m <sup>2</sup> /a)	477	208	401	283	237	335	183
TEDI (kWh/m <sup>2</sup> /a)	293	100	186	117	80	126	80
GHGI (kgCO <sub>2</sub> e/m <sup>2</sup> /a)	72	35	51	43	34	51	27
Electricity Consumption (kWh/m <sup>2</sup> /a)	93	18	105	55	51	66	39
Natural Gas Consumption (kWh/m <sup>2</sup> /a)	384	190	296	229	186	269	153
Annual Energy Cost [\$ /m <sup>2</sup> ]	25.43	10.49	25.09	16.94	14.63	20.22	11.44



**Fig. 2.** Modelled EUI by end-use and TEDI for the existing buildings (EB) and the recommended bundle from the schematic design (SD).

efficiency boiler, as in bundle 1, and an earth tube for conditioning outdoor air along with electric baseboard heaters. It was observed that higher performing building envelopes were needed for these buildings to achieve the GHG targets in comparison to the bundles that opted for heat pumps. Two of the three teams that explored a gas heat pump in bundles 2–4, ended up recommending electric heat pumps. The recommended retrofit design bundles proposed by all teams used heat pumps as their primary heating system with six of the seven teams proposing electric heat pumps and only Manor House Gas proposing a gas-engine heat pump. A noted difference between the heating systems proposed by each design team was whether they used centralized or decentralized (in-unit) heat pumps.

Mechanical cooling was included in most retrofit bundle options, and in all proposed schematic designs. Six of the seven teams chose to deliver cooling through the new heat pumps. The only exception being Crown Manor which had a separate centralized heating system, re-using the existing heating infrastructure, and a decentralized cooling system. In addition to the upgrade HVAC systems, updated unit-level controls (programmable thermostats) were recommended.

All teams recommended decentralized ventilation systems in the units to improve indoor air quality and make-up for the loss of incoming fresh air through infiltration as a result of air sealing. The common recommendation was having a heat or energy recovery ventilator (HRV/ERV) with some integrated with the distributed heat pumps. In addition to the in-unit ventilation, five of the six buildings replaced or improved their make-up air units ventilating common areas to include heating

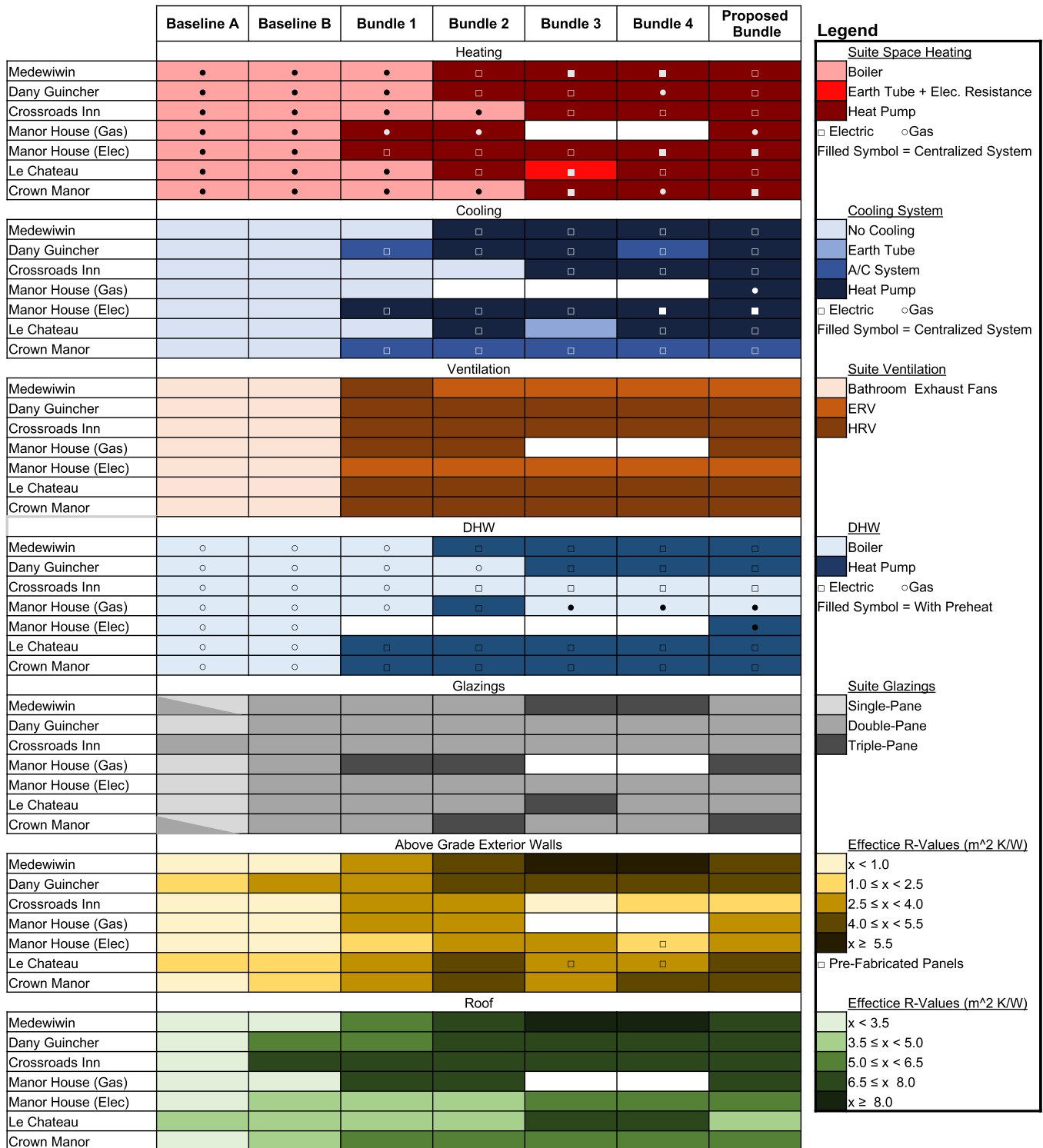
coils to temper the outdoor air.

Similar to the space heating systems proposed in the retrofit bundles, high-efficiency gas boilers were commonly proposed for domestic hot water (DHW) heating for bundle 1 to achieve 50 % GHG emission reductions. Heat pumps were commonly proposed for bundles 2–4 to achieve 80 % GHG emission reductions. Two buildings did not opt for DHW heat pumps. The design team for Crossroads Inn did not explore DHW heat pumps in any of their retrofit bundle options, as it was deemed to add to much cost, maintenance and uncertainty to the building’s operation. The Manor House Elec team did consider a DHW heat pump in one of their retrofit bundles, but recommended retaining the existing high-efficiency gas boiler, which was installed in 2017 (6 years old). It is observed from Fig. 3 that all DHW systems that are fuelled by natural gas equipment also incorporate water preheating in their system.

The addition of photovoltaic panels was considered by three teams, but only recommended by two design teams: Medewiwin and Crown Manor. Concerns over photovoltaics included inadequate structural capacities of roofs, integration with the existing building’s aging electrical system, and low production during the peak winter months.

