HVAC ENERGY EFFICIENCY AND INDOOR AIR QUALITY IN HEALTH CARE FACILITIES

Vancouver Coastal Health Case Studies

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Nomenclature

ach	air changes per hour
AHU	air handling unit
AQO	air quality objective
AQG	air quality guidelines
ASHRAE	the American Society of Heating, Refrigerating and Air-Conditioning Engineers
ATACH	the Alliance for Transformative Action on Climate and Health
BCCDC	British Columbia Centre for Disease Control
BCS	building control system
BRP	Building Readiness Plan
CAAQS	Canadian Ambient Air Quality Standards
CFD	computational fluid dynamics
CO_2	carbon dioxide
COP26	the 26th UN Climate Change Conference in Glasgow
CSA	Canadian Standards Association
DCV	demand controlled ventilation
DDC	direct digital control
DV	displacement ventilation
DX	direct expansion
EES	Energy and Environmental Sustainability
EGG	air quality egg sensor
EPA	United States Environmental Protection Agency
EUI	energy use intensity
FMO	facilities maintenance & operations staff
GHG	greenhouse gas
GWP	global warming potential
HEPA	high efficiency particulate air [filter]
HVAC	heating, ventilation, and air conditioning
I/O ratio	indoor to outdoor concentration ratio of target pollutant
IAQ	indoor air quality

IESVE	IES Virtual Environment
IPCC	Intergovernmental Panel on Climate Change
IRMM	infection risk management mode
LCR	Long-term care residence
MERV	minimum efficiency reporting value according to ASHRAE Standard 52.2
MERV-A #-A	minimum efficiency reporting value according to ASHRAE Standard 52.2 Appendix J, where # represents the numeric value from Table J-2
MHC	mental health centre
MV	mixing ventilation
NAAQS	National Ambient Air Quality Standards
NEMA	National Electrical Manufacturers Association
NFD	National Forestry Database
O_3	ozone
PCIC	Pacific Climate Impacts Consortium
PM	particulate matter
PM_{10}	inhalable particles, with diameters that are generally 10 micrometres and smaller
$PM_{2.5}$	fine inhalable particles, with diameters that are generally 2.5 micrometres and smaller
RC	Rehabilitation centre
RCPs	Representative Concentration Pathways
RH	relative humidity
RTU	packaged rooftop units
SV	stratum ventilation
UW	University of Washington
VAV	variable air volume
VCH	Vancouver Coastal Health
VOC	volatile organic compound
VSD	variable speed drive
WHO	World Health Organization

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Executive Summary

Vancouver Coastal Health (VCH) delivers health care services to over 1.25 million residents (25% of the province's population), with many facilities located in the Lower Mainland region and seven other sites outside of the Lower Mainland. As a health care provider, VCH is obligated to deliver the best care possible for patients. As the employer, VCH is responsible for safeguarding the well-being of employees. As a large energy consumer, VCH also has the duty to do its share to reach the goals of the Paris Agreement. These missions are aligned with the core value of health care, which is to "do no harm." It means no harm to patients, to employees, and to the global population who suffer from the climate crisis. The objective of this project is to collect current best practices for HVAC system operation and indoor air quality (IAQ) improvement through literature reviews and site visits. Information gathered by the project could add to the organizational knowledge and facilitate the accomplishment of VCH's missions.

Health care facilities are heavily regulated to ensure their proper operation. For HVAC systems, ASHRAE Standard 170 and CSA Z317.2:19 are the most commonly used standards by regulatory bodies in North America. Although the two standards share a common goal, there are differences in the requirements. The ASHRAE and CSA standards both require a minimum of 2 ach outdoor air change rate for many space types. However, the CSA standard is more stringent and requires a higher minimum total air change rate than ASHRAE. The CSA standard requires two-stage filtration of at least a combination of MERV-8 and MERV-13 filters, and the filters are required to have the same MERV-A rating as well to minimize degradation. In comparison, the ASHRAE standard only requires a single MERV-8 filter for the same spaces, and there is no explicit requirement for MERV-A rating in the main body of the standard. The recent pandemic and extreme weather conditions, such as heat waves and wildfire smoke episodes, have prompted the creation of more guidelines and standards to aid building managers in responding to these events. During the course of the project, ASHRAE published the Standard 241 "Control of Infectious Aerosols" on July 7, 2023, to offer guidance on building operations during public health emergencies. On August 18, 2023, ASHRAE published the draft of Guideline 44 "Protecting Building Occupants from Smoke During Wildfire and Prescribed Burn Events" for full public review. It is anticipated that these standards will be incorporated or referenced in codes and regulations. A review of these standards, case studies, and other literature offered valuable insights into how the HVAC operation could be improved at the selected sites.

Three site visits were conducted to document the current operation of the HVAC system and existing issues. The information gathered through observations and discussions with facility managers was compiled and checked against standards to reveal any shortcomings. Indoor air quality is another focus of this project, with $PM_{2.5}$ being the target pollutant. The health effects and regulations of $PM_{2.5}$ were thoroughly reviewed. Evaluation of the $PM_{2.5}$ levels at each site relied on sensors installed for a previous research project. By following established energy retrofit frameworks and consolidating the findings, recommendations were formed that could be beneficial for the selected sites as well as for other assets in the VCH building portfolio. Figure 1 shows a summary of the recommendations. People should be the focus in long-term planning. The end goal of the organization should be to operate a set of smart buildings that could interact with people, i.e., employees, patients, and visitors, and respond to the demands in an energy-efficient manner. The engineering and technology-related retrofits could be achieved in the short term and prepare the building for the establishment of a holistic occupant feedback system that not only protects the well-being of the people but also “does no harm” to the environment.

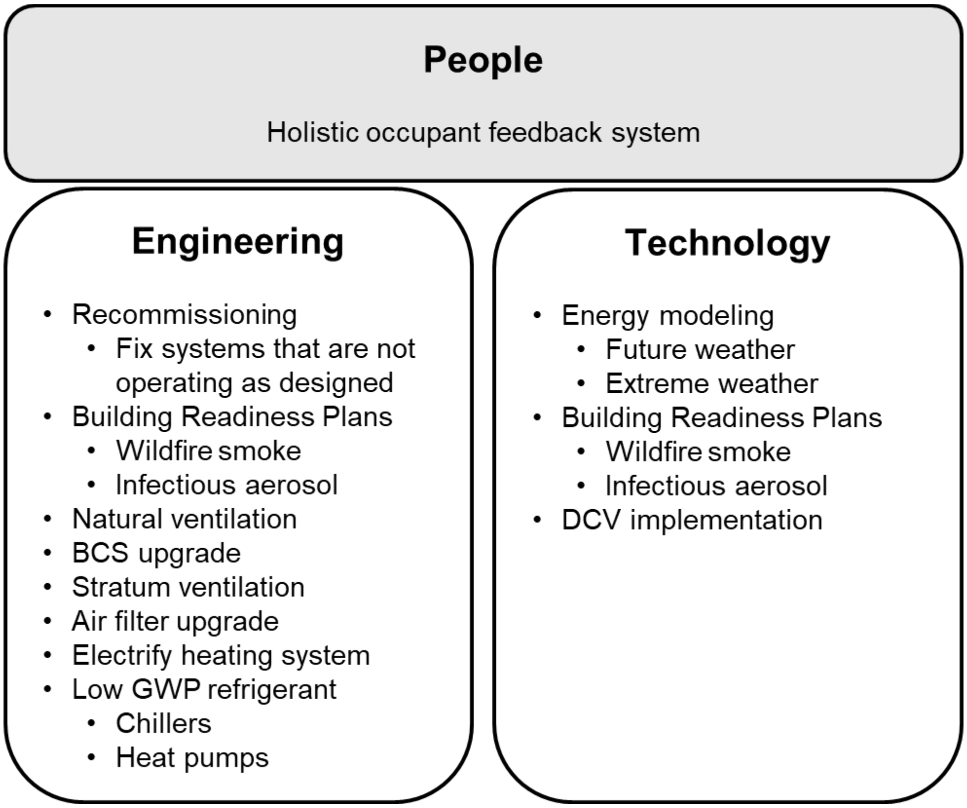

Figure 1. Retrofit recommendations summarized in three categories.

1 Introduction

In the global effort to combat climate change, the health care sector is recognized as a significant contributor to carbon pollution, accounting for 5.2% of global emissions (Bhopal & Norheim, 2023). The COP26 Health Programme was established to deliver two key initiatives, i.e., to develop 1) climate resilient and 2) low carbon health care systems (WHO, 2023a). The Alliance for Transformative Action on Climate Change and Health (ATACH) was formed to provide a platform for achieving the two initiatives. As a member state of the World Health Organization (WHO), Canada has joined ATACH and formally committed to building a climate resilient and low carbon health care sector (WHO, 2023b). However, no commitment has been made to achieve net zero in health care by a specific target year (WHO, 2023b). Although the challenges associated with these commitments seem daunting, Boyd et al. (2021) argued that "at the core of health care is the duty of care and to do no harm" and "health care has a moral imperative to find ways to heal patients without sickening others in our communities and in future generations." In addition, climate-related actions could provide many business benefits for health care organizations that would result in high-quality and cost-effective service for all stakeholders (Boyd et al., 2021). To honour the nation's commitment to ATACH, and eventually reach the net zero target, the Canadian Medical Association proposed nine strategies as follows (CMA, 2023), and strategies 4, 8 and 9 are of particular interest to this report:

1. Expand virtual care.
2. Create a robust primary health care system to alleviate pressure on hospitals.
3. Support healthy living, including addressing the determinants of health and encouraging healthy eating and active living.
4. Use energy efficiently, shifting to renewable energy sources and reducing the need for fossil-fueled generators in hospitals.
5. Practice sustainable prescribing, including reusable packaging when appropriate.
6. Focus on community care to ensure health promotion and disease prevention, especially in rural and remote communities.
7. Reduce waste through recycling and medical device reprocessing programs.
8. Prepare for future climate emergencies with training and preparedness plans.
9. Implement climate-resilient infrastructure, such as flood doors and improved ventilation.

Buildings are responsible for 40% of the global energy consumption and one-third of the global greenhouse gas (GHG) emissions (IEA, 2021). A net zero future heavily depends on the energy and emission reduction of all new and existing buildings. The Survey of Commercial and Institutional Energy Use conducted by Statistics Canada in partnership with Natural Resources Canada has shown that hospital campuses have one of the highest average energy use intensities among the surveyed building types, only second to restaurants (Statistics Canada, 2022a, 2022b). The survey data showed that, across Canadian provinces, hospital campuses had an average energy use intensity (EUI) of 2.54 GJ/m^2 compared to commercial and institutional buildings' 1.31 GJ/m^2. In BC, the most recent data from the building benchmarking program showed similar patterns (see Figure 2), where health care related facilities as a group, i.e. General & Surgical Hospital, Specialty Hospital, Long Term Care Home, Medical Office, and Urgent Care Clinic, produced the highest GHG emissions (Ramslie & Eden, 2023).

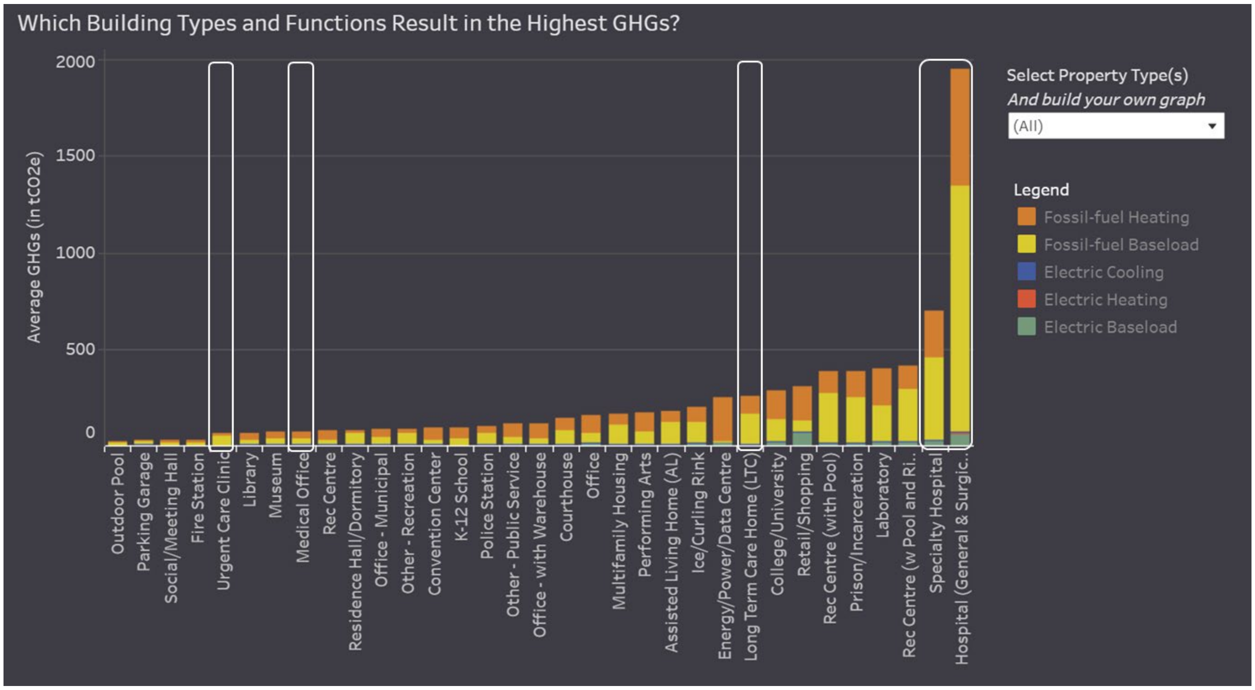

Figure 2. GHG emissions of different building types enrolled in Building Benchmark BC. Health care related building types are marked by white boxes. The figure is adapted from Ramslie and Eden (2023).

As we experience the increased occurrence of unusual weather events, the end-use energy demand in BC is expected to continue rising in the foreseeable future across all industries. Figure 3 shows the projected total energy end-use demand and electricity end-use demand through 2050 (Canada Energy Regulator, 2023a) based on the Canada net-zero scenario (Canada Energy Regulator, 2023b). The total demand will incur a 13% increase by 2050 compared to 2023, and the electricity demand will more than double the 2023 level.

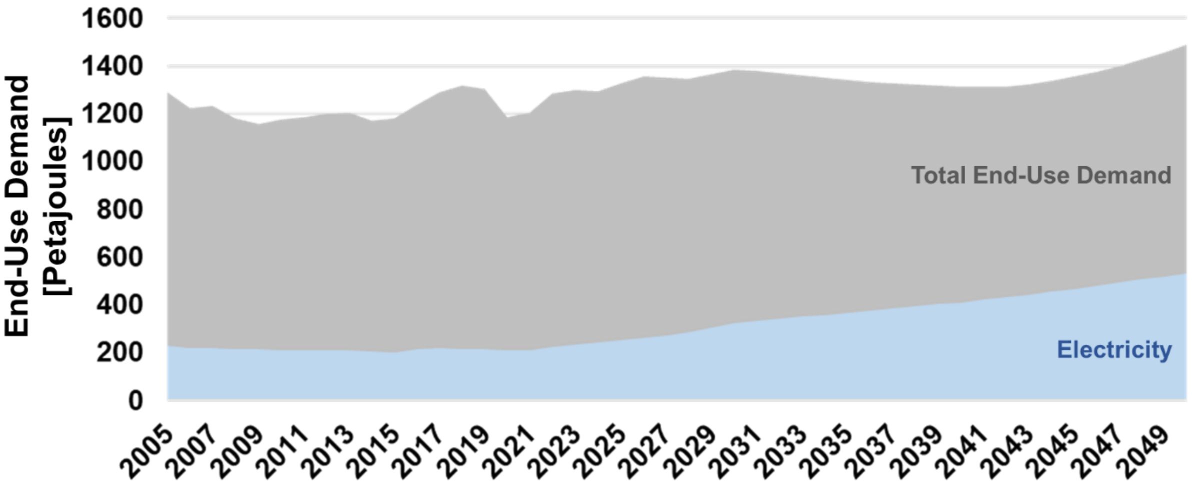

Figure 3. Energy end-use demand projections to 2050, including total demand and electricity demand.

VCH delivers health care services to over 1.25 million residents (25% of the province's population), with many facilities located in the Lower Mainland region and seven other sites outside of the Lower Mainland. The total energy use of VCH has remained steady since 2007, averaging 328 eGWh per year as shown in Figure 4 (Jones, 2023; Vancouver Coastal Health, 2022). A small increase could be observed in 2022 due to the addition of new facilities. However, VCH has managed to reduce energy-use intensities while increasing the organization's total building footprint, largely because of the reduced use of fossil fuels. As shown in Figure 4, the electricity-use intensity has remained unchanged compared to fossil fuel.

Recent extreme heat events in 2021 and 2022 in the Pacific Northwest have tested the electrical grids in the region to their limits. Anticipating the incoming extreme heat in the summer of 2021, BC Hydro issued a release assuring customers that the grid has enough capacity to meet the additional demand (BC Hydro, 2021). Nevertheless, during the weekend following the release, hundreds of residents in the Lower Mainland region experienced power outages due to blown transformers caused by extreme heat (Nesbit, 2021). South of the border, the Seattle region also experienced similar heat waves. In July 2022, the high temperature led to the failure of a splice connecting the University of Washington (UW) campus utilities to the Seattle City Light power grid (Rule, 2022). As a result, two-thirds of the chilled water capacity on campus was lost for two hours, leaving many buildings without air conditioning. In preparing for the upcoming heat wave in August 2023, the Seattle City Light has requested the UW campus to reduce its power usage, which resulted in power outages in 12 campus buildings and curtailed cooling for most of the other campus buildings. Considering that most of the campus buildings have recovered to pre-pandemic occupancy level, the impact on occupants' health and well-being will be more profound compared to 2022.

