Natural Resources Canada Ressources naturelles Canada

CanmetENERGY

Leadership in ecoInnovation

Deep Retrofit Measurement and Verification Protocol for Residential Buildings

Prepared by:
Dr. Brock Conley, Research Engineer, Building and Renewables, Housing and Buildings
Natural Resources Canada, CanmetENERGY

2023.05.31

"CanmetENERGY- Ottawa leads the development of energy science and technology solutions for the environmental and economic benefit of Canadians."

CANADA AWARDS FOR EXCELLENCE PRIX CANADA POUR L'EXCELLENCE 2019

GOLD RECIPIENT EXCELLENCE, INNOVATION & WELLNESS RÉCIPIENDAIRE OR EXCELLENCE, INNOVATION et MIEUX-ÊTRE

Disclaimer:

Neither Natural Resources Canada nor any of its employees makes any warranty express or implied or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of its contents. Reference in the report to any specific commercial product, process, service or organization does not necessarily constitute or imply endorsement, recommendation or favouring by Natural Resources Canada. The views and opinions of authors expressed in this report do not necessarily state or reflect those of Natural Resources Canada.

Funding for this work was provided by Natural Resources Canada through the Greener Neighbourhoods Pilot Program.

Cat. No. M154-161/2023E-PDF

ISBN 978-0-660-49743-3

Table of Contents

1. Introduction 1
1.1 Objective 1
1.2 Scope of Protocol 1
2. Building Data 2
3. Final Remarks 8
4. References 8
5. Appendix A – Measurement and Monitoring 10
5.1 Energy Consumption and Generation 10
5.2 Thermal Comfort and Indoor Air Quality 12
5.3 Hygrothermal 13
6. Appendix B – Verification and Analysis 15
6.1 Energy Consumption and Generation 15
6.2 Thermal Comfort and Indoor Air Quality 16
6.3 Building Envelope Durability 17

Tables and Figures

Table 1: Building characteristic data for pre- and post-retrofit. 2

Table 2: Monitoring and measurement summary 7

Table 3: Energy monitoring summary 11

Table 4: Thermal comfort and air quality monitoring summary 13

Table 5: Hygrothermal and weather monitoring summary 14

Table 6: Thermal comfort and air quality analysis summary 16

Table 7: Mould index values and levels of mould growth 17

Table 8: Material sensitivity classes to mould growth (American Society for Heating, Refrigeration and Air-Conditioning Engineers, 2021) 18

1. Introduction

1.1 Objective

The purpose of a Measurement and Verification (M&V) Protocol (Protocol, hereafter) is to provide a standard to quantify the impact of deep retrofit (DR) projects, to create a template for monitoring plans and to facilitate uniform and comparable evaluation criteria, and data for DR projects for Part 9 and Part 3 Residential Buildings in Canada. An M&V Protocol provides building managers, building operators, building performance engineers, and researchers with the necessary information to create a monitoring plan and verify the performance of a DR.

This Protocol provides standard and advanced **measurement**, **analysis** (energy, thermal comfort, and building envelope), and **verification** of pre- and post-retrofit building performance. With broader adoption, more DR data sets can capture the same information, and projects can be directly compared with minimal effort.

1.2 Scope of Protocol

The scope of the Protocol includes guidelines to:

- Establish baseline or pre-retrofit energy and indoor environmental quality performance;
- Measure energy consumption (and generation, if applicable), indoor environmental quality, and hygrothermal performance within envelope assemblies post-retrofit;
- Identify key performance indicators (KPIs) for each building;
- Select proper equipment used for monitoring building energy consumption, moisture transport and indoor environmental quality (IEQ);
- Analyze the measured energy, moisture and IEQ data;
- Catalog the relevant building characteristics needed to evaluate the effectiveness of energy conservation measures (ECMs);
- Collect qualitative and quantitative pre- and post-retrofit building characteristics and performance information;
- Provide an example case study of a DR with M&V data.

The scope does not include guidance on the following:

- Enhanced estimation of lifecycle (embodied and operational) carbon of the building;
- Affordability assessment of a deep energy retrofit;
- Construction workflows, details, and timelines;
- Occupant surveys;
- Product information, or design strategies for deep energy retrofits, etc.