#### 4.2.2. Envelope

Table 3 shows summarizes the envelope improvements. All seven design teams considered upgrading the exterior walls by re-cladding over the existing cladding and adding exterior insulation. Over-cladding is an established, market-ready approach that can be installed



**Fig. 3.** Proposed solutions for each bundle from least performant (Baseline A on the left) to most performant (Bundle 2–4) on the right. The colour and symbols indicate the system or performance level being proposed (Refer to legend on the right for encoding). The tables indicate a convergence toward specific design solutions. Manor House – Gas was only required to develop 2 bundles.

with minimal intrusiveness to the existing structure and minimal disruption to tenants. Pre-fabricated panels inspired by the Energie-sprong project were considered, but were generally deemed to be a nonviable solution in the current marketplace. This was partly because of the immaturity of the local industry, and difficulty working around the many balconies of some buildings. However, there are plans to proceed with the use of pre-fabricated panels on the Le Chateau

rehabilitation, where the balconies are to be replaced.

Windows and patio doors were typically upgraded to double-pane if the existing glazing was single-pane and/or at the end of their service life. Two of the final schematic design bundles opted for triple-glazed windows, one of which was the design that utilized a gas heat pump for space and DHW heating. Triple-pane windows were necessary to reduce space heating load as much as possible, making 80 % GHG

**Table 3**  
Summary of the envelope upgrades for the recommended schematic design bundles.

	Medewiwin	Dany Guincher	Crossroads Inn	Manor House (Gas)	Manor House (Elec)	Le Chateau	Crown Manor
Wall Effective R-value [m <sup>2</sup> K/W]	5.3	4.4	2.82	2.6	2.5	4.4	4.2
Roof Effective R-value [m <sup>2</sup> K/W]	7.0	7.0	7.0	6.9	5.28	4.4 (No Change)	5.28
Glazing U-value [W/m <sup>2</sup> K]	1.48–2.12	1.55	2.9	1.35	1.48–1.82	1.56 – 1.59	1.05 – 1.61
Glazing SHGC	0.27–0.35	0.38	0.71	0.21	0.30	0.27–0.34	0.30
Infiltration Rate [L/s/m <sup>2</sup> @ 5 Pa]	0.125	0.20	0.1	0.25	0.20	0.25	0.25

emission reductions achievable.

Added wall and roof insulation were considered for all buildings. Above grade wall insulation was improved to an effective R-value of 2.5–5.3 m<sup>2</sup>K/W. Several teams recommended wall insulation with effective R-values slightly below the prescriptive code minimum for new construction of R = 2.78 m<sup>2</sup>K/W in British Columbia. A number of teams considered higher R-values in one of their bundles than what was recommended, but chose thinner insulation because of the diminishing returns relative to increasing capital costs. Effective R-values of retrofitted roofs ranged from 5.3 to 7.0 m<sup>2</sup>K/W. Le Chateau, had a roof renewal three years prior and it was decided to retain its existing roof assembly, while achieving some thermal improvements by improving air tightness at duct penetrations for fireplace exhausts. Modelled infiltration rates are brought down to City of Vancouver's maximum rates for new construction or lower.

#### 4.2.3. Energy and carbon emissions

The energy performance and carbon emissions of the recommended design bundles are shown in Table 4 with a breakdown of EUI end-uses in Fig. 2.

## 5. Discussion

The 80 % GHG reduction target would be met by all buildings except for the Manor House Gas building, which still achieved a significant 70 % reduction. Buildings which went fully electric were able to achieve less than 1 kgCO<sub>2</sub>e/m<sup>2</sup> of emissions. Reductions in TEUI ranged from 45 – 81 % (qualifying as deep retrofit under the traditional definition), and TEDI was reduced by 57–81 %. The greatest reductions were for the Medewiwin building, partly because it had the most inefficient envelope and systems and had more room for improvement. This fits with the median values from the NREL ResStock database for an enhanced enclosure/DHW/Heat pump upgrade [69]. The median savings for a MURB of this vintage in Climate Zone 4 are 67 % for emissions and 66 % for energy. Comparing to British Columbia Step Code's requirements, all recommended bundles except Crossroads Inn would meet the Step 2 requirement of a TEUI < 130 kWh/m<sup>2</sup>/a, and four of the seven would meet the Step 2 requirement of a TEDI < 45 kWh/m<sup>2</sup>/a. The Crown Manor's recommended bundle would achieve Step 3 (TEDI < 120 kWh/m<sup>2</sup>/a and TEDI < 30 kWh/m<sup>2</sup>/a) [61]. For Crossroads Inn to achieve Step 2 a more intensive envelope upgrade would be required to reduce its TEDI, and a reduction in its operating loads (elevator, fans and pumps) would be required to lower its TEUI.

Results of a life cycle carbon analysis found that the embodied

carbon of the retrofit bundles ranged from 25 to 125 kgCO<sub>2</sub>e/m<sup>2</sup> and averaged at approximately 60 kgCO<sub>2</sub>e/m<sup>2</sup>. The substantial reduction in operation emissions outweighed the additional embodied carbon produced from the retrofit. Bundles 1 achieved 40 year lifetime emissions reductions relative to Baseline B of between 39 and 59 %, and Bundles 2 to 4 achieved emissions reductions of between 60 and 87 %. According to a Carbon Leadership Forum database, the embodied carbon of new residential construction averages 314 kgCO<sub>2</sub>/m<sup>2</sup> [70]. When combined with very low operational GHGI, the embodied carbon saved by retrofitting will overcome that of demolition and building anew to the code minimum. The majority of embodied carbon emissions are from envelope improvements. Embodied emissions correlated to TEDI where a bundle with higher embodied carbon would generally result in a lower TEDI.

As Fig. 3 shows, the design teams converged toward common solutions. They are ASHP pumps for space heating and cooling, air to water heat pumps for domestic hot water, HRV/ERVs, adding insulation while overcladding, and double-pane windows. This pre-determined bundle of measures is likely applicable to most low-rise MURBs of this age and construction in ASHRAE climate zones 4 and 5. There were some areas of non-convergence that were often based on factors specific to each building and its owners needs. A common example was the decision of whether to recommend a new distributed or a centralized heating system. This decision was based on a number of factors including whether the existing hydronic system could be re-used, whether there would be space to install distributed heat pumps on the exterior, maintainability, and intrusiveness during construction. Other reasons for divergence were whether an item was recently installed and had not reached the end of its expected service life (Le Chateau roof, Manor House DHW), and the design team's judgment and experience with that type of equipment (Crossroads Inn DHW). It is interesting to note, that all teams recommended adding wall insulation, which is often considered a cost-prohibitive measure. This decision was helped by the fact that (1) claddings were approaching their end-of-life and it is opportunistic to address both it and the poor thermal performance simultaneously, (2) the low thermal resistance of the existing walls offered a greater scope for energy savings, (3) the efficiency gains offered by heat pumps alone were not fully sufficient to overcome the operational costs of switching from gas to more expensive electricity (Discussion in 5.1.2). The viability for adding wall insulation may decrease for newer buildings with claddings in serviceable condition and/or walls with better thermal resistance. The recommended bundles also converged toward market-ready solutions over innovative solutions. This is favoured by the social housing operators who prefer less risk.

