Sub-Hourly Fuel & Electricity Usage Analysis using HOT2000 and EnergyPlus

Results Comparison Report

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Executive Summary

This report details the development of a translator to convert HOT2000 (.h2k) files, the standard for residential building energy modelling in Canada, into the Home Performance XML (HPXML) format. HOT2000, while widely used, primarily provides annual energy consumption estimates. To gain a more detailed understanding of energy usage, particularly at hourly and sub-hourly resolutions, this project aimed to leverage the EnergyPlus simulation engine via the open-source HPXML-OpenStudio (OS) workflow. The output of this project is an open-source translator that can be used by researchers, government, and industry to gain greater insights into the Canadian building stock, conduct more accurate planning around new policy and incentive objectives, and assess the impact of new and innovative approaches to addressing housing affordability and climate change mitigation and adaptation.

The approach involved developing a command-line interface using Python to map and translate data fields from HOT2000 files to the HPXML format. This report details the process that integrated heating, cooling, ventilation, and domestic hot water (DHW) systems into the translation process. This enables a more comprehensive representation of a house's energy performance in EnergyPlus. The translated HPXML files can then be run in EnergyPlus to generate detailed hourly energy consumption profiles. Comparisons were made between the energy modelling results of HOT2000 and OS-HPXML to identify areas of alignment and misalignment. The translator was also assessed in accordance with ASHRAE 140, and in its current “under-development” state passes all 2024 RESNET HERS acceptance criteria except for one heating delta test case, indicating a high degree of promise and confidence in the process.

The next steps for this project include expanding the scope of the translator to support multi-unit residential buildings (MURBs) and incorporating a broader set of operating conditions. Further work will focus on improving the translator's robustness and addressing identified areas of misalignment in the translation of systems and other building components through discussions with the development teams of both HOT2000 and HPXML.

This translator will unlock significant opportunities for analyzing the Canadian housing stock with unprecedented detail. It can be used for:

- Detailed analysis of energy usage patterns, including peak demand identification and the effectiveness of time-dependent energy efficiency measures.
- Informing policy development related to energy efficiency, affordability, and building codes by providing more accurate building energy performance data.
- Analyzing the resilience of homes to extreme weather events through hourly temperature and load simulations.
- Evaluating the performance and grid impacts of innovative technologies such as heat pumps, solar PV, and energy storage in the Canadian context.
- Improving electricity infrastructure planning by providing detailed hourly electricity demand profiles for different housing types.
- Leveraging the existing wealth of data from the EnerGuide Rating System by enabling the translation of thousands of HOT2000 archetype models for advanced analysis.

This work provides a foundational platform for a deeper understanding of residential energy use in Canada, supporting evidence-based decision-making for a more energy-efficient and resilient housing sector. The open-source repository can be accessed at: https://github.com/canmet-energy/h2k_hpxml

Table of Contents

Table of Figures

Table of Tables

Background

HOT2000 is the de facto residential building energy modelling software in Canada and is used to deliver the EnerGuide Rating System program. It is used for performance path code compliance, incentive compliance and verification at various levels of government, and a number of other voluntary programs throughout the country such as ENERGY STAR for New Homes and the CHBA Net Zero Label. To date, millions of homes across Canada have been evaluated with the EnerGuide Rating System using HOT2000 (NRCan 2024).

HOT2000 effectively acts as the “language” by which technical and performance information about residential buildings in Canada is communicated and shared. A wealth of data has been collected in the XML-based HOT2000 file format (.h2k files), that has been used to inform building research endeavours, including studies that have formed the foundation for changes to the building codes across Canada.

However, HOT2000 is not without limitations. The simulation engine itself is based on a combination of first principles equations and calibration curves based on data from across Canada. As a result, it has underperformed in certain circumstances relative to other internationally recognized energy modelling engines (Parekh, et al. 2018). Additionally, HOT2000 simulation results are limited primarily to annual totals, with a handful of results available on a monthly basis. Efforts in the past have looked to derive more information from the inputs and results of HOT2000 files (Brideau 2020).

Through the adoption of increasingly strict performance requirements for buildings, the need for increased resiliency measures, and new housing technologies, annual analyses can fall short of accurately assessing the performance benefits of many modern approaches to improving the quality of the residential building stock in Canada. The scope of concerns around residential construction is growing in Canada, broadening from a lens that has historically viewed “energy” as the ultimate metric to assess the quality of a building to consider many other factors such as resilience, affordability, peak load implications, emissions, and environmental impact.

It follows that the processes and tools used to assess the housing stock throughout the country should be modernized, for both new and existing homes. In an effort to reduce barriers and ease uptake, an effective modernization process should work with and build upon existing systems in place, improving upon weaknesses of current processes but leveraging areas of strength. While the downsides of HOT2000 are often the subject of scrutiny, it does have many areas of strength: it is very lightweight and easy to use relative to most energy modelling tools, and its data collection process is designed for repeatability and consistency.

A recent endeavour in the United States has overseen the development of a portable data format, Home Performance XML (HPXML). The initiative is undertaken by the National Renewable Energy Laboratory (NREL), and the format is designed to collect, store, and transfer housing data. Additionally, NREL has developed a workflow around this data format that allows HPXML files to be opened and run by OpenStudio (OS), a software platform that performs whole-building energy simulation using the EnergyPlus (E+) engine (NREL 2024). This simulation engine is internationally recognized and produces a suite of outputs far beyond the scope of annual summary performance statistics

This project aims to leverage NREL's work in creating the OS-HPXML workflow and develop a process to translate .h2k files into HPXML files so that they may be run in E+ using the OS-HPXML workflow.

Project Objectives

The primary objective of this project is to develop and implement a methodology for translating building energy models from the HOT2000 (.h2k) file format into the Home Performance XML (HPXML) format. This translation process aims to facilitate the use of the EnergyPlus simulation engine, accessed via the HPXML-OpenStudio (OS) workflow, to analyze the energy performance of Canadian residential buildings with a higher degree of granularity than is possible with HOT2000 alone. Specifically, this phase of the project focuses on expanding the translator's capabilities to include the translation of all key building systems, including heating, cooling, ventilation, and domestic hot water (DHW) systems, which were not fully addressed in the initial envelope-focused phase. This will result in an open-source translator, available on Github[1], that can be used by anybody in Canada for building performance analysis.

To support this objective, a detailed comparison of energy modelling results generated by both HOT2000 and OS-HPXML was performed on a set of housing archetype files. By analyzing the differences and correlations in predicted energy consumption and loads, this project seeks to identify areas of alignment and potential discrepancies between the two simulation engines, particularly concerning the modelling of various mechanical systems. This comparative analysis will contribute to a better understanding of the strengths and limitations of each tool and inform future efforts to refine the translation process for improved accuracy and reliability.

Ultimately, the successful development and validation of this H2k-HPXML translator is intended to provide significant opportunities for advanced analysis of Canada's residential building stock. This includes the ability to generate hourly and sub-hourly energy usage profiles, which are essential for understanding peak demand, evaluating time-dependent energy efficiency measures, assessing resilience to extreme weather, and analyzing the impact of new technologies. By leveraging Natural Resources Canada's (NRCan) extensive database of HOT2000 archetype files, this project aims to provide a foundational platform for evidence-based decision-making in the housing sector, supporting the development of more energy-efficient, affordable, and resilient homes for Canadians.

[1] Public Github available at: https://github.com/canmet-energy/h2k_hpxml

Systems Translation Methodology

Based on the definition of Systems in HPXML, the following HOT2000 sections were included within the scope of this translation process:

- Heating/Cooling Systems
- Domestic Hot Water
- Ventilation
- Generation

Descriptions of the translation process for each type of heating, cooling, ventilation, domestic hot water, and generation system capable of being defined in HOT2000 is described in the following sections.

Primary Heating Systems

Primary heating systems, referred to as “Type 1” systems in HOT2000, are broken down into five types:

- Baseboards/Hydronic/Plenum Heaters
- Furnace
- Boiler
- Combo Heating/DHW
- CSA P.9-11 tested Combo Heating/DHW

Baseboards/Hydronic/Plenum Heaters

Primarily used to model electric baseboard heating, these primary heating systems are modelled using the `ElectricResistance` heating system type in HPXML. This type of heating system does not require any branching translation logic or a linked HVAC distribution system. Inputs align identically between HOT2000 and HPXML for this primary heating system type.

Furnaces

Most furnaces defined in HOT2000 use the `Furnace` heating system type in HPXML with an attached Air Distribution (regular velocity) HVAC distribution system object. This pattern applies to all HOT2000 furnaces and equipment types that use electricity, natural gas, oil, and propane as their energy source.

Systems that use wood in HOT2000, while included under the “Furnace” heading, have more appropriate representations in HPXML. Table 1 displays HOT2000’s wood furnace equipment types and how they have been mapped to HPXML heating systems and HVAC distribution systems.

HOT2000 has four types of wood fuel: mixed wood, softwood, hardwood, and wood pellets. HPXML only has two categories: wood and wood pellets. Any equipment that uses wood pellets in HOT2000 is also defined with a wood pellet heat source in HPXML, while all other HOT2000 wood types are mapped to the “wood” fuel type in HPXML.

Table 1. Wood primary heating systems map.

H2k Equipment Type	HPXML Heating System Type	HPXML HVAC Distribution
Advanced airtight wood stove	Stove	None
1st option (advanced airtight wood stove) with catalytic converter	Stove	None
Conventional furnace	Furnace	AirDistribution (regular velocity)
Conventional stove	Stove	None
Pellet stove	Stove	None
Masonry heater	Fireplace	None
Conventional fireplace	Fireplace	None
Fireplace insert	Fireplace	None

The HPXML `Furnace` object accounts for fuel type, pilot light energy consumption, heating capacity, heating efficiency (AFUE), and auto-sizing factor. Flue diameter (if applicable) is not an input that is accounted for directly in HPXML.

Boilers

All boilers defined in HOT2000 use the `Boiler` heating system type in HPXML (In-unit, not Shared). Additionally, all boilers are connected to a hydronic HVAC distribution system, and given the subtype “radiator”. HPXML boilers may *not* be connected to air distribution systems. For wood-fired boilers, the only two equipment types in HOT2000 are “Conventional Boiler” and “Outdoor Wood Boiler”, both of which are mapped to boilers in HPXML, with the latter given a `UnitLocation` of “other exterior”. The `Boiler` object accounts for the same inputs as the `Furnace` object.

Combo Heating/DHW

Combo Heating/DHW systems can be represented in HPXML by modelling a `Boiler` heating system with an associated water heating system given the type “space-heating boiler with storage tank” or “space-heating boiler with tankless coil”. However, a water heating system of either of these types is not allowed an independent efficiency input, meaning its efficiency is derived from the efficiency of the connected boiler, in a manner that cannot be directly manipulated by the user. As such, the translation process does not use HPXML’s built-in “combi” hot water system and instead specifies a separate boiler and hot water heating system to better reflect the difference or decoupling of efficiency values between the two operations (space heating and water heating) reflected in a HOT2000 simulation. The heating side of combos is modelled using the `Boiler` object in HPXML, and there are no major differences compared to modelling a typical non-combo boiler.

CSA P.9-11 Tested Combo Heating/DHW

Referred to simply as “P.9-11 Systems”, these combos differ in their definitions from typical Combo Heating/DHW systems in HOT2000. A separate set of efficiency metrics is provided, mainly: Thermal Performance Factor (TPF), Composite Space Heating Efficiency (CSHE), and Water Heating Performance Factor (WHPF). The TPF metric is attempting to be a blended metric that reflects the overall performance of a P.9-11 system based on a standardized set of operating conditions.

After testing both types of Combo systems, it was decided not use HPXML’s built-in “combi” water heaters as their water heating efficiency calculations are opaque and coupled to the efficiency of the primary heating system. Tests determined that using the TPF as an overall system efficiency resulted in 1.5 times the water heating energy consumption in HPXML compared to HOT2000. Similar to the regular Combo systems, P.9-11 systems are modelled using separate boiler and hot water heating systems in HPXML.

Supplementary Heating Systems

In HOT2000, supplementary heating systems are most often used to account for fireplaces, stoves, space heaters, and secondary furnaces or boilers. They can be modelled as never used, or have a fraction of the time that they are to be used, although EnerGuide procedures only allow modelling these heating systems as being either “never” or “always” used. When these systems are used, their energy is assumed to contribute to heating a space *before* the primary heating system or heat pump is used. The primary heating system or heat pump will then be used to provide whatever remaining heating energy is needed to maintain the house’s set point.

After running a simulation, the results section of the HOT2000 file reports the following metrics associated with primary and supplementary heating systems:

- Primary heating energy consumption: The fuel energy consumed by the primary heating system.
- Secondary heating energy consumption: The sum of the fuel energy consumed by the heat pump and the first and second supplementary heating systems, if any combination of those systems is present in the file.
- Supplementary heating energy consumed: The fuel energy consumed by up to five supplementary heating systems allowed in a HOT2000 model.

In HPXML, multiple heating systems are modelled by using the `FractionHeatLoadServed` parameter, which must sum to 1 across all heating systems present in the home. However, as described above, the only similar metric provided in the HOT2000 file is the *consumption* of each system, not the *load* served by each system. Neither the inputs nor the outputs of the HOT2000 file provide any indication of the fraction of the heating load served by each heating system.

In theory, calculations could be performed that could determine the approximate heat provided by each system by multiplying each system’s consumption by its efficiency. However, this is complicated by the following factors:

- The overall seasonal efficiency of each system is not known, particularly for heat pumps.
- The secondary heating consumption metric is a blend of fuel energy consumption for up to three different types of systems.

- The supplementary heating systems, when set to “always on” can produce heat energy that exceeds the energy required by the building to maintain its setpoint.

These factors mean that an appropriate estimation of the fraction of *load* served by each system is difficult to determine. As such, at the moment the translator simply assumes the fraction of load served is equal to the fraction of floor area served by each supplementary heating system (input in the HOT2000 interface). Further testing and understanding of the logic behind supplementary heating systems in HOT2000 would be required to refine this translation process and produce results with better alignment. In the case of a home with supplementary heating systems whose use is set to “always”, the primary heating system’s fraction of load served is equal to the fraction of the remaining floor area not served by supplementary systems.