2. Building Data

The building characteristics listed in Table 1, should be documented pre- and post-retrofit, and used to quantify the impact of a deep retrofit. The information listed in Table 1 is commonly captured in energy modeling and can be easily exported from the model. However, a thorough description can provide added value.

Table 1: Building characteristic data for pre- and post-retrofit.

Characteristic	Pre-retrofit	Post-retrofit
Building Information	• Estimated date of construction • Estimated building footprint • Conditioned floor area • Number of floors • Building orientation • Number of suites/occupants • City and (optional) address	• List all changes to reflect the post-retrofit parameters
Building Condition Assessment	• Major whole building maintenance required at the time of retrofit design	• Remaining maintenance post-retrofit and estimated time until major renovation required

Roof and Attic	• Existing construction – material and thickness • Azimuth • Pitch • Effective R-value	• New construction – material and thickness • Azimuth • Pitch • Effective R-value
Above Grade Walls	• Existing construction – material and thickness • Effective R-Value • Estimated above-grade wall area	• New construction – material and thickness • Effective R-Value • Changes in above-grade wall area if any
Foundation, Slab and Footings	• Existing conditions • Deficiencies (e.g., cracks or damage) • Structural limits • Assembly and U-value	• List of all rehabilitation and remediation tasks, if applicable • New assembly and U-value
Windows	• Frame and window construction • U-value and Solar heat gain coefficient (SHGC) • Window to wall ratio (WWR)	• New frame and window construction • U-value and SHGC • WWR
Air Tightness	• Measured air changes per hour at 50 Pa (ACH50) according to ASTME779, ASTME1827-11, CGSB-149 or equivalent standard	• Measured post-retrofit ACH50 according to ASTME779, ASTME1827-11 CGSB-149 or equivalent standard
Ventilation	• Existing mechanical ventilation flow and exhaust rates; or passive ventilation included in the building	• New mechanical ventilation flow and exhaust rates; or passive ventilation included in the building

Heating	• Existing heating system, including any applicable parameters (e.g., fuel source, efficiency, capacity, specifications, etc.)	• New heating system, including any applicable parameters (e.g., fuel source, efficiency, capacity, specifications, etc.)
Cooling	• Existing cooling system, including any applicable parameters (e.g., fuel source, efficiency, capacity, specifications, etc.)	• New cooling system, including any applicable parameters (e.g., fuel source, efficiency, capacity, specifications, etc.)
Hot Water	• Existing domestic hot water system, including any applicable parameters (e.g., fuel source, efficiency, capacity, specifications, etc.)	• New domestic hot water system, including any applicable parameters (e.g., fuel source, efficiency, capacity, specifications, etc.)
Controls	• Thermostat setpoints and setbacks • BAS for larger buildings	• Thermostat setpoints and setbacks • BAS for larger buildings
Energy Consumption and Operational GHG Emissions	• Measured/estimated annual energy consumption for a minimum 1-year period (utility data or measured) • For constant loads, spot or short-term metering is acceptable • Associated GHG emissions estimated from emission factors in Appendix A	• Measured annual energy consumption for a minimum 1-yr post-retrofit • For constant loads, spot or short-term metering is acceptable • Associated GHG emissions estimated from emission factors in Appendix A
Renewable Energy Generation	• Size or Capacity (e.g., PV array) • Azimuth • Pitch	• Size or Capacity (e.g., PV array) • Azimuth • Pitch

	• Measured amount of generation for a minimum 1-year period	• Measured generation for a min. 1-year period
Occupant Comfort	• Measured interior temperature and humidity according to Appendix A or by occupant survey	• Measured interior temperature and humidity according to Appendix A
Indoor Air Quality	• Measured indoor pollutants according to Appendix A	• Measured indoor pollutants according to Appendix A

In addition to the building characteristics that can be cataloged by the existing building design documents and energy assessments, it is recommended to capture additional data through continuous monitoring. Table 2 shows the monitoring required to verify that the building is high performing, comfortable, and has a durable building envelope. The table headings sub-categorize each metric based on the necessity, number of measurements required, and frequency. The table headings are as follows:

Category: Type of monitoring and data collection for the building retrofit.

Sub-Category: A subset of the monitoring and data collection category.