**Table 4**  
Energy performance of recommended schematic design bundles. Number in brackets is the reduction relative to the Baseline A – existing conditions.

	Medewiwin	Dany Guincher	Crossroads Inn	Manor House (Gas)	Manor House (Elec)	Le Chateau	Crown Manor
TEUI [kWh/m <sup>2</sup> /a]	93 (–81 %)	70.3 (–66 %)	222 (–45 %)	128 (–55 %)	119 (–50 %)	107 (–68 %)	76 (–58 %)
TEDI [kWh/m <sup>2</sup> /a]	55 (–81 %)	40 (–60 %)	80 (–57 %)	40 (–66 %)	33 (–59 %)	49 (–61 %)	22 (–72 %)
Operational GHGI [kgCO <sub>2</sub> e/m <sup>2</sup> /a]	1 (–99 %)	1 (–97 %)	9 (–82 %)	14 (–67 %)	7 (–79 %)	1 (–98 %)	0.6 (–98 %)
Whole Life Carbon Analysis [40 years kg CO <sub>2</sub> e/m <sup>2</sup> ]	138.7	113.3	480	--	182.1	102	269.9
CEDI [kWh/m <sup>2</sup> ]	7	1	50	7	4	10	12.2
Annual Energy Cost [\$ /m <sup>2</sup> ]	5.02 (–80 %)	9.89 (–6 %)	27.63 (+10 %)	9.96 (–41 %)	12.26 (–16 %)	13.44 (–34 %)	8.00 (–30 %)

Selecting from this default bundle can streamline the schematic design process by removing the need to conduct costly parametric exploration of the design space and redirecting resources elsewhere. These resources could be put towards conducting further investigations of the building, optimization of these measures in design development, or saving the money toward design development and construction. Wider spread adoption of this default bundle could help drive market transformation and increase the network of suppliers and tradespeople to install and maintain these systems. Streamlining can reduce the entry cost of beginning a deep retrofit project, allowing more prospective building owners interested in decarbonizing their buildings to enter the process.

The projected energy, emissions and cost savings need to be confirmed once the retrofit has been implemented. There are plans to perform measurement and verification (M&V) in accordance with the International Performance Measurement and Verification Protocol (IPMVP) for all six buildings once the retrofits have been implemented and operated for 12 months [71]. In addition to operational costs, there are plans to validate the LCCA, and IEQ improvements post-construction.

### 5.1. Life cycle cost analysis

Life cycle cost analyses were performed for each retrofit bundle using National Institute of Standards and Technology (NIST) Handbook 135 procedures [72]. Class C capital cost estimates were provided by all design teams. These were combined with the operational energy and maintenance costs to calculate the NPV of all bundles. Assumptions for

$$NS = (NPV_{bundle,e} + NPV_{bundle,m} + NPV_{bundle,c}) - (NPV_{baseline,e} + NPV_{baseline,m} + NPV_{baseline,c}) \quad (2)$$

$$NS_e = NPV_{bundle,e} - NPV_{baseline,e}$$

the life cycle cost calculations are listed below. The real discount rate and general inflation rate are based on values the local housing providers use in their assessments and deviate from the NIST Handbook 135.

- A real discount rate of 5.00 %
- A general inflation rate of 2.00 %
- 40 year analysis period
- Zero incentives
- Capital costs include contingencies (20–30 %) as estimated by cost consultants.
- Non-energy capital expenditures (structural/seismic, restoring of affected finishes) are included.
- Recurring capital expenditures are included
- Residual values are not included
- No additional revenue from monthly rent increases. Increase revenue from additional units (Crown Manor) are included

Common fuel prices were used for the analysis. Fuel prices were assumed to increase relative to 2022 dollars based on projections based on forecasts from BC Hydro, FortisBC and Canada Energy Regulator [73–75]. Four gas price forecasts analysis were used in the analysis. This include the reference scenario used as the baseline fuel price (+38 % after 40 years), diversified energy scenario (+100 %), and an accelerated electrification scenario (+747 %). Different rate forecasts for electricity were not considered because they do not vary greatly from one another, and therefore did not significantly influence the analysis as much as gas prices. Starting gas prices were based on FortisBC's rate structure for small commercial buildings and baseline electricity prices based on BC Hydro's residential step rates as of August 1, 2022. The

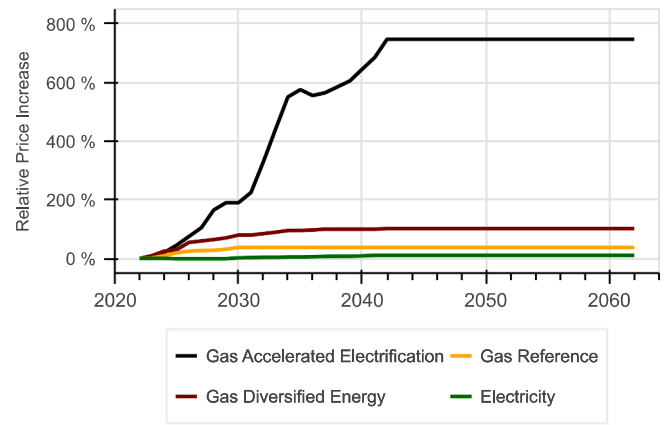


Fig. 4. Fuel price forecasts 2022–2062 relative to 2022 \$CAD.

change in fuel prices are shown in Fig. 4. All forecasts include the federal government's carbon tax.

In the analyses below, the values presented are the net savings (NS) of the bundles relative to the Baseline B – business as usual scenario.

$$NS = NPV_{bundle_n} - NPV_{baseline_B} \quad (1)$$

The net savings calculation can be broken down into its energy (e), maintenance (m), and capital (c) expenditure cost components. The NPVs in the following equations indicate expenses and are all negative.

#### 5.1.1. Baseline analysis

The results of the life cycle costs analysis are presented in Table 5 for the recommended bundle using the reference gas price scenario. The net savings for all recommended options are negative meaning capital expenditure costs outweigh the benefit of reduced energy and maintenance costs over the analysis period, and there isn't a viable payback period from an economic perspective. Normalized net savings of  $-456.6$  to  $-2073$  \$/m<sup>2</sup> and  $-23.7$  k to  $-161$  k \$/unit were calculated. For the project to break even over the 40-year analysis period, an incentive equivalent to the calculated net savings would be required.

Fig. 5 shows the performance improvements in terms of GHGI, TEUI and TEDI as a function of the bundle's NS. There is no definitive statistical correlation between the net savings of all bundles and their performance, the best being an  $R^2 = 0.42$  for GHGI relative to Baseline B. They are all negative correlations, meaning that more ambitious performance targets result in poorer net savings. Many building's data points are clustered together. This is a consequence of many of the bundles having the same performance objectives. The data is sparse, and a parametric examination of the design space, with different performance objectives (eg. net-zero, or smaller retrofit bundles) would help determine if there is a statistical correlation between net savings and performance.