Supplementary heating systems do not have a special type of system object in HPXML, and are represented by the same `Furnace`, `Boiler`, `Stove`, and `Fireplace` objects used for primary heating systems.

Radiant Heating

HOT2000 provides inputs to define radiant heating distribution systems. Those inputs are the effective temperature and percentage of floor area served for six different radiant system location options:

- Attic ceiling
- Flat roof
- Floors above crawl space
- Slab on grade
- Floors above basement
- Basement

The H2k-HPXML translator defines radiant heating through the HVAC distribution object. By default, all hydronic distribution systems are given the type “radiator”. However, if radiant heating is specified in HOT2000, this type will be changed to either “radiant floor” or “radiant ceiling”. The selection is made based on which of the above locations is given the largest floor area served. Multiple radiant heating systems are not defined since the HPXML model only uses one heated zone.

Additional Openings

Additional Openings are used to model flues or combustion air supplies. These do not have a direct equivalent in HPXML. Instead, the presence of any Additional Openings or flues connected to heating systems or hot water systems will change the value of the HPXML parameter `HasFlueOrChimneyInConditionedSpace` to TRUE.

Multiple Systems

These heating systems can only be defined for multi-unit residential buildings (MURBs) in HOT2000, and are therefore outside of the scope of the current translation process.

Air Conditioning

HOT2000 only allows the modelling of permanent air conditioning; no window or room air conditioners are considered in its models. As such, the air conditioner model in HOT2000 can be represented by either the central air conditioner or the mini-split model in HPXML.

In general the inputs align quite well between the two models, where both engines account for the cooling capacity, annual cooling efficiency, sensible heat fraction, fan power, crankcase heater power, and auto-sizing factors. However, whether both engines interpret all of these inputs in the same manner is unclear.

HPXML allows seasonal cooling efficiency to be input using either SEER or SEER2. However, the development of the translator started before HOT2000 v11.13, which allows SEER2 as an input, and currently, SEER2 is not supported by the translator. If the COP is provided for an air conditioner, Equation 1 is used to convert it into SEER.

$$SEER = {(COP - 1.428)}/{0.115} \qquad (1)$$

HPXML also allows detailed performance data (capacity and COP and different outdoor temperature points) to be input. This input method is not currently used by the translator, but could be utilized in an effort to ensure both engines are using the exact same cooling performance curves.

Air Source Heat Pumps

Similar to air conditioners, air source heat pumps (ASHPs) are modelled using either the central heat pump or mini-split objects in HPXML, depending on the equipment type selection in HOT2000.

Inputs between the two engines reflect those used by air conditioner systems with the addition of annual heating efficiency, heating capacity, and back-up heating system type (integrated or separate). HPXML only allows heating performance to be defined in terms of HSPF and HSPF2. Similar to the conversion process from COP to SEER, Equation 2 is used to calculate the equivalent HSPF when heating efficiency is input using COP in the HOT2000 file.

$$HSPF = {(COP - 0.78)}/{0.376} \qquad (2)$$

Without using the detailed performance inputs, the ASHP inputs in HPXML allow for the inclusion of a heating capacity at -8.3˚C, in addition to the standard heating capacity (at 8.3˚C). To better match the expected performance of an ASHP modelled in HOT2000, a heating capacity retention of 56% is applied to the model based on the heat pump capacity curve used in HOT2000.

HPXML allows backup heating systems (the Type 1 system when a heat pump is defined in HOT2000) to be defined as either “separate” or “integrated”. In the H2k-HPXML translator, the systems are assumed to be integrated if they utilize the same distribution system. This means that most furnaces are defined as integrated backup systems, while baseboards, boilers, and combos are modelled as separate. Integrated backup systems consider the capacity, fuel type, and efficiency of the equipment.

When a heat pump is modelled with a "balanced" switchover type in HOT2000, a switchover temperature is not defined in HPXML which allows it to use its own internal logic (based on system sizes and loads) to determine when the backup is used. When a restriction temperature is provided in HOT2000, this temperature is explicitly accounted for in the translation process via the `BackupHeatingSwitchoverTemperature` parameter. The "unrestricted" option is only meant to be used for ground and water source heat pumps in HOT2000, but if used for ASHPs, a value of -40˚C is applied. Should such a system be defined, a warning is logged for the user to review.

Ground Source Heat Pumps

Ground source heat pumps (GSHPs) in HPXML use nearly all the same inputs as ASHPs but require heating efficiency in COP and cooling efficiency in EER. The conversion from COP to EER is provided in Equation 3.

$$EER = 3.412 * COP \tag{3}$$

While details about geothermal loops can be defined, these specifications are not provided at this time, allowing HPXML to use its default assumptions.

Water Source Heat Pumps

Water source heat pumps are modelled identically to GSHPs in HOT2000. Currently, the translator uses the "water-loop-to-air" heat pump type to represent these systems in HPXML. However, it is unclear whether this assumption is appropriate, or whether the way HOT2000 interprets WSHPs better matches the assumptions used in HPXML's ground source heat pump model.

Water Heating Systems

In HOT2000, domestic hot water (DHW) system types are defined based on a combination of selections in the "energy source" and "tank type" fields. The mapping of each tank type for all non-solar DHW systems is provided in Table 2 through Table 5.

Table 2. Electric water heater tank type map.

HOT2000 Tank Type	HPXML Water Heater Type
Conventional tank	storage water heater
Conserver tank	storage water heater
Instantaneous	instantaneous water heater
Tankless heat pump	heat pump water heater
Heat pump	heat pump water heater
Integrated heat pump	heat pump water heater

Table 3. Gas and propane water heater tank type map.

HOT2000 Tank Type	HPXML Water Heater Type
Conventional tank	storage water heater
Conventional tank (pilot)	storage water heater
Tankless coil	instantaneous water heater
Instantaneous	instantaneous water heater
Instantaneous (condensing)	instantaneous water heater
Instantaneous (pilot)	instantaneous water heater
Induced draft fan	storage water heater
Induced draft fan (pilot)	storage water heater
Direct vent (sealed)	storage water heater
Direct vent (sealed, pilot)	storage water heater
Condensing	storage water heater

Table 4. Oil water heater tank type map.

HOT2000 Tank Type	HPXML Water Heater Type
Conventional tank	storage water heater
Tankless coil	instantaneous water heater

Table 5. Wood water heater tank type map.

HOT2000 Tank Type	HPXML Water Heater Type
Fireplace	storage water heater
Wood stove water coil	storage water heater
Indoor wood boiler	storage water heater
Outdoor wood boiler	storage water heater
Wood hot water tank	storage water heater

HPXML accepts inputs for fuel type, water heater tank type, tank location, tank volume, fraction of DHW load served, heating capacity, uniform energy factor (UEF) or energy factor (EF), UEF usage bin, tank insulation, and hot water temperature. The only inputs in HOT2000 that are missing in HPXML are the pilot light energy consumption and flue diameter.

Solar Domestic Hot Water

When modelling a solar DHW system, HPXML inputs require the fraction of DHW load provided by the solar DHW system. While this value is not present in the inputs of the DHW section, it can be extracted from the hot water section of the results in the HOT2000 file. This is one of the few areas in the translation process that relies on the results section of the HOT2000 file, and will not function on HOT2000 files that do not have simulation results.

Drain Water Heat Recovery

Drain Water Heat Recovery (DWHR) in HPXML has three inputs: the facilities connected (all in the case of a house), the DWHR configuration, and the efficiency. The configuration field is referred to as `EqualFlow`, and should be set to TRUE "…if the DWHR supplies pre-heated water to both the fixture cold water piping *and* the hot water heater potable supply piping."[2] It is believed

[2] https://openstudio-hpxml.readthedocs.io/en/latest/workflow_inputs.html#drain-water-heat-recovery

that this configuration approximately matches the DWHR configuration definition in HOT2000, and this field is translated based on this assumption.

Water Fixtures

HPXML requires the explicit definition of water fixtures, which are used to model hot water consumption via the shower(s) and faucets in the home. These inputs accept a US-gpm rating that can be aligned with the specifications in the HOT2000 files. However, in the OS-HPXML workflow, the simulated hot water flow rates through the clothes washer, dishwasher, and fixtures are derived based on both the inputs and calculated "actual" flows that would result based on a standardized set of equations that consider other factors such as occupancy and weekday schedules to calculate actual flow. This means that hot water consumption in the resulting HPXML simulation results can deviate from the expected consumption assumed in the HOT2000 file.

To mitigate this discrepancy, the WaterFixturesUsageMultiplier parameter was used to better align total hot water consumption between the two engines. A calibration procedure was performed to determine an adjustment factor that could be used to estimate the discrepancy between the expected and actual simulated fixture flow rate, which would then inform the fixture usage multiplier parameter. This calibration is shown in Figure 1, and is only valid for houses with three occupants, which is aligned with standard operating conditions. At the moment, standard operating conditions are hard-coded into the translator.

Testing revealed that this adjustment factor is imperfect, and hot water consumption can vary by up to 5% between the simulation engines which can result in greater than desired differences in water heating energy consumption. The analysis required to fully align consumption involves integrating operating conditions and water use schedules, which has not yet been performed.

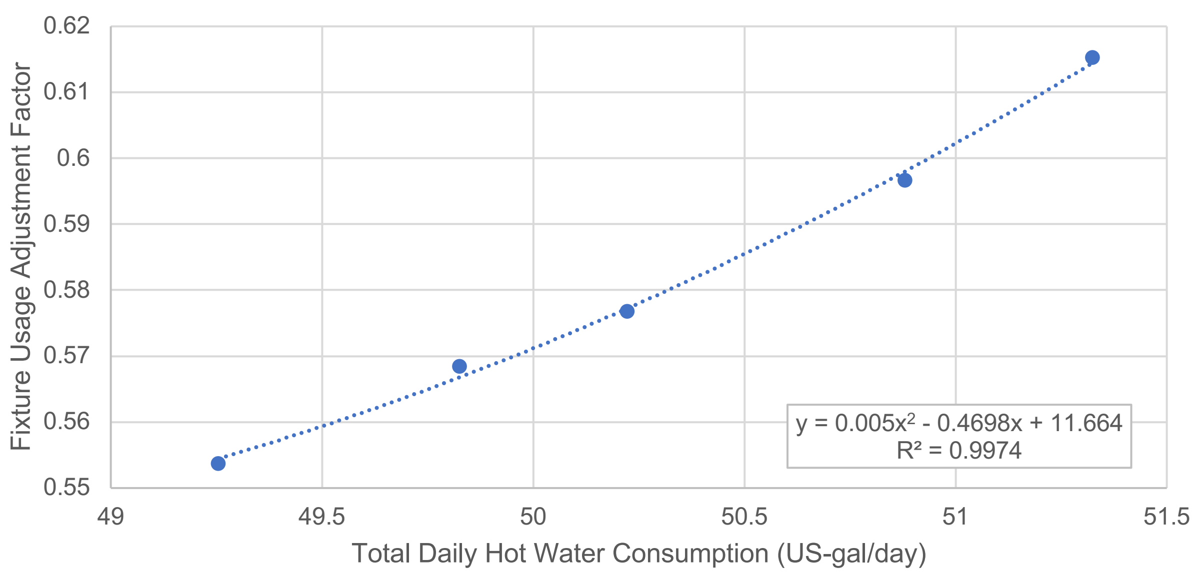

Figure 1. Water fixture usage multiplier adjustment factor for a house with three occupants.

Ventilation Systems

HOT2000 allows the modelling of XXX types of ventilation systems: bathroom fans, range hood fans, utility fans, and heat recovery ventilators (HRVs). All of these systems can be modelled either connected to the whole house ventilation system or as a supplemental ventilation system that uses an independent operation schedule. Dryers are not included in this section of the HPXML file, and are accounted for (including exhaust flows) in the appliance section of the file.

HPXML allows the modelling of mechanical ventilation fans connected to the whole house ventilation system or local ventilation fans, used to model range hoods or bathroom fans.

Bathroom and Range Hood Fans

Any bathroom or range hood defined in HOT2000, regardless of whether defined in the whole-house or supplemental ventilation section, must be modelled as a local ventilation fan in HPXML. While it is much more common for these systems to be modelled as supplemental ventilation in HOT2000 (which matches the definition of a local fan in HPXML), the alternative is still possible. In the case when a bathroom or range hood is defined in the whole-house section of the HOT2000 file, the hours of operation for the resulting HPXML local ventilation system are set equal to the hours of operation of the whole-house system.

Utility Fans

When a utility fan is modelled in HOT2000 that is connected to the whole-house ventilation system, it is modelled as either an exhaust-only, supply-only, or balanced whole building ventilation fan in HPXML. If supply and exhaust flow rates are within 5%, a balanced fan is modelled, otherwise, either a supply-only or exhaust-only fan is modelled based on which flow rate is greater.

A supplemental utility fan does not have a direct HPXML representation, as local ventilation fans can only be defined as kitchen or bathroom fans. As such, a supplemental utility fan modelled in HOT2000 is modelled in HPXML as “used for whole building ventilation”, but its hours of operation are equal to the hours specified in the supplemental utility fan screen in HOT2000.

Heat Recovery Ventilators

HOT2000 does not distinguish HRVs from energy recovery ventilators (ERVs), as it does not conduct a hygrothermal analysis. As such, all HRVs defined in HOT2000 use the HRV ventilator type in HPXML. The HPXML file only accepts one efficiency, the sensible recovery efficiency (SRE), and the low-temperature efficiency value in the HOT2000 file cannot be directly accounted for without an additional adjustment factor in the translation process, a calculation which has not been attempted at this time.