Metric: The scientific measure used to evaluate performance.

Unit: The unit of measure for the given metric.

Tier: The tier of measurement and verification that each category satisfies.

> Tier 1 represents standard M&V limited to whole building energy and indoor conditions.
>
> Tier 2 represents detailed M&V, including all Tier 1 measurements, sub-metering energy consumption, and refined indoor environment quality assessment.
>
> Tier 3 represents advanced M&V that includes all Tier 1 and 2 measurements with hygrothermal monitoring for above-grade and roof assemblies and on-site weather measurements.

Level: The data resolution for the project. Unit-Level means each suite (MURB), or unit (low rise residential) should be measured for a given metric. Sample-level means a representative sample of suites or units within a multi-unit project should be measured for the given metric. Project-level means there should be one project-level measurement for the given metric.

Measured or Derived: Whether the metric is measured or derived from other data collection.

Minimum Frequency: The suggested minimum frequency that the metric will be collected. In cases where the metrics are not expected to change (i.e., remain constant), monitoring can be done over a brief period (e.g., a few weeks or months). This is called *spot metering*.

Table 2: Monitoring and Measurement Summary

Category	Sub-Category	Metric	Units	Tier	Level	Measured / Derived	Min Frequency
Energy	Electrical use	Total Building and/or Suite	kWh	1	Unit	Measure	Hourly
		Space Heating and Cooling	kWh	2	Unit	Measure	Hourly
		DHW	kWh	2	Unit	Measure	Hourly
		Ventilation	kWh	2	Unit	Measure	Hourly
		Baseloads*	kWh	2	Sample	Measure/Derive*	Spot Meter
	Alternate Fuel	Total Building and/or Suite		1	Unit	Measure	Hourly
	Generation	On-Site PV/other	kWh	1	Unit	Measure	Hourly
GHG	Emissions	Operational	kg_{CO2e}	1	Unit	Derive**	Hourly
		Embodied	Kg_{CO2e}	2	Unit	Derive**	-
Indoor Environment Quality	Air Quality	CO_2	ppm	1	Sample	Measure	Hourly
		Radon	pCi/L_{air}	2	Sample	Measure	Once
		PM 2.5, PM 10	$\mu g/m^3$	2	Sample	Measure	Daily (Average)
		VOCs	ppm	2	Sample	Measure	Daily (Average)
	Thermal Comfort	Indoor Temp	°C	1	Unit	Measure	Hourly
		Indoor RH	%RH	1	Unit	Measure	Hourly
Weather		Exterior Temp	°C	2	Project	Measure	Hourly
		Exterior RH	%RH	2	Project	Measure	Hourly
		Wind Speed and Direction	m/s and °	3	Project	Measure	Hourly
		Precipitation	mm	3	Project	Measure	Hourly
		Solar radiation	W/m^2	3	Project	Measure	Hourly
Hygrothermal	Above Grade	Sheathing Temperature	°C	3	Sample	Measure	Hourly
		Sheathing Moisture Content	%MC	3	Sample	Measure	Hourly
		Sheathing Relative Humidity	%RH	3	Sample	Measure	Hourly
	Roof or Attic	Temperature	°C	3	Sample	Measure	Hourly
		Relative Humidity	%RH	3	Sample	Measure	Hourly
		Wood moisture content	%MC	3	Sample	Measure	Hourly

*The baseloads include lighting and plug loads and can be derived by subtracting the sum of the energy used for space conditioning, ventilation, and DHW from the total energy consumption.

**Derivation of embodied and operational GHG and carbon equivalents are provided in Appendix B.

3. Final Remarks

The objective of this document is to create a data collection and analysis template for deep energy retrofits for low-rise residential buildings. Through this Protocol, a robust and comparable dataset of deep energy retrofits across projects can be created, and the effectiveness of the energy conservation measures using pre- and post-retrofit monitoring could be verified.

Furthermore, the Protocol suggests monitoring locations, measurement frequencies, and key performance indicators to guide engineers, architects and building operators to successfully perform deep energy retrofit data monitoring and verification.

For more information about the measurement and verification of residential building retrofits, a detailed description of each activity is provided in the attached appendices. Additional resources regarding monitoring and verification are available through the IPMVP by Efficiency Valuation Organization (Efficiency Valuation Organization, 2023), and CalTRACK (CalTRACK, 2018).