To determine the chance a deep retrofit project will deliver net cost savings, a good starting point would be to calculate the  $NPV_{baseline,e}$ , which is the maximum amount of energy cost savings possible (assuming the building achieves net-zero energy and  $NPV_{bundle,e} = 0$ ). For NS to have a chance of being positive, the life-time capital expenditure ( $NPV_{bundle,c} - NPV_{baseline,c}$ ) can not exceed  $NPV_{baseline,e}$ . All six buildings' initial capital expenditure (not including recurring capital expenses at 15-year intervals) exceeds the life-time energy costs of the

**Table 5**  
Life Cycle Cost Analysis Results – Net Savings (NS) of recommended Bundle vs. Baseline B in 2022 dollars.

	Medewiwin	Dany Guincher	Crossroads Inn	Manor House (Gas)	Manor House (Elec)	Le Chateau	Crown Manor
NS [\$]	−615 k	−456 k	−2088 k	−6660 k	−8074 k	−2214 k	−2276 k
NS [\$/m <sup>2</sup> ]	−456	−775	−1417	−1723	−2073	−938	−922
NS [\$/unit]	−23.7 k	−41.4 k	−40.1 k	−133 k	−161 k	−92.2 k	−81.3 k
NS <sub>capital</sub> [\$]	−1590 k	−487 k	−2028 k	−7191 k	−9270 k	−3255 k	−3309 k
NS <sub>energy</sub> [\$]	713 k	10.6 k	−60.8 k	559 k	166 k	285 k	164 k
NS <sub>maintenance</sub> [\$]	261 k	20.9 k	0	−28.9 k	1029 k	756 k	−24.0 k

baseline building. With the current market conditions, these retrofits will not deliver a desirable payback period without incentives. Having this value in mind from the outset will help building owners budget appropriately for deep retrofits. There are three primary contributors to the poor net savings in this analysis: 1) The low cost of energy, especially natural gas in British Columbia, 2) the high capital costs, and 3) not accounting for externalities, such as improved climate resilience, IEQ, seismic resistance, etc.

### 5.1.2. Fuel prices

All buildings except one (Crossroads Inn) are estimated to save energy costs over the 40 year analysis period, however most of the buildings have savings less than \$5,000/year. The low energy cost savings can be explained by the discrepancy between the price of gas relative to electricity per unit of energy. The base electricity price used in the analysis was initially 3.4 times more expensive than gas, which essentially means you need to save 70.5 % in energy through fuel-switching in combination with other measures to break even financially, and that number does not even consider capital costs. This is an economic barrier to fuel switching. To obtain meaningful cost savings, the building must have poor existing performance with several low-hanging fruit measures to be addressed (Medewiwin), fuel prices need to be higher (closer to those in Europe and other countries), or the price gap between electricity and gas must shrink. Another option for closing the net savings gap would be through on-site generation. Some teams observed that on-site generation through photovoltaics would provide positive net savings in isolation, but upgrades to the roof structure and electrical system upgrades would be cost-prohibitive.

To reinforce the impact of gas prices on net savings, the NPV calculations were performed using the other rate forecasts. Compared to the reference forecast, the NPV<sub>baseline,e</sub> increased by 17.7–22.6 % using the diversified forecast, and by 156–200 % under the accelerated electrification forecast. Fig. 6 shows how near retrofit bundles are to achieving positive net savings. The diversified forecast would not make the NS positive for any buildings, but one building (Medewiwin) would achieve positive NS with both Bundle 1 and its recommended bundle. The next closest to achieve positive NS was the Crossroads Inn, which interestingly had the poorest NS under the reference rate forecast. Crossroads Inn and Medewiwin were the two largest gas consumers, and the higher prices help their retrofits more than lesser consumers. A further observation regarding prices, deep retrofits insulate the financial returns from fluctuations in energy prices and provide more long-term cost certainty. Fig. 6 does not include economic co-benefits such as improvements in GHGI, climate resilience, or indoor environmental quality.

### 5.1.3. Capital expenditure and incentives

The other way to improve the financial viability of these projects is to rein in capital expenditure. It should be noted that the Class C estimates include non-energy related items and contingencies which inflate the initial capital costs. Energiesprong project costs had reduced by over 50 % compared to initial prototypes, with a goal of 70 % [60], and it is hoped that a similar decrease will happen as the Canadian industry scales over time. The question is how much of a decrease would be required to make the retrofits viable?

Under the reference rate forecast, the most viable building (Medewiwin) could break even with a 39 % reduction in capital costs. Some buildings have very low or negative energy savings which makes defining an upper limit on capital costs reduction meaningless (reductions ≈ 100 %). Under the diversified energy rate forecast, a capital cost reduction between 25 and 93 % would be required. Under the accelerated electrification forecast, one building can achieve positive net savings, while the other buildings required between 3 % and 65 % reductions in capital costs. These values are roughly inline with Energiesprong's 70 % goal and could be achievable in the Canadian context.

The NS Gap can be overcome through incentives in the short term, though it would be preferable in the long-term to reduce capital expenditure, through market forces and innovation. Small incentives were obtained for Le Chateau and Crown Manor (< \$200k) and larger incentives for Medewiwin and Manor House (> \$1M). Only Medewiwin's incentive would be enough to close the NS gap entirely.

### 5.2. Overheating risk assessment

Teams completed overheating risk assessments using the City of Vancouver's 20 and 200 h thresholds. Teams were instructed to simulate passive measures (natural ventilation, fixed shading over windows, cool roofs) to see if the buildings could meet the requirements without needing mechanical cooling. In today's climate none of the buildings would be able to achieve the City of Vancouver's stricter 20 h limit for supportive housing, and only two would be able to achieve the general 200 h limit. All teams reached the same conclusion that passive cooling strategies alone were not suitable for maintaining comfortable and safe living conditions for all tenants under this stricter criteria, and mechanical cooling would be required. The findings demonstrated that the addition of mechanical cooling should be expected for buildings of this archetype, and reinforced one of the benefits of recommending heat pump installation, namely a heat pump can supply both heating and cooling.

A more in-depth analysis of the overheating risk assessment could not be made reliably. Estimates ranged from 40 to over 1500 h exceeding the temperature thresholds – a difference of over an order of magnitude which was very concerning. Reasons for this wide range include differences in approaches modelling natural ventilation and operable windows, weather files used, thermal mass of lightweight construction, and how the overheating metric was reported (worst-case unit, average unit, etc.). There was no indoor temperature data available for teams to validate their numbers against. As a result, this made it difficult to form any robust conclusions or observe any trends in the data provided. This highlights the need for standardized reporting methodology if overheating risk assessments are to be a core component of deep retrofit design analysis. Conversely, we can argue that overheating risk assessments are redundant for projects based on the results of this study. Existing MURBs in this region are unlikely to meet the 20 or 200 h criteria now and in the future. Mechanical cooling systems will be necessary to meet this criteria.