Solar Photovoltaic Generation

All solar photovoltaic (PV) inputs between the two engines align except for the method of describing a solar array’s size: HOT2000 uses the solar array area (m^2), while HPXML uses the maximum power output (kWp) of the array. To determine the peak power of the array at standard test conditions (STC), 1000 W/m^2, Equation 4 is used.

$$P_{STC} = A_{array} * \eta_{STC} * 1000\ W/m^2 \qquad (4)$$

Where P_{STC} is the peak power (W) at STC, A_{array} is the array area (m^2), and η_{STC} is the module efficiency at STC (%).

Results & Discussion

Performance Evaluation

The performance of building energy simulation software is most often assessed in accordance with ANSI/ASHRAE Standard 140-2023 (ASHRAE 2023). This standard defines a series of test cases (descriptions for building energy models) for building energy simulation whose results can be compared to a set of reference results. Although the standard itself does not define acceptance criteria, HERS BESTEST provides a methodology for evaluating building energy simulation software against acceptance range criteria (Judkoff and Neymark 1995). Based on a recently tightened set of performance criteria for their HERS software accreditation services, RESNET provides a set of ASHRAE 140 acceptance criteria that software can be evaluated against (RESNET 2021). It should also be noted that RESNET recently tightened their acceptance criteria in November 2024, relative to their previously published set in 2020. To date, no software packages have received their official accreditation based on this set of 2024 tightened acceptance criteria.

The OS-HPXML workflow has modelled these test cases and passes all acceptance criteria for the 2024 RESNET HERS tests. The results are available in the public OS-HPXML Github[3]. Before comparing the fuel consumption results of the H2k-HPXML translator, it is worthwhile to understand how files generated by the translator compare against this set of acceptance criteria.

The Class II test cases were modelled in HOT2000 and passed through the H2k-HPXML translator. Their heating and cooling load results were then compared to the 2024 RESNET HERS set of acceptance criteria. While these results are very promising, as with all of the other results presented in this report, they represent a snapshot in time of a process that is still actively in development and will change and improve over time. Additionally, as the alignment of this process with ASHRAE 140 is beyond the scope of this project, only a preliminary attempt at evaluating the translator has been attempted. While some obvious problem areas were addressed through this process, minimal fine-tuning has been performed at this time, and there are many opportunities for further improvement.

This test procedure found that all annual heating and cooling load test cases passed the acceptance criteria. The results for the annual heating and cooling load test cases are presented in Table 6 and Table 7.

Additionally, all annual heating and cooling load deltas except for one passed acceptance criteria, with results presented in
Table 8 and Table 9. However, the single heating load delta case that falls outside of acceptance criteria does so by only 0.31 MBtu (~0.32 GJ), or 4% of the acceptance range. This test case represents the comparison of the "all south-facing windows" model to the base case, which is also the case in which HPXML results are closest to the edge of the acceptable range.

It is worth noting that the translator passes *all* acceptance criteria for the 2020 RESNET HERS Class II test cases.

[3] https://github.com/NREL/OpenStudio-HPXML/blob/master/workflow/tests/base_results/results_ashrae_140.csv

Because this lone problematic test case aims to assess the differences in estimated building performance associated with fenestration location (i.e. comparing the heat losses and solar gains associated with evenly distributed windows compared to all south-facing windows), it follows that the translation process around windows could be refined. Currently, window U-values and SHGCs are read directly from the Components section of the HOT2000 file. However, there are three separate methods of defining windows in HOT2000: Standard codes, user-defined codes with overall window characteristics, and user-defined codes with legacy inputs. The test cases evaluated used the “overall window characteristics” input method. However, none of the three window input methods allow a direct application of user-defined U-values and SHGC to the windows. The values applied to the window components themselves have gone through an internal calculation in HOT2000 that takes into account the actual window size, frame thickness, and a variety of other factors. As such, altering the approach to the translation process, accompanied by a better understanding of HOT2000’s interpretation of window inputs, could help refine this process.

Additionally, HPXML features a variety of different window inputs. For now, the simplified window model is used to allow for the direct entry of U-values and SHGCs. However, research shows that there are known trade-offs in EnergyPlus when using this method (Kohler, et al. 2019). As such, the method of defining windows in HPXML when generating files through the translator could also be evaluated.

Table 6. Annual heating load results compared to RESNET HERS 2024 acceptance criteria

Heating	Range Max (MBtu)	Range Min (MBtu)	Heating Load (MBtu)	Pass/Fail
L100AC	61.35	48.07	51.47	pass
L110AC	82.96	74.30	77.04	pass
L120AC	48.09	35.98	37.76	pass
L130AC	49.95	39.74	43.96	pass
L140AC	51.97	45.72	48.42	pass
L150AC	55.54	39.13	40.25	pass
L155AC	58.15	42.17	43.63	pass
L160AC	63.40	48.30	52.39	pass
L170AC	74.24	58.15	62.09	pass
L200AC	137.68	121.76	123.83	pass
L202AC	146.84	126.71	130.98	pass
L302XC	81.73	24.59	45.24	pass
L304XC	70.27	27.72	42.36	pass
L322XC	91.66	57.57	66.35	pass
L324XC	56.47	48.33	49.53	pass

Table 7. Annual cooling load results compared to RESNET HERS 2024 acceptance criteria

Cooling	Range Max (MBtu)	Range Min (MBtu)	Cooling Load (MBtu)	Pass/Fail
L100AL	58.66	42.50	50.44	pass
L110AL	61.33	47.72	54.37	pass
L120AL	51.69	41.15	46.86	pass
L130AL	41.85	31.54	36.07	pass
L140AL	29.35	21.03	24.19	pass
L150AL	73.48	50.55	62.50	pass
L155AL	59.72	36.63	47.21	pass
L160AL	68.60	52.26	61.82	pass
L170AL	47.58	34.16	41.19	pass
L200AL	73.51	57.07	63.64	pass
L202AL	60.72	50.19	54.27	pass

Table 8. Annual heating load deltas compared to RESNET HERS 2024 acceptance criteria

Heating	Range Max (MBtu)	Range Min (MBtu)	Heating Load Delta (MBtu)	Pass/Fail
L110AC-L100AC	29.62	17.53	25.57	pass
L120AC-L100AC	-9.44	-16.08	-13.71	pass
L130AC-L100AC	-5.89	-12.92	-7.51	pass
L140AC-L100AC	0.24	-12.14	-3.05	pass
L150AC-L100AC	-3.37	-10.90	-11.21	fail
L155AC-L150AC	6.42	-0.56	3.38	pass
L160AC-L100AC	4.54	-1.96	0.92	pass
L170AC-L100AC	15.14	8.15	10.62	pass
L200AC-L100AC	79.06	71.16	72.36	pass
L202AC-L200AC	11.26	3.20	7.15	pass
L302XC-L100AC	22.68	-25.78	-6.23	pass
L302XC-L304XC	11.47	-3.14	2.88	pass
L322XC-L100AC	32.01	7.79	14.88	pass
L322XC-L324XC	38.95	5.49	16.82	pass

Table 9. Annual cooling load deltas compared to RESNET HERS 2024 acceptance criteria

Cooling	Range Max (MBtu)	Range Min (MBtu)	Cooling Load Delta (MBtu)	Pass/Fail
L110AL-L100AL	6.91	0.69	3.93	pass
L120AL-L100AL	-0.22	-8.24	-3.58	pass
L130AL-L100AL	-9.74	-18.53	-14.37	pass
L140AL-L100AL	-20.48	-30.58	-26.25	pass
L150AL-L100AL	15.77	7.51	12.06	pass
L155AL-L150AL	-11.15	-16.52	-15.29	pass
L160AL-L100AL	12.76	6.75	11.38	pass
L170AL-L100AL	-6.58	-12.95	-9.25	pass
L200AL-L100AL	17.59	11.62	13.20	pass
L200AL-L202AL	14.14	5.12	9.37	pass

Fuel Consumption Comparison

An analysis was performed on files run in HOT2000 and through the H2k-HPXML translator followed by the OS-HPXML workflow (this process referred to as the H2k-OS-HPXML workflow), to assess areas of misalignment between the two engines and identify potential sources of error. It utilized a subset of archetypes from the set of existing housing archetypes developed by CanmetENERGY (NRCan 2019), referred to as the “6000 archetypes”. These archetypes were translated and a subset of 30 archetypes were selected that showed the greatest alignment between the two engines for three metrics: Auxiliary heating energy, design heating load, and design cooling load. By selecting archetypes whose envelope performance showed minimal deviation between HOT2000 and OpenStudio, the analysis could attempt to isolate potential issues with the translation of the Systems themselves.

It is worth noting that, while the auxiliary heating energy metric provides a very direct indication of how much energy will be required by mechanical systems to maintain the set point of the home, an equivalent metric representing the cooling requirement does not exist. The design cooling load is used as a proxy, but this metric is not always correlated to the amount of cooling energy required over the course of the year.

The 30 archetypes were then replicated and their mechanical systems were altered to reflect common mechanical system configurations observed in HOT2000 files. In total, 27 different mechanical system configurations were modelled across the subset of 30 archetypes to look at the alignment between the engines and identify potential sources of error.

It is worth noting that the results of this analysis represent a snapshot in time of the performance and accuracy of the translator. Readers should not interpret any results presented as representing a “best possible outcome” associated with this translation process. Rather, these results reflect the very first attempt at aligning these two simulation engines and due to the vast number of system configurations it is not possible within the scope of this project to dig into every possible system to maximize alignment between the two engines. Because the output of this project is an open-source translator, its accuracy will be improved over time through the contribution of a wide range of industry experts.

While the authors believe the results to be quite promising, there is still much work that can be done to improve the accuracy of the translation and better align the results of the two engines where appropriate. It is also worth noting that there may be areas where near-identical results between the two engines is *not* the desired outcome. Readers should proceed with an open mind, acknowledging the fact that different simulation engines will inevitably produce different results.

For all scatterplots that compare HPXML consumption (GJ) to H2k consumption (GJ), the yellow diagonal line represents the y=x line, displaying where equality between the engine results would be. Points above the line represent HPXML estimates that are greater than those of HOT2000.

Electrically Heated Homes

Electricity usage estimates for electrically heated (non-heat pump) homes are displayed in Figure 2 and Figure 3. While both of these systems have space heating systems with 100% efficiency (electric resistance), the main difference is that electric furnaces have an additional HVAC distribution system and associated fan power consumption. In both cases, results show good agreement.

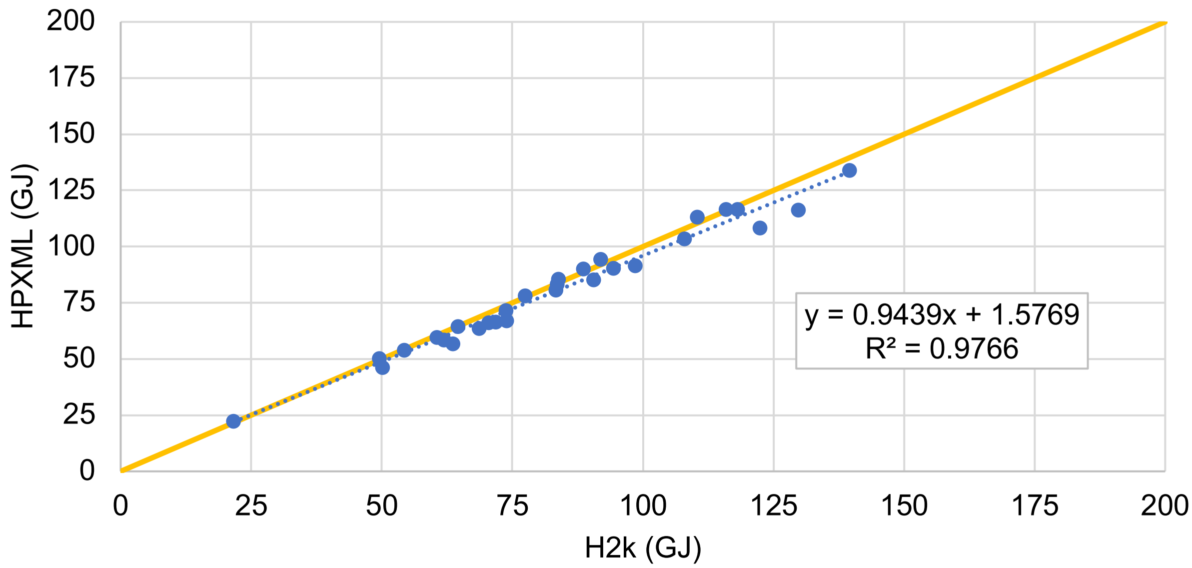

Figure 2. Space heating electricity consumption for homes with baseboard heating.

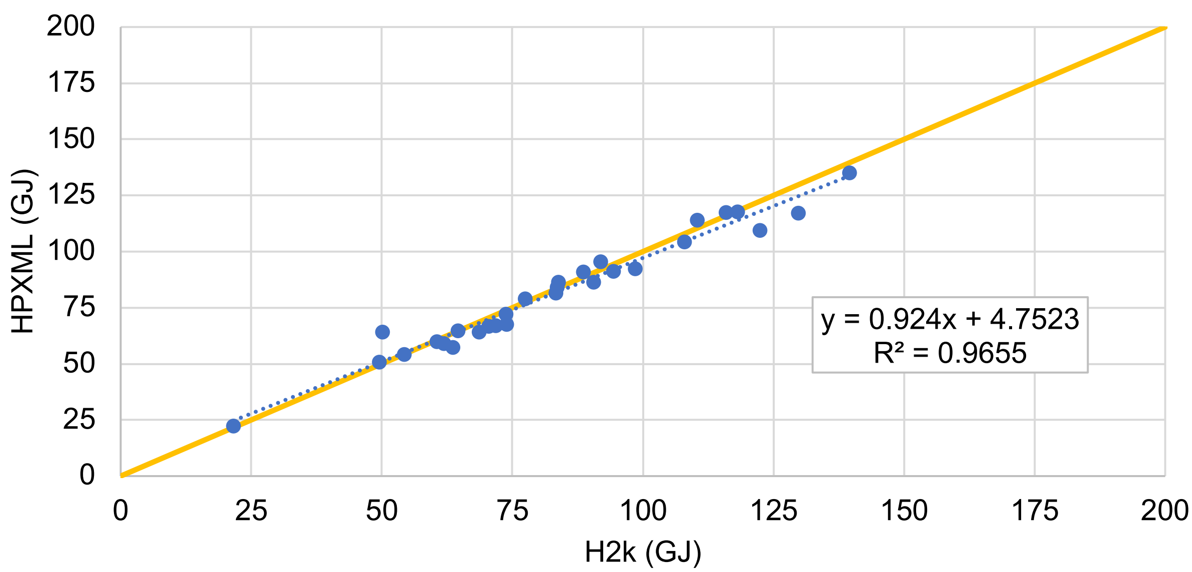

Figure 3. Space heating electricity consumption for homes with electric furnaces.