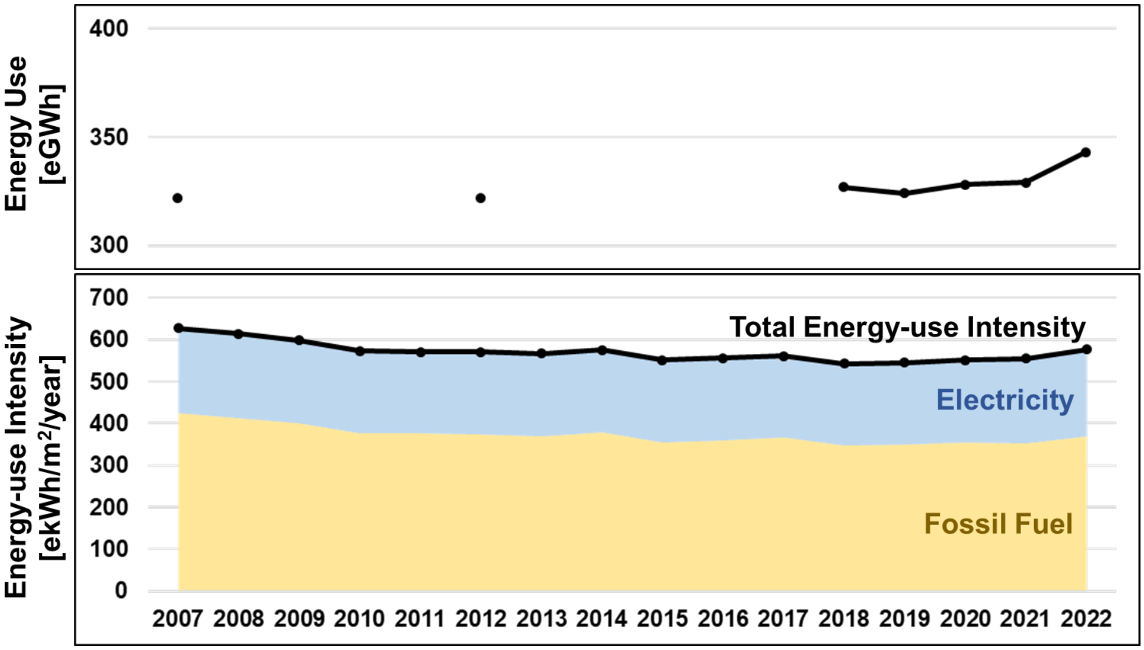

Figure 4. VCH total energy use and energy-use intensity from 2007 to 2022.

Climate researchers have produced an ensemble of weather models under different emission scenarios to predict what the future entails. The Intergovernmental Panel on Climate Change (IPCC) selected four Representative Concentration Pathways (RCPs) as the basis for climate predictions, i.e., RCP2.6, RCP4.5, RCP6.0, and RCP8.5 (IPCC, 2023). Each RCP represents a specific scenario with an expected level of GHG emissions. In Canada, the government usually employs three out of the four RCPs, i.e., RCP2.6, RCP4.5, and RCP8.5 (Environment and Climate Change Canada, 2018). A short summary of the key differences among the three RCPs is provided in Table 1.

Table 1. Projected future global emissions and average warming levels associated with different RCPs.

Scenarios	Future Global Emission	Average Warming Level (°C) (by 2090)
RCP2.6	Low	0.9 – 2.3
RCP4.5	Medium	1.7 – 3.2
RCP8.5	High	3.2 – 5.4

To incorporate future climate scenarios into research on buildings and their occupants, many organizations produced future weather files based on the RCPs for specific locations of interest. The weather files enable architects, modellers, researchers, etc., to better understand the impact of global warming on different types of buildings through energy modelling software. A reference health care building was created in IES Virtual Environment (IESVE) (Integrated Environmental Solutions, 2023) to demonstrate the use of future weather files and the impact on building performance. A view of the building and detailed inputs of the energy model are provided in Appendix I. The building is situated in Vancouver, BC, and a future weather file for the year 2050 produced by the Pacific Climate Impacts Consortium (PCIC) based on RCP8.5 for the Vancouver region is used (PCIC, 2023). The simulation results are compared with the same building using current weather files representative of the year 2020. Figure 5 shows the projected ambient air temperature increase in the 2050s. In Vancouver, the peak cooling day typically occurs in July, while the peak heating day typically falls in December. It is estimated that the average ambient air temperature will rise from 18.89 °C to 20.91 °C in July and from 4.95 °C to 6.13 °C in December.

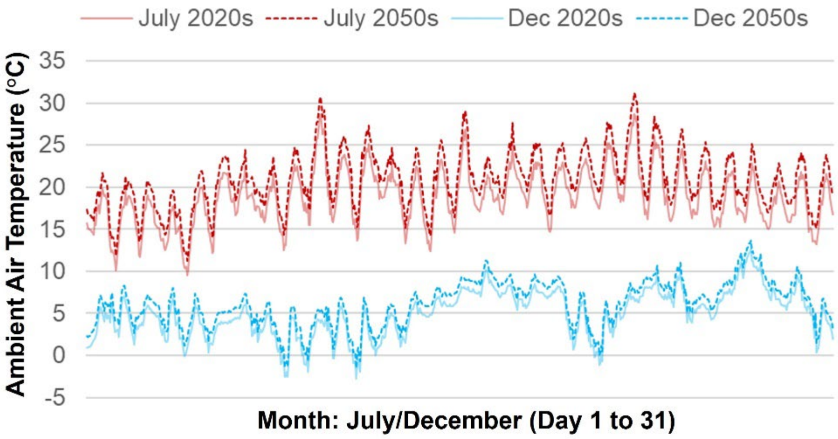

Figure 5. Projected future (2050s) ambient air temperature in Vancouver, BC, compared to current conditions (2020s).

The climate in the Vancouver region has determined that most of the buildings are heating-dominant. From Figure 6, approximately 60% of the site energy use is for heating under both current and future weather conditions. The lower site EUI in the 2050s is the result of projected warmer winter temperatures, which reduced the total heating energy use. Figure 7 shows that the increased cooling energy use of 5.94 MWh in the future warmer summer is more than offset by the 65.10 MWh of saved heating energy. From this perspective, even under the high emission scenario, in the next 30 years, the gradually warmed weather does not appear to have much negative impact on the buildings' energy use pattern. However, the future weather files do not consider the increased occurrence of abnormal, extreme weather events, which have disrupted normal building operations in the past.

This project aims to provide a review of the current operations at selected VCH facilities and offer recommendations for practical strategies to reduce the energy consumption and carbon emissions of HVAC systems. To deliver care to patients and safeguard the well-being of other occupants, maintaining good indoor air quality at each facility is also of paramount importance. The recommendations will consider both the emission and air quality aspects and inform building operation protocol updates and retrofit efforts.

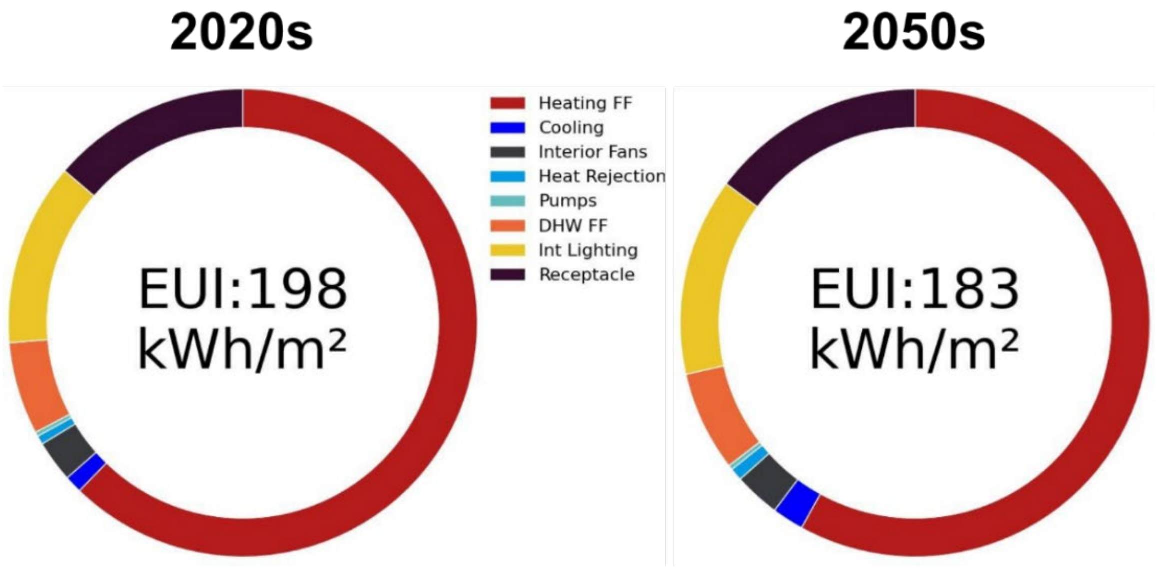

Figure 6. IESVE energy model site energy use intensity and breakdown.

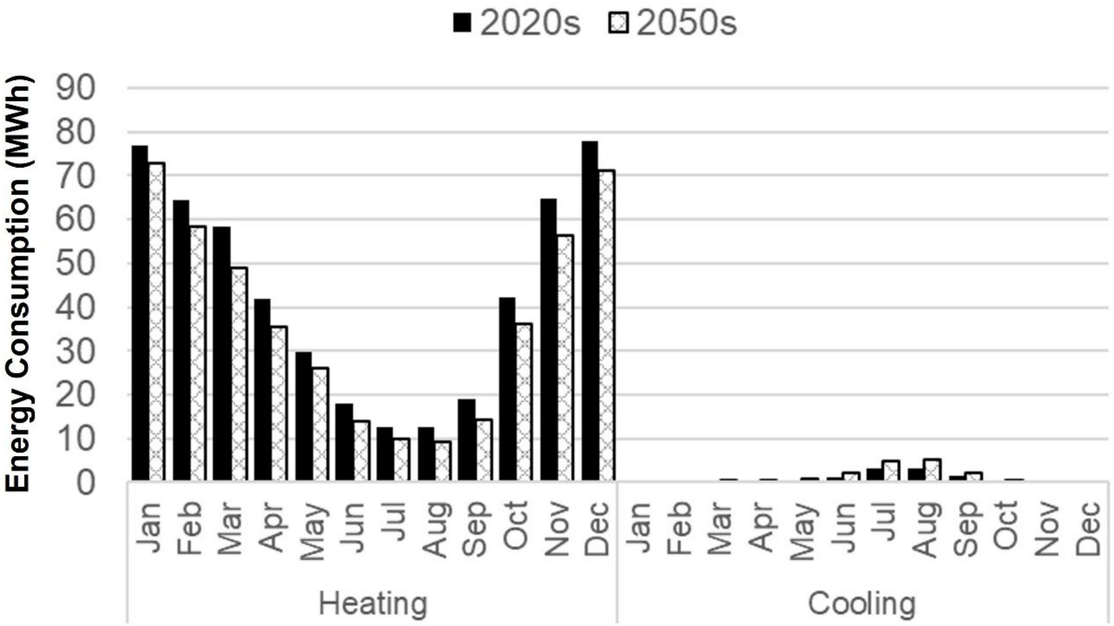

Figure 7. IESVE simulated monthly heating and cooling energy consumptions using the 2020s and 2050s weather files.

2 Literature Review

2.1 Air quality and particulate matter (PM)

When the air quality of an indoor environment is evaluated, the set of parameters of interest often involves relative humidity (RH), air temperature, carbon dioxide (CO_2), particulate matter (e.g., $PM_{2.5}$ and PM_{10}), volatile organic compounds (VOC), and ozone (O_3). Each of these parameters plays a role in how occupants perceive the overall quality of the indoor environment. One of the main concerns regarding indoor air quality pertains to microscopic particles. Particles less than 10 μm in diameter, or PM_{10}, are categorized as inhalable particles, and particles less than 2.5 μm in diameter, or $PM_{2.5}$, are further classified as fine inhalable particles (U.S. EPA, 2023a). While the coarse fraction of PM_{10} (with diameters between 2.5 μm and 10 μm) can only reach the upper respiratory tract, $PM_{2.5}$ can easily enter the lower respiratory tract, alveolus, and the bloodstream. Therefore, $PM_{2.5}$ is recognized as the pollutant that poses the greatest risk to health (U.S. EPA, 2023a), and it will be the focus of this report. Major sources of indoor $PM_{2.5}$ include outdoor air pollution, cooking, cleaning activities, combustion activities, biological contaminants, printers, and indoor chemical reactions (U.S.

EPA, 2023c). Health care facilities usually have more stringent regulations on indoor activities, and particulates from ambient air are the most significant source of indoor $PM_{2.5}$.

2.1.1 $PM_{2.5}$ and health

The specific health impact of $PM_{2.5}$ on humans has been studied extensively for decades and continues to be a focus of air quality research. Early in the 1990s, Dockery et al. (1993) studied the association between air pollution and mortality in six U.S. cities and found statistically significant and robust correlations between various pollutants, including $PM_{2.5}$, and the mortality rate of the selected six communities. Davidson et al. (2005) discussed the association of ambient PM concentrations with illnesses, including respiratory problems, changes in heart rhythms, heart attacks, and severe respiratory and heart malfunctions. As discussed by Feng et al. (2016), ambient $PM_{2.5}$ has also been shown to cause adverse health effects such as airway damage, cardiovascular impairments, and diabetes mellitus. Large cohort studies in Asia, Europe, North America, as well as at the global level, have demonstrated the contribution of $PM_{2.5}$ to the global burden of disease (Burnett et al., 2018; Cesaroni et al., 2013; Cohen et al., 2017; Li et al., 2018; Pope III et al., 2019). More recent studies have discovered evidence to connect ambient $PM_{2.5}$ pollution to pregnancy losses (Xue et al., 2021) and clinical antibiotic resistance (Zhou et al., 2023).

2.1.2 Ambient $PM_{2.5}$ regulations

The evidence gathered in the literature has prompted health organizations and government agencies to take action to protect people from ambient air pollution. Concentration limits of $PM_{2.5}$ are established by regional and national governing bodies, as well as by the World Health Organization (WHO), and the limits are periodically updated to reflect the current understanding of the $PM_{2.5}$ health impact. In most regulations, there is a daily average limit and an annual average limit. Government agencies rely on the limits and $PM_{2.5}$ monitoring data to issue air quality advisories to the public. Keeping the regulatory limits up to date with new research findings ensures that air quality advisories effectively inform the public regarding the exposure risks. For example, the U.S. Environmental Protection Agency (EPA) established the U.S. National Ambient Air Quality Standards (NAAQS) for PM and set the primary standard for 24-hour mean $PM_{2.5}$ of 65 $\mu g/m^3$ in 1997 (U.S. EPA, 2013). It was replaced with a 24-hour mean $PM_{2.5}$ of 35 $\mu g/m^3$ in 2006. While the 24-hour limit remains unchanged ever since, on January 6, 2023, the EPA issued a proposal to revise the annual limit from 12 $\mu g/m^3$ to within the range of 9 $\mu g/m^3$ to 10 $\mu g/m^3$ (U.S. EPA, 2023b). Albeit a significant step forward for the public, some experts argued that the proposed range would not be sufficient to provide a margin of safety for human health (Furlow, 2023). A summary of the $PM_{2.5}$ concentration limits introduced by different standards is given in Table 2. It is clear that there is a consensus to gradually lower the enforced limit to improve the ambient air quality.

Table 2. Summary of the $PM_{2.5}$ concentration limits in different standards.

Standards	**Averaging Period**			
	24-hour [μg/m^3]		**Annual [μg/m^3]**	
	Previous Ver.	Current Ver.	Previous Ver.	Current Ver.
WHO AQG (WHO, 2021)	25	15	10	5
CAAQS (CCME, 2023)	28	27	10	8.8
NAAQS (U.S. EPA, 2013)	65	35	15	12

The BC province usually experiences good air quality. Under the current Air Quality Health Index model in BC, 96% of the time, the health risk is in the “Low” category, i.e., the air quality is ideal for outdoor activities, based on data from 2009 through 2020 (Haga, 2022). To continue improving air quality in BC, the province has set more aggressive targets, i.e., Air Quality Objective (AQO), than required by CAAQS. For $PM_{2.5}$, the 24-hour AQO is 25 μg/m^3, and the annual AQO is 8 μg/m^3 (Government of British Columbia, 2009). The 1-hour $PM_{2.5}$ concentration in Vancouver from July 1, 2022, through August 21, 2023, is shown in Figure 8. The data is obtained from the Vancouver Clark Drive air monitoring station (Government of British Columbia, 2023). Although some fluctuations and a few exceedances could be observed for hourly $PM_{2.5}$, the 24-hour average is able to maintain below the CAAQS target limit as well as the provincial AQO, except on two occasions in fall 2022 when the region is impacted by wildfire smoke.

2.1.3 Indoor $PM_{2.5}$ Exposure and Monitoring

While the health impact of elevated concentrations of ambient $PM_{2.5}$ is now well documented, understanding of the exposure indoors is still limited, which resulted in a lack of regulations on indoor $PM_{2.5}$. However, this trend is rapidly changing as the building industry recognizes the need to monitor and mitigate against poor IAQ, considering that people in developed countries spend up to 90% of their time indoors (Klepeis et al., 2001). Organizations recognize that employees’ health and well-being drive business productivity and impact the bottom line (Kosonen & Tan, 2004; Park & Yoon, 2011; Saari et al., 2006; Tham, 2016; Wargocki et al., 1999; Wargocki et al., 2000; Wyon, 2004). Considering that people generally have less control of the indoor environment as compared to their dwellings, IAQ in commercial and institutional buildings has gained a great deal of attention. As a result, voluntary guidelines such as the WELL Building Standard (IWBI, 2022), the RESET Air Standard (GIGA Ltd., 2018), and Fitwel® Standard (CfAD, 2021) were developed to complement the prominent green building rating systems that are primarily focused on environmental and economic sustainability. The WELL, RESET Air, and Fitwel standards seek to enhance the overall building performance and sustainability by adding the human health dimension, and IAQ is a major performance category for all three standards. A summary of the recommended indoor $PM_{2.5}$ levels in WELL, RESET Air, and Fitwel standards is given in Table 3. It is worth noting that these standards were heavily influenced by regulations in the US and the recommended levels are often similar to the NAAQS limits.

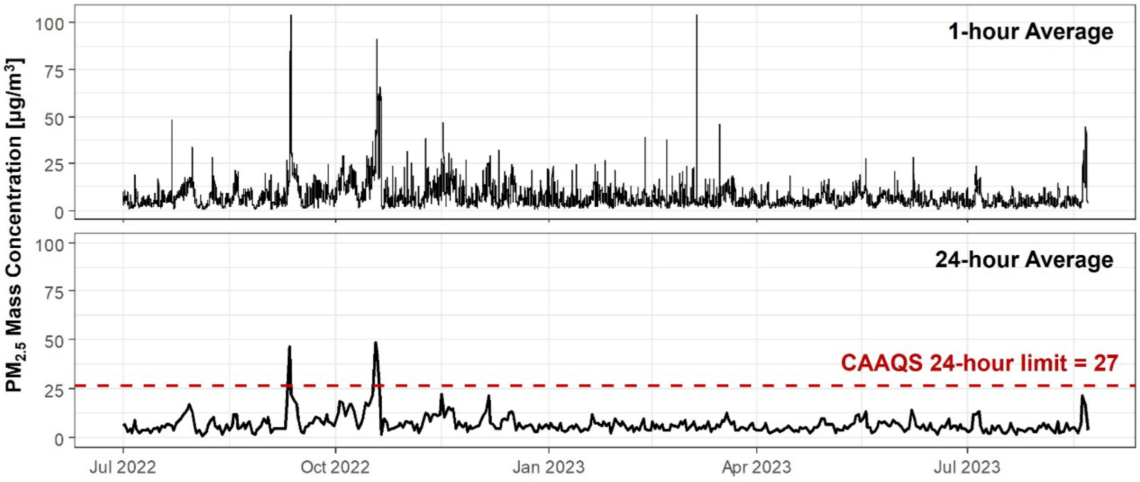

Figure 8. 1-hour $PM_{2.5}$ concentration in Vancouver from July 1, 2022 through August 21, 2023.