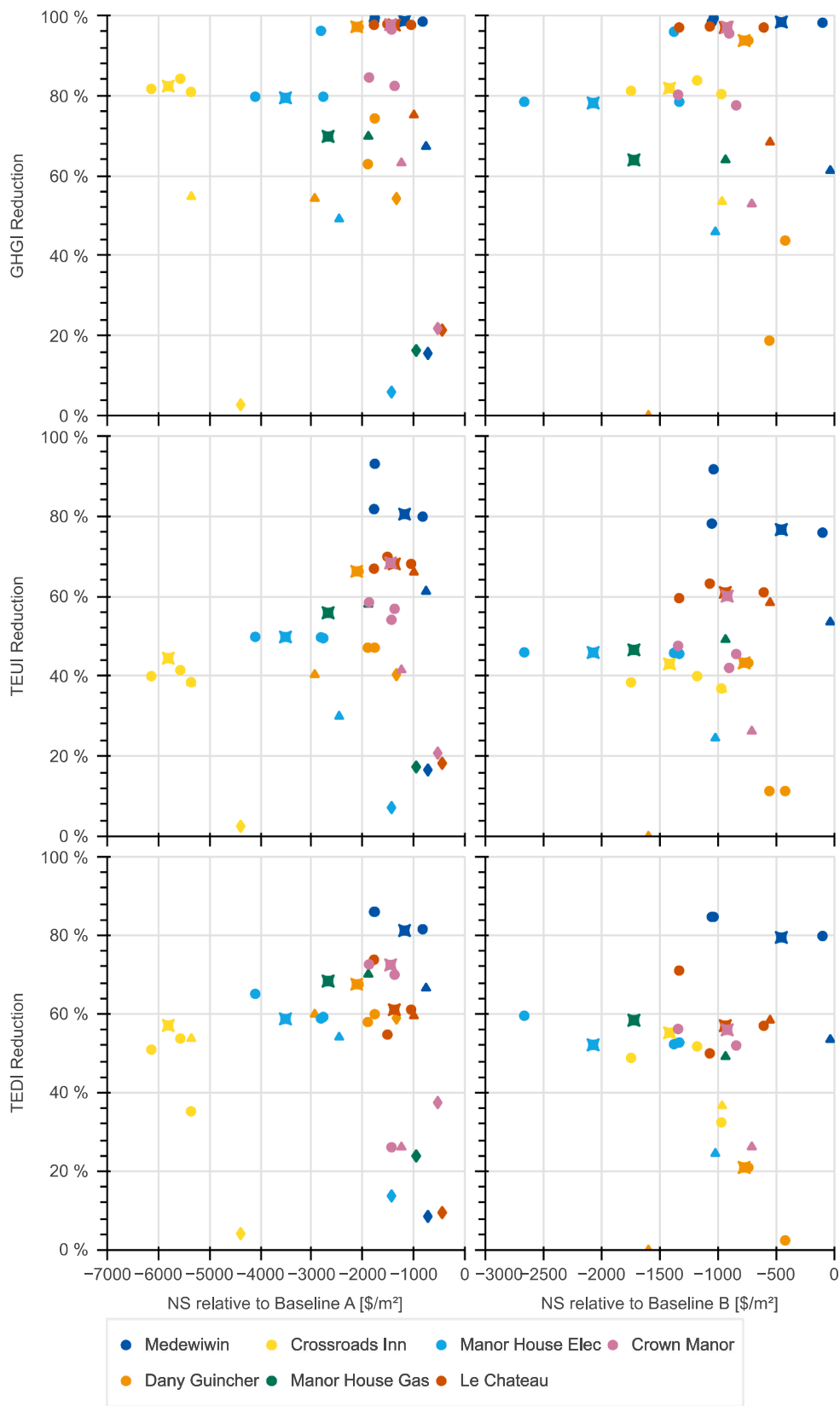
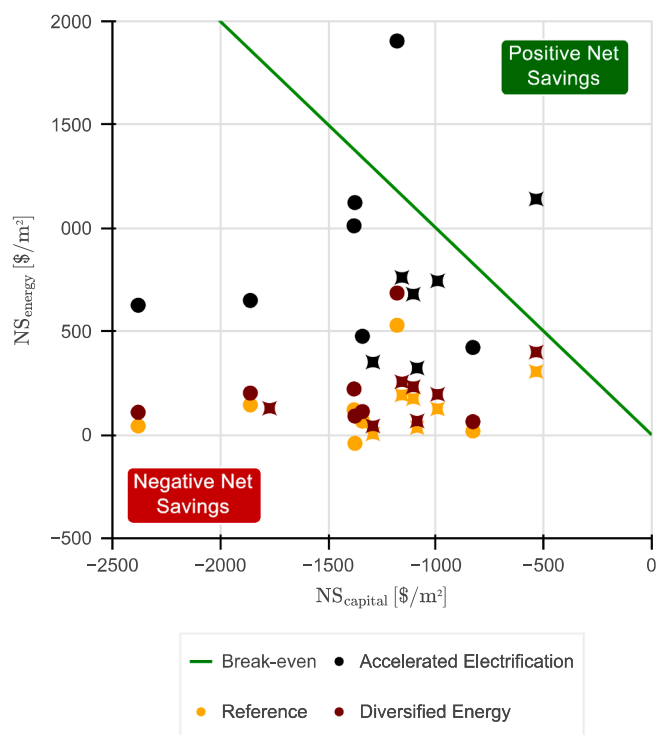


Fig. 5. Performance improvements relative to NS. Diamond markers denote Baseline B, triangle markers denote Bundle 1, circle markers denote Bundle 2-4, and the star markers denote the recommended bundle.



**Fig. 6.** Normalized capital and energy cost savings under different gas price forecasts. Star markers are for Bundle 1 and circle markers are for Bundle 5. Bundles near or above the green line are financially viable. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

## 6. Conclusions

The schematic design for deep retrofits of six existing low-rise MURBs in British Columbia have been completed with the primary goal of reducing operational carbon emissions by 80%. A meta-analysis of the schematic design reports assessing the technical solutions being proposed, performance gains and estimated savings, and a life cycle cost analysis. The key findings of the meta-analysis are:

- a convergence toward common technical solutions which includes a default bundle consisting of electric air source heat pumps for space heating, electric air-to-water heat pumps for DHW in tandem with ventilators, added wall and roof insulation, air sealing, and at minimum double-pane windows
- The recommended bundles are projected to reduce TEUI by 45–81%, and TEDI by 57–81%. All schematic designs achieved the 80% GHGI target, except one which chose to retain gas systems for the space heating and DHW.
- An overheating risk analyses showed that buildings of this archetype would unlikely be able to meet the City of Vancouver's strict overheating criteria and that mechanical cooling would be necessary.
- In the current economic climate, none of the schematic designs would produce positive net cost savings or a desirable payback period for the building owners. Incentives would be required. The relatively low cost of gas in British Columbia is the primary economic barrier to decarbonization via deep retrofits and economic viability would only improve if higher gas price forecasts became reality, or if the capital costs of deep retrofits were to be reduced through market transformation.

The convergence in the solutions found by design teams means the schematic design process can be streamlined by eliminating the need to perform extensive exploration of the design space for each prospective

retrofit. This allows time and resources to be saved or devoted elsewhere. This default bundle identified in these schematic designs can be applied to low-rise MURBs in ASHRAE climate zones 4 and 5 as a starting point, with minor adjustments that account for building-specific factors or owner needs. The streamlining of the schematic design process can reduce time and resources needed to execute a deep retrofit project from beginning to end, and by reducing an entry cost barrier that will allow more prospective building owners to consider deep retrofits. There are long-term plans to continue evaluating the six buildings post-construction. A measure & verification program will ensure that the projected savings and improvements in IEQ are being achieved along with analysis of the as-built bundles and costs. Construction is scheduled to be completed for all six buildings by 2025.