For more information and guidance on deep retrofit monitoring and verification for residential buildings, please contact the Prefabricated Exterior Energy Retrofit (PEER) team at CanmetENERGY-Ottawa.

4. References

American Society for Heating, Refrigeration and Air-Conditioning Engineers. (2020). *ASHRAE Standard 55: Thermal Environmental Conditions for Human Occupancy.* Atlanta, GA: American Society for Heating, Refrigeration and Air-Conditioning Engineers.

American Society for Heating, Refrigeration and Air-Conditioning Engineers. (2021). *ASHRAE Standard 160: Criteria for Moisture-Control Design Analysis for Buildings.* Atlanta, GA: American Society for Heating, Refrigeration and Air-Conditioning Engineers.

American Society for Heating, Refrigeration and Air-Conditioning Engineers. (2022). *ASHRAE Standard 62.2: Ventilation and Acceptable Indoor Air Quality in Residential Buildings.* Atlanta, GA: American Society for Heating, Refrigeration and Air-Conditioning Engineers.

CalTRACK. (2018). *CalTRACK Technical Documentation*. Retrieved from CalTRACK: https://docs.caltrack.org/en/latest/index.html

Efficiency Valuation Organization. (2023, March 13). *International Performance Measurement and Verification Protocol (IPMVP)*. Retrieved from Efficiency Valuation Organization Website: https://evo-world.org/en/products-services-mainmenu-en/protocols/ipmvp

International Organization for Standardization. (2019). *Greenhouse gases - Part 2: Specification with guidance at the project level for quanitfication, monitoring and report of greenhouse gas emission reductions or removal enhancements.*

Natural Resources Canada. (2023, May 18). *Material Carbon Emissions Estimator (MCE2)*. Retrieved from Natural Resources Canada: https://natural-resources.canada.ca/maps-tools-and-publications/tools/modelling-tools/material-carbon-emissions-estimator/24452

5. Appendix A – Measurement and Monitoring

This section outlines the baseline monitoring needed to perform measurement and verification (M&V) activities pre- and post-retrofit for residential buildings. The protocol lists three main activities to monitor before and after the retrofit:

1. Energy Consumption and Generation;
2. Thermal Comfort and Indoor Air Quality;
3. Hygrothermal Monitoring.

These parameters can be used to quantify the energy and GHG consumption of the pre- and post-retrofit building, the indoor comfort and thermal resilience, and the moisture durability of the pre- and post-retrofit building.

5.1 Energy Consumption and Generation

The energy consumed by a building can be tracked through utility data, or sub-metering of energy end uses in the building. Detailed data provided by sub-metering enables a better understanding of occupant behaviour and the energy used by individual loads. Data logging the main electricity import (or export, if applicable), and main equipment (e.g., HVAC, ventilation, DHW, photovoltaic array, etc.), as well as main gas meter and alternative fuel burning (e.g., gas, oil, or wood, etc.) equipment if applicable, is essential in evaluating the building energy performance.

In **summary**, the purpose of energy monitoring is:

- ➔ To assess the energy savings post-retrofit by whole building monitoring and sub-metering energy use in a comparable and reliable manner;
- ➔ To verify that the building performs as designed and modeled; and
- ➔ To improve the building system commissioning, and diagnosing faults, issues, and inefficient energy consumption.

When **selecting monitoring location**, it is important to capture information that can be used to:

- ➔ Provide a comparison to building performance modeling (model calibration);
- ➔ Calculate the post-retrofit energy (and associated GHG) savings; and
- ➔ Capture on-site conditions that may be ignored in the modelling.