Air Source Heat Pumps

Space heating electricity consumption for ASHPs is presented in Figure 4. This test involved simulating central ASHPs in HPXML using the three available compressor types: single stage, two stage, and variable speed, to determine if these parameters had a significant impact on the *annual* consumption associated with ASHPs. Variable speed compressors appear to result in annual consumption values 4% lower than single-stage compressors, on average for the data points included in this test. However, all results show very good heating consumption alignment between the two engines. A better understanding of HOT2000's internal assumptions would assist in determining which selection is the most appropriate for central ASHPs. Mini-split ASHPs all assume that the systems are variable speed.

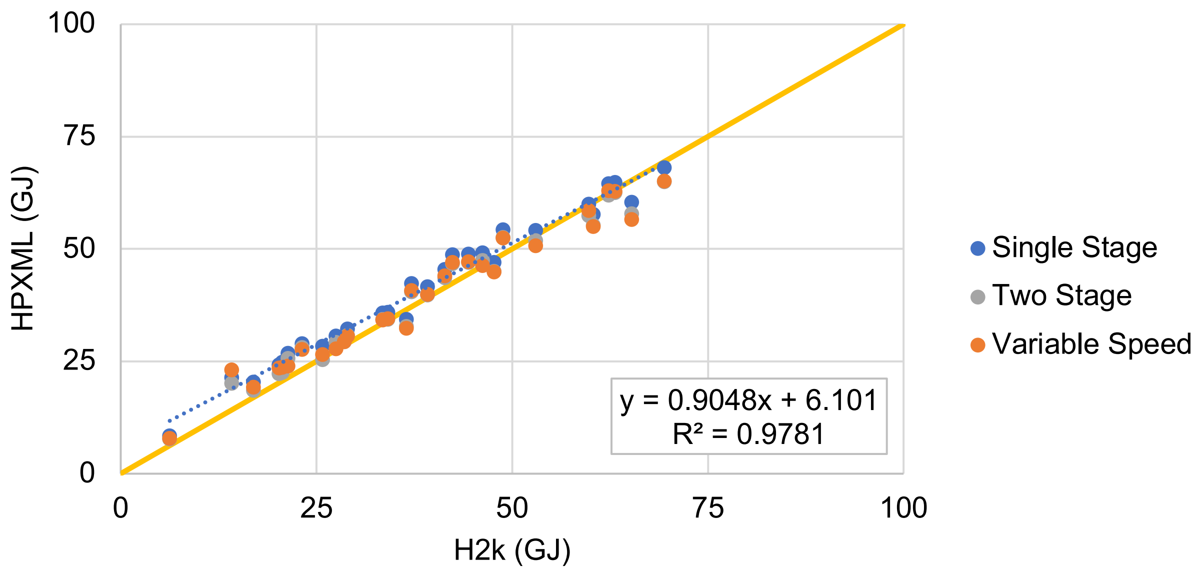

Figure 4. Space heating electricity consumption for homes with ASHPs.

Natural Gas & Propane Heated Homes

Natural gas and propane appliances are modelled very similarly in both HOT2000 and HPXML. Figure 5 displays the natural gas consumption for a home with a condensing furnace (AFUE = 95%), and Figure 6 displays the propane consumption for an induced draft fan propane furnace (AFUE = 82%). Both cases demonstrate very close alignment between the two engines.

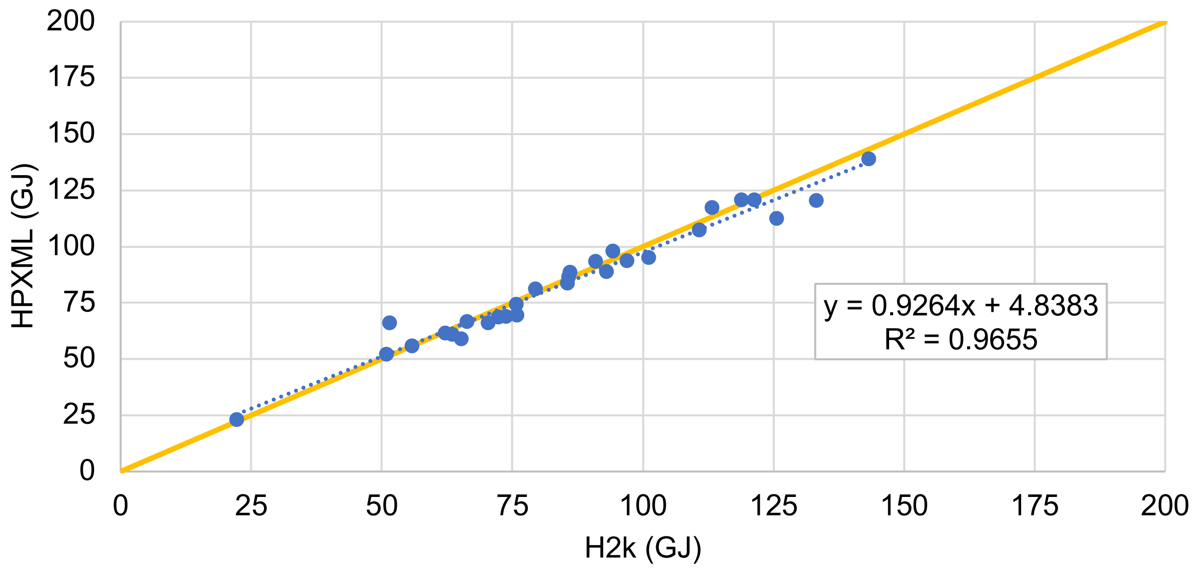

Figure 5. Space heating natural gas consumption for homes with natural gas furnaces.

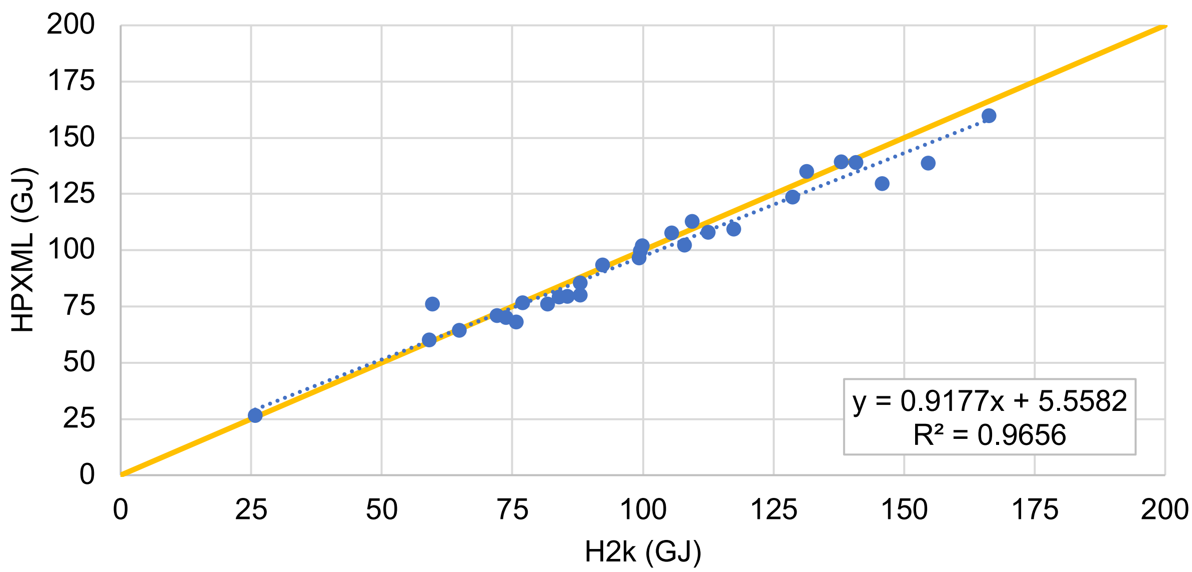

Figure 6. Space heating propane consumption for homes with a propane furnace.

Oil Heated Homes

Two separate oil heating systems were modelled, a furnace and a boiler, the results of which are displayed in Figure 7 and Figure 8, respectively. Both systems were modelled with AFUE = 85%, and the differences lie in the connected HPXML distribution systems, where furnaces are connected to air distribution and boilers are connected to hydronic distribution systems. In both cases, strong alignment is observed between the two engines.

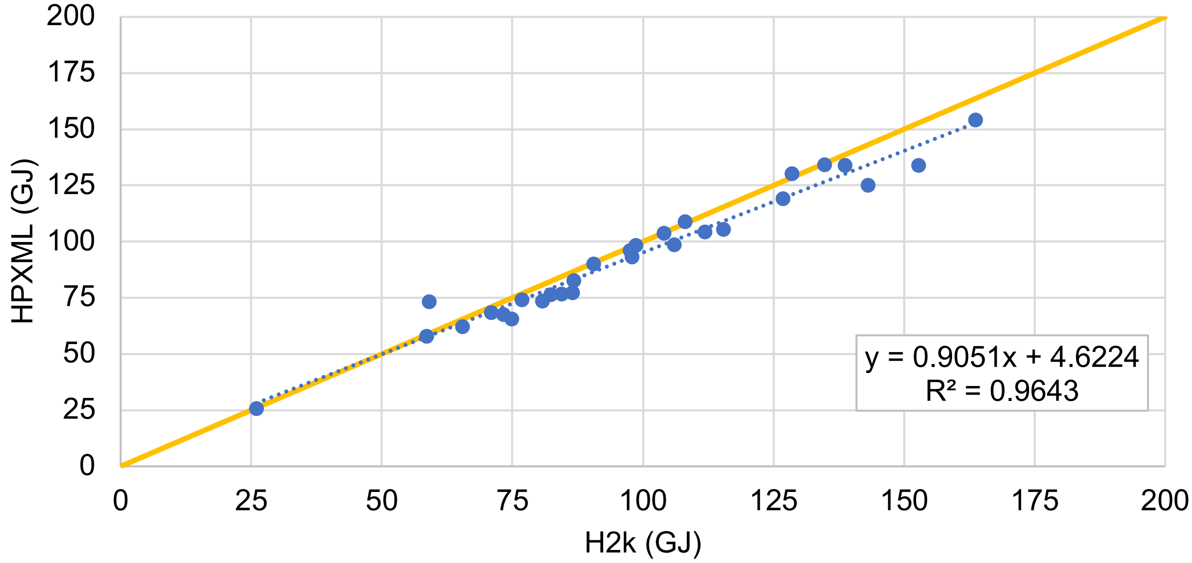

Figure 7. Space heating oil consumption for homes with an oil furnace.

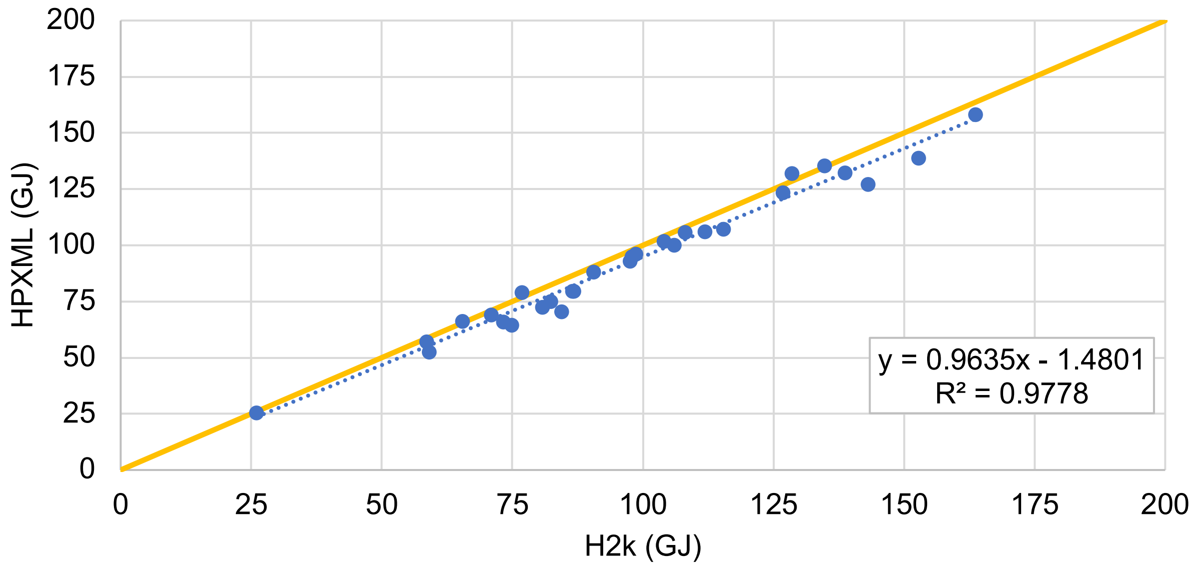

Figure 8. Space heating oil consumption for homes with an oil boiler.

Wood Heated Homes

Two wood fuel types were tested: mixed wood (“wood” in HPXML), and wood pellets. For both fuel type, three different equipment types were tested: a furnace, a fireplace, and a stove. The results for the mixed wood appliances are presented in Figure 9, and the results for wood pellet appliances are pictured in Figure 10. While strong alignment is observed in all cases, the furnace results deviate the most from equality, although to a minor extent (< 5%). This could indicate that this equipment type would be better represented by a stove or fireplace in HPXML.