Table 3. Recommended indoor $PM_{2.5}$ levels from voluntary guidelines.

Guidelines	Recommended $PM_{2.5}$ Level ($\mu g/m^3$)
WELL	Basic: 15 Enhanced (Tier 1): 12 Enhanced (Tier 2): 10
RESET Air	Acceptable: 35 High Performance: 12
Fitwel	25

The WELL, RESET, and Fitwel communities have grown tremendously over the last few years after their introduction, as seen by the number of buildings certified globally. The healthy building community finds that while occupant expectations are major drivers for improving our understanding regarding IAQ, there are several barriers. First, information asymmetry exists between outdoor and indoor PM. In North America, while long-term measurements are available for ambient PM through national/federal, provincial/state, or local air pollution control agencies (CCME, 2023; U.S. EPA, 2013), indoor PM data are usually scarce. Second, the indoor PM level is not only influenced by ambient PM but also affected by other indoor sources, including particle emission and resuspension, which are often linked to human activities (McDonagh & Byrne, 2014a, 2014b; National Academy of Engineering, 2022; Qian et al., 2014; Tian et al., 2014). The current measurement schemes based on best practices are to place at least one calibration grade or commercial grade monitor at each type of regularly occupied space within a maximum monitoring range of 500 m^2 (GIGA Ltd., 2018). While this approach may attempt to measure the variability, it cannot be generalized. Third, there are technological barriers. Data from the monitors need to be compiled, analyzed, and converted into understandable information for the building operators to take action. As discussed in Burt and Bayer (2021), monitoring devices in the market showed large variability in terms of applicability, practicality, plausibility, and accuracy. The need to obtain long-term data for assessing IAQ is further complicated by what parameters to prioritize in the measurement scheme. There is no definitive method for the placement of monitors to represent well-mixed air. Furthermore, there is no established method for consolidating the measurement results from the individual spots. From the mitigation standpoint, the measurements from the particular spot needing improvement may not even coincide with the mechanical zone to take building-level actions. As a result, continuous indoor air quality monitoring is still not a widely adopted practice except in certain high-risk spaces in industrial or health care settings.

2.2 HVAC Operation in Health Care Facilities

The HVAC system is the most crucial component in health care facilities. A properly functioning HVAC system provides desired thermal comfort and indoor air quality to patients and employees and ensures the facility is in compliance with government regulations. On the other hand, the HVAC system represents the largest energy end uses in hospitals. It is estimated that, in the US health care systems, 52% of the energy is consumed for space heating (29%), cooling (11%), and ventilation (12%) (Bawaneh et al., 2019). In Canada, the figure is estimated to be

60%, with 43% for space heating, 3% for space cooling, and 14% for fans and pumps of the ventilation system (Natural Resources Canada, 2018).

Table 4. HVAC system design parameters for selected spaces in nursing homes, mental health facilities, and rehabilitation facilities.

Space Function	Min Outdoor (ach)	Min Total (ach)	Design Temperature (°C)	Design RH (%)	Min Filter Efficiency
Nursing Homes					
Patient rooms	2	4	22-24	30-60	MERV-8 + MERV-13
Resident Room[(1)]	2	2	21-29	< 60	MERV-14
Mental Health Facilities					
Patient rooms	2	4	22-24	30-60	MERV-8 + MERV-13
Inpatient bedroom	2	2	NR	NR	MERV-8
Outpatient rooms	2	3	21-24	NR	MERV-8
Rehabilitation Facilities					
Occupational therapy	2	6	20-24	30-60	MERV-8 + MERV-13
Physiotherapy areas	3	9	22-24	30-60	MERV-8 + MERV-13
Inpatient physical therapy	2	6	22-27	< 65	MERV-8
Outpatient therapy areas	2	3	21-24	NR	MERV-8

Note:
(1) Parameters from ASHRAE 170 are listed in shaded rows. Parameters from CSA Z317.2 are not shaded.

Two of the most commonly consulted standards in North America for designing health care facilities' HVAC systems are the ASHRAE Standard 170 (ASHRAE, 2021) and the CSA Z317.2 Standard (CSA Group, 2021). Instead of creating separate standards from scratch, regulatory bodies often refer to these well-accepted industry standards to determine compliance. An excerpt of required air changes per hour (ach), design temperature and RH, and filter efficiency from CSA Z317.2 and ASHRAE 170 is presented in Table 4 for selected spaces. These spaces correspond to the selected VCH facilities for this project. It can be seen that the two standards share common grounds regarding the minimum outdoor air change rate. The CSA standard appears to have more stringent requirements for other parameters. In particular, the CSA Z317.2 requires that filters meet the requirements of both MERV and MERV-A tests in accordance with ASHRAE Standard 52.2 (ASHRAE, 2017), which is not required explicitly in

ASHRAE 170. The MERV-A rating is obtained when the filter undertakes an optional separate procedure to test its likely efficiency degradation when put into use in real-life conditions.

Over the history of the development of these ventilation standards, the well-mixed space was one of the underlying core assumptions, and it resulted in the conclusion that dilution was the logical solution to indoor pollution (Burley, 2021). Burley (2021) reasoned that this assumption had led to an emphasis on increasing air change rate and air filtration as the main mechanism to remove indoor air pollutants. Findings from recent studies, however, have contradicted some of the conventional wisdom. The ASHRAE-funded research on Standard 170 (Mousavi et al., 2019) conducted a thorough review of the requirements in the standard and found that 71% of the requirements had no sound scientific evidence from relevant research. Building on these findings, Barolin and English (2023) collected empirical data from an operating hospital and argued that there was no added value to increase the outdoor air change rate above 2 ach because no improvement in air quality was observed from the data. The energy implication is potentially significant because increased ventilation rate is usually associated with increased energy consumption and carbon emissions.

In the wake of the COVID-19 pandemic, coupled with major wildfire smoke episodes in the Pacific Northwest region, indoor air filtration has attracted increasing attention from the public. As shown in Table 4, the CSA standard typically requires two-stage filtration with MERV-8 pre-filter and MERV-13 final filter. Previous studies on filter performance have shown that the most penetrating particle size is around 0.3 μm (see Figure 9). While the MERV-rated filters have below 80% efficiency in this size range, HEPA filters could achieve 99.97% efficiency. Regardless of the efficiency drop, it is clear that filters with higher MERV ratings are more effective in eliminating particles of other sizes in the $PM_{2.5}$ family. Part of the reason that filters rated MERV-14 and above are not a mandatory requirement in the standards is that there are concerns regarding the pressure drop caused by higher MERV ratings and the capability of the HVAC system to maintain the required airflow with better filters. However, a performance study conducted by Li et al. (2019) did not find a strong correlation between pressure drop and MERV ratings. Bohanon et al. (2023) suggested that MERV-13 filters could be required across the board by ASHRAE to reduce occupants' exposure to $PM_{2.5}$. In the Canadian health care context, since MERV-8 and MERV-13 are already required by CSA Z317.2, a potential upgrade to MERV-14 filters should be discussed to boost the performance of the HVAC systems.

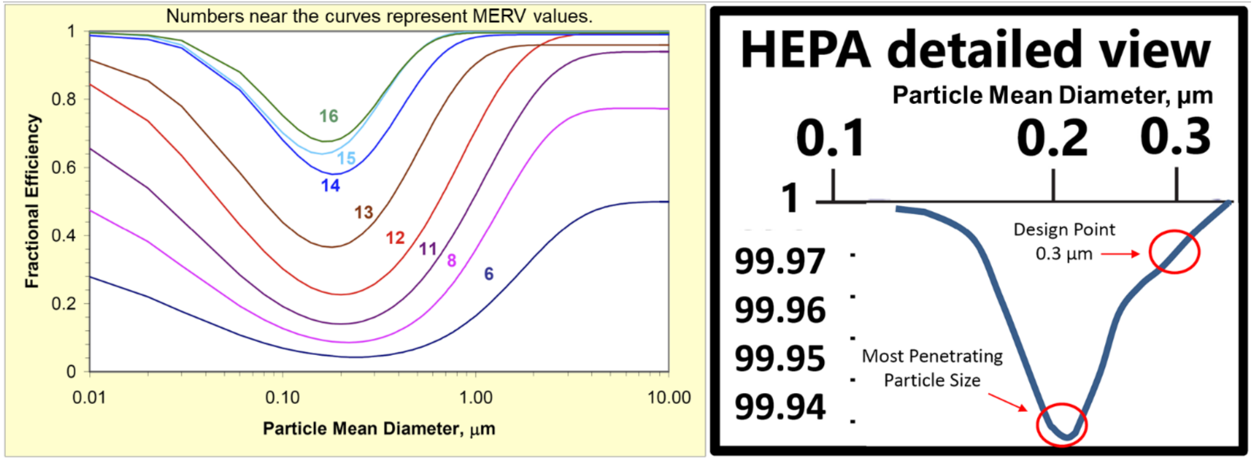

Figure 9. MERV and HEPA filter efficiencies for different particle sizes (ASHRAE Epidemic Task Force, 2021b).

2.3 Perceived indoor air quality

Although air quality is generally treated as an objective parameter of the indoor environment, the occupants' perceived air quality is often not. ASHRAE discussed the complexity of human perceptions regarding indoor environments in its published Guideline 10 (ASHRAE, 2011). Many unknowns still exist in assessing the effect of the interactions of environmental parameters on human perception. Therefore, ASHRAE suggested keeping all environmental parameters within acceptable limits to minimize the effect of interactions. This usually requires investments in monitoring devices to collect physical data for each environmental parameter of interest, which could be costly. For a lot of the existing buildings, building managers and facilities services could only rely on complaints received from occupants to identify air quality issues.

Numerous studies have shown that our senses are not always reliable for detecting subtle changes in pollutant levels. In a way, it creates some opportunities for adopting certain energy-saving measures without compromising occupants' satisfaction. Melikov and Kaczmarczyk (2012) analyzed the interaction among pollutants, air temperature, and relative humidity and the impact of the interaction on perceived air quality. The findings suggested that elevated air movement could improve occupants' air quality perception when air temperature and relative humidity were kept high to save energy. Son et al. (2023) conducted experiments in residential settings using $PM_{2.5}$ as the target pollutant and suggested that occupants could only detect air quality deterioration when the level of $PM_{2.5}$ concentration exceeded 80 µg/m^3.

Few complaints occurred when the $PM_{2.5}$ was maintained below 60 μg/m^3, which was well above the various recommended indoor concentration limits. Another recent study carried out in classrooms discovered that students' perceived air quality, odour intensity, thermal acceptability and thermal sensation were not significantly affected when the indoor CO_2 level was increased from around 700 ppm to 1000 ppm, as long as the room air temperature was kept low at around 22 °C (Yang et al., 2021).

If occupant satisfaction with the perceived indoor air quality is the only metric employed to evaluate the environment, some energy-saving measures could be justified by playing with the interactions of environmental parameters. However, it will be difficult to gauge the impact of each parameter separately. Deploying monitoring devices is crucial to ensure that indoor pollutants or other parameters of interest are kept at a level that has minimal health impact on occupants.

2.4 Wildfire Smoke Impact

In recent years, communities in the US and Canada have experienced an increasing number of smoke episodes resulting from wildfires. In Canada, data from the National Forestry Database (NFD) (CCFM, 2023) show that although the total number of forest fires continues to decrease due to advanced technologies and mitigation strategies, the number of large fires (with a size larger than 100 ha) has maintained momentum (see Figure 10). With the anticipated continuing warming of the climate, wildfire smoke episodes in urban areas are expected to increase in frequency and magnitude.

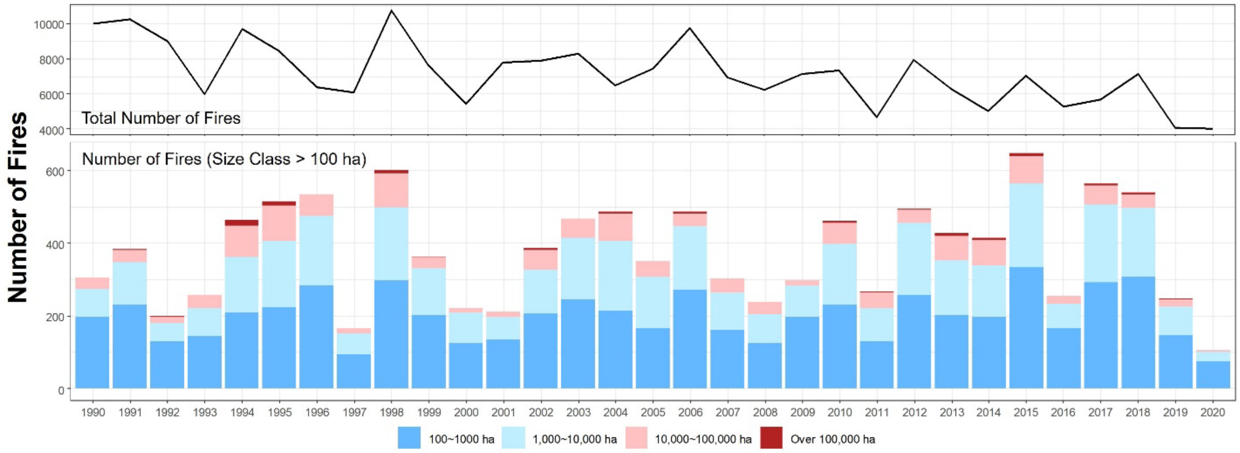

Figure 10. Total number of forest fires and number of large fires (size > 100 ha) based on data from NFD.

Smoke generated by wildfire contains large amounts of $PM_{2.5}$ and VOCs (Laing & Jaffe, 2019). The VOCs could further go through chemical reactions to produce additional $PM_{2.5}$. During wildfire smoke episodes, government agencies usually advise people to stay indoors. The assumption is that buildings could provide a certain level of protection against ambient air pollution. However, the public should be aware that even large commercial buildings with centralized HVAC systems and high-quality filters do not always provide adequate protection. Unpublished $PM_{2.5}$ infiltration data from a study the author conducted in a commercial office space in Seattle, WA, is shown in Figure 11. The office space was served by an AHU with MERV-8 pre-filter and MERV-14 final filter. During a smoke episode, the $PM_{2.5}$ level at the outdoor air intake and indoor space was measured to estimate the infiltration. The measurements were taken during unoccupied hours, and the outdoor air intake dampers were controlled to be fully open or fully closed. The results show that if the facilities staff do not intervene and the dampers are operating in a fully open position, 45% of the outdoor PM2.5 could enter the building. On the other hand, by closing the damper and recirculating the indoor air, only 14% of the $PM_{2.5}$ could infiltrate the building.

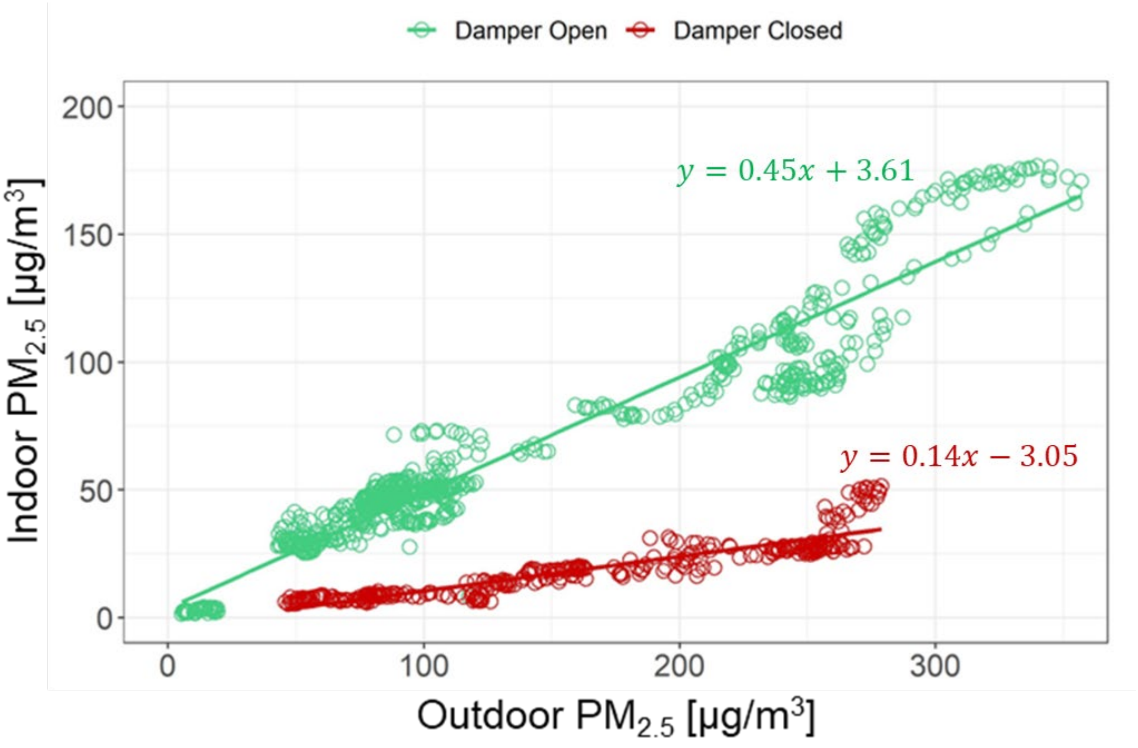

Figure 11. Outdoor $PM_{2.5}$ infiltration under different ventilation system operation modes during a wildfire smoke episode.

To provide guidance for facility managers on building operation strategies during smoke episodes, ASHRAE proposed a planning framework, i.e., ASHRAE Guideline 44P (ASHRAE, 2020), for use in commercial buildings. Although not intended for residential buildings, health care facilities could adopt the framework with the support of qualified HVAC staff and consultants. As described in detail by Javins et al. (2021), the planning framework called for the preparation of a Smoke Readiness Plan and the establishment of an implementation process when smoke-related air quality alerts are issued. Figure 12 illustrates the recommended actions before, during and after wildfire season.