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The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Financial support was provided by Natural Sciences and Engineering Research Council of Canada (Rebuild Initiative) and the Pembina Institute.

## CRediT authorship contribution statement

**Michael Gutland:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Katelyn Munro:** Visualization, Data curation. **Kevin Cant:** Project administration. **Rajeev Kotha:** Project administration, Data curation. **Ralph Evins:** Supervision, Funding acquisition.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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## References

- [1] Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency, (2018).
- [2] Haley, B., & Torrie, R. (2021). *Canada's Climate Retrofit Mission*. Efficiency Canada. <https://www.energycanada.org/wp-content/uploads/2021/06/Retrofit-Mission-FINAL-2021-06-16.pdf>.
- [3] Kennedy, M., & Frappé-Sénéclauze, T.-P. (2021). *Canada's Renovation Wave*. Pembina Institute. <https://www.pembina.org/reports/canadas-renovation-wave.pdf>.
- [4] Hermelink, A., Schimschar, S., Offermann, M., John, A., Reiser, M., Pohl, A., Grözinger, J., Esser, A., Dunne, A., Meeusen, T., Quaschnig, S., & Wegge, D. (2019). *Comprehensive study of building energy renovation activities and the uptake of nearly zero-energy buildings in the EU*. European Commission, Directorate-General for Energy. <https://doi.org/10.2833/14675>.
- [5] *Sectoral GHG Targets Modelling Methodology*. (2021). Government of British Columbia. [https://www2.gov.bc.ca/assets/gov/environment/climate-change/action/cleanbc/bc\\_sectoral\\_ghg\\_targets\\_modelling\\_methodology.pdf](https://www2.gov.bc.ca/assets/gov/environment/climate-change/action/cleanbc/bc_sectoral_ghg_targets_modelling_methodology.pdf).
- [6] *Comprehensive Energy Use Database*. (2020). [dataset]. Natural Resources Canada. [https://oe.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/comprehensive\\_tables/list.cfm](https://oe.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/comprehensive_tables/list.cfm).
- [7] *National Inventory Report 1990–2021: Greenhouse Gas Sources and Sinks In Canada—Part 3*. (2023). Environment and Climate Change Canada.