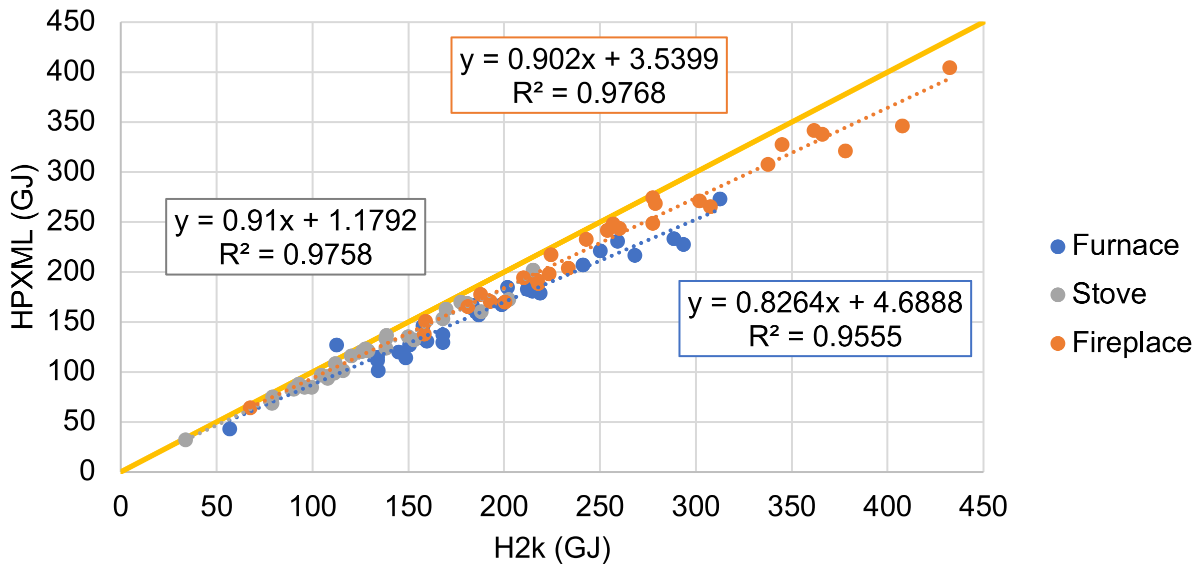

Figure 9. Space heating mixed wood consumption for homes heated with wood appliances.

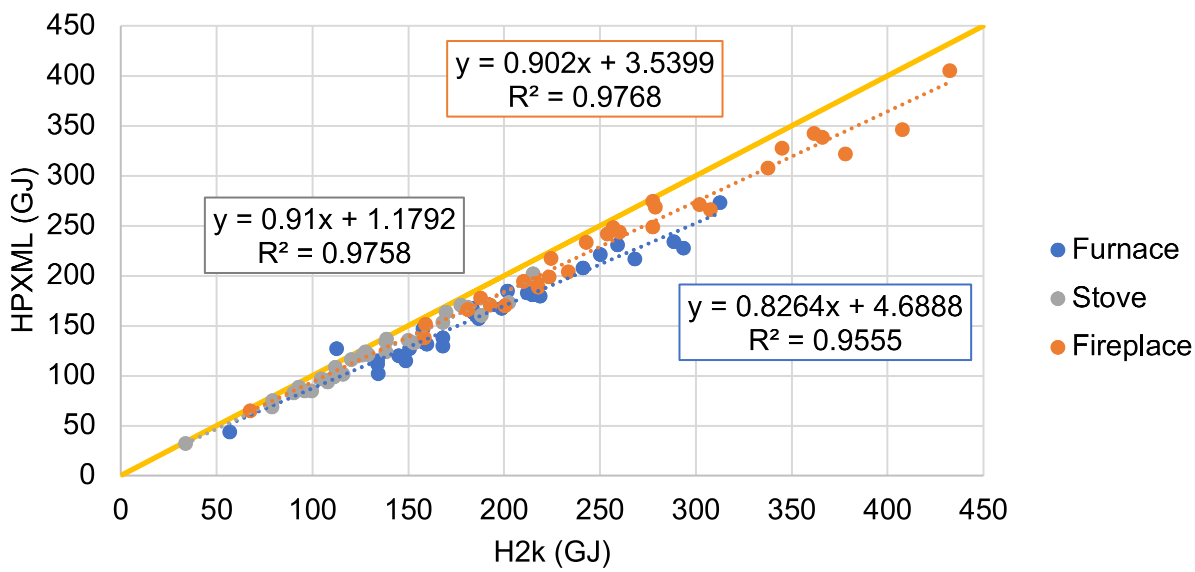

Figure 10. Space heating wood pellet consumption for homes heated with wood pellet appliances.

Combo Heating Fuel Consumption

The space heating natural gas consumption for combo and P.9-11 combo systems is presented in Figure 11 and Figure 12, respectively. Stronger alignment is observed for standard combo systems, which use the heating equipment AFUE as the efficiency in both engines. The equivalent HPXML boiler modelled for P.9-11 combo systems uses the CSHE, which appears to deviate from equality at higher levels of consumption. This model could be further refined with a better understanding of how HOT2000 interprets the various efficiency inputs for P.9-11 systems and determines an equivalent space heating efficiency.

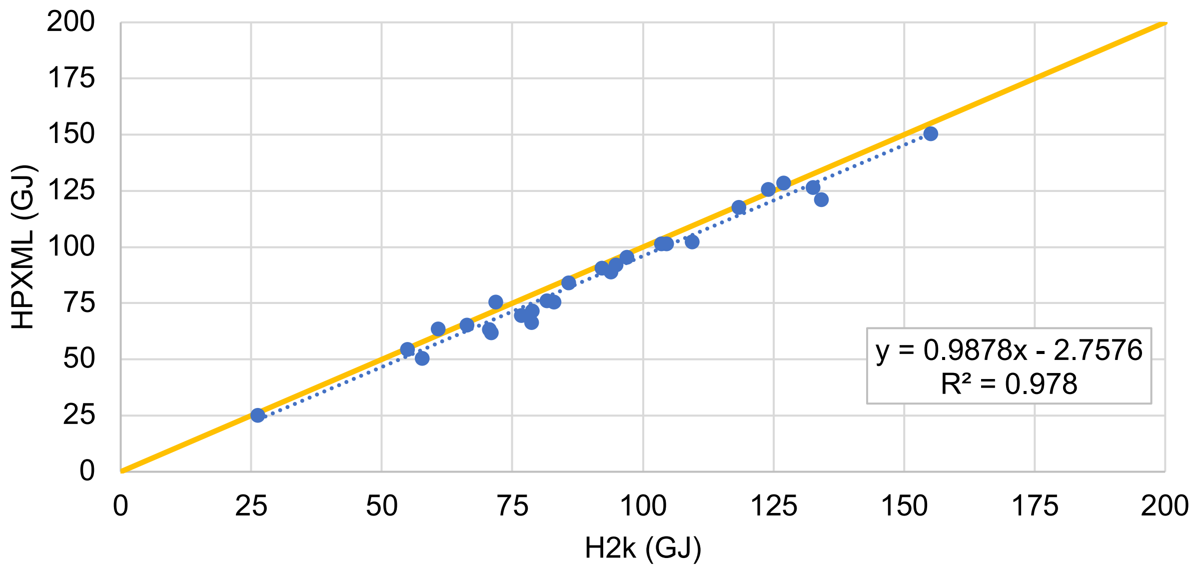

Figure 11. Space heating gas consumption for combo heating/DHW systems.

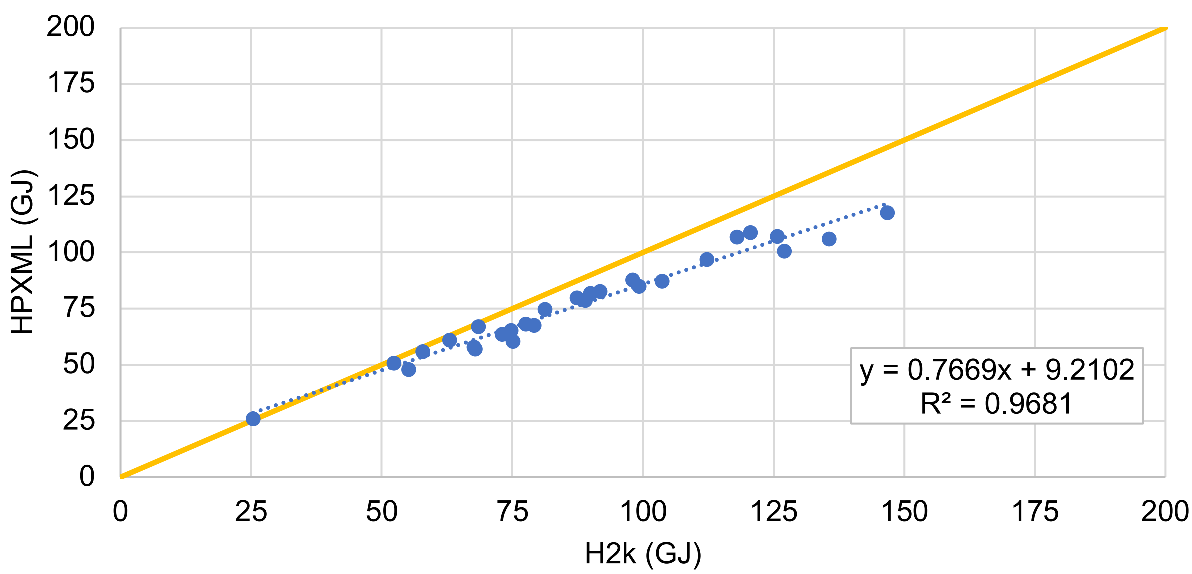

Figure 12. Space heating gas consumption for P.9-11 combo systems.

Hot Water Fuel Consumption

Despite initial efforts to align hot water consumption between the engines, the calculation of total hot water consumption in HPXML is complex and relies on knowledge of hot water fixture schedules. While this information is available in the HPXML codebase, it hasn't been integrated into the H2k-HPXML translator yet because of its relationship to occupancy, which is influenced by the operating conditions modelled. At this time, the H2k-HPXML translator only supports standard operating conditions, which assumes a fixed three occupants for households. Future work in the development of the H2k-HPXML standard should focus on the full alignment between operating conditions, which includes hot water usage. Since this step has not yet been completed, all hot water results are presented with HPXML consumption normalized to match the hot water consumption assumed in the HOT2000 simulation.

Figure 13 displays normalized DHW system natural gas consumption results for a gas storage tank and a gas TOU system. Two types of discrepancies are observed. The first is a deviation of slope from the line of equality, best demonstrated by the gas storage tank results. The cluster of points in the middle represents systems in Ottawa and Montreal, while the lower and upper clusters represent points in Vancouver and Edmonton, respectively. The observed deviation appears to be correlated to heating degree day (HDD) of the weather location, where locations with colder temperatures result in an overestimate of HPXML consumption relative to HOT2000, and locations with warmer temperatures exhibit the opposite. It is speculated that this result is due to differences in assumptions in ground and water inlet temperatures between the two engines.

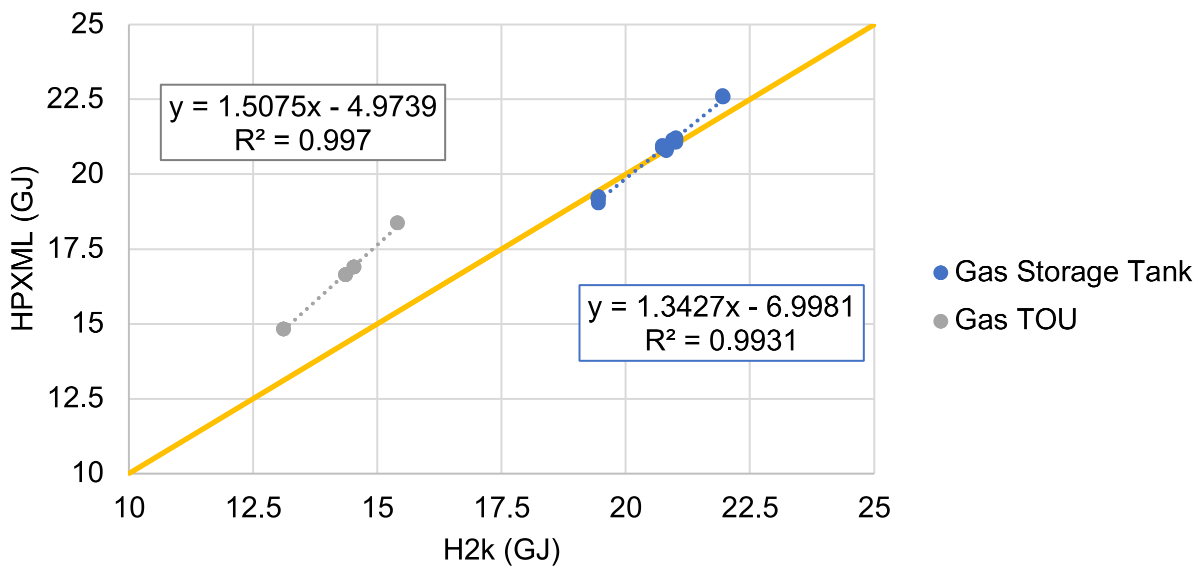

Figure 13. Normalized DHW system natural gas consumption for two natural gas-powered systems.

