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Assessing the Thermal Comfort and Peak-Shifting Capabilities of Electric Thermal Storage Technology in the Yukon

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SUMMARY

The Yukon Electric Thermal Storage (ETS) Demonstration Project is an opportunity to assess the viability of thermal storage technology in northern climates. The key idea behind ETS technology is through storing heat during periods of low electricity demand, electricity consumption during periods of high demand is reduced. On a sufficiently large scale, this could reduce peaks in electricity demand across the grid. Regardless of what benefits of peak-shifting may produce, ETS heating systems must still fulfil their primary purpose in providing satisfactory thermal comfort to occupants.

Quantitative electrical and thermal data, as well as qualitative survey data, was collected in the Yukon's 2021-22 heating season to evaluate ETS performance in meeting thermal comfort expectations while maintaining peak-shifting capabilities. Empirical thermal comfort models were used to predict thermal comfort in ETS participant homes. The model results were then compared with survey responses from occupants to validate their outputs. The ability of ETS systems to draw power during off-peak times was assessed by analysing the sum of power drawn during on-peak and off-peak times. The power draw during off-peak times was compared with thermal comfort model outputs and outdoor temperatures to identify any notable correlations between the three variables. This analysis found ETS systems provided satisfactory thermal comfort while consistently drawing power to store as heat during off-peak times, providing peak-shifting capabilities without affecting occupant comfort.

KEYWORDS

Thermal storage, Heating, Thermal comfort, Peak shifting, Demonstration project

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INTRODUCTION

The Yukon Electric Thermal Storage (ETS) Demonstration Project ("the ETS Project"), funded primarily by Natural Resources Canada, involves over 40 participants and nearly 100 ETS units currently being studied to assess the viability of ETS technology in the Yukon, and in a northern context more generally. The Yukon Conservation Society manages the installation and operation of, and data collection from, all ETS units. The ETS units are comprised of space heaters, furnaces, and hydronic heaters from two ETS manufacturers.

For all ETS systems, including those in the ETS Project, the fundamental concept behind the technology is the separation of heat production and heat delivery. Heat is produced electrically, typically with resistance heating elements or a heat pump, and stored as latent or sensible heat in a material with a high thermal mass, usually within an insulated housing. The production of heat is controlled to primarily occur during periods of low electricity demand from the power grid or when there is a surplus of intermittent renewable power that may otherwise be curtailed. Generally, heat is stored during "off-peak" times and released during "on-peak" times. Heat is released either passively through natural convection, actively with a fan or pump, or a mix thereof.

Using ETS to achieve this separation of heat production from heat delivery has been successfully implemented – in southern jurisdictions, for the most part – to reduce peak demand on power grids, encourage a higher penetration of intermittent renewables, and ancillary services including frequency response and black start support. This project represents the first widespread implementation of multiple types of residential ETS systems in northern North America, including Alaska and all northern Canadian regions.

ETS systems have the potential to reduce the peak demand on the Yukon Integrated System, which serves most Yukon communities, by shifting electric heating loads from on-peak to off-peak times. Currently in the Yukon, rapidly rising winter heating peaks – driven by the increasing popularity of traditional non-storage electrical heat, especially in new builds [1] – are being met with rented fossil fuel generators, at great expense to the utility, ratepayers, and the environment. By reducing the Yukon's peak electricity demand, widespread adoption of ETS could result in reduced greenhouse gas emissions and economic benefits by reducing the portion of electricity generated from fossil fuels.

An important aspect of heating systems is thermal comfort; individuals expect their heating systems to provide heat reliably, responsively, and consistently. If ETS systems cannot satisfy occupant's thermal comfort needs, their other benefits risk not being realized. Using a mixture of sensor data and occupant surveys sourced from the ETS project, an analysis of participant thermal comfort during the 2021-2022 Yukon heating season (September 1st, 2021 through April 1st, 2022) is conducted to assess ETS' ability to meet northern resident's thermal comfort needs. Further, the thermal comfort characteristics of ETS systems are compared with an analysis of ETS power draw during typical on-peak and off-peak periods to assess the system's ability to balance the needs of occupants with the core motivation of shifting electricity demand.

METHODOLOGY FOR DETERMINING THERMAL COMFORT

Multiple indoor temperature and relative humidity sensors were installed in participant homes to gather quantitative data throughout the common living spaces. To take advantage of the multiple sensors while keeping the analysis parsimonious, data was averaged across sensors within participant homes. This could not be done with the raw data as sensors were not synchronized to log data at the same time (such a strategy is impractical). To ensure sensor data was on the same timescale, data was averaged from 5-minute resolution to 1-hour. The 1-hour resolution was chosen as a balance between ensuring the averages were estimated with a moderate sample size while still being able to capture variability at a high temporal resolution. The ETS systems themselves have a suite of on-board sensors to capture a multitude of variables at a high resolution, including power draw. Surveys were circulated to participants to obtain qualitative data on their ETS experiences.

There is a large body of literature on estimating thermal comfort from temperature, mean radiant temperature (MRT), relative humidity, air flow, human activity, and clothing [2]. The most common empirical model is the Predicted Mean Vote (PMV) method developed by Fanger [3], which converts model inputs to an expected response on a seven-point scale shown in Table 1.

Table 1: PMV thermal sensation scale

Hot	Warm	Slightly warm	Neutral	Slightly cool	Cool	Cold
+3	+2	+1	0	-1	-2	-3

The PMV model outputs can be thought of as the expected response from a large sample of occupants. In the ETS demonstration project the large sample assumption will not be valid on a home-to-home basis as the number of occupants in residential homes will be minimal. Due to this, individual characteristics and preferences will be magnified. However, the PMV approach has value in assessing overall thermal comfort across a large sample of homes as individual factors are averaged out. PMV model outputs from -0.5 to +0.5 are considered optimal by ASHRAE [4]. Gagge [5] noted that the PMV model was invariant to changes in relative humidity and developed a process to better account for this variable, known as the 2-Node-Model. The 2-Node-Model uses all the same inputs as Fanger's PMV model. Using project sensor data, the model inputs for temperature and relative humidity are accounted for. MRT is often assumed to be equivalent to air temperature, but this approach is known to underestimate MRT and introduce error in the thermal comfort model [6]. To account for this, air temperature and MRT data from a Montreal office building was analyzed. Montreal was the coldest locale with readily available winter data for indoor MRT and air temperature [7] [8], and is assumed to be an adequate substitute for Whitehorse. A mean difference of -0.72 °C was found between air temperature and MRT data; thermal comfort models in this study used the air temperature data corrected by this mean difference as MRT. Air speed was not measured and was assumed to be 0.1 m/s following a CIBSE recommendation [9, p. 4]. Typical human activity was assumed to be 1.0 met, corresponding to sitting at rest [4]. A minimal level of human activity will require the heating system to provide more heat than a higher level of human activity. Clothing was assumed to be 1.01 clo as a typical winter outfit taken from values in [4]. All model inputs set to fixed values are assumed to be an average about the unknown true value that changes throughout time and the space in a home. Fanger's PMV and Gagge's 2-Node-Model are used to assess thermal comfort within the ETS demonstration project. The findings from the thermal comfort models are compared with results from a survey circulated to ETS demonstration project participants in January 2022.

METHODOLOGY FOR ASSESSING PEAK SHIFTING CAPABILITIES

During the ETS Project