- [8] A. Zhivov, R. Lohse, What Is Deep Energy Retrofit? in: A. Zhivov, R. Lohse (Eds.), *Deep Energy Retrofit: A Guide to Achieving Significant Energy Use Reduction with Major Renovation Projects* Springer International Publishing, 2020, pp. 5–7, [https://doi.org/10.1007/978-3-030-30679-3\\_2](https://doi.org/10.1007/978-3-030-30679-3_2).
- [9] C. Binkley, M.F. Touchie, K.D. Pressnail, Meta-Analysis of Energy Consumption in Multi-Unit Residential Buildings in the Greater Toronto Area, *Toronto Atmospheric Fund* (2018). [https://taf.ca/custom/uploads/2018/02/University\\_of\\_Toronto\\_Report\\_MURB\\_Energy\\_Performance\\_Analysis\\_GTA\\_2012-06-20.pdf](https://taf.ca/custom/uploads/2018/02/University_of_Toronto_Report_MURB_Energy_Performance_Analysis_GTA_2012-06-20.pdf).
- [10] *Canada's Housing Supply Shortages: Estimating what is needed to solve Canada's housing affordability crisis by 2030.* (2022). Canada Mortgage and Housing Corporation. [https://assets.cmhc-schl.gc.ca/sites/cmhc/professional/housing-markets-data-and-research/housing-research/research-reports/2022/housing-shortages-canada-solving-affordability-crisis-en.pdf?rev=88308aef-f14a-4dbb-b692-6ebbdcd79a0&gl=1\\*ibb6zd\\*ga\\*NzQ0MzU4ODk0LjE2OTYwMDcxNDI.\\*ga\\_Cy7T7RT5C4\\*MTY5NjAwNzE0MjE4LjE2OTYwMDcxNDI.\\*gcl\\_au\\*MzQyNzI4ODk0LjE2OTYwMDcxNDI](https://assets.cmhc-schl.gc.ca/sites/cmhc/professional/housing-markets-data-and-research/housing-research/research-reports/2022/housing-shortages-canada-solving-affordability-crisis-en.pdf?rev=88308aef-f14a-4dbb-b692-6ebbdcd79a0&gl=1*ibb6zd*ga*NzQ0MzU4ODk0LjE2OTYwMDcxNDI.*ga_Cy7T7RT5C4*MTY5NjAwNzE0MjE4LjE2OTYwMDcxNDI.*gcl_au*MzQyNzI4ODk0LjE2OTYwMDcxNDI).
- [11] E. Fraser, I. Rockwell, N. Hamid, S. Menon, N. Paliwal, Acquisition and Preservation of Affordable Rental Housing in Canada, *McGill University* (2022). [https://www.mcgill.ca/maxbellschool/files/maxbellschool/3\\_cmhc.pdf](https://www.mcgill.ca/maxbellschool/files/maxbellschool/3_cmhc.pdf).
- [12] Tsenkova, S. (2023). Perspective Chapter: Reimagining Affordable Housing through Adaptive Reuse of Built Heritage. In Prof. Alessandra Battisti (Ed.), *Future Housing* (p. Ch. 7). IntechOpen. <https://doi.org/10.5772/intechopen.110072>.
- [13] *EnerGuide Rating System—Standard Version 15.* (2015). Natural Resources Canada.
- [14] *Deep Building Enclosure Energy Retrofit Study – Final Report.* (2017). RDH Building Science. <https://www.bchousing.org/sites/default/files/rcg-documents/2022-04/Deep-Building-Enclosure-Energy-Retrofit-Study.pdf>.
- [15] Aldrich, R., & Williamson, J. (2014). *Conway Street Apartments: A Multifamily Deep Energy Retrofit.* Consortium for Advanced Residential Buildings. <https://www.nrel.gov/docs/fy15osti/63159.pdf>.
- [16] *Retrofitting Arleta Manor: A TowerWise Case Study.* (2019). The Atmospheric Fund. <https://taf.ca/custom/uploads/2019/09/Retrofitting-Arleta-Manor-September-2019.pdf>.
- [17] *Sundance Housing Cooperative: Creating a Sustainable Future.* (2019). <https://sundancecoop.org/sundance-retrofit-project/>.
- [18] Lohse, R., Mørck, O. C., & Zhivov, A. (Eds.). (2023). *Deep Energy Retrofit—Case Studies: Business and Technical Concepts for Deep Energy Retrofit of Public Buildings; Energy in Buildings and Communities Programme; Annex 61, Subtask A.* Springer International Publishing. <https://doi.org/10.1007/978-3-031-17517-6>.
- [19] *Creating a market for net zero multi-storey buildings.* (2023). Energiesprong Global Alliance. <https://energiesprong.org/creating-a-market-for-net-zero-multi-storey-buildings/>.
- [20] B. Agar, Barriers to deep retrofits: Regulatory solutions from across Canada, *Pembina Institute* (2020). <https://www.pembina.org/pub/regulatory-retrofit-solutions>.
- [21] A. Zhivov, R. Lohse, J. Shonder, C. Nasser, H. Staller, O. Moerck, M. Nokkala, Business and technical concepts for deep energy retrofit of public buildings, *ASHRAE Transactions* 121 (2) (2015) 111–129.
- [22] Calder, D. (2020). *The Case for Deep Retrofits.* The Atmospheric Fund. <https://taf.ca/publications/the-case-for-deep-retrofits/>.
- [23] *Decarbonizing Canada's Large Buildings: Summary Report.* (2021). Canada Green Building Council. [https://portal.cagbc.org/cagbcdocs/advocacy/2021\\_CaGBC\\_Decarbonization-Retrofit-Costing-Study\\_2DEC21\\_EN.pdf](https://portal.cagbc.org/cagbcdocs/advocacy/2021_CaGBC_Decarbonization-Retrofit-Costing-Study_2DEC21_EN.pdf).
- [24] J.F. Azcarate-Aguerre, M. Conci, M. Zils, P. Hopkinson, T. Klein, Building energy retrofit-as-a-service: A Total Value of Ownership assessment methodology to support whole life-cycle building circularity and decarbonisation, *Construction Management and Economics* 40 (9) (2022) 676–689, <https://doi.org/10.1080/01446193.2022.2094434>.
- [25] R. Cluett, J. Amann, S. Ou, Building Better Energy Efficiency Programs for Low-Income Households (A1601), *American Council for an Energy-Efficient Economy* (2016). <https://www.aceee.org/research-report/a1601>.
- [26] M.A. Brown, A. Soni, M.V. Lapsa, K. Southworth, M. Cox, High energy burden and low-income energy affordability: Conclusions from a literature review, *Progress in Energy* 2 (4) (2020) 042003, <https://doi.org/10.1088/2516-1083/abb954>.
- [27] A. Dreihobl, L. Ross, R. Ayala, How high are household energy burdens? *American Council for an Energy-Efficient Economy* (2020). <https://www.aceee.org/research-report/u2006>.
- [28] L. Tozer, H. MacRae, E. Smit, Achieving deep-energy retrofits for households in energy poverty, *Buildings and Cities* 4 (1) (2023), <https://doi.org/10.5334/bc.304>.
- [29] Less, B., & Walker, I. (2014). *A Meta-Analysis of Single-Family Deep Energy Retrofit Performance in the U.S.* Environmental Energy Technologies Division - Lawrence Berkeley National Laboratory. <https://eta-publications.lbl.gov/sites/default/files/a-meta-analysis.pdf>.
- [30] *Capital project: Retrofit of sustainable affordable housing.* (2023). Federation of Canadian Municipalities - Green Municipal Fund. <https://greenmunicipalfund.ca/funding/capital-project-retrofit-sustainable-affordable-housing>.
- [31] *CleanBC Building Innovation Fund.* (2021). CleanBC. <https://www2.gov.bc.ca/gov/content/industry/electricity-alternative-energy/energy-efficiency-conservation/programs/cleanbc-building-innovation-fund>.
- [32] *CleanBC Social Housing Incentives.* (2023). CleanBC. <https://www.betterbuildingsbc.ca/incentives/cleanbc-social-housing-incentives/>.
- [33] *Deep Retrofit Accelerator Initiative.* (2023). Natural Resources Canada. <https://natural-resources.canada.ca/energy-efficiency/buildings/deep-retrofit-accelerator-initiative/24925>.
- [34] *Energy Efficiency Retrofit Program.* (2021). BC Housing. <https://www.bchousing.org/projects-partners/asset-management-redevelopment/energy-efficiency-retrofit-program>.
- [35] *Pre-Retrofit Funding for multi-unit residential buildings.* (2023). Canada Mortgage and Housing Corporation. <https://www.cmhc-schl.gc.ca/professionals/project-funding-and-mortgage-financing/funding-programs/all-funding-programs/canada-greener-affordable-housing-program/pre-retrofit-funding>.
- [36] *Preservation Funding for community housing.* (2023). Canada Mortgage and Housing Corporation. <https://www.cmhc-schl.gc.ca/professionals/project-funding-and-mortgage-financing/funding-programs/all-funding-programs/preservation-funding>.
- [37] S. Bucking, M. Rostami, J. Reinhart, M. St-Jacques, On modelling of resiliency events using building performance simulation: A multi-objective approach, *Journal of Building Performance Simulation* 15 (3) (2022) 307–322, <https://doi.org/10.1080/19401493.2022.2044906>.
- [38] M.S. Zuraimi, Z. Tan, Impact of residential building regulations on reducing indoor exposures to outdoor PM 2.5 in Toronto, *Building and Environment* 89 (2015) 336–344, <https://doi.org/10.1016/j.buildenv.2015.03.010>.
- [39] E. Diaz Lozano Patiño, D. Vakalis, M. Touchie, E. Tzekova, J.A. Siegel, Thermal comfort in multi-unit social housing buildings, *Building and Environment* 144 (2018) 230–237, <https://doi.org/10.1016/j.buildenv.2018.08.024>.
- [40] *Pre-and Post-retrofit Survey Analysis.* (2018). The Atmospheric Fund. <https://taf.ca/custom/uploads/2018/07/Pre-and-Post-Retrofit-Survey-Analysis-July-2018.pdf>.
- [41] *Extreme Heat and Buildings: An Analysis of the 2021 Heat Dome Related Deaths in Community Housing in British Columbia.* (2022). BC Housing. <https://www.bchousing.org/sites/default/files/media/documents/Extreme-Heat-Report%2B2022.pdf>.
- [42] *Extreme Heat and Human Mortality: A Review of Heat-Related Deaths in B.C. in Summer 2021.* (2022). British Columbia Coroners Service. [https://www2.gov.bc.ca/assets/gov/birth-adoption-death-marriage-and-divorce/deaths/coroners-service/death-review-panel/extreme\\_heat\\_death\\_review\\_panel\\_report.pdf](https://www2.gov.bc.ca/assets/gov/birth-adoption-death-marriage-and-divorce/deaths/coroners-service/death-review-panel/extreme_heat_death_review_panel_report.pdf).
- [43] M. Quick, M. Tjepkema, The prevalence of household air conditioning in Canada, *Health Reports* 34 (7) (2023) 19–26, <https://doi.org/10.25318/82-003-x202300700002-eng>.
- [44] Laouadi, A., Bartko, M., Gaur, A., & Lacasse, M. (2022). *Climate Resilience Buildings: Guideline for management of overheating risk in residential buildings* (CRBCPI-Y4-10). National Research Council Canada.
- [45] A By-law to amend Building By-law No. 12511 regarding carbon emissions, air filtration, and embodied carbon limits, *City of Vancouver Building By-law No.13345* (2022).
- [46] *Ashrae, ASHRAE Guideline 55–2020—Thermal Environmental Conditions for Human Occupancy, American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2020.*
- [47] Á. Broderick, M. Byrne, S. Armstrong, J. Sheahan, A.M. Coggins, A pre and post evaluation of indoor air quality, ventilation, and thermal comfort in retrofitted cooperative social housing, *Building and Environment* 122 (2017) 126–133, <https://doi.org/10.1016/j.buildenv.2017.05.020>.
- [48] C. Gabel, G. Elholm, M.K. Rasmussen, T.H. Broholt, S.R. Jensen, S. Petersen, T. Sigsgaard, The HOME-Health (HOUSing, environMent, and Health) Study; Description of a Danish natural experiment, designed as a longitudinal study with repeated measurements, providing internal- and external validity of the study, 11786302231181489, *Environmental Health Insights* 17 (2023), <https://doi.org/10.1177/11786302231181489>.
- [49] U. Haverinen-Shaughnessy, M. Pekkonen, V. Leivo, T. Prasauskas, M. Turunen, M. Kivistä, A. Aaltonen, D. Martuzevicius, Occupant satisfaction with indoor environmental quality and health after energy retrofits of multi-family buildings: Results from INSULAtE-project, *International Journal of Hygiene and Environmental Health* 221 (6) (2018) 921–928, <https://doi.org/10.1016/j.ijheh.2018.05.009>.
- [50] E.M. Wells, M. Berges, M. Metcalf, A. Kinsella, K. Foreman, D.G. Dearborn, S. Greenberg, Indoor air quality and occupant comfort in homes with deep versus conventional energy efficiency renovations, *Building and Environment* 93 (2015) 331–338, <https://doi.org/10.1016/j.buildenv.2015.06.021>.
- [51] *Canadian Interagency Forest Fire Centre.* (2023). Fire Statistics. <https://ciffc.net/statistics>.
- [52] M. Mazzucato, Mission-oriented innovation policies: Challenges and opportunities, *Industrial and Corporate Change* 27 (5) (2018) 803–815, <https://doi.org/10.1093/icc/dty034>.
- [53] *Energiesprong (Energy Leap) (Policy Measure Fact Sheet).* (2017). European Constructor Sector Observatory.
- [54] D. Brown, Business models for residential retrofit in the UK: A critical assessment of five key archetypes, *Energy Efficiency* 11 (6) (2018) 1497–1517, <https://doi.org/10.1007/s12053-018-9629-5>.
- [55] D. Brown, P. Kivimaa, S. Sorrell, An energy leap? Business model innovation and intermediation in the 'Energiesprong' retrofit initiative, *Energy Research & Social Science* 58 (2019) 101253, <https://doi.org/10.1016/j.erss.2019.101253>.
- [56] M. Carver, B. Conley, J. Armstrong, *Enclosure Design of a Prefabricated Net-Zero Energy Townhouse Retrofit, Science and Technology, Toronto, 2022.*
- [57] *ReCover.* (2023). <https://www.recoverinitiative.ca/our-story>.
- [58] *Reframed Lab.* (2023). <https://reframedinitiative.org/lab/>.
- [59] *Retrofit Accelerator.* (2023, September). <https://taf.ca/programs/retrofitaccelerator/>.
- [60] *Energiesprong: A Dutch Approach to Deep EnergyRetrofits and Its Applicability to the New York Market* (18–10). (2018). New York State Energy Research and Development Authority. <https://www.nyserda.ny.gov/All-Programs/RetrofitNY-Program/Resources-and-Reports>.
- [61] *British Columbia Building Code 2018.* (2018). National Research Council of Canada.
- [62] A.J. Cannon, S.R. Sobie, T.Q. Murdock, Bias Correction of GCM Precipitation by Quantile Mapping: How Well Do Methods Preserve Changes in Quantiles and