To create a comparable and reliable energy and GHG consumption dataset, here is a list of **guidelines for monitoring**:

- ➔ Meter the whole building and suite's total energy consumption, as well as any on-site generation that may exist to find the net-energy consumption of the building;
- ➔ Sub-meter at the circuit level and/or by major end use (DHW, heating, cooling, etc.) using a power monitoring system and current transducers;
- ➔ Capture the fuel and energy types for each major end-use to find the carbon emissions and carbon-saving potential for a post-retrofit building;
- ➔ Measure the pre-retrofit building performance and weather for a period of at least 12 months, if possible. The building performance can be normalized to the weather to quantify the energy efficiency upgrades made to the building (See IPMVP for more information (Efficiency Valuation Organization, 2023));
    - o If measuring the pre-retrofit building performance is not feasible, a full year of utility billing data with the highest resolution available before the retrofit can be used instead.
- ➔ Measure the DHW draws from the building using a flow meter and temperature measurements at the tank inlet and outlets; and
- ➔ A minimum of 12 months of monitoring after the deep energy retrofit has been completed. An on-going M&V plan should be considered to ensure the persistence of the performance benefits of the deep retrofit program.

It is also important to classify the fuel type to determine the operational carbon emitted by the building. The operational emissions calculation can be straightforward if the consumption is directly associated with fossil-fuel consumption. However, when the building interacts with the grid, the generational mix significantly affects carbon emissions attributed to energy consumption.

Table 3: Energy monitoring summary

Metric	Measurement or Information	Recommended Measurement Frequency
On-site generation	Electrical energy from roof-mounted PV, building integrated PV, or other energy generation systems	Sub-hourly preferred, the hourly minimum
Energy Consumption	Electrical energy – whole building	Sub-hourly preferred, hourly minimum
	Electrical energy – circuit level by major end-use, (e.g., heating, cooling, DWH, etc.)	Sub-hourly preferred, hourly minimum
	Electrical energy baseloads lighting, plug loads, appliances, etc.	Hourly preferred, daily minimum
	Alternate fuel (e.g., natural gas, propane) consumption – whole building	Hourly preferred, daily minimum
Water	Domestic hot water consumption	Hourly preferred, daily minimum

5.2 Thermal Comfort and Indoor Air Quality

With increased building airtightness, mechanical ventilation to provide fresh, outdoor air is needed to ensure the indoor air quality is maintained. ASHRAE 62.2 (American Society for Heating, Refrigeration and Air-Conditioning Engineers, 2022) prescribes the requirements for ventilation rates and minimum fresh air rates in residential buildings. Pollutants may be localized within a building, so the average concentration of an air pollutant can be misleading when interpreted as the sole indicator of good indoor air quality and thermal comfort.

In summary, the **purpose** of thermal comfort and indoor air quality monitoring is:

- ➔ To measure the impact of retrofit on indoor air quality and thermal comfort;
- ➔ To ensure the building HVAC system provides sufficient ventilation and exhaust to ensure occupants comfort and safety; and
- ➔ To provide a set of interior conditions that could be used to refine or calibrate energy and hygrothermal models.

Select **monitoring locations** that:

- ➔ Ensure the conditioned space is comfortable and healthy for the occupant's post-retrofit.

To create a comparable and reliable indoor air quality dataset, here is a list of **guidelines for monitoring**:

- ➔ Measure temperature, relative humidity, and CO_2 in the building's occupied zones at a height of 0.6-1.7 m.
    - o If it is only feasible to measure one zone, monitoring a space with typical occupancy (e.g., the main living space or common areas, or at the thermostat) could be sufficient;
    - o Avoid exposure to direct sunlight or place near sources of heat and humidity (kitchen, space heaters, television, etc.).
- ➔ Measure the key air pollutants (radon, particulate matter <2.5μm, particulate matter <10μm, CO_2) pre- and post-retrofit in each zone.
    - o If it is only feasible to measure one zone, monitoring a zone with a typical occupancy (e.g., the main living space or common areas, or at the thermostat) would be sufficient.

When feasible, here are additional valuable areas in the building:

- ➔ Measure the temperature and air pollutants in zones (e.g., bedrooms) prone to overheating and discomfort.

Table 4: Thermal comfort and air quality monitoring summary

Metric	Measurement or Information	Notes
Zone Comfort	Temperature & Relative Humidity	Hourly minimum
Zone Pollutants	CO_2, CO, Particulate (e.g., <2.5μm, <10μm), Radon	Hourly minimum
Outdoor	Temperature & Relative Humidity	Hourly preferred Daily average (min)

5.3 Hygrothermal

The heat, air and moisture flow within the building envelope can potentially change post-retrofit after the addition of new control layers (e.g., thermal, air and moisture, etc.). As such, the building enclosure performance should be monitored to ensure that materials sensitive to decay are not exposed to such conditions that reduce their useful service life. Under design conditions, when the heat, air and moisture transfer through the enclosure would be drastically changed from its original state and/or there is a noted risk in the assembly (e.g., use of innovative materials, interior insulation, building with existing moisture-related issues before retrofit, etc.), hygrothermal monitoring should be considered to ensure there are no long-term issues.