The second area of discrepancy appears to be related to the type of tank. In the OS-HPXML workflow, the inputs of DHW systems are manipulated with two functions prior to the creation of the DHW system that the OS simulation engine acts on. The first calculates the actual volume of the tank based on its storage capacity, and the second calculates the U-value of the tank, the UA-value, and the "conversion efficiency" of the tank. These calculations are transparent in the OS-HPXML code repository and reference published sources. It also appears as if the interpretation of a DHW system's energy factor (EF) may differ between HOT2000 and HPXML, where HPXML refers to the EF as the "Label EF". Whether this interpretation is consistent between the engines is uncertain, but it appears as if HPXML attempts to calculate "actual" performance from "label" ratings, in a similar manner to appliance consumption (clothes washer, dishwasher, dryer, etc.). Aligning appliance consumption required using the inverse of HPXML's equations designed to calculate "actual" consumption from "label" ratings, since HOT2000 defines appliance consumption in terms of actual values. As such, it may be possible that a similar approach must be taken for DHW systems, which would involve calculating an equivalent "label" rating to input into the HPXML file such that both systems would act on the "actual" efficiency of the DHW tank. This effort is not necessarily difficult but has not yet been attempted because it requires a more thorough understanding of interpretations in both HOT2000 and OS-HPXML, and conversations with both development teams should follow this work.

Figure 14 displays consumption for three common types of electric DHW systems: a heat pump water heater (HPWH), storage tank, and TOU system. While strong correlations are observed, the additional alignment steps noted previously would help to account for the remaining discrepancies observed.

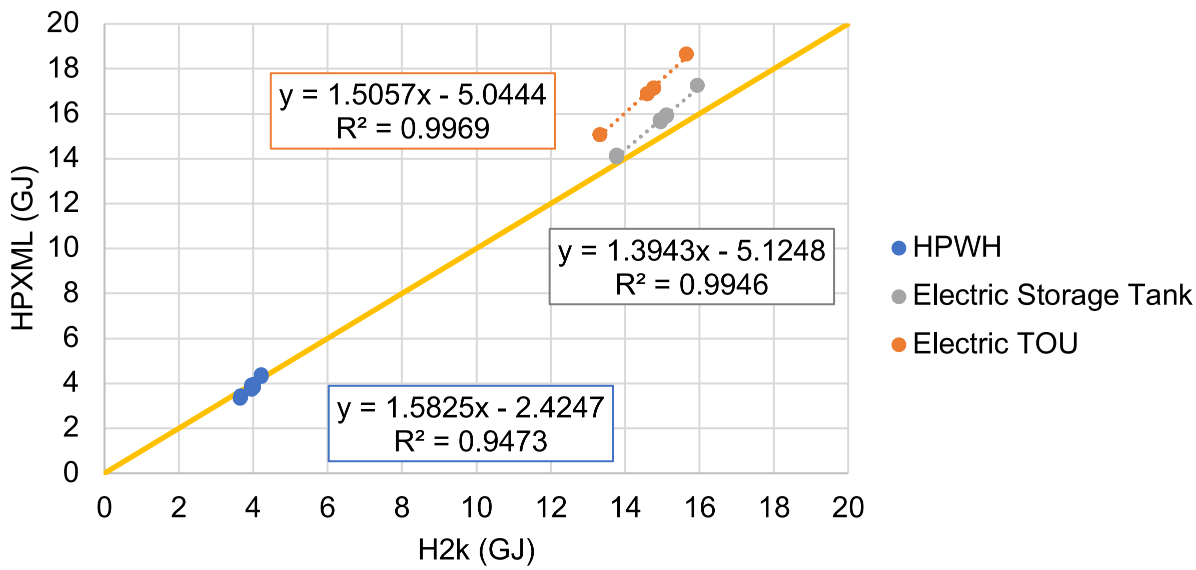

Figure 14. Normalized DHW system consumption for electrically powered systems.

DHW system consumption for standard combo and P.9-11 combo systems is presented in Figure 15 and Figure 16, respectively. The same observations noted for other DHW systems hold for combo DHW consumption. However, further alignment of P.9-11 combo systems would benefit from greater transparency in how HOT2000 interprets system efficiencies to determine an equivalent water heating efficiency.

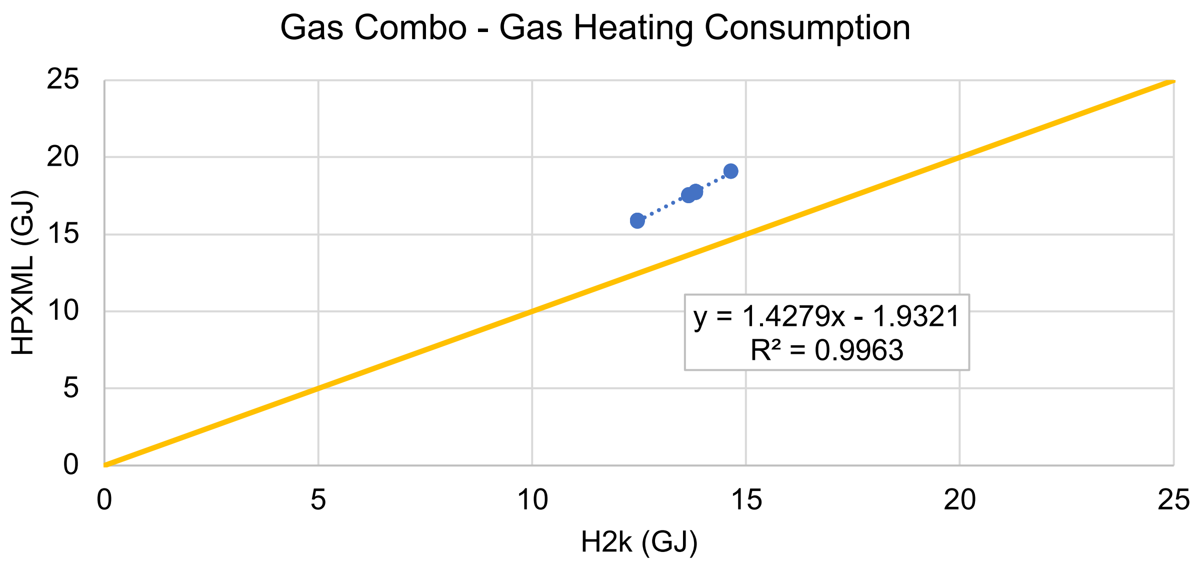

Figure 15. Normalized DHW system consumption for natural gas powered combo systems.

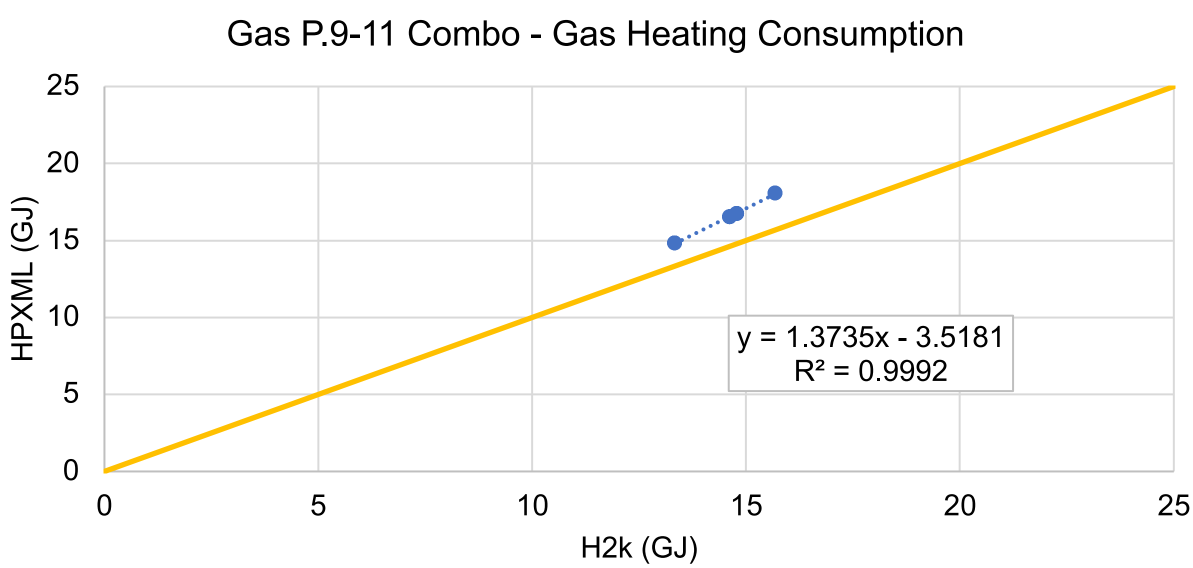

Figure 16. Normalized DHW system consumption for natural gas powered P.9-11 combo systems.

Cooling Electricity Consumption

Cooling system energy consumption shows the greatest deviation between the engines relative to other fuel consumption end uses. This result is somewhat expected due to previous tests of the HOT2000 simulation engine. However, reasons for discrepancies in results are difficult to pinpoint because, as previously noted, there is no cooling season equivalent of the “auxiliary heating energy” metric provided in the set of HOT2000 results.

Figure 17 presents electricity consumption results for both engines for homes using air conditioning (AC) and ASHPs for cooling. These results include a highlighted point for each system, indicated by the large outlined diamond, which represents the same underlying home. Deviation between the engines was expected to an extent, due to the fact that the envelope alignment metric used was the peak cooling load and not an equivalent “auxiliary *cooling* energy” metric, but the surprising result is that cooling consumption appears to typically be higher for HOT2000 simulations. There are many potential factors that could cause this, some of which are investigated below.

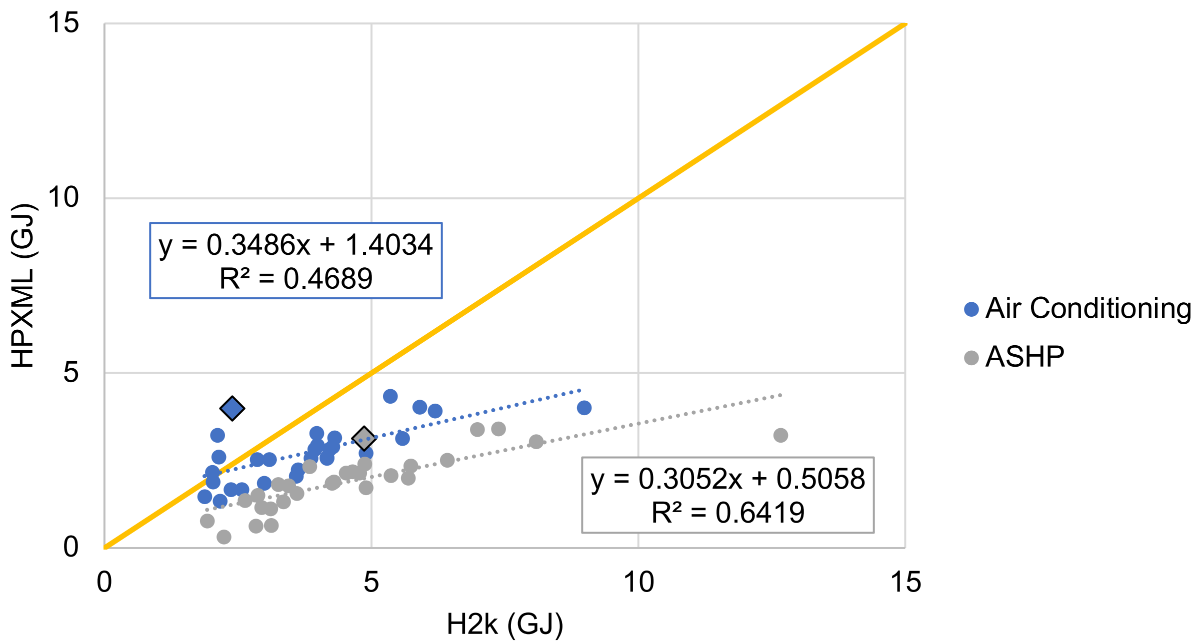

Figure 17. Cooling system electricity consumption for central AC and ASHP systems – prior to cooling alignment.

First, the archetype highlighted in Figure 17 was investigated, which is indicated by the outlined diamond points. Table 10 summarizes the data behind these highlighted points.

Table 10. ERS-EX-63775 AC and ASHP annual cooling consumption results.

System Type	SEER	HOT2000 Capacity (kW)	HOT2000 Annual Cooling (GJ)	HPXML Annual Cooling (GJ)
AC	16	9	2.4	4.0
ASHP	16	13	4.9	3.8

For archetype ERS-EX-63775, HOT2000 estimates a peak cooling load of 7.9 kW, while HPXML estimates 8.0 kW, results that are in very close alignment. However, the ASHP system was sized for heating, which resulted in an oversized cooling system in HOT2000. As a result, the HOT2000 cooling consumption results are two times greater than when the home uses an AC sized for cooling, while the HPXML cooling energy consumption estimates show much better alignment between the two systems. In the HPXML case, both systems were sized for cooling. It is unclear why the system size had such a large impact on the HOT2000 cooling load result.

The analysis was repeated for a set of 240 existing housing archetypes, displayed in Figure 18. This number of archetypes derives from the number of models with cooling systems (both AC and ASHP) from a random sample of 10% of the 6000 existing housing archetype files. These results show a tighter correlation but still show that the H2k-OS-HPXML workflow seems to underestimate cooling energy consumption compared to HOT2000.

However, while this result may seem surprising, both the OS-HPXML workflow and the H2k-OS-HPXML workflows pass all cooling tests defined by the 2024 set of RESNET HERS criteria, providing a high degree of confidence in the HPXML results. These results show that the (somewhat established) notion that HOT2000 "underpredicts cooling" may occur in certain situations, but is not true in a generalized sense. It is unclear if HOT2000 simulation results have ever before been compared *en masse* to the results of another simulation engine in the manner outlined in this project. These results suggest that HOT2000 tends to *overestimate* cooling loads relative to EnergyPlus. nevertheless, it is still worthwhile to determine which situations lead to over or underestimation of cooling load results.