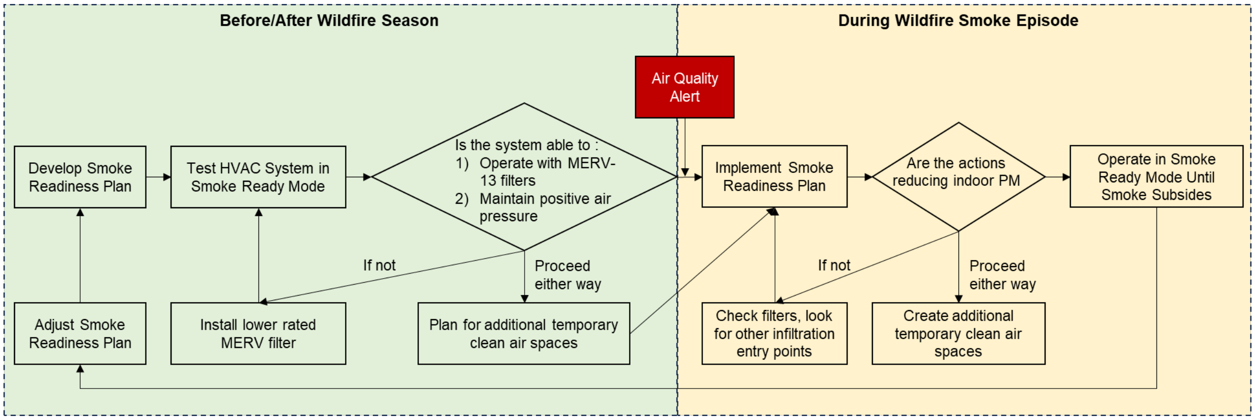

Figure 12. Flowchart for making a building smoke ready. Adapted from Javins et al. (2021).

2.5 Indoor Airborne Transmission of Viruses

The COVID-19 pandemic introduced additional challenges for building managers and occupants. Studies have suggested that SARS-CoV-2 could be spread by airborne transmissions (Bourouiba, 2020; Peng et al., 2020; van Doremalen et al., 2020; Yu et al., 2004) and that respiratory particles could be generated when people breathe, speak, cough, or sneeze (Cook, 2020). Compared to the larger droplets produced when coughing and sneezing, which usually can only travel up to six meters (Xie et al., 2007), small airborne particles could reach meters or tens of meters in the indoor air (Morawska & Cao, 2020).

To protect occupants in the buildings, government agencies, health authorities, and other industry organizations worked together and quickly released guidelines to help building managers and occupants reduce exposure to the virus (ASHRAE Epidemic Task Force, 2021a; Engineering Canada, 2021; PSPC, 2023; U.S. CDC, 2023). As discussed by Risbeck et al.

(2022), the central theme of these guidelines is to facilitate the effective removal of infectious particles. Assuming well-mixed indoor air, the processes associated with the removal include ventilation, filtration, deactivation, and deposition (Risbeck et al., 2022). In large commercial and institutional buildings, the success of the ventilation and filtration processes depends on the proper tuning and operation of the HVAC system. To better prepare the buildings for future epidemics, ASHRAE collected opinions from international experts and research findings from COVID-related studies to date, and published Standard 241 to "establish minimum requirements for control of infectious aerosols to reduce risk of disease transmission in the occupiable space of buildings" (ASHRAE, 2023).

Table 5. Sample tasks for BRP (ASHRAE, 2023).

Function	Building Readiness Tasks
Ventilation	Provide as much outside air as the HVAC system can accommodate while maintaining acceptable indoor conditions.
	Disable demand-controlled ventilation.
	Limit occupancy in areas with inadequate ventilation.
	Assess Energy Recovery Ventilation systems for cross-contamination and adjust airflow as necessary.
	Ensure outdoor air intake has sufficient separation distance from contaminant sources (cooling tower, exhaust fan, pedestrian walkway, etc.).
Filtration	Use at least MERV-13 filters in all recirculating systems.
	Ensure good seal on filters (tape, gasket, sizing, etc.).
	Use in-room HEPA filters in areas with limited system filtration capabilities.
Pressurization and Exhaust	Resolve any significant building pressurization issues.
	Provide negative pressure in each restroom using a toilet exhaust system.
	Ensure that base building restrooms not connected to the central exhaust system have functioning exhaust and provide signage for occupant-controlled fans.
Other HVAC Practices	Identify any spaces with healthcare, high occupant density or vulnerable population; create a plan for additional measures (portable HEPA filters, upper room UVGI).
	Communicate with tenants regarding risk mitigation for tenant owned and operated HVAC equipment.

Bahnfleth and Sherman (2023) gave an overview of Standard 241 following its publication. Similar to the Smoke Ready Mode when dealing with wildfire smoke per ASHRAE Guideline 44P, ASHRAE Standard 241 introduced the concept of infection risk management mode (IRMM). The IRMM will be activated when increased protection from infectious aerosol exposure is needed. To provide building managers with greater flexibility, Standard 241 also defined equivalent clean airflow (ECA) so that air cleaning does not solely depend on bringing in large amounts of outdoor air. This measure offers building manager alternatives when outdoor conditions are compromised, such as during smoke episodes. The standard requires more extensive testing for mechanical filters and air cleaners than other ASHRAE ventilation standards and pushes buildings to adopt filters of MERV-A 11-A rating or above. Indeed, high-efficiency filtration could provide clean air with only a small increase in energy cost and should be considered first for any mitigation strategies (Zaatari et al., 2023). Another important element of the standard is the requirement for the creation of a Building Readiness Plan (BRP). The BRP outlines the action items for the building to comply with Standard 241 when IRMM is activated. A sample of the tasks that could be included in BRP is presented in Table 5.

3 Energy Retrofit Framework and Precedent Projects

3.1 Energy Retrofit Framework

There are widely accepted and well-established energy retrofit frameworks for commercial and institutional buildings (Hendron et al., 2013; Natural Resources Canada, 2018; U.S. DOE, 2021). The major components of these frameworks are applicable to all types of commercial and institutional buildings. Figure 13 illustrates the staged retrofit approach to improve the energy performance of a facility (Natural Resources Canada, 2018).

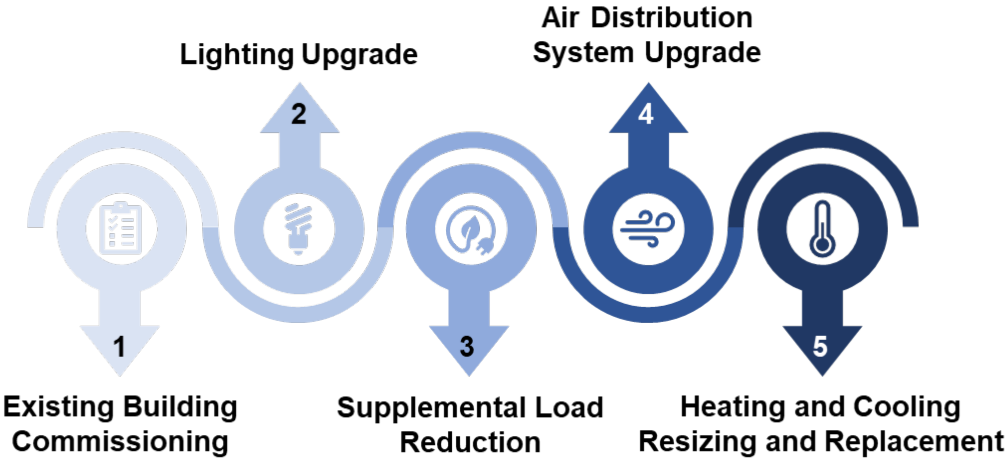

Figure 13. Recommended major retrofit stages.

Being a significant energy user among all of the commercial and institutional building types, there lies great potential for health care facilities to achieve energy savings and emission reductions. Hendron et al. (2013) described in detail some cost-effective retrofit measures that could be implemented to replace existing HVAC systems in the facility. A summary of these measures is as follows:

- Heating and Cooling
    - Improve hospital chiller and cooling tower design and controls.
    - Install a coil bypass to reduce pressure drop when there is no heating and cooling demand.
    - Install a stack economizer to recover waste heat.
    - Install boiler controls to allow reset of hot water temperature.
    - Add controls to stage chillers.
    - Install a water-side economizer to bypass the chiller.
    - Install an air-side economizer.
    - Add evaporative cooling to improve condenser performance.
    - Add a small condensing boiler to handle the base load and summer load, with the current inefficient boiler operating only when heating loads are the highest.
    - Install variable speed drives (VSDs) on chilled-water and hot water pumps.
    - Install an Energy Management System and replace pneumatic controls with direct digital control (DDC).
    - Replace oversized, inefficient fans and motors with right-sized NEMA premium efficiency motors.
    - Convert constant volume air handling system to variable air volume (VAV).
- Ventilation
    - Upgrade to demand controlled ventilation (DCV).
    - Add energy recovery to the ventilation system.

To examine the application of these proposed measures, several health care facility construction and retrofit projects were identified and reviewed as precedents. The subsequent section gives an overview of the measures adopted by these actual projects and provides some ground truth.

3.2 Precedent Projects

Several health care facility construction and retrofit cases were selected to identify potential energy retrofit measures that could be beneficial for VCH assets. An overview of the characteristics of the case facilities is given in Table 6.

Table 6. Overview of the building characteristics of the selected case studies.

Facility	Location	Completion	Area (m^2)	Use
Louis-H. LaFontaine Hospital (Kafesdjian, 2011)	Montreal, QC	2006	139,355	Hospital
Pierre-Boucher Hospital (Desmarais, 2011)	Longueuil, QC	2006	46,452	Hospital services
Abbotsford Regional Hospital & Cancer Centre (Marmion, 2012)	Abbotsford, BC	2008	61,756	Acute care hospital and cancer treatment
Harborview-Norm Maleng (Iverson, 2010)	Seattle, WA	2008	23,690	Level 1 trauma center
Advocate Lutheran General Hospital (Noorts & Murphy, 2011)	Park Ridge, Ill	2009	35,303	Hospital
Swedish Issaquah Hospital (McClanathan, 2013)	Issaquah, WA	2011	32,795	Acute care hospital
Humber River Hospital (Monteiro & Frayne, 2017)	Toronto, ON	2015	167,225	Regional acute care hospital
Tin Shui Wai Hospital (Leung, 2022)	Hong Kong	2016	59,000	Hospital

The selected cases all participated in the competition for the ASHRAE Technology Award. Each case presented a set of energy efficiency measures to achieve its energy-saving targets. A summary of these measures related to HVAC systems is given in Table 7. Information gathered from the frameworks and these precedent projects offers some general directions when considering retrofit measures for VCH facilities that are appropriate for the location and building functions. Nevertheless, these measures have been put into use and proved to be practical and effective in achieving energy savings.

Table 7. Energy efficiency measures implemented by the case study hospitals related to HVAC systems.

Implemented Energy Efficiency Measures	
Boilers	**Chillers**
• High-efficiency (87.5~92%) boilers • Variable speed multistage feed water pumps • Glycol coil to preheat incoming combustion air • Primary variable flow heating water system • Hot water temperature reset	• Counter-flow configuration • Chiller water temperature reset control • Variable primary flow chilled water system • Integrate hot water system with chilled water system
AHUs	**Heat Pumps**
• Low-temperature heating loops • Bypass damper control • Exhaust air heat recovery system • Demand control ventilation • Variable frequency drives (VFD) • Low-velocity coils and filters • MERV-14 filters • Increased AHU size to reduce air velocity	• Closed-loop geothermal heat pump system • Water-to-water heat pump to reuse condenser side energy from the cooling tower • Solar heating
Heat Recovery	**Other**
• Boiler heat reclaim system • Condenser water heat recovery system • Heat recovery from exhaust air through chilled water coils • Enthalpy wheels (75% efficiency) • Full-load heat rejection to the runaround system, eliminating the need for a cooling tower • 100% outside air AHUs with heat exchangers to maintain higher supply air temperature for perimeter zones using recovered heat	• Replace pneumatic controls with direct digital controls • Measurement and verification plan • CFD analysis for site airflow • Prefabricated AHUs • Outdoor air airflow measuring stations • Precise pressure controls • Flexible HVAC system design • 100% outdoor air supply to high risk areas

4 Existing Systems and Indoor Air Quality

Site visits were conducted by the author to three selected VCH facilities, i.e., a Long-term Care Residence, a Rehabilitation Centre, and a Mental Health Centre, to observe the operation of the HVAC systems. Existing asset reports for the facilities were reviewed prior to the site visits. The site visit to each facility was accompanied by a member of the facility staff. In addition, $PM_{2.5}$ measurements were obtained from each facility to evaluate the current indoor air quality on site. The measurements were taken by Air Quality Egg (EGGs) sensors (Wicked Device LLC, 2021) installed in 2020 at the three facilities for a previous research project conducted by VCH and Health Canada on low-cost sensors (Nguyen et al., 2021). Note that the EGGs have not been calibrated since 2020. Although there are no specific calibration requirements from the manufacturer, the accuracy of the readings could decline over time.

The hourly averaged ambient $PM_{2.5}$ data was collected from two government monitoring stations, i.e., Vancouver Clark Drive and Richmond South (Government of British Columbia, 2023). The Vancouver Clark Drive station is in close proximity to the Rehabilitation Centre and Mental Health Centre, while the Richmond South station is close to the Long-term Care Residence.

4.1 Long-term Care Residence (LCR)

4.1.1 System Description

The LCR is a three-storey residential care facility constructed in 1994 with a gross area of 12,321 m^2 and a net room area of 10,833 m^2. The largest categories of room use are living accommodations (30.21%) for senior residents and traffic circulation (21.70%).

Heating is provided on-site with three hot water boilers, i.e., B-1, B-2, and B-3. Boilers B-1 and B-2 are natural gas only and used for space heating. Boiler B-3 is used for water heating. It is dual fuel and could also be powered by diesel oil by following a switchover procedure. B-1 and B-2 are each capable of covering the space heating needs, while the other serves as the backup unit. If B-3 is out of service, B-1 and B-2 could take over the water heating function.

Figure 14. The heat pump system consists of (a) outdoor units, (b) indoor ceiling-mounted units serving the lounge areas, and (c) indoor wall-mounted units serving the Rehabilitation Service office.

Originally, space cooling was only provided by a water-cooled chiller equipped with a cooling tower. Refrigerant R-134a is used in the chiller system. A packaged unitary rooftop AC unit serves as the main electrical vault. A heat pump project was completed in 2022 to increase the cooling capacities of the building. The lounge areas on all three floors are cooled by the heat pumps through ceiling-mounted indoor units, and the Rehabilitation Service office is cooled through wall-mounted indoor units, as shown in Figure 14.

The conditioned air is distributed to different building spaces by 14 AHUs operating on a 24/7 schedule. The typical layout of the ventilation system in a resident room is shown in Figure 15. Four of the AHUs (AHU-1, 2, 3, and 4) are connected to a heat recovery system installed in 2021. The heat recovery system captures waste heat from exhaust air using glycol and water and reuses it for domestic water heating and AHU preheat coils. In each AHU, the incoming outside air is filtered by a MERV-8 pre-filter and a MERV-13 final filter. Figure 16 shows the filter installation in AHU-10. The pre-filters are changed approximately every six months, and the final filters are changed based on the manufacturer's recommendations.

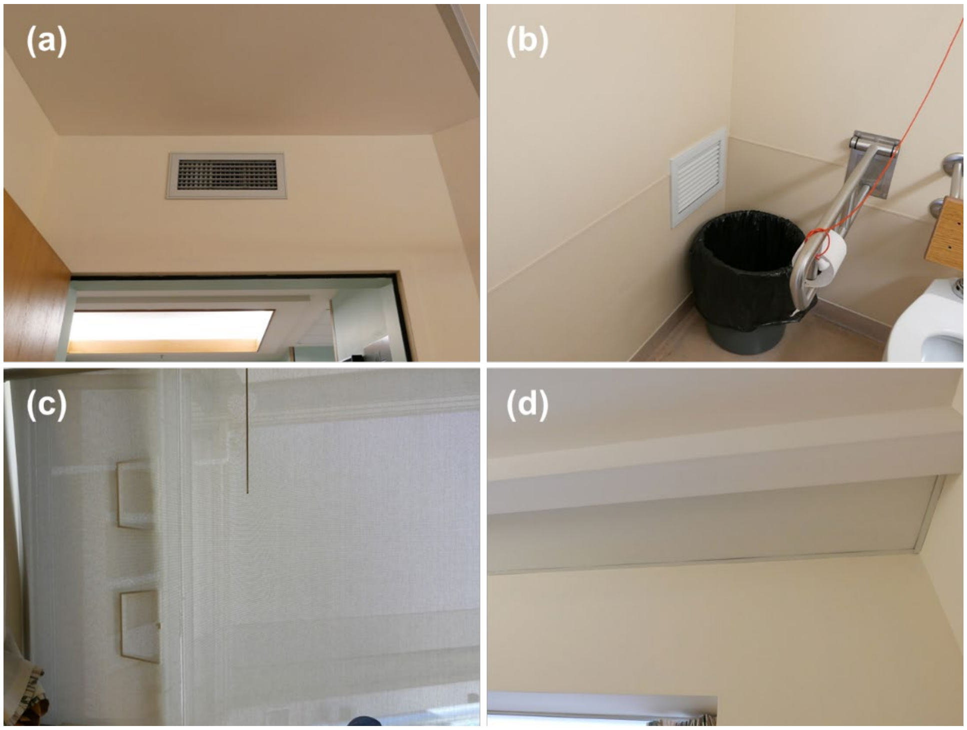

Figure 15. HVAC system terminal units for a typical resident room include (a) supply air diffuser above the door frame, (b) return air grille located in the washroom, (c) operable windows, (d) radiant ceiling panels above the window for perimeter heating.