- Extremes? *Journal of Climate* 28 (17) (2015) 6938–6959, <https://doi.org/10.1175/JCLI-D-14-00754.1>.
- [63] *ClimateData.ca*. (2023). [dataset]. <https://climatedata.ca/>.
- [64] L. Ricketts, J.F. Straube, Corridor Pressurization System Performance in Multi-Unit Residential Buildings, *ASHRAE Transaction* 120 (2014). <https://scholar.google.com/scholar?oi=bibs&cluster=15070258699880824850&btnI=1&hl=en>.
- [65] Ashrae, ASHRAE Guideline 14–2014—Measurement of Energy, Demand, and Water Savings, *American Society of Heating, Refrigerating and Air-Conditioning Engineers*, 2014.
- [66] *Energy Modelling Guidelines Version 2.0*. (2018). City of Vancouver Planning, Urban Design and Sustainability Department.
- [67] Morrison Hershfield Ltd. (2020). *Building Envelope Thermal Bridging Guide* (1.4). B. C. Hydro. <https://www.bchydro.com/content/dam/BCHydro/customer-portal/documents/power-smart/business/programs/BETB-Building-Envelope-Thermal-Bridging-Guide-v1-4.pdf>.
- [68] *National Energy Code of Canada for Buildings 2020*. (2020). National Research Council of Canada.
- [69] J. Brossman, L. Lixi, B. Polly, E. Present, J. Irwin, *State Level Residential Building Stock and Energy Efficiency & Electrification Package Analysis* [Tableau Dashboard], National Renewable Energy Laboratory (2023). <https://public.tableau.com/app/profile/nrel.buildingstock/viz/StateLevelResidentialBuildingStockandEnergyEfficiencyElectrificationPackagesAnalysis/Introduction>.
- [70] Simonen, K., Rodriguez, B., Barrera, S., & Huang, M. (2017). *CLF Embodied Carbon Benchmark Database* [dataset]. <https://digital.lib.washington.edu/researchworks/handle/1773/38017>.
- [71] *International Performance Measurement and Verification Protocol—Core Concepts* (EVO 10000-1:2022). (2022). Efficiency Valuation Organization.
- [72] J. Kneifel, D. Webb, *NIST Handbook 135: Life Cycle Costing Manual for the Federal Energy Management Program* (2022 Edition), National Institute of Standards and Technology, 2022.
- [73] British Columbia Hydro and Power Authority (BC Hydro), and FortisBC Energy Inc. (FEI) Energy Scenarios—FEI Supporting Commentary Regarding the Supply Resource Impacts, Rate Impacts and Associated GHG Emission Impacts. (2022). Fortis BC. [https://docs.bcuc.com/Documents/Proceedings/2022/DOC\\_67461\\_2022-08-12-FEI-Stage2-Submission.pdf](https://docs.bcuc.com/Documents/Proceedings/2022/DOC_67461_2022-08-12-FEI-Stage2-Submission.pdf).
- [74] *Canada's Energy Future 2021 Data Appendices*. (2021). Canada Energy Regulator. <https://apps.cer-rec.gc.ca/ftppndc/dflt.aspx?GoCTemplateCulture=en-CA>.
- [75] *FortisBC Energy Inc. And BC Hydro Energy Scenarios—Stage Two*. (2022). BC Hydro. [https://docs.bcuc.com/Documents/Proceedings/2022/DOC\\_67462\\_B-14-BCH-Stage2-Submission.pdf](https://docs.bcuc.com/Documents/Proceedings/2022/DOC_67462_B-14-BCH-Stage2-Submission.pdf).