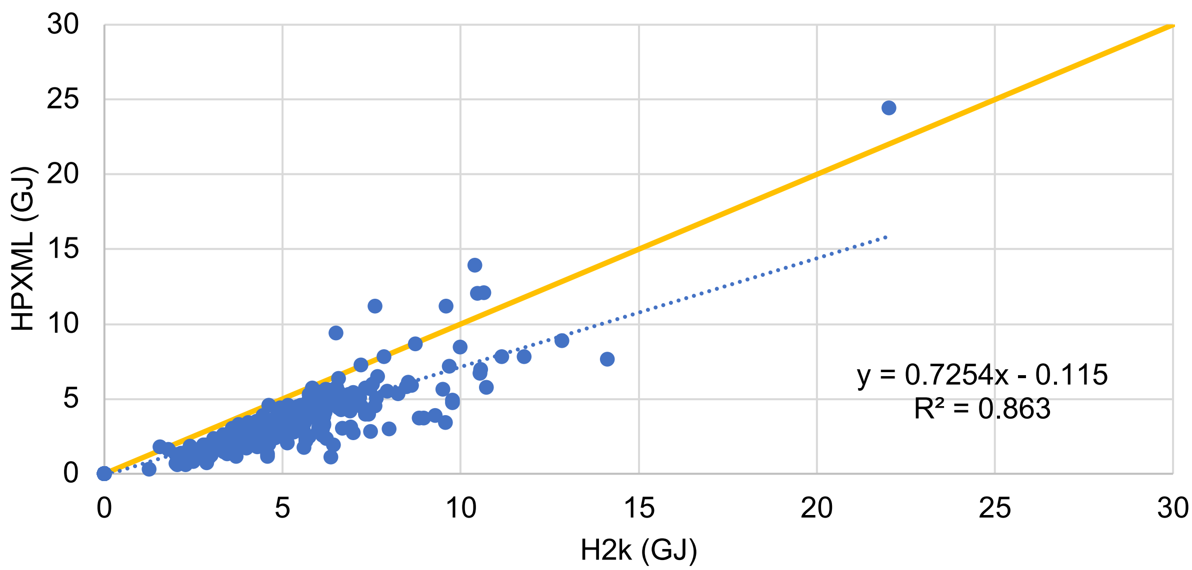

Figure 18. Cooling consumption comparison for a set of 240 existing housing archetypes – prior to cooling alignment.

It is still worth highlighting that, in its current form, the key metrics considered by the translator when creating cooling systems are the system's size and the system's efficiency. A better understanding of assumptions in both engines (i.e. how to they each interpret a SEER rating and convert it into COP?) would help to ensure the translator is fully aligned.

To further investigate cooling load behaviour, an analysis was performed on a separate set of archetype files based on a National Building Code analysis on overheating performed by CanmetENERGY (Purdy, et al. 2019). This analysis, referred to as the PCF-1617 analysis, looked at how HOT2000 and EnergyPlus would estimate peak cooling loads and seasonal cooling energy consumption and created a matching set of archetype files for both simulation engines. These archetype files were created manually and independently for each engine, and can therefore be used to help identify potential issues with the H2k-HPXML translator developed within this project.

The analysis involved four archetypes labelled A through D, each representing a different window-to-wall ratio (WWR), which were duplicated and re-oriented such that windows were facing the north-south and east-west directions, resulting in a set of eight distinct archetype files.

An investigation of solar heat gain coefficient and WWR was performed. Duplicates of the eight archetype files were created, one set with a lower SHGC on all windows, and one set with a higher SHGC on all windows. These HOT2000 files were run through the H2k-OS-HPXML workflow, and the differences in estimated cooling energy consumption were investigated for a 14.5 SEER AC. The results of this analysis, which display the difference in cooling GJ electricity consumption, are displayed in Figure 19. In this figure, positive numbers indicate that HPXML overestimates cooling consumption relative to HOT2000. These results show that higher SHGCs and higher WWRs, both of which would result in higher overall cooling loads, result in HPXML estimating greater cooling energy consumption relative to HOT2000. This demonstrates that the HPXML approach may be better at assessing overheating for homes at greater risk.

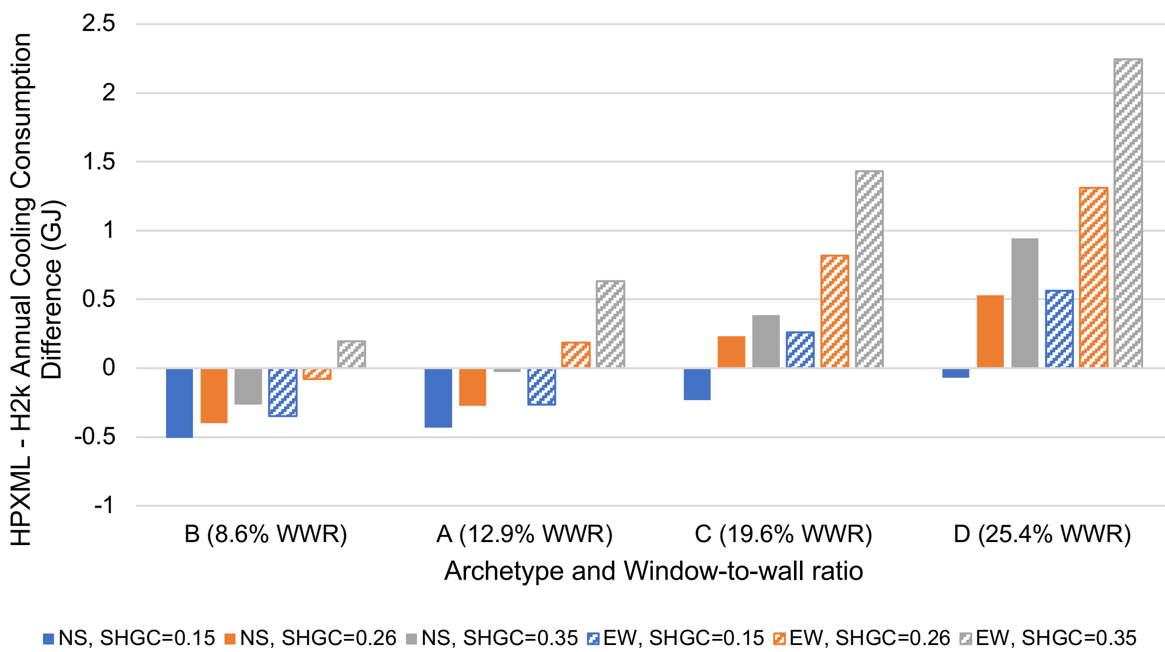

Figure 19. Investigation of window to wall ratio and SHGC on cooling energy consumption.

The most recent publication on testing HOT2000 to ASHRAE 140 (Parekh, et al. 2018) contains the quote (in the section discussing the limitations of the test and test cases):

> *Solar heat gains in cases with south windows will be at the limit (or beyond) what HOT2000 is designed to simulate due to the cases having very high window area (over 20% of the floor area)…*

This would indicate that the areas that displayed the greatest discrepancy in the ASHRAE 140 test cases (where HOT2000 underestimated consumption relative to other engines), occur under the same conditions in which HPXML overestimates cooling consumption relative to HOT2000 (higher WWRs and higher SHGCs). It is worth noting that EnergyPlus was not one of the engines included in the reference results of HOT2000's ASHRAE 140 analysis, although the DOE-2.1E engine was included, which is the predecessor to EnergyPlus (US-DOE 2014).

A further investigation of the PCF-1617 files was performed, which involved passing the HOT2000 files through the H2k-OS-HPXML workflow and opening the resulting OpenStudio Model (OSM) files in the OS interface to verify their cooling load estimates. Afterwards, the independently created OSM files were opened in the OS interface and their cooling load estimates were logged. Figure 20 compares these results.

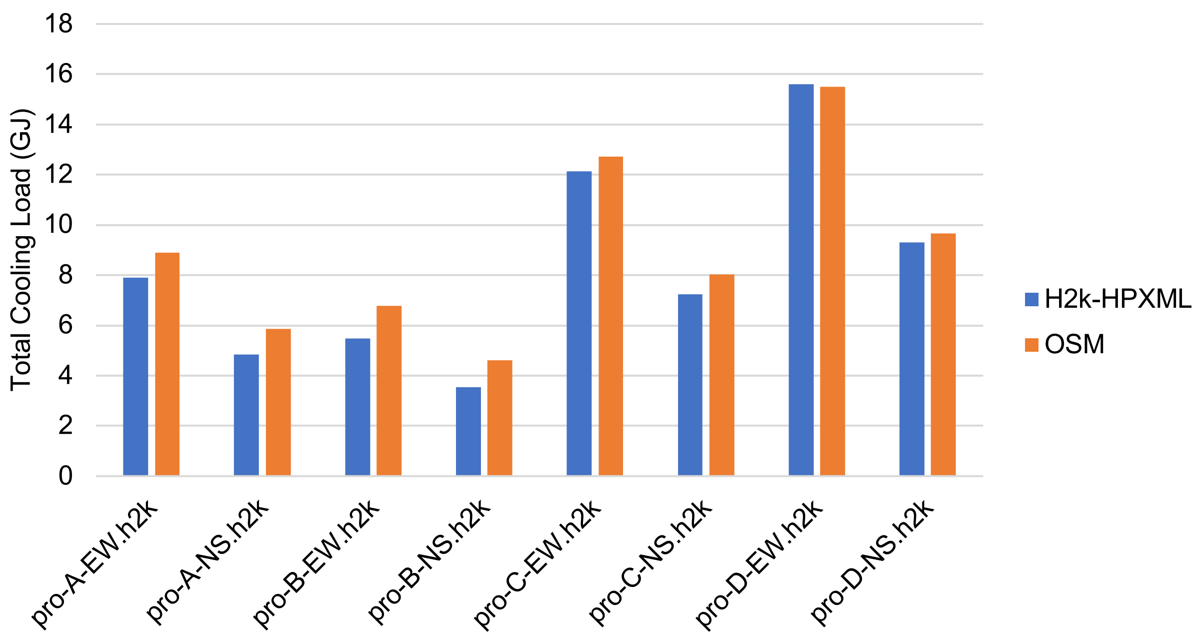

Figure 20. Comparison of cooling loads from H2k-HPXML, and independently generated OSM files representing the same house models.

These results show that the cooling loads estimated via the H2k-OS-HPXML workflow are in line with those estimated by the set of independently created OSM files, providing confidence that the translator is not missing critical information throughout its conversion process.

While these results, in conjunction with the RESNET HERS results, provide confidence in the process developed, some questions remain that can still be addressed to help further refine the process:

- How do HOT2000 and HPXML interpret cooling system inputs? For example, how are SEER ratings converted into values used to calculate system performance? Does either engine attempt to account for part-load performance associated with oversized systems?
- What ranges of inputs related to cooling loads are outside of the conditions HOT2000 was designed to simulate?
- Are heat losses and gains through windows being properly accounted for by the windows produced from the translation process?
- Are there defaults being applied in the OS-HPXML workflow, which influence cooling mode calculations, that are not appropriate for regions with low cooling loads (relative to the US), and if so, how should those defaults be adjusted?

Applications & Implications

While the previous section focused on the alignment of results between HOT2000 and OS-HPXML, the most useful aspects of this work involve that which the OS-HPXML workflow does *differently* from HOT2000. Most of these factors stem from the fact that OS-HPXML produces simulation results on an hourly basis, which can be used to gain a vast set of insights into the performance of residential buildings.

The H2k-HPXML translator opens up many doors, allowing for analyses that were not previously possible on Canada's building stock at scale. For example, it will allow for a detailed analysis of energy usage patterns, allowing for the identification of peak demand periods, analyzing the effectiveness of time-dependent energy efficiency measures, and improving the overall accuracy of energy consumption forecasting in Canada. This can enable the evaluation of novel peak-saving electrification technologies in a Canadian context such as ultra-insulated envelope measures, dual-fuel heat pumps, GSHPs, battery energy storage, and solar PV. Future work can incorporate electric vehicles' impacts on peak load as well, a "system" that is currently supported by HPXML but not HOT2000. This translator will act as the foundational platform to assess innovative housing technologies in Canada.

This work also enables the connection of building planning to utility planning. Currently, utilities rely on internal rules of thumb to assess, for example, how many houses should be connected to a transformer. This type of analysis can integrate the building construction and retrofit processes with utility planning processes, allowing all of these interdependent systems to be designed and implemented in an informed way, moving away from siloed planning activities.

The translator can also be used to investigate resilience to extreme weather events. The outputs of the OS-HPXML simulation include details on when backup systems switch on and the internal zone temperature of the building. Studies could investigate the impact of passive solar construction practices on overheating or the impact of thermal mass on the ability to "ride through" power outages during cold temperature snaps. Active resiliency measures can also be investigated, for example, evaluating the potential of battery energy storage to maintain livable conditions during power outages.

There is also a significant advantage in the fact that this system can leverage the vast amounts of existing data that NRCan has been collecting over the years through the EnerGuide Rating System program. Millions of homes, along with statistically representative subsets such as the 6000 archetypes, can be easily translated through this process, allowing for the rapid, large-scale assessment of Canada's building stock.

While it is outside of the scope of this project to conduct detailed analyses on Canada's building stock using the tools available through the H2k-OS-HPXML workflow, this report presents three example analyses that focus on key areas of research and concern: peak load implications of electrification, operating cost implications of electrification, and resiliency to extreme weather. All simulation results in this section were generated using the "NRCan-arch4" new construction housing archetype in the OTTAWA INTL climate zone. This archetype represents a 2100 ft^2, two-storey house with a basement.

It is also worth noting that OpenStudio is extremely customizable, in terms of the outputs it can provide. The outputs used for the following analysis were those produced by the OS-HPXML workflow "out of the box", and do not represent the limits of the types of outputs that can be analyzed.

Electrification and Peak Loads

Peak load analyses can be complex, and can occur in many different contexts, for example, on a single-home or multiple-home basis. A common technique that electric utilities use to assess peak loads involves the use of load distribution curves (LDCs). These graphs plot the observed or expected load against the fraction of the year that will experience at least that amount of load.

Figure 21 displays three load distribution curves, produced using outputs of the H2k-OS-HPXML workflow, representing an ASHP using different temperature cutoff settings. Below the specified cutoff temperatures, the heating system switches to a natural gas furnace as a backup. These curves show, for this particular home, that a heat pump with a cutoff of -5˚C can expect to have electrical loads over 2 kW for 5% of the year, while a cutoff of 5˚C results in loads over 2 kW for only 16 hours of the year (0.2%). The particular heat pump system modelled used a two-stage compressor, which is why the overall peak across all three configurations was similar.