In **summary**, the purpose of hygrothermal monitoring is to:

- ➔ Assess whether the safe built-in moisture content of the existing cladding has been met; and
- ➔ Understand the performance of the existing and new enclosure assemblies following the retrofit, and how closely they match the modelled performance for durability concerns.

When **selecting monitoring locations** on the above grade walls or roof assemblies, they should be selected such that (in order of priority):

- ➔ A comparison to hygrothermal modelling can be made;
- ➔ Conditions that may cause long-term moisture-related issues and are ignored or not represented in a 1D hygrothermal model; and
- ➔ Each of the four orientations.

To *compare to the modelled results*, here is a list of **guidelines for selecting sensor locations**:

- ➔ RH sensors are typically installed in cavities (surrounded by air) to measure ambient conditions of the surrounding air while temperature sensors are typically installed on assembly surfaces to measure surface temperatures;
- ➔ RH/T sensors should always capture the elevations that are most susceptible to wetting and/or moisture damage and should be monitored, at a minimum;
- ➔ Moisture content sensors are typically placed in locations where hygroscopic materials may be exposed to extended periods of wetting.

When monitoring larger areas, MC is typically monitored at the top and bottom of the areas; and

- Second storeys (where applicable) should be monitored as conditions may vary from the first storey due to outbound/inbound air leakage (resulting from stack effect), re-entrant looping (air, driven by buoyancy effects, that leaks from the conditioned space, into the wall assembly, then back into the conditioned space such that the air leakage path may not be identified by blower door testing).
  - This is also true for attic spaces, which should be monitored when a unique configuration is used.

When feasible, additional useful sensor locations could be as follows:

- Monitor locations with spatial variations (2- and 3-D) in the heat, air and moisture flows (e.g., thermal bridge points, penetrations, joints and leakage paths etc.);
- Monitor locations that may have a heightened condensation risk due to thermal bridging or dew point;
- Monitor locations that may be exposed to additional wetting from driving rain or splash back compared to what could be modelled;
- Monitor locations that have a higher risk of increased air leakage; and
- Monitor moisture content at critical structural attachment locations where air leakage may occur such as rim joists, rim panels, and panel joints.

Furthermore, the weather needs to be monitored. The outdoor temperature, rainfall, wind speed and direction, solar radiation, and barometric pressure are values that will be used for verification of the building envelope performance. It is preferred that a weather station is placed on-site to capture the conditions. An alternative solution is a weather station nearby, within 20 km of the building site, such as an airport.

Table 5: Hygrothermal and Weather Monitoring Summary

Metric	Measurement or Information	Notes
Wood-based surfaces e.g., existing sheathing, new sheathing, wood framing	Temperature Moisture content	Hourly minimum Accurate to ±1.0 °C Hourly minimum Accurate to ±1.0%
Cavities and airspaces	Temperature Relative humidity	Hourly minimum Accurate to ±1.0 °C Accurate to ±3.0%
Outdoor	Rain, wind speed, wind direction, solar radiation, barometric pressure	On-site hourly preferred or weather station within 20km with hourly data

6. Appendix B – Verification and Analysis

This section provides an outline for verification of building performance using the above building monitoring. This analysis may not suit all building types and is limited to a high-level scope. For an example of how to use the measurement and verification of the post-retrofit buildings, visit the OCH-PEER Case study analysis from a demonstration project performed in Ottawa, ON between 2020 and 2022.

6.1 Energy Consumption and Generation

Energy consumption and generation are essential to evaluating the home energy efficiency and the effectiveness of the ECMs from the retrofit. The key performance indicators should be analyzed pre- and post-retrofit.