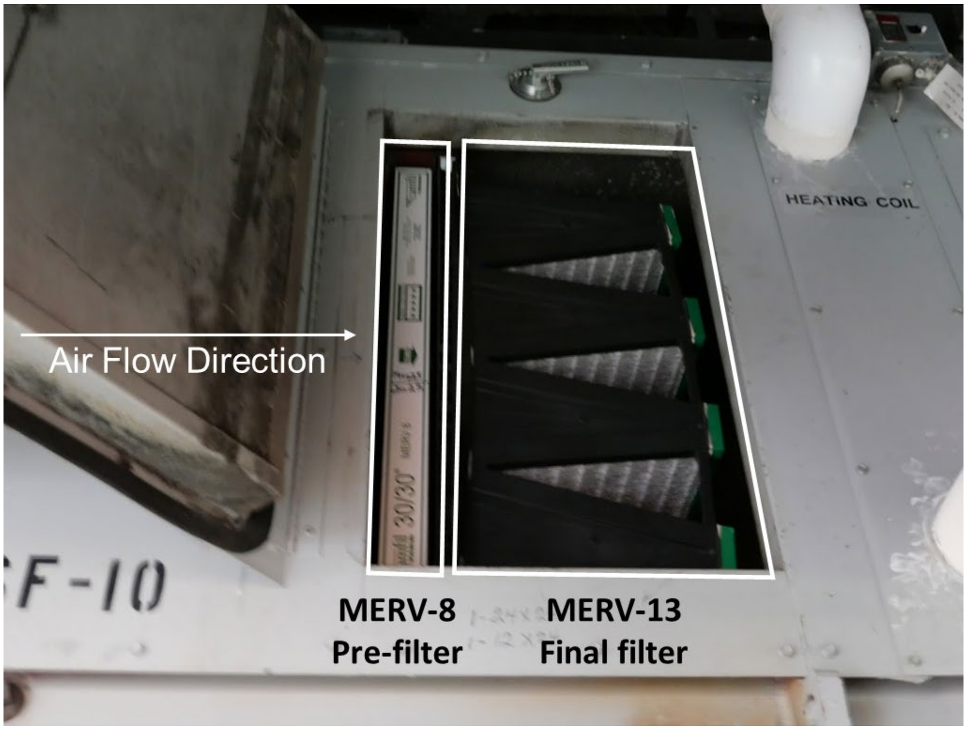

Figure 16. Air filters installed in AHU-10 include a MERV-8 pre-filter and a MERV-13 final filter.

Being part of a main hospital campus, the LCR does not have facilities staff on-site outside of business hours. In case of HVAC system malfunctions, the building staff is required to contact the main hospital campus and request assistance.

4.1.2 Indoor Air Quality

Eight EGG sensors were originally installed on-site, and four remained in the facility at the time of the visit. Only one sensor is currently online and can be accessed through the web portal. However, the most recent $PM_{2.5}$ data available from this sensor appeared to be from July 30, 2021, through August 30, 2021. The reported $PM_{2.5}$ levels dropped to zero and remained at zero afterward. It is suspected that the sensor experienced functionality issues and could not reliably detect the particles. The ambient $PM_{2.5}$ data was obtained from the Richmond South monitoring station.

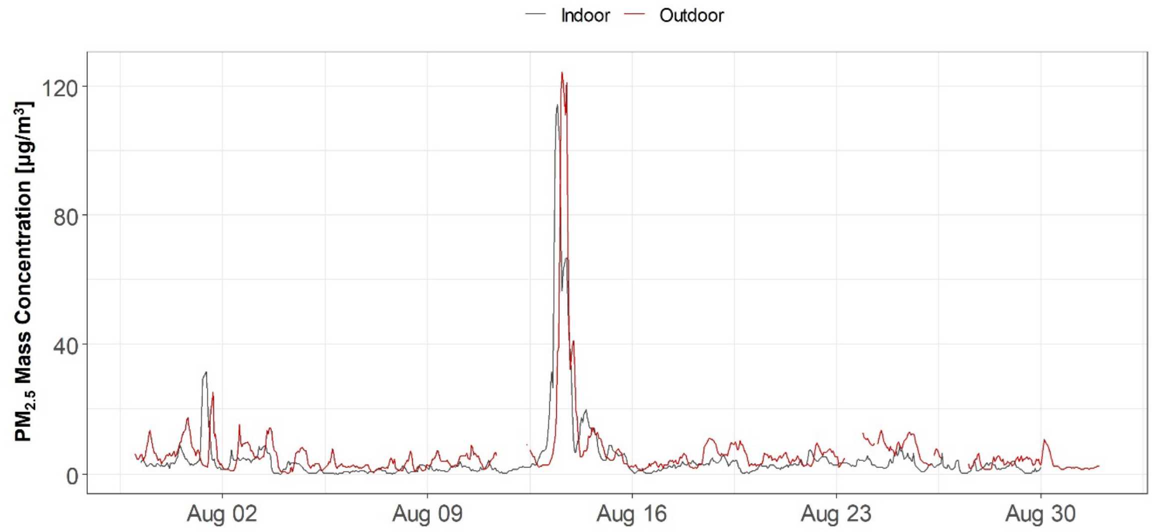

Figure 17. Indoor and outdoor hourly averaged $PM_{2.5}$ concentrations. Indoor data was from on-site sensors, and outdoor data was from the Richmond South monitoring station.

Figure 17 shows the comparison of indoor and outdoor $PM_{2.5}$ at the site. The indoor concentration appears to be significantly impacted by the ambient air. The region was impacted by wildfire smoke from August 13 to August 16, and elevated ambient $PM_{2.5}$ levels could be observed. The indoor/outdoor ratio (I/O ratio) of $PM_{2.5}$ is estimated to be 0.58 during the smoke episode and 0.18 during normal conditions, as shown in Figure 18. However, the low R^2 values suggest a weak correlation. The fit could be improved with functional on-site ambient $PM_{2.5}$ monitoring. Note that this data is before the cooling upgrade completed in 2022 and, therefore, does not reflect the current conditions of the building.

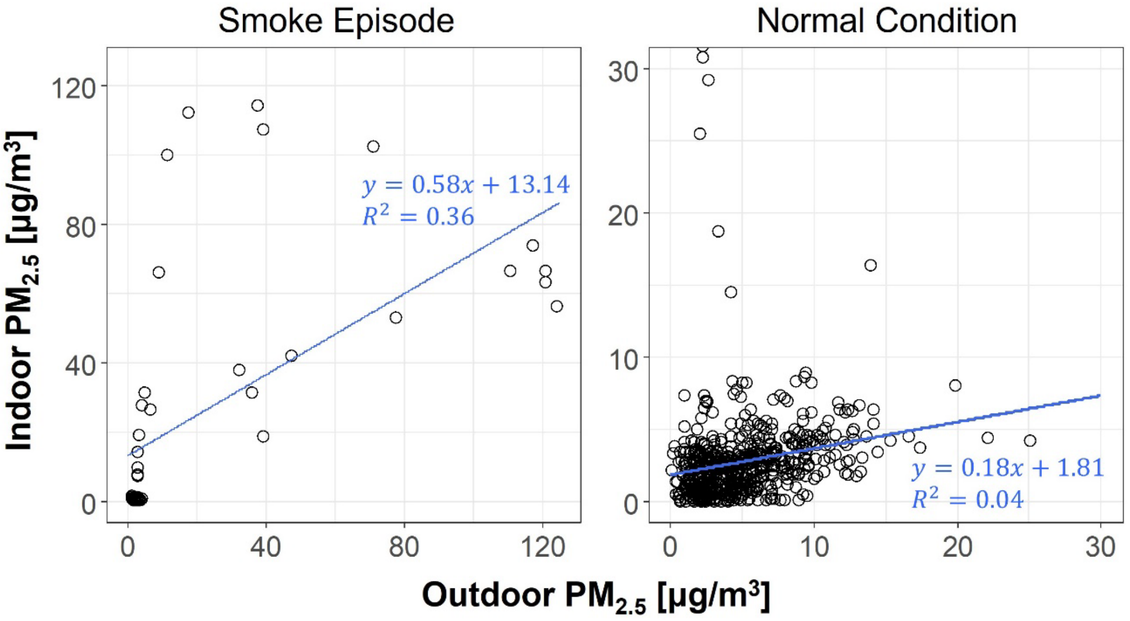

Figure 18. Estimated indoor/outdoor ratio of $PM_{2.5}$ for the smoke episode and normal conditions.

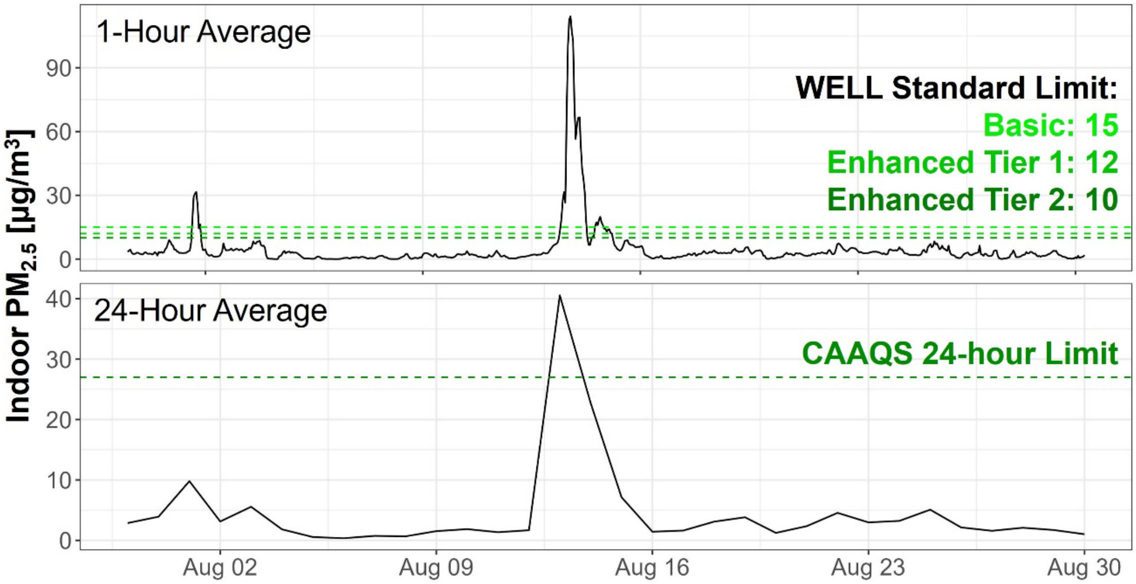

Figure 19. Hourly and daily average $PM_{2.5}$ levels in LCR compared to recommended limits.

The hourly and daily averaged $PM_{2.5}$ levels in LCR in August 2021 are compared with the recommended limits given by the WELL standard and CAAQS in Figure 19. Under normal weather conditions, the $PM_{2.5}$ level was well within the CAAQS required limit and maintained below the 10 μg/m^3 limit required for Enhanced Tier 2 in WELL standard. During the smoke episode, the $PM_{2.5}$ level did exceed both the WELL and CAAQS limits. Overall, the facility was able to provide good air quality with the $PM_{2.5}$ level exceeding either the hourly or daily limits less than 10% of the time, as the data suggests in Table 8.

Table 8. The number of hours and days where the indoor $PM_{2.5}$ level exceeded the recommended limits In LCR.

Recommended Limits	**# of Exceedance**	**% of Exceedance**
Hourly $PM_{2.5}$ Level		
WELL Basic	33 hours	4.47%
WELL Enhanced Tier 1	42 hours	5.68%
WELL Enhanced Tier 2	45 hours	6.09%
Daily $PM_{2.5}$ Level		
CAAQS	1 day	3.13%

4.2 Rehabilitation Centre (RC)

4.2.1 System Description

The RC campus consists of two buildings, i.e., the New Building, constructed in 1972, and the Old Building, constructed in 1941. The New Building is a five-storey structure with a gross area of 13,727 m^2 (net room area of 13,032 m^2) providing acute care services. The Old Building is a two-storey medical clinic with a gross area of 5,247 m^2 (net room area of 5,178 m^2).

Both buildings have similar room use patterns. Temporary assessment and treatment areas, administrative offices, and traffic circulations are the major room use components. The New Building also has overnight patient areas (10.91%) providing general or intensive care.

Currently, the RC campus does not generate heating on-site. The New Building relies on steam fed from a nearby acute care hospital campus directly to air handling units to heat incoming outside air. Hot water is also generated through steam-to-water heat exchangers for perimeter and unit heaters, which use hot water coils. The hot water is also used by the Old Building for space heating.

Cooling in the New Building is provided by a water-cooled chiller with a cooling tower. Refrigerant R-134a is used in the chiller system. A dedicated DX system is present to provide cooling for AHU-7. Most of the areas in the Old Building do not have active cooling, except for the Gym and Workout room, which are served by rooftop units RTU-6 and RTU-7.

In the New Building, conditioned air is distributed through AHUs. Figure 20 and Figure 21 show the typical layout of heating and ventilation elements inside patient rooms. Air filters in the AHUs include a MERV-A 8-A pre-filter and a MERV-A 13-A final filter. Pressure drops across the filters are monitored to inform the facility staff about the condition of the filters.

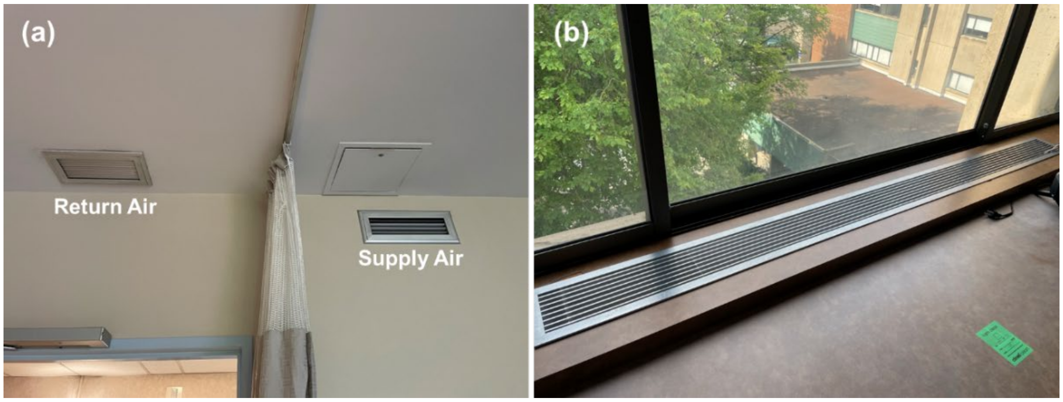

Figure 20. HVAC system terminal units for a typical patient room in RC New Building include (a) supply air diffuser and return air grille at the ceiling level and (b) perimeter radiant heater.

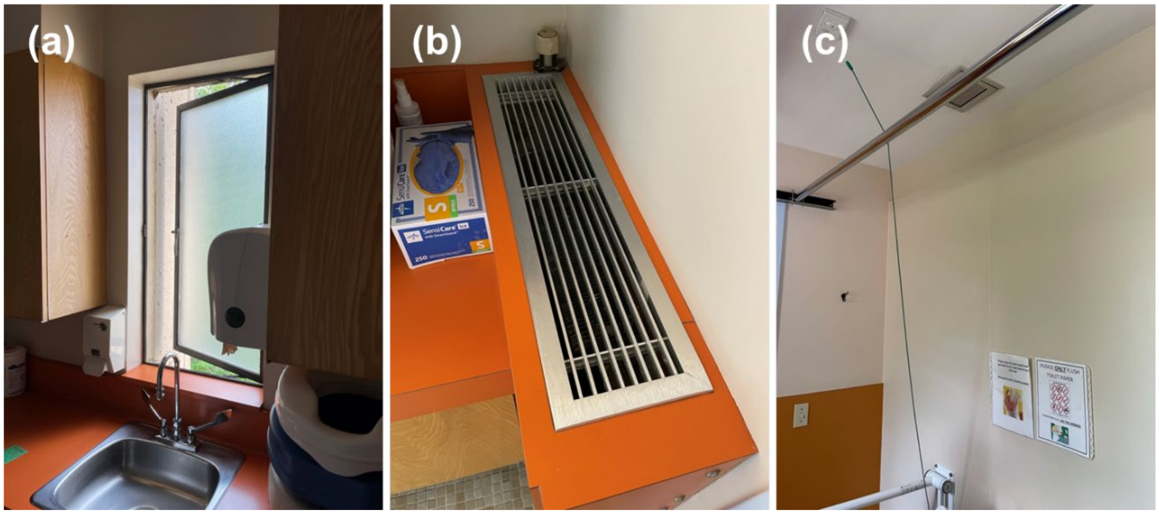

Figure 21. HVAC system terminal units for a typical patient washroom in RC New Building include (a) operable window, (b) radiant heater, and (c) return air grille.

In the Old Building, the corridors and common spaces are heated locally by unit heaters and radiant heaters, as shown in Figure 22. A typical office is only equipped with a perimeter radiant heater without any cooling system. As shown in Figure 23, occupants often rely on personal fans when the room temperature rises. It is worth noting that windows on the upper levels of both buildings are locked by the facilities, and only windows on the main level can be opened.

The existing control system for the two buildings is not fully upgraded. Some of the systems, including radiators and thermostats in patient rooms, are still using pneumatic instead of digital controls.

Figure 22. Heating units and exhaust fans in the Old Building include (a) ceiling fan heater, (b) perimeter radiant heater, and (c) ceiling exhaust fans.

Figure 23. The typical layout of offices in the Old Building includes (a) perimeter unit heater and operable windows and (b) personal fans.

4.2.2 Indoor Air Quality

Nine EGG sensors were originally installed in the New Building, and eight remained in the facility at the time of the visit. Six sensors are currently online and can be accessed through the web portal. The $PM_{2.5}$ data from July 1, 2022, through August 22, 2023, was obtained. The ambient $PM_{2.5}$ data was obtained from both on-site on the 4F roof and from the Vancouver Clark Drive monitoring station.

Figure 24 shows the comparison of ambient $PM_{2.5}$ measurements between the on-site sensor and the government monitoring site. Although a close to 1:1 ratio could be observed, many discrepancies remain, which resulted in a low R^2 value.

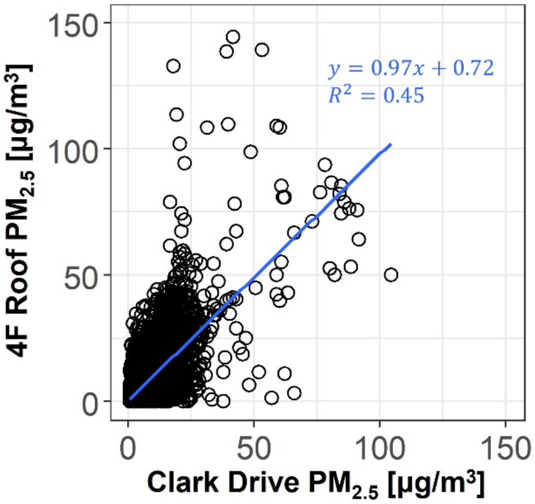

Figure 24. Comparison of ambient $PM_{2.5}$ measurements from on-site sensors and Clark Drive monitoring station.