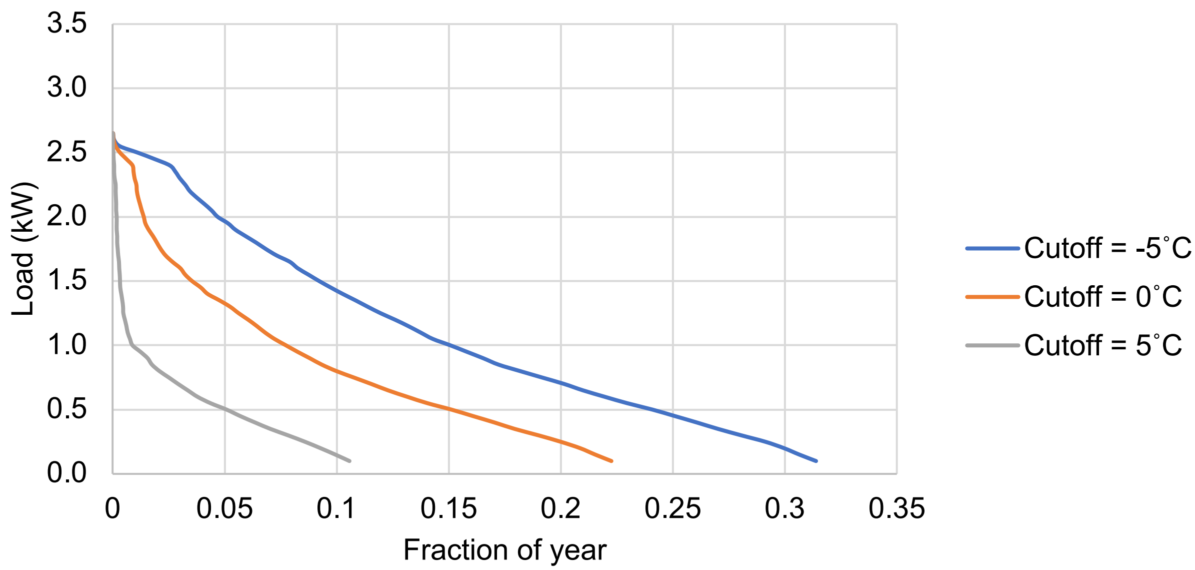

Figure 21. Load distribution curves associated with different heat pump cutoff temperatures.

This analysis can be repeated across multiple homes of varying types, for example, in a new development or existing homes in a neighbourhood, to help assess the likelihood that peak loads across different buildings will coincide. Measures can be analyzed to design systems that result in lower and less coincident peak loads to help utility planning and reduce overall system costs.

Electrification and Operating Costs

While simulations on an annual basis are useful in assessing the overall potential energy savings associated with a given upgrade measure, they are less useful in assessing the operating cost savings potential of measures. A key example of this arises in jurisdictions that charge electricity based on time-of-use billing. A brief analysis in this section looks at the differences in estimating operating costs that arise when performing annual and hourly analyses in Ontario.

Certain electricity consumption tends to be more aligned with the higher-priced TOU periods, for example, cooling energy consumption tends to occur in the middle of the day, during on-peak summer billing. This means that, if assessing the cost of cooling using an average TOU price, those results will underestimate costs relative to reality, since more consumption will be shifted into the on-peak periods. Conversely, solar energy production, which offsets electricity during on-peak periods, will have its cost benefits *underestimated* when assessed on an annual average basis. These examples illustrate how different technologies or measures can have their benefits mischaracterized through a high-level annual analysis.

To investigate this using the H2k-OS-HPXML workflow, the NRCan-arch4 archetype was modelled with three different system configurations: an electric furnace and air conditioner, an ASHP with back-up electric furnace (sized for cooling), and the same ASHP with back-up electric furnace with 13 kW of solar PV. Table 11 displays the difference in operating cost estimates for this illustrative case.

Table 11. Example of operating cost differences when analyzing electricity costs on an annual or hourly basis.

System	Consumption (kWh)	Operating Cost (Annual Avg.)	Operating Cost (TOU)	Percent Difference
Elec. Furnace + AC	38,904	$ 4,888	$ 5,130	4.7%
ASHP	28,724	$ 3,609	$ 3,820	5.5%
ASHP+PV	19,751	$ 2,482	$ 2,472	-0.4%

While this particular example may only show modest differences in cost estimates, these types of analyses can ensure that measures being proposed to homeowners are accurately reflecting their cost implications. They can also be used to help identify pathways for homeowners that utilize solutions that complement each other to reduce costs, such as the combination of solar PV with an ASHP installation, which can offset ASHP consumption at some of the more expensive times of day.

The HPXML file created from the H2k translator can include custom utility bill schedules, reflecting a variety of cases, which will allow the OS-HPXML workflow to automatically account for custom utility billing when it performs its cost calculations. The same is true for emission schedules, allowing for the calculation of emissions based on hourly emission factors.

Resiliency to Extreme Weather

The OS-HPXML workflow provides a number of ways to assess the ability of a mechanical system (or lack thereof) to meet the loads experienced by a home. Two of those metrics that can be easily analyzed are the "unmet hours" metric and the zone temperature. Unmet hours, presented separately for both heating and cooling, represent the number of hours in the year that the zone does not reach the desired set point.

The NRCan-arch4 archetype was run in three different configurations: without a cooling system, with an undersized (2 kW) air conditioner, and with an auto-sized (6.7 kW) air conditioner. Table 12 displays these high-level summary results for the three test cases.

Table 12. Summary results for overheating analysis.

Configuration	Unmet Cooling Hours	Maximum Zone Temperature (˚C)
No Cooling	2712	34.3
2 kW AC	933	28.9
Auto-sized AC	3	25.3

Figure 22 displays the hourly zone temperature over time for a two-day period in late summer (starting August 31st). This period contains the hour of the year with the maximum observed zone temperature. While this analysis used the default Canadian Weather Year for Energy Calculations (CWEC) weather file, it could be repeated with climate data that represents more extreme conditions (including future climate data). These types of results can help industry and government better plan for extreme weather events, and develop policies and plans that ensure Canadians are adequately prepared for such events.

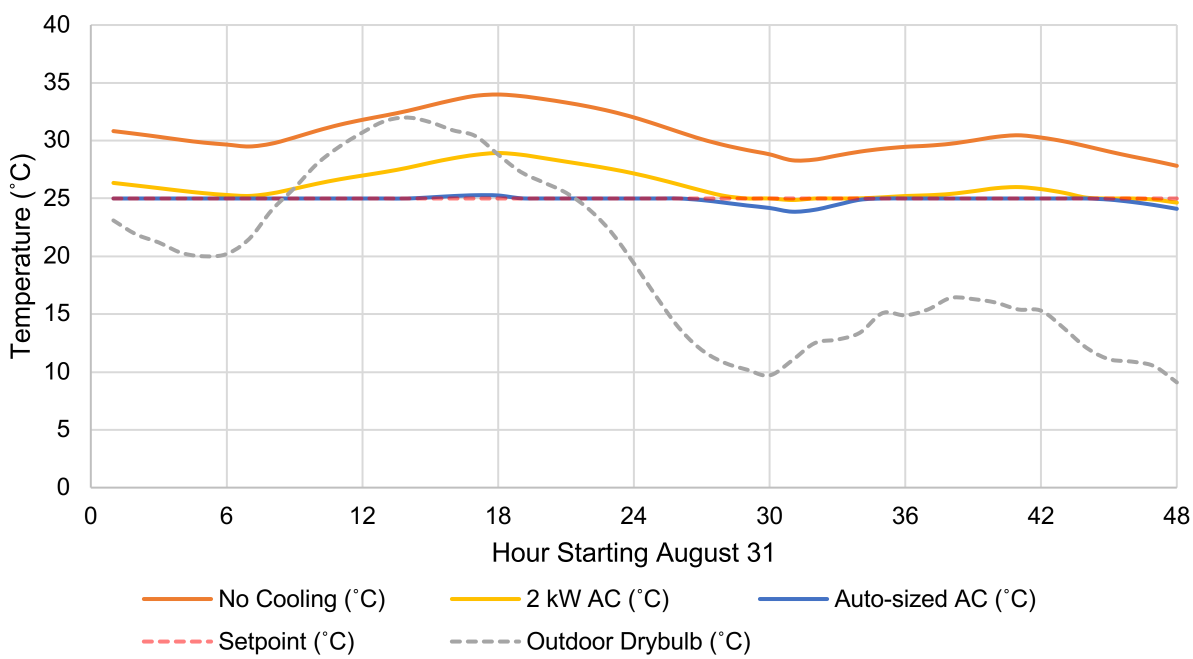

Figure 22. Zone temperature over time for a two-day period in late-summer for different cooling system configurations.

Summary of Areas of Misalignment

A summary of the remaining areas of misalignment, with respect to the “Systems” section of the HPXML file, is presented below. These represent areas where future work can help improve the translator.

- **Efficiency Input Discrepancies for Heating Systems:** HPXML Furnaces and Boilers require efficiency input in AFUE, while Stoves and Fireplaces use Percent (steady state) efficiency. HOT2000 allows both of these types of efficiencies to be input for all primary heating systems. This can result in a misalignment of efficiencies between the engines, for example, if a HOT2000 furnace is defined with a steady state efficiency. An understanding of the relationship between AFUE and steady-state efficiency used in HOT2000 would allow for a more accurate translation process.
- **Lack of Direct Equivalents for Flues and Additional Openings:** Flue diameters and Additional Openings do not have equivalent representation in HPXML. If any flues are specified within the .h2k file, the field in HPXML named `HasFlueOrChimneyInConditionedSpace` is set to TRUE.
- **Assumptions of Fraction of Heat Load Served by Supplementary Heating:** HOT2000 does not explicitly define the fraction of heating *load* served by each heating system. The translator currently assumes this fraction is equal to the fraction of floor area served by each supplementary heating system, which may not always reflect the actual operation and heating energy contribution of these systems.
- **Simplified Modelling of Radiant Heating**: While radiant heating systems can be defined, the translator currently assigns either "radiant floor" or "radiant ceiling" based on the largest floor area served, and multiple radiant heating systems are not defined due to HPXML using only one heated zone.
- **P.9-11 Combo Efficiency Assumptions:** A more thorough understanding of HOT2000’s internal assumptions would help to derive a more representative overall heating efficiency input for the HPXML translation.
- **Unaddressed Cooling Consumption Discrepancies:** Further analysis is required to better align the cooling system section of the translation process.
- **Water-loop-to-air Heat Pump Interpretation:** It is unclear whether HOT2000’s water source heat pump should be modelled as a “water-loop-to-air” system or a ground source heat pump in HPXML.
- **Potential Differences in Interpretation of DHW System EF:** There appears to be uncertainty in whether HOT2000 and HPXML interpret the DHW system's EF consistently, with HPXML seemingly trying to calculate "actual" performance from "label" ratings. This might require a similar reverse-engineering approach as used for appliance consumption to ensure accurate translation of DHW system efficiency.
- **Handling of Default EFs for Combo Heating/DHW Systems:** Combo Heating/DHW systems do not write their energy factor to the .h2k file when using default values. At the moment, the system uses the efficiency of the heating system as a fallback for this energy factor if not written to the file and warns the user that they should use user-specified energy factor values. With a map of default combo EFs used in HOT2000, this could be remedied.
- **Complexity of Hot Water Consumption Alignment:** Despite efforts to align hot water consumption, the calculation in HPXML is complex and relies on hot water fixture schedules, which are not fully integrated into the translator and are linked to occupancy assumptions (currently hardcoded to three occupants based on standard operating

conditions). This can lead to variations in water heating energy consumption between the two engines.

- **Treatment of Utility Fans**: Supplemental utility fans in HOT2000 do not have a direct HPXML equivalent (as local ventilation fans are limited to kitchen and bathroom). They are modelled in HPXML as "used for whole building ventilation" but with their operation hours based on the supplemental utility fan settings, which might not fully capture their intended function.
- **Simplified HRV Translation:** The HRV's low-temperature efficiency value in HOT2000 is not directly accounted for in HPXML.

Conclusions and Next Steps

This project has successfully achieved a significant milestone in the effort to enhance the analysis potential of Canada's residential building stock by developing a translator capable of converting HOT2000 files to the HPXML format. The resulting translation process supports all non-MURB inputs in the HOT2000 file structure, which includes all mechanical systems included in HOT2000. This enables the utilization of the EnergyPlus simulation engine, accessed through the OS-HPXML workflow, to generate detailed hourly and sub-hourly energy consumption profiles, a level of granularity previously unavailable through HOT2000 alone. Initial comparisons between the two simulation engines have yielded promising results, laying the groundwork for a deeper understanding of their respective strengths and limitations in modelling various system configurations.

The development of this translator unlocks many opportunities for future research and analysis crucial for the Canadian housing sector. It provides a powerful tool to investigate peak electricity demand, evaluate the effectiveness of time-dependent energy efficiency measures, and assess the resilience of homes to extreme weather events. Furthermore, it facilitates the impact analysis of innovative technologies such as heat pumps, solar photovoltaic systems, and energy storage on residential energy use and grid infrastructure. By enabling the translation of NRCan's extensive database of HOT2000 archetype files, this project provides a foundation for large-scale, data-driven insights to inform policy development and support the transition towards a more energy-efficient, affordable, and resilient housing future for Canadians.

Next Steps

Moving forward, efforts will focus on further refining the translator, addressing identified gaps and expanding its scope to support MURB simulations and assess a wider range of operating conditions. Ongoing comparisons and collaborations with the development teams of both HOT2000 and HPXML will be critical to address identified areas of misalignment and ensure the accuracy and robustness of the translation process. The continued development and application of this translator promises to yield valuable insights for researchers, policymakers, and industry stakeholders working towards a more sustainable and efficient built environment in Canada.

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