Key performance indicators for pre- and post-retrofit building performance include:

- ➔ Total Annual (monthly, weekly) energy consumption, and generation, if applicable (kWh), and energy savings (kWh, %);
- ➔ End-use Annual (monthly, weekly) energy consumption, and generation, if applicable (kWh), and end-use savings (kWh, %);
  - Space heating
  - Space cooling
  - Domestic Hot Water
- ➔ Peak end-use energy demand, and generation if applicable (kW).

Other performance indicators if it is feasible to evaluate:

- ➔ Normalized energy consumption or energy costs;
  - Normalised energy consumption and/or cost per useful living area
  - Normalised energy consumption and/or cost per heating/cooling degree days
- ➔ Primary energy consumption and/or carbon emissions equivalent; and
- ➔ Lifecycle assessment of embodied energy and/or carbon.

The building total and normalized building energy consumption and generation will be used to verify the effectiveness of and savings from the energy conservation measures post-retrofit. The total annual energy consumption and generation will determine energy efficiency and savings for the project as well as provide a comparison to other projects of similar investment. The annual sub-metered energy end-use will help commission and evaluate the impact of specific energy conservation measures. Normalizing the energy consumption by floor area and/or cost of energy would provide a robust data set that would be comparable to other monitored deep energy retrofit projects.

The embodied and operational carbon emissions can be estimated based on the building characteristics. Material Carbon Emissions Estimator (MCE^2) tool estimates the emissions required to manufacture the building materials and estimates the carbon emission from building operation using the results from energy modelling (Natural Resources Canada, 2023). When measured data is available, calculating the operating emissions by following the procedure from ISO 14064 GHG Project International Standard – Part 2 for project level quantification (International Organization for Standardization, 2019). For carbon estimating, this can be done at the design stage and the verification stage of the project.

6.2 Thermal Comfort and Indoor Air Quality

Occupant comfort and indoor air quality are governed by the ASHRAE Standard 55 (American Society for Heating, Refrigeration and Air-Conditioning Engineers, 2020) comfort criteria and ASHRAE Standard 62.2 (American Society for Heating, Refrigeration and Air-Conditioning Engineers, 2022). Ensuring that the indoor environment is comfortable and healthy for occupants post-retrofit is critical.

Key performance indicators include:

- ASHRAE 55 thermal comfort models;
- CO_2 concentration.

The two thermal comfort models are available from ASHRAE 55: the adaptive thermal comfort model and the Fanger Predicted Mean Vote (PMV). The models can be used to calculate the expected thermal comfort range for a given set of conditions. The adaptive thermal comfort model uses the outdoor temperature to set the bounds for a comfortable interior setpoint. The adaptive model is limited to naturally ventilated buildings, which should not be the case post-retrofit, and is limited to a range of 5-35 °C. The Fanger PMV uses the basis of the skin temperature for the sensation of thermal comfort by estimating the heat balance at the skin surface. The PMV is a function of six variables: air temperature, mean radiant temperature, air velocity, air humidity, clothing, and activity level. For residential buildings, the expected metabolic rate and clothing levels can be estimated, and the expected comfortable range is shown in the ASHRAE Standard 55 comfort chart.

Table 6: Thermal comfort and air quality analysis summary

Method	Relationship	Notes and limitations
ASHRAE 55, 2020 Adaptive Comfort Model (American Society for Heating, Refrigeration and Air-Conditioning Engineers, 2020)	$T_{comfort} = 0.31 \cdot T_{a_{out}} + 17.8$	Limited to 5-35 °C for naturally ventilated buildings.

ASHRAE 55, 2020 Analytical Comfort Model (American Society for Heating, Refrigeration and Air-Conditioning Engineers, 2020)	A graphical method based on operative temperature, relative humidity, metabolic rate, and clothing level.	For mechanically heated and cooled buildings.
Concentration of CO_2 (American Society for Heating, Refrigeration and Air-Conditioning Engineers, 2022)	$C_{CO_2} = \frac{PQC_{CO_2} + \frac{S}{V}}{Q}$	

6.3 Building Envelope Durability

The building envelope monitoring is essential to ensuring that the enclosure is performing as expected at different interior loads and changing weather outside. The temperature, relative humidity and moisture content monitoring will be used to calculate the key performance indicators of long-term durability for building envelopes.