The hourly averaged time series of $PM_{2.5}$ is shown in Figure 25. Data from the sensor installed on the roof (4F Roof) appears to follow ambient $PM_{2.5}$ collected from the Vancouver Clark Drive air monitoring station in terms of the general trend. One of the basement locations (Bsmt out 48C) shows higher $PM_{2.5}$ levels and fluctuations compared to the other four indoor locations. As shown in Figure 8, two smoke episodes could be observed on September 11, 2022 and October 18, 2022. It appears in Figure 25 that the ambient $PM_{2.5}$ was also elevated in March 2023. However, the indoor data in March was not processed due to missing time labels. The estimated $PM_{2.5}$ I/O ratio is shown in Figure 26. The indoor $PM_{2.5}$ level was calculated as the average of the five indoor locations, and the data from the on-site roof sensor was used for outdoor $PM_{2.5}$. The HVAC system with MERV-8 and MERV-13 filters appears to be able to maintain a 0.4 I/O ratio regardless of the ambient air condition.

The hourly and daily averaged $PM_{2.5}$ levels in RC New Building from July 2022 through August 2023 are compared with the recommended limits given by the WELL standard and CAAQS in Figure 27. Note that the $PM_{2.5}$ levels were also averaged over different locations. Under normal weather conditions, the $PM_{2.5}$ level was well within the CAAQS required limit and maintained below the 10 µg/m^3 limit required for Enhanced Tier 2 in WELL standard most of the time. During the smoke episode, the $PM_{2.5}$ level did exceed both the WELL and CAAQS limits.

Overall, the facility was able to provide good air quality with the $PM_{2.5}$ level exceeding either the hourly or daily limits less than 10% of the time, as the data suggests in Table 9.

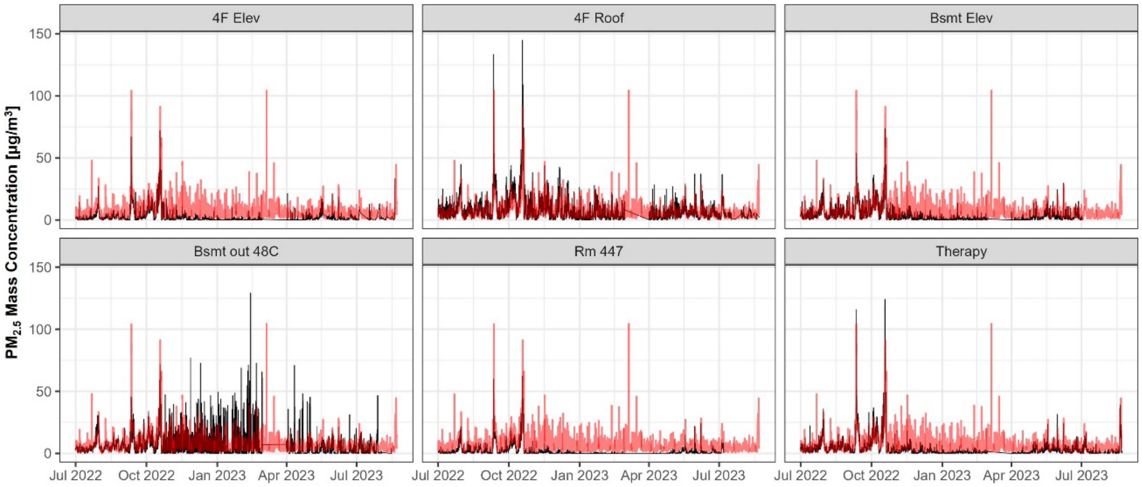

Figure 25. One-hour average PM2.5 collected from six EGGs located in the RC New Building is shown in black. Ambient PM2.5 data from the Vancouver Clark Drive air monitoring station (Government of British Columbia, 2023) is shown in red.

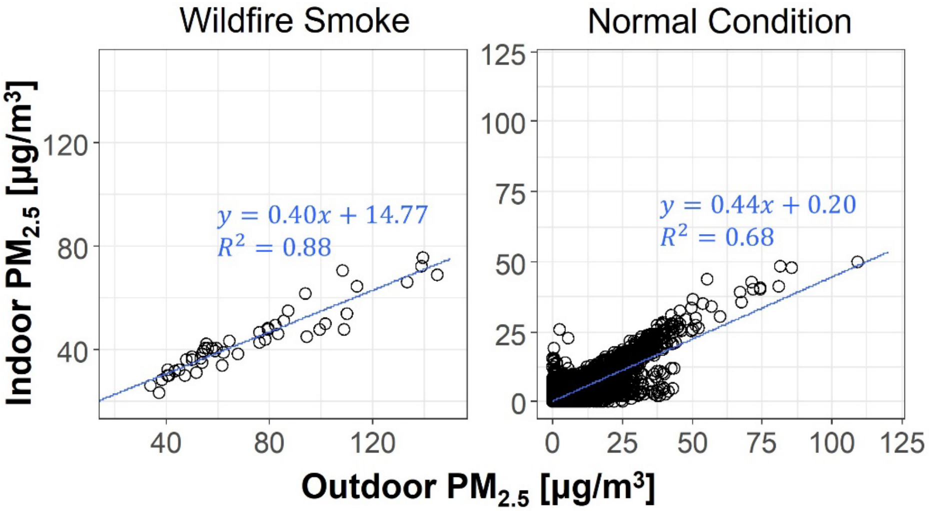

Figure 26. Indoor/Outdoor ratio of $PM_{2.5}$ calculated using spatially averaged indoor $PM_{2.5}$ concentration and outdoor $PM_{2.5}$ concentration from on-site EGG device on the roof.

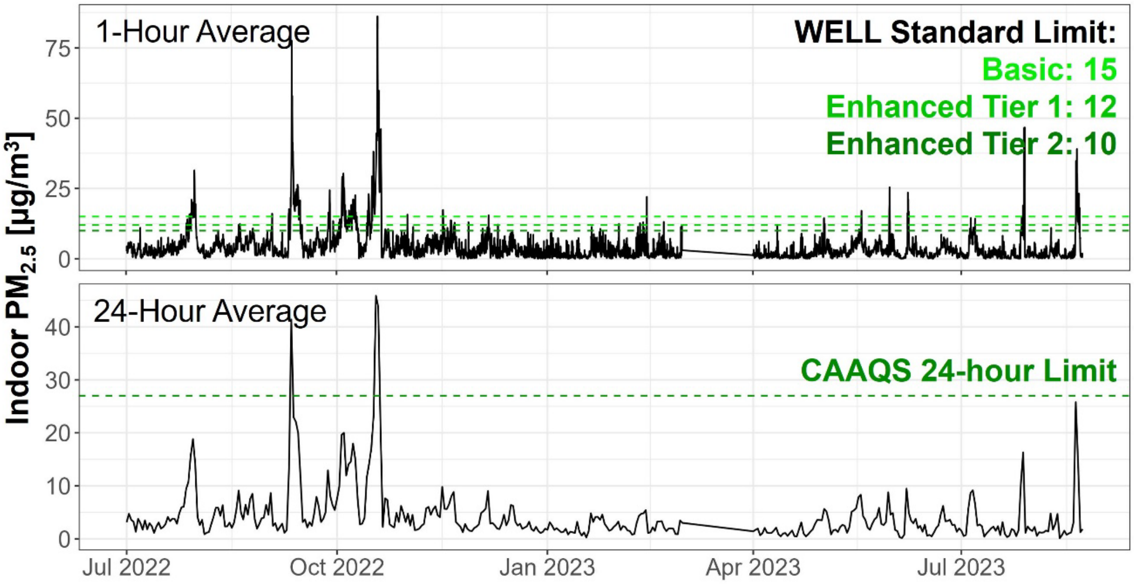

Figure 27. Hourly and daily average $PM_{2.5}$ levels in RC New Building compared to recommended limits.

Table 9. The number of hours and days where the indoor $PM_{2.5}$ level exceeded the recommended limits in RC New Building.

Recommended Limits	# of Exceedance	% of Exceedance
Hourly $PM_{2.5}$ Level		
WELL Basic	439 hours	4.76%
WELL Enhanced Tier 1	608 hours	6.59%
WELL Enhanced Tier 2	780 hours	8.45%
Daily $PM_{2.5}$ Level		
CAAQS	3 days	0.77%

4.3 Mental Health Centre (MHC)

4.3.1 System Description

The MHC building is a LEED Gold certified nine-storey psychiatric long-term care facility completed in 2017. The building has a gross area of 11,920 m^2 and a net room area of 11,026 m^2. The room type breakdown shows that traffic circulation takes up one-quarter of the floor areas, and patient care rooms make up the second largest category. Nearly 13% of the floor areas are reserved for building systems and equipment.

A four-module heat recovery chiller located on the rooftop is the primary source of heating and cooling for the entire building. The heat recovery chiller uses refrigerant R-410A in the system. Two gas boilers serve as the primary backup system for heating. The steam and condensate system on the hospital campus serves as the secondary backup system for heating. Patient rooms are also equipped with radiant ceiling heating systems to provide additional heating capacity.

Two AHUs are responsible for distributing conditioned air to the whole building. Floors 1-3 are served by AHU-1, and floors 4-8 are served by AHU-2. Common spaces, such as circulation areas, are served by four-pipe active chilled beams and VAV boxes (see Figure 28). Patient rooms, on the other hand, are served by radiant ceiling heating systems and VAV boxes (see Figure 29). Air filters in both AHUs include a MERV-A 8-A pre-filter and a MERV-A 13-A final filter.

The CO_2 levels in the building are monitored by the control system with an upper limit set at 1,000 ppm. If the CO_2 concentration remains above the limit for more than ten minutes, an alarm will be sent to the FMOs to investigate. However, the CO_2 sensors do not have the ability to alter the HVAC system's operation automatically.

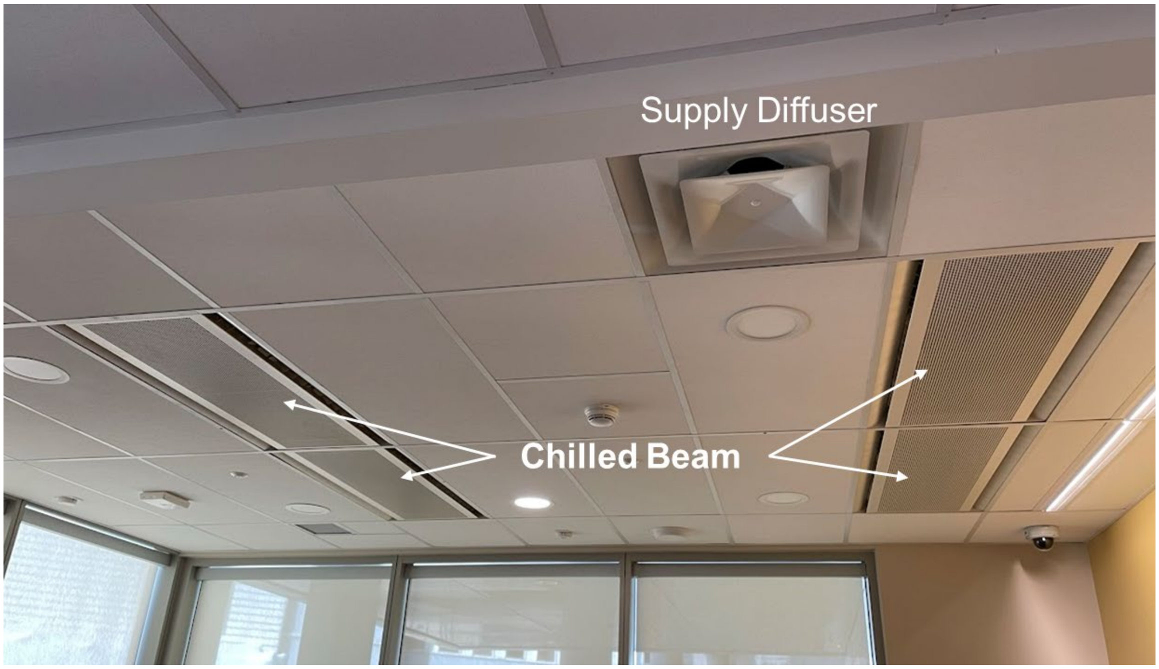

Figure 28. The MHC building's common areas are served by active chilled beams and supply diffusers connected to VAV boxes.

Figure 29. Ventilation terminal units in MHC patient rooms.

4.3.2 Indoor Air Quality

Eleven EGG sensors were originally installed in MHC, and nine remained in the facility at the time of the visit. Eight sensors are currently online and can be accessed through the web portal. The $PM_{2.5}$ concentration data collected from the EGGs is shown in Figure 30. The $PM_{2.5}$ data from July 1, 2022, through August 22, 2023, was obtained. It appears that the indoor $PM_{2.5}$ levels follow the trend of the ambient $PM_{2.5}$ and are, in general, lower in the summer months.

Because no ambient $PM_{2.5}$ is available from the on-site sensors, data from the RC roof sensor was used to estimate the I/O ratio. The estimated $PM_{2.5}$ I/O ratio is shown in Figure 31. The indoor $PM_{2.5}$ level was calculated as the average of the eight indoor locations. The HVAC system with MERV-8 and MERV-13 filters appears to perform well and maintain a below 0.3 I/O ratio regardless of the ambient air condition.

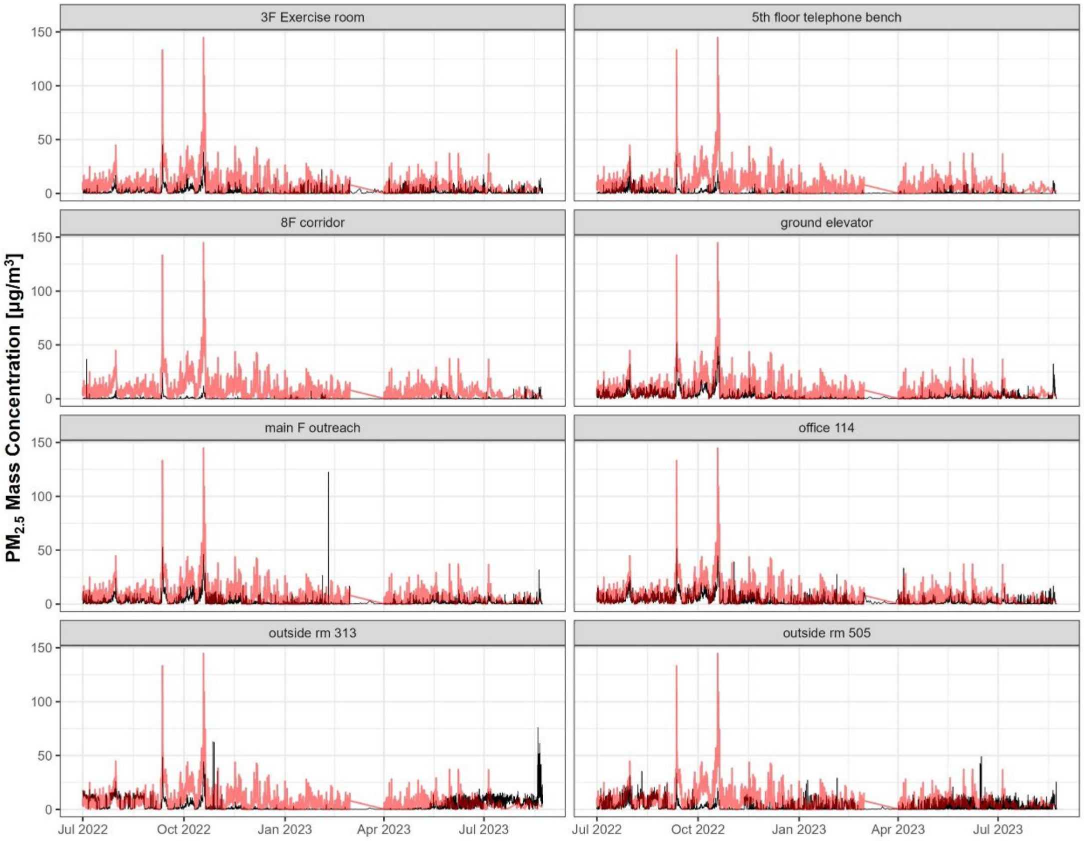

Figure 30. One-hour average $PM_{2.5}$ collected from eight EGGs located in the MHC building is shown in black. Ambient PM2.5 data from the Vancouver Clark Drive air monitoring station is shown in red.

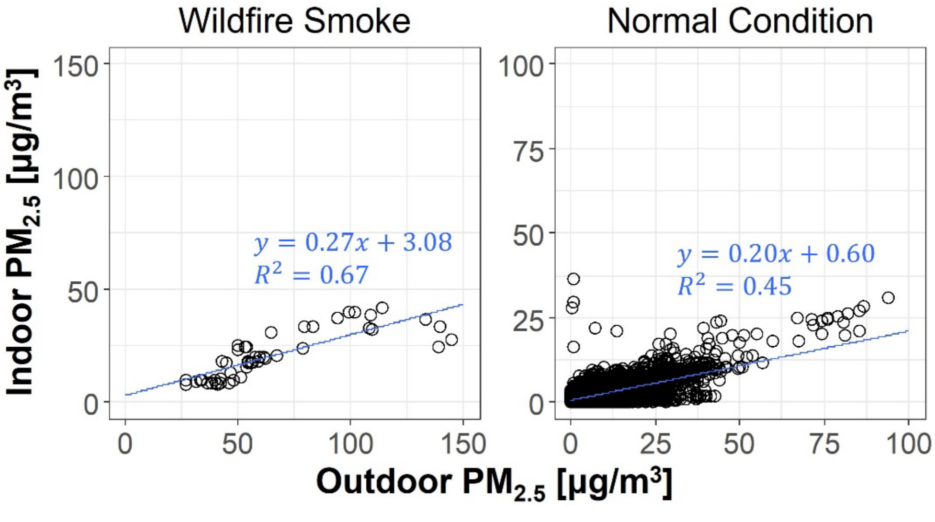

Figure 31. Indoor/Outdoor ratio of $PM_{2.5}$ calculated using spatially averaged indoor $PM_{2.5}$ concentration and outdoor $PM_{2.5}$ concentration from EGG device on the roof of RC.

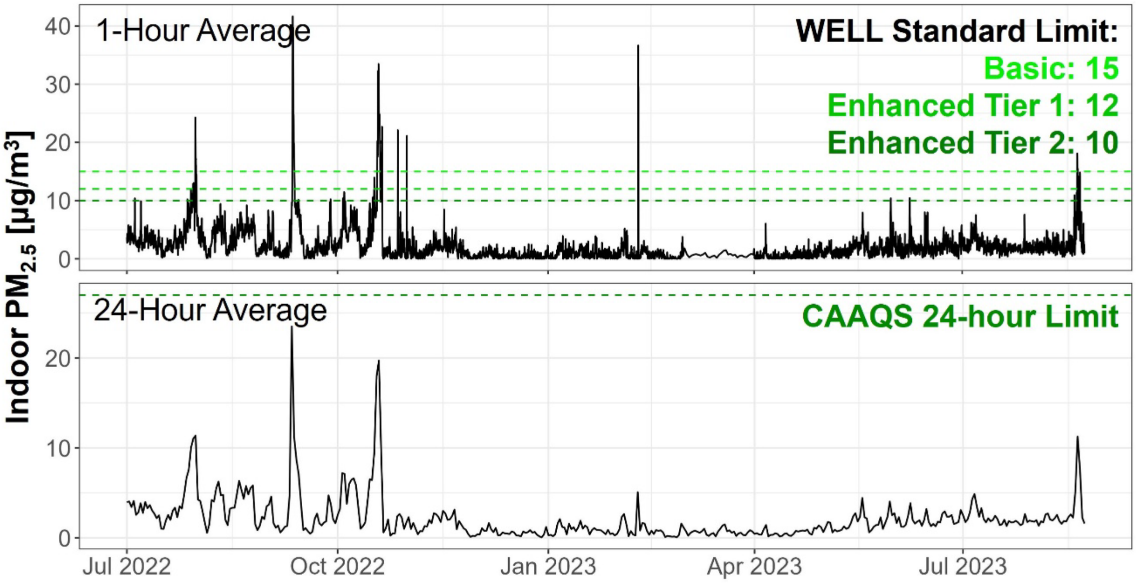

Figure 32. Hourly and daily average $PM_{2.5}$ levels in MHC compared to recommended limits.

The hourly and daily averaged $PM_{2.5}$ levels in MHC from July 2022 through August 2023 are compared with the recommended limits given by the WELL standard and CAAQS in Figure 32. Note that the $PM_{2.5}$ levels were also averaged over different locations. Under normal weather conditions, the $PM_{2.5}$ level was well within the CAAQS required limit and maintained below the 10 μg/m3 limit required for Enhanced Tier 2 in WELL standard most of the time. During the smoke episode, the $PM_{2.5}$ level did exceed the WELL standard limits for short periods, but the 24-hour average never exceeded the CAAQS limit. Overall, the facility was able to provide excellent air quality, with the $PM_{2.5}$ level exceeding either the hourly or daily limits less than 2% of the time, as the data suggests in Table 10.

Table 10. The number of hours and days where the indoor $PM_{2.5}$ level exceeded the recommended limits in MHC.

Recommended Limits	**# of Exceedance**	**% of Exceedance**
Hourly $PM_{2.5}$ Level		
WELL Basic	79 hours	0.85%
WELL Enhanced Tier 1	109 hours	1.17%
WELL Enhanced Tier 2	171 hours	1.83%
Daily $PM_{2.5}$ Level		
CAAQS	0 days	0%

5 Issues and Recommendations

The following recommendations are formed based on observations and discussions with facility managers during the site visits, as well as the measures taken by the precedent projects. The order of the recommendations follows the process illustrated in Figure 13 with a focus on existing building commissioning, air distribution system upgrades, and heating and cooling systems. Recommendations related to occupant behaviours and alternative energy will be given at the end.

5.1 Recommissioning

It is recommended that the health care facility conduct recommissioning every three to five years (Hendron et al., 2013). The purpose is to identify areas where the building systems are not operating as designed and perform appropriate corrections. During the site visit of MHC, two major issues were discussed. The first issue involved the heating and cooling coil orientations in both AHU-1 and AHU-2. Record drawings showed that in each AHU, the heating coil should be installed before the cooling coil so that incoming outdoor air could be preheated to prevent the cooling coil from freezing in winter. However, the actual installation had the installation order reversed, with the cooling coil installed between the heating coil and the outdoor air intake. Furthermore, the freezestat was installed after the heating coil, which provided no protection for the cooling coil.

A second issue exists for AHU-2. AHU-2 was designed to be a dual-duct system with heating and cooling coils installed in both ducts to condition the mixture of return air and fresh outside air. The return air was to be mixed with the outside air in a mixing chamber before the mixture split and entered into two ducts to be conditioned by the air filters and the heating/cooling coils. The intent was to pre-condition the outside air with the return air to reduce energy consumption. However, the actual installation did not set up the mixing chamber, with the outside air going through one duct and the return air through the other duct. The two air streams only mix after being conditioned by the coils. There is a lost opportunity for energy savings by not using the return air to pre-condition the outside air.

At RC, during a review of the system operation schedules, it was noted that AHU-8 was programmed to operate on Sundays but not Saturdays for no apparent reason. Other AHUs also appear to have irregular schedules, as listed in Table 11.

Table 11. HVAC schedule from the DDC system at RC.

System	Schedule
AHU-1	24/7
AHU-2	Mon - Sun: 7 a.m. – 8 p.m.
AHU-3	Mon - Sun: 7 a.m. – 10 p.m.
AHU-4	Mon - Sun: 5:15 a.m. – 6:30 p.m.
AHU-5	24/7
AHU-6	24/7
AHU-7	Mon – Fri: 5 a.m. – 8 p.m. Sat – Sun: 5 a.m. – 3 p.m.
AHU-8	Mon – Fri: 7 a.m. – 5 p.m. Sat: Off Sun: 7 a.m. – 5 p.m.
AHU-9	Mon – Fri: 8 a.m. – 6 p.m.
Music Studio	Local control by users
RTU-6	Mon – Sun: 7 a.m. – 7 p.m.
RTU-7	Mon – Sun: 7 a.m. – 7 p.m.

The issues with AHU-1 and AHU-2 at MHC were only discovered after a low temperature in winter caused the cooling coil in AHU-2 to burst, which resulted in water damage. The operation schedule issue at RC could incur excess energy consumption if the system is operating without any demand. It is recommended that all facilities schedule periodic recommissioning processes to ensure that systems are installed and operated as designed.

5.2 Create Building Readiness Plans

As discussed in sections 2.4 and 2.5, ASHRAE has called for building owners and managers to prepare building readiness plans for extreme weather conditions such as wildfire smoke episodes as well as for public health emergencies such as COVID-19 pandemic. Facility managers of the three sites voiced similar interests in establishing easy-to-implement procedures to respond to abnormal conditions. Currently, the three facilities do not have pre-determined operation protocols for wildfire smoke episodes, and the operation remained the same during COVID-19 pandemic since no COVID patients were treated at the three facilities. It is recommended that VCH task facility managers with drafting the building readiness plans for each building. Resources should be allocated to ensure that the plans can be successfully implemented when activated. This includes material resources to enhance HVAC system performance as well as time resources for facility staff training.

As global warming continues to exert influences on the climate, it is difficult to predict with some certainty what future extreme events could occur at a given location. The essence of the ASHRAE 44P framework and Standard 241 is to emphasize the importance of flexible HVAC system design and continuous training of the facilities staff. Buildings in the future are expected to be versatile and switch between different operation modes to provide maximum protection for the occupants under abnormal conditions.

5.3 Energy Modelling with Future Weather Files

Energy models are often the most effective tool for estimating energy savings of retrofit measures. A correctly built, verified, and validated energy model is often the best approach to estimating the impact of retrofit measures on building energy consumption. This is particularly true for deep energy retrofit when the building envelope is involved (SBC, 2021). Although this report does not consider the building envelope, it is recognized that some VCH buildings already have existing energy models, and some buildings could require energy models in the future for other projects. For example, the MHC building has an energy model built by consultants as part of the LEED certification process. When conducting analysis using the energy models, VCH may consider adding the requirement for analysts and consultants to incorporate future weather files into the analysis. As an example, UBC's Climate Ready Requirements require the use of PCIC future climate files for the thermal comfort modelling of buildings (UBC, 2020).

To go one step further, future extreme weather files could also be included in the modelling process. The extreme weather file enables the user to assign probabilities to certain weather events, e.g., heat waves, and evaluate the combined effect of global warming and extreme weather on the future energy consumption of the building. As of now, publicly available extreme weather files are scarce compared to future weather files. It is anticipated that increased research efforts (Argonne National Laboratory, 2023) could lead to the wide availability of the weather file for major urban locations.

5.4 Natural Ventilation as Supplement

Despite the recent increase in heat waves and wildfire smoke episodes, Vancouver's climate still creates some favourable conditions for natural ventilation, especially in the summer months when the nighttime temperature often drops to around 15 °C or below. In the areas where patient safety would not be compromised by operable windows, VCH facilities should consider adding natural ventilation capabilities to reduce the cooling system energy consumption. At a minimum, by conducting night flush in summer when ambient temperature allows, the cooling load during daytime could be reduced. Figure 33 shows the lobby area of LCR. The upper windows could potentially be motorized to allow natural ventilation in the lobby.

Figure 33. Upper windows in the lobby area of LCR.

However, special attention should be paid to the RH levels of the ambient air. Although rainfalls are rare in the summer in Vancouver, the ambient RH could remain above 60%. Indoor RH needs to be monitored to ensure that natural ventilation does not cause humidity issues inside the facility. The motorized window should be carefully designed to minimize unwanted air infiltration, which could result in increased heat loss during winter and offset the energy savings obtained in summer.

5.5 Modernize Building Control System (BCS)

A modern HVAC system requires digital controls for all of the major components. Digital controls could enable fast responses with more accurate outcomes and less energy compared to pneumatic controls. In addition, streamlined implementation of building readiness plans could not be realized without an advanced and efficient control system. Investment should be made to upgrade any existing pneumatic controls in VCH buildings and to ensure major HVAC components are connected to the BCS. For example, pneumatic controls still exist in RC for radiators and thermostats in some patient rooms. Five out of the seven RTUs are currently not connected to the building control system and are controlled locally.

During the visit to the LCR, it was observed that staff and residents often leave the exterior doors open when accessing the outdoor areas through the lounges. When the cooling system is in operation, these openings increase the cooling load of the lounge area and result in increased energy consumption. The same situation also occurs in patient rooms where staff keeps the windows open when attending to patients to remove smells and leaves the window open even when patients are taken out of the room for prolonged periods. To mitigate the energy implications of these actions, building managers could consider installing window and door-opening sensors and connecting them to BCS to regulate the ventilation rate for the affected area accordingly. When BCS detects an extended opening period of a window or a door, the ventilation rate of the adjacent area could be lowered to reduce energy waste. Alternatively, windows and doors could be motorized and programmed to be closed after a pre-determined amount of time has elapsed. This is suitable when the ventilation rate cannot be adjusted for the area due to technical or compliance issues.

5.6 Implement and Enhance DCV

As discussed in section 2.2, recent studies suggest that the minimum outdoor air change rate of 2 ach should be adequate for non-critical areas of the health care facilities (Barolin & English, 2023). It is logical to advocate for the wider application of DCV to reduce unwarranted ventilation for spaces with less demand. Many of the VCH facilities have already installed sensors to monitor CO_2 levels in various spaces. The operation of these sensors should be reviewed to confirm that the information collected by these sensors is indeed being used by facility staff to adjust system operations. At present, CO_2 sensors installed at RC and MHC do not have control over the ventilation rate. A further enhancement could be the implementation of algorithms allowing the sensors to regulate the ventilation rates of the monitored spaces.

5.7 Alternative Air Distribution Method

The conventional mixing ventilation (MV) method with overhead air distribution terminals is still prevalent in existing health care facilities, as observed from the site visits. The COVID-19 pandemic has triggered increased interest in displacement ventilation (DV). The DV system delivers cold supply air from the floor level at low velocity. The supply air rises due to buoyancy and exhaust from the ceiling with captured sensible heat, therefore creating stratified temperature distribution in the space (Khankari, 2019). Studies have shown that DV system could provide better thermal comfort and air quality compared to MV, and reduce energy consumption at the same time (Hans & Pappas, 2020; Johnson & Burroughs, 2022; Khankari, 2019). However, Li et al. (2011) cautioned that DV application in hospitals could be problematic when 1) the pollutants were denser than the room air, 2) the pollutants were injected into the thermally stratified zone without any positive buoyancy force, and 3) disturbances to the room air were strong. The author concluded that DV should not be used in either single-patient or multiple-patient wards for infectious aerosol control purposes (Li et al., 2011).

Stratum ventilation (SV) system offers yet another way to deliver conditioned air. SV system includes air supply terminals placed on the side wall above the head height of occupants to distribute air directly to the breathing zone (Yao & Lin, 2014). The supply air diffuser in Figure 29 is an example of SV system air supply terminal. A study conducted by Lu et al. (2020) found that SV system had higher effectiveness in removing indoor air contaminants and minimized exposure risk of health care workers in hospital wards. Moreover, life cycle cost analysis has shown that SV system is the best option for small-to-medium sized rooms to mitigate GHG emissions under normal cooling loads when compared with MV and DV systems (Fong et al., 2017). It is therefore recommended that VCH explore the potential application of SV system in patient rooms. Caution should be taken when designing the SV system supply diffusers. When the horizontal air velocity is too high, occupants may experience discomfort and alter the diffuser operation without the knowledge of facility staff. One instance was observed during the visit at RC where the patient intentionally blocked the air supply diffuser on the sidewall with paper to reduce the air velocity.

5.8 Improve Filter Performance

As required by CSA Z317.2:19 (CSA Group, 2021), air filters in Canadian health care facilities should be rated by both MERV and MERV-A methods as defined in ASHRAE 52.2 (ASHRAE, 2017). VCH facilities should conduct reviews of the purchased air filters for MERV-A ratings. For filters that do not bear MERV-A ratings, the vendor should be contacted to obtain additional rating information in order to determine if the filters could be kept in use.

During the site visits, it was observed that the installation of air filters in most of the AHUs is similar to the configuration shown in Figure 16. The MERV-8 pre-filter and MERV-13 final filter are placed adjacent to each other. CSA Z317.2:19 section 6.7.5 requires that the first stage of filtration be installed upstream of the air-conditioning equipment and the second stage of filtration be located downstream of the supply air fan. It could be argued that by placing the

MERV-13 filter downstream of the supply air fan in the positively pressurized section, the fan energy required to move air through the filter would be reduced. It is therefore recommended that building managers consider the possibility of correcting the placement of pre- and final filters to comply with CSA Z317.2:19.

5.9 Electrify Heating Systems

The majority of VCH's energy use still relies on fossil fuels, as shown in Figure 4. It is consistent with other health care facilities in BC, according to the benchmarking data in Figure 2. Most of the fossil fuel is consumed for heating purposes in BC's climate. By electrifying heating systems, the organization could reduce its reliance on fossil fuels and cut down carbon emissions. LCR currently provides space and water heating with two natural gas boilers and one dual-fuel boiler. The two gas boilers could potentially be replaced by electric boilers with higher efficiencies. One of the gas boilers could be kept as the backup boiler for emergencies or meeting peak demand.

5.10 Low GWP Refrigerant

Chillers at the three selected sites are using either refrigerant R-410A or R-134a to provide cooling. Both refrigerants are considered high-global warming potential (high-GWP) refrigerants (California Air Resources Board, 2023). The U.S. EPA has moved forward with rulemaking to restrict the use of R-410A and R-134a in comfort-cooling chillers (Carrier, 2022). In Canada, the importation of R-134a is also restricted (CBSA, 2018). These regulations will result in decreased supplies and increased prices. VCH should start exploring low GWP refrigerant solutions for heat pumps and chillers (U.S. EPA, 2022).

5.11 Holistic Occupant Feedback System

In an interview study conducted by Afroz et al. (2020), the outcomes suggested that direct occupant feedback, e.g., complaint logs, was not always sufficient in pinpointing the root cause of building functionality issues. A more holistic feedback system incorporating many data sources and advanced HVAC controls with a simplified fault detection process could dramatically increase the building operators' efficiency in responding to occupants' requests. Nojedehi et al. (2023) proposed a framework to collect occupant feedback regarding thermal comfort and indoor air quality through mobile or wearable devices to support fault detection and diagnostics of building control systems. Compared to occupant surveys conducted at discrete times with time limits, this framework allows occupants to voice their opinions at their convenience. It is more likely to learn the occupants' perceptions of thermal comfort and indoor air quality through this framework than conducting numerous surveys, which could easily cause survey fatigue.

The Energy and Environmental Sustainability (EES) team currently conducts an annual GreenCare survey (EES Team, 2023) across four health authorities in BC, including VCH. The survey measures the success of sustainability programs and initiatives and provides insights into staff knowledge of environmental issues. Because of the broad aspects covered by the survey, it is not practical to introduce detailed questions regarding indoor air quality or other environmental quality metrics. Some sample questions designed specifically for indoor environmental quality surveys in office buildings (Kim et al., 2020) are given in Appendix II and could be adapted to health care settings. However, it is understandable that distributing additional surveys could likely cause survey fatigue due to the workload of health care workers. Nevertheless, these questions could be used when possible to gauge the perceptions of workers, patients, and visitors regarding the indoor environmental quality of the facilities.

In the long term, VCH facilities could be transformed into a network of connected smart buildings. Within each building, operational data is collected at any given time from three streams, i.e., engineering systems, occupant behaviour, and environmental sensors. Engineering systems cover the data reporting from the conventional building control system and provide information regarding the operation of the centralized systems as designed. Occupant behaviour data is collected through mobile and wearable devices with voluntary participation. Other occupant monitoring technologies could also be employed given that they are non-intrusive, privacy-preserving, and low-cost. Environmental sensors include a set of monitoring devices that measure parameters such as CO_2, $PM_{2.5}$, VOCs, window and door openings, etc. Data from the sensor supplements the engineering system and could reveal the gap between actual and designed indoor environment conditions. The Energy-Smart Building program developed by the Microsoft Corporation (Fernandes et al., 2018) could serve as an example of the platform for developing a holistic occupant feedback system. Much work is needed to collaborate with the employees and other building users to establish accepted data collection schemes.

5.12 On-site Solar Energy Generation

During the site visits, it was observed that available roof areas at RC and LCR could be utilized for solar energy generation. Generated electricity could reduce energy costs and offset some carbon emissions from fossil fuel consumption. If coupled with a battery storage system, the electricity could be stored and used to support peak demand reduction and provide secondary backup power. Rough estimates of the solar energy production at the RC and LCR sites are generated using the PVWatts Calculator (NREL, 2023). As shown in Figure 34, the generated power could supply 30-40% of the electricity consumption from March through September. During winter months, the production is low and can only cover below 20% of the consumption. The inputs for the PVWatts Calculator can be found in Appendix III.