Key performance indicators include:

- ➔ Peak Mould Index during monitoring;
- ➔ Peak wood moisture content;
- ➔ Hours above the critical relative humidity for materials sensitive to mould growth; and
- ➔ Effective R-value of the roof, above-grade wall, and below-grade assemblies.

The measurements within the envelope can be used to evaluate the envelope's durability using the procedures for moisture analysis outlined in ASHRAE 160. The mould index is a mathematical-empirical model that predicts mould growth as a function of the material substrate and surface conditions (temperature, relative humidity, roughness). ASHRAE 160 (American Society for Heating, Refrigeration and Air-Conditioning Engineers, 2021) defines that an assembly is safe and durable when the mould index on surfaces sensitive to mould growth is below three.

Table 7: Mould index values and levels of mould growth

Mould Index Value	Potential Level of Mould Growth
0	No growth
1	Small amounts of mould on the surface (microscopic), initial stages of local growth
2	Several local mould growth colonies on the surface (microscopic)
3	Visual findings of mould on the surface, <10% coverage, or <50% coverage of mould (microscopic)
4	Visual findings of mould on the surface, 10-50% coverage, or >50% coverage of mould (microscopic)
5	Plenty of growth on the surface, with >50% coverage (visual)
6	Heavy and tight growth, coverage of about 100%

The mould growth index can be calculation using the following equation:

$$\frac{dM}{dt} = \frac{1}{7 \cdot \exp(-0.68lnT - 13.9lnRH + 0.14W - 0.33SQ + 66.02)} k_1 k_2$$

Where,

k_1 is the intensity coefficient that depends on mould growth level;
k_2 is the limit of the growth intensity when the mould index level approaches the peak value;
W(0=pine, 1=spruce), SQ(0 for sawn, 1 for kiln dried) are factors for timber materials;
T is the surface temperature, in °C, RH is the relative humidity at the surface.

Using the measured temperature and relative humidity, the mould index can be calculated using the hourly measured data pre- and post-retrofit using numerical calculation tools (e.g., MatLAB, Excel etc.).

For sensitive materials, the measured hours above critical surface relative humidity (RH_{crit}) can be used as a key performance indicator for moisture resiliency. The critical relative humidity for sensitive materials is described with the relationship below based on the measured surface temperature. The longer the measured relative humidity is greater than the critical relative humidity, the worse the performance and drying potential in the building envelope.

Table 8: Material sensitivity classes to mould growth (American Society for Heating, Refrigeration and Air-Conditioning Engineers, 2021)

Sensitivity Class	Materials
Very sensitive	Pine sapwood
Sensitive	Glued wooden boards, Polyurethane (PUR paper surface, spruce)
Medium resistant	Concrete, aerated and cellular concrete, glass wool, polyester wool
Resistant	PUR polished surface

$$RH_{crit} = \begin{cases} -0.00267T^3 + 0.16T^2 - 3.13T + 100, & when\ T < 20\ °C \\ 80\%, & when\ T \geq 20\ °C \end{cases}$$

Using the monitored data, the hygrothermal performance of the building envelope can be determined to be SAFE, or UNSAFE depending on the peak mould index for the monitored period and compare different post-retrofit designs with the number of hours above the critical relative humidity.

Contact:
Dr. Brock Conley
Research Engineer
Natural Resources Canada, CanmetENERGY
Buildings and Renewables Group

Brock.Conley@nrcan-rncan.gc.ca

About CanmetENERGY

Natural Resources Canada's CanmetENERGY is the Canadian leader in clean energy research and technology development. Our experts work in the fields of clean energy supply from fossil fuel and renewable sources, energy management and distribution systems, and advanced end-use technologies and processes. Ensuring that Canada is at the leading edge of clean energy technologies, we are improving the quality of life of Canadians by creating a sustainable resource advantage.

Head Office	Devon, Alberta	Ottawa, Ontario	Varennes, Quebec
580 Booth Street	1 Oil Patch Drive	1 Haanel Drive	1615 Lionel-Boulet Boulevard
Ottawa, ON	Devon, AB	Ottawa, ON	Varennes, QC
Canada	Canada	Canada	Canada
K1A 0E4	T9G 1A8	K1A 1M1	J3X 1S6

Canada