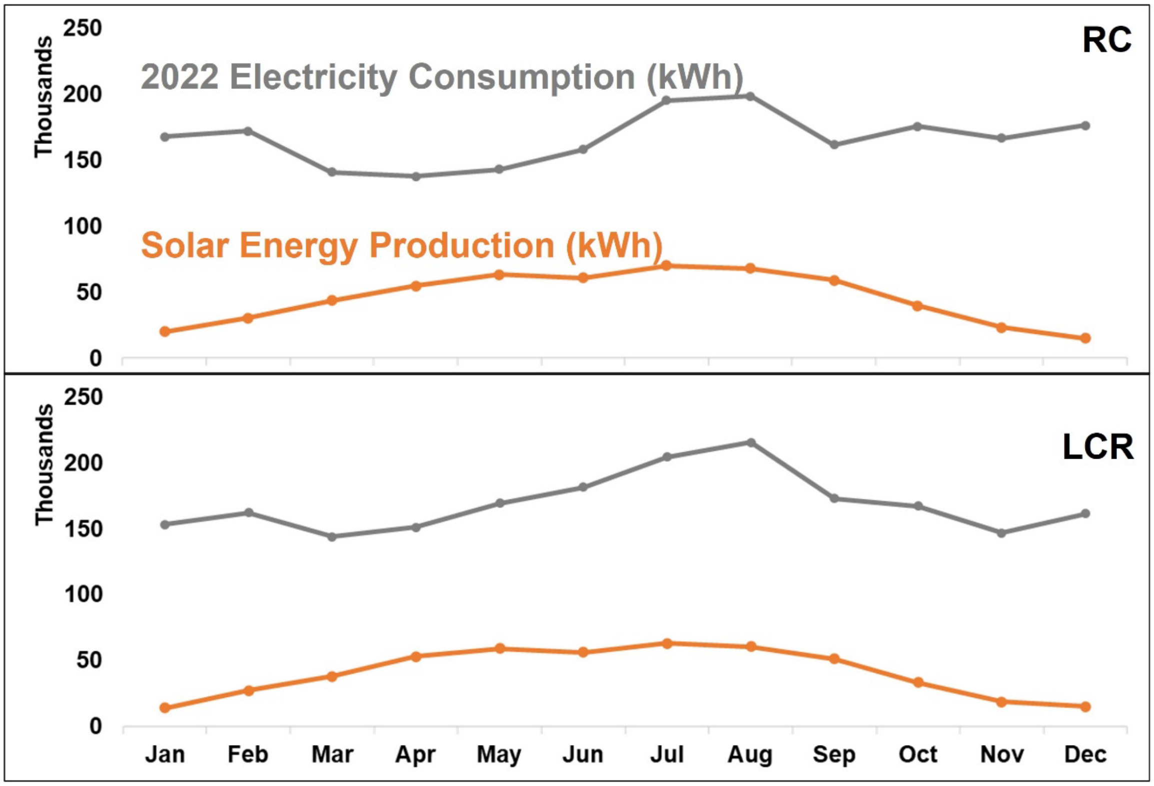

Figure 34. Estimated solar energy production compared to actual electricity consumption at RC and LCR.

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Appendix I

A 3D overview of the reference health care building used for energy modelling with future weather files is shown in Figure 35. Input parameters of the building construction materials, building operations, and HVAC systems are listed in Table 12.

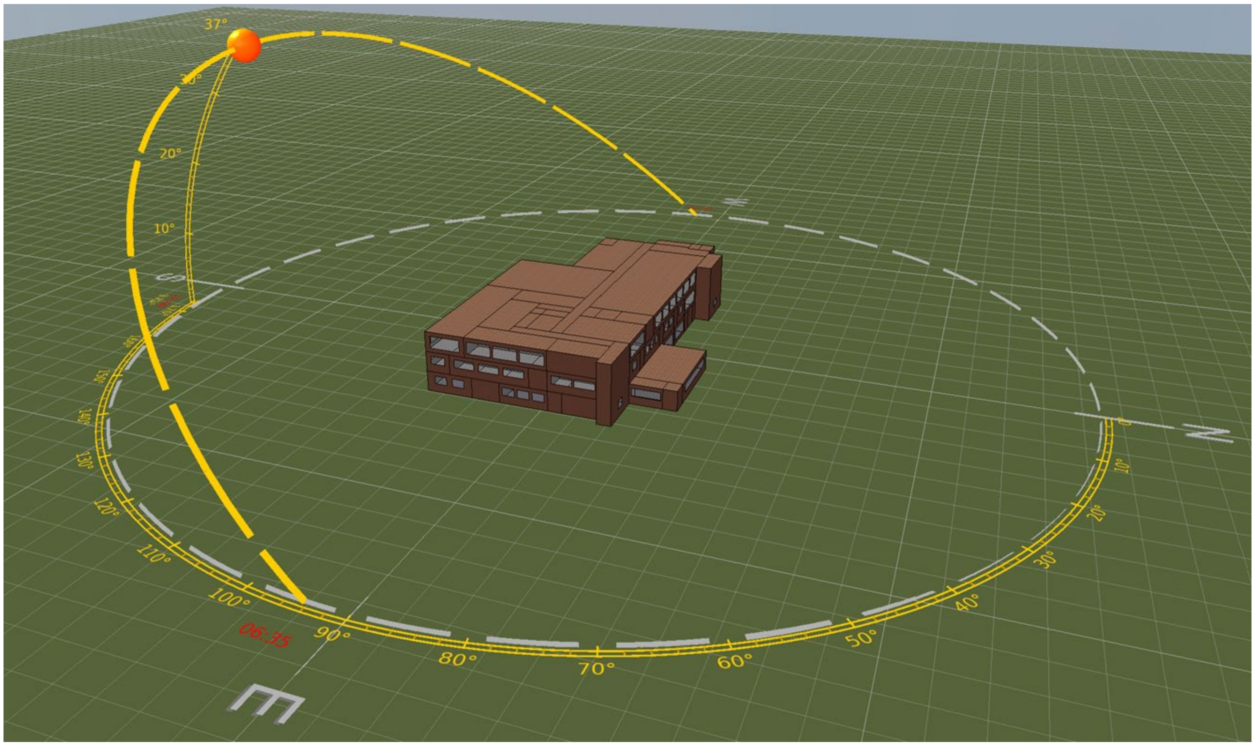


Figure 35. 3D view of the reference health care building used for energy modelling in IESVE with future weather files.

Table 12. Input parameters for the energy modelling conducted in IESVE.

Category	Existing Building
General	
Building Location	Vancouver Harbour, BC (49.26° N, 123.11° W)
Code References	NECB 2017
Building Type	Health care clinic
Weather File	2020s_CAN_BC_Vancouver.Intl.AP.718920_CWEC2016.epw 2050s_CAN_BC_Vancouver.Intl.AP.718920_CWEC2016.epw
Modelled Floor Area	3791 m^2
Simulation Software	IES Virtual Environment 2023.1.0.0
Building Operation	
Operation Schedule	24/7
Cooling Setpoints and Setbacks	Main setpoint: 23.89 °C, Setback setpoint: 26.27 °C
Heating Setpoints and Setbacks	Main setpoint: 21.11 °C, Setback setpoint: 15.56 °C

Category	Existing Building
Envelope Construction	
Roof (R-value)	5.3023
Wall (R-value)	3.6919
Doors Swinging (U-value)	2.1997
Window-To-Wall Ratio	21%
Fenestration (U-value)	1.6
Solar Heat Gain Coefficient (SHGC)	0.3945
Air Infiltration (L/s-m2 of façade)	0.25
Internal Loads	
Occupancy (m2/person)	20
Lighting Power Density (W/m2)	8.8
Equipment Power Density (W/m2)	7.5
Elevators (kW)	5
HVAC – Plant Systems	
Heating Plant Type	Natural-Draft Non-Condensing Boiler
Heating Plant Fuel Sources	Natural Gas
Heating Plant Efficiency (%)	80%
Hot Water Loop Temperature (Supply/DeltaT)	82.22°C / 27.78 °C
Cooling Plant Type	EWC Chiller with VSD Pump
Cooling Plant Efficiency (COP/EER)	6.43 COP
Cold Water Loop Temperature (Supply/DeltaT)	6.67 °C/ 6.67 K
Pump Power	69.74 W/(L/s)
HVAC – Air Systems	
System Type	VAV Reheat
Heating Fuel Source	Natural Gas
Supply Air Temperature (°C)	32.22 °C (Heating) / 12.78 °C (Cooling)
Supply Airflow (L/s)	2.39 L/s/m^2
Minimum Outdoor Airflow (L/s)	0.97 L/s/m^2

Appendix II

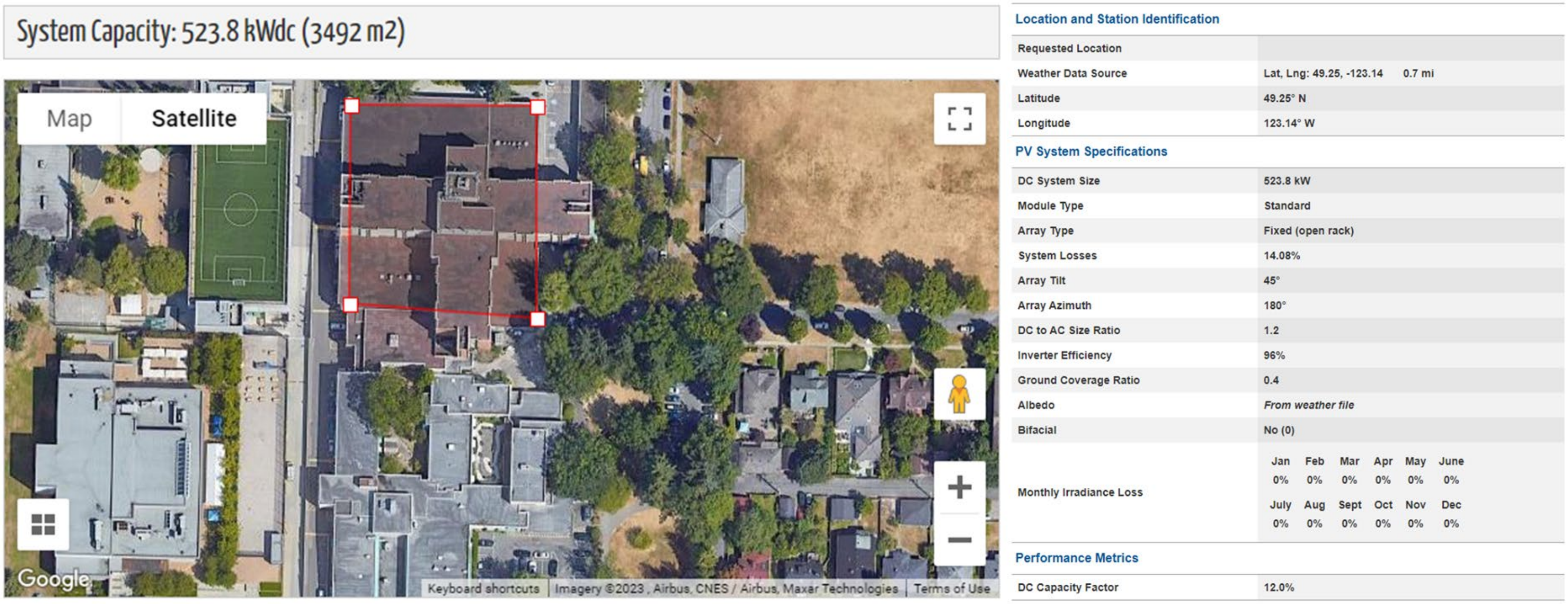
Table 13. Sample questions of an indoor environmental quality survey for office buildings.

Questions	Type
Please indicate how dissatisfied/satisfied you are with the following work features listed below.	
The work you do.	7-point Likert scale from “Very Dissatisfied” to “Very Satisfied”
The physical working conditions you have (light, temperature, noise, etc.).	
The organization’s management.	
The personal relationships with your coworkers.	
The organization considered overall.	
The functioning of your work team.	
The coordination among members of your work team.	
The opportunities to participate in the decisions that affect your work team.	
Thinking over the past two weeks, how often have you experienced the following emotions.	
Tense	7-point Likert scale from “Never” to “All the Time”
Worried	
Uneasy	
Miserable	
Depressed	
Gloomy	
Please indicate the extent of your satisfaction with each of the following aspects of your current physical workspace.	
Amount of noise from other people’s conversations while you are at your workstation.	7-point Likert scale from “Very Unsatisfactory” to “Very satisfactory”
Frequency of distractions from other people.	
Degree of enclosure of your work area by walls, screens, or furniture.	
Level of visual privacy within your work area.	
Distance between you and other people with whom you work.	
Level of privacy for conversations.	
Amount of background noise (i.e., not speech) you hear at your workstation.	
Size of your personal workspace to accommodate your work, materials, and visitors.	
Your ability to alter physical conditions in your work area.	
Aesthetic appearance of your work area.	
Air movement in your work area.	
Overall air quality in your work area.	
Temperature in your work area	
Quality of lighting in your work area.	

Amount of lighting on the desktop.	
Amount of lighting for computer work.	
Amount of reflected light or glare on the computer screen.	
Your access to a view of outside from where you sit.	
Please indicate the extent of your agreement with the following statements.	
I am satisfied with the extent of control I have over aspects of my physical workspace (e.g., lighting, noise, privacy).	7-point Likert scale from “Strongly Disagree” to “Strongly Agree”
I am satisfied with the extent of control I have over the indoor air quality in my personal workspace.	
My input was solicited in the planning process, prior to any space renovation or modifications.	
My input was seriously considered in the planning process, prior to any space renovation or modifications.	
I trust that this building can protect me from harmful air outside.	
I believe that this building can protect me from seasonal smoky conditions outside.	

Appendix III

The input system parameters for estimating the solar energy generation using PVWatts are provided in Figure 36 and Figure 37. In calculating the system capacity, the applicable roof area was drawn over a Google satellite image and a 1 kW/m^2 solar energy generation rate was assumed by default. As can be seen from the selected roof areas for solar installation, the estimation was very conservative considering rooms needed for maintenance and other rooftop equipment. A lot of the roof areas were not included such as the RC Old Building.



System Capacity: 523.8 kWdc (3492 m2)

Location and Station Identification

Requested Location	
Weather Data Source	Lat, Lng: 49.25, -123.14 0.7 mi
Latitude	49.25° N
Longitude	123.14° W

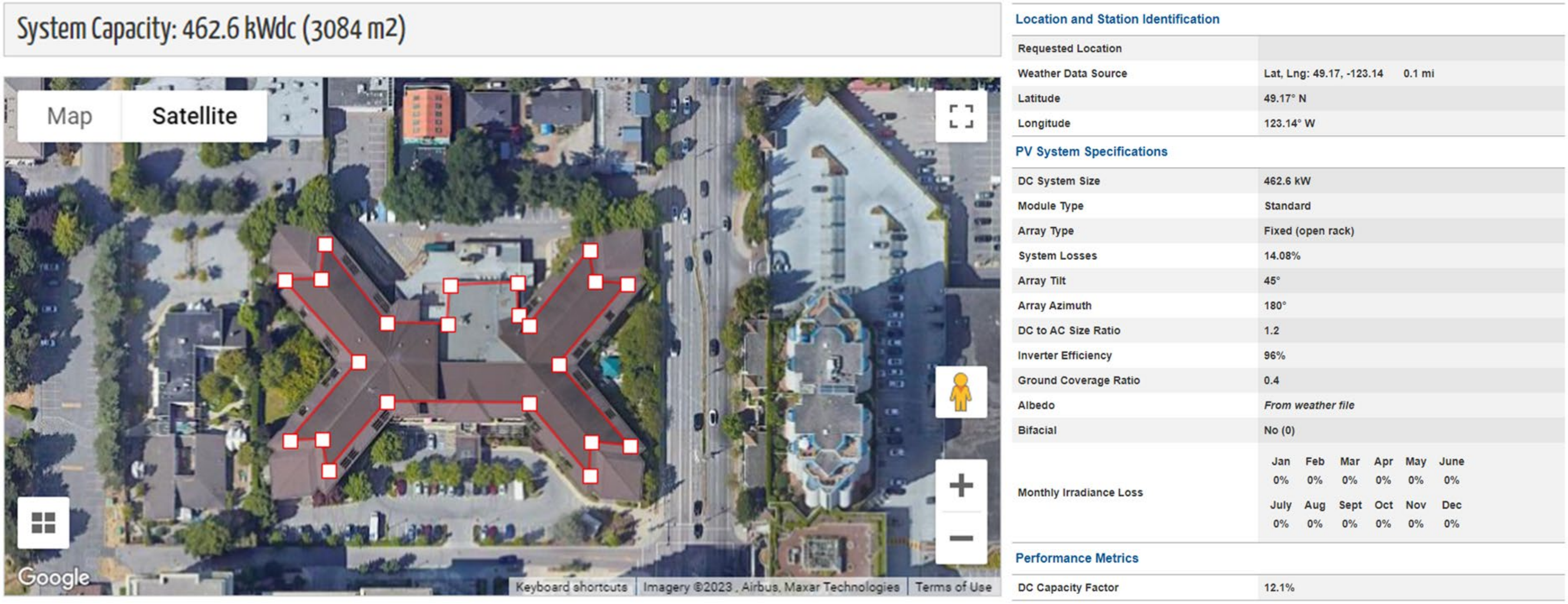
PV System Specifications

DC System Size	523.8 kW
Module Type	Standard
Array Type	Fixed (open rack)
System Losses	14.08%
Array Tilt	45°
Array Azimuth	180°
DC to AC Size Ratio	1.2
Inverter Efficiency	96%
Ground Coverage Ratio	0.4
Albedo	*From weather file*
Bifacial	No (0)
Monthly Irradiance Loss	Jan 0%, Feb 0%, Mar 0%, Apr 0%, May 0%, June 0% July 0%, Aug 0%, Sept 0%, Oct 0%, Nov 0%, Dec 0%

Performance Metrics

DC Capacity Factor	12.0%

Figure 36. PVWatts calculator inputs for RC.



System Capacity: 462.6 kWdc (3084 m2)

Location and Station Identification	
Requested Location	
Weather Data Source	Lat, Lng: 49.17, -123.14 0.1 mi
Latitude	49.17° N
Longitude	123.14° W
PV System Specifications	
DC System Size	462.6 kW
Module Type	Standard
Array Type	Fixed (open rack)
System Losses	14.08%
Array Tilt	45°
Array Azimuth	180°
DC to AC Size Ratio	1.2
Inverter Efficiency	96%
Ground Coverage Ratio	0.4
Albedo	*From weather file*
Bifacial	No (0)
Monthly Irradiance Loss	Jan 0%, Feb 0%, Mar 0%, Apr 0%, May 0%, June 0% July 0%, Aug 0%, Sept 0%, Oct 0%, Nov 0%, Dec 0%
Performance Metrics	
DC Capacity Factor	12.1%

Figure 37. PVWatts calculator inputs for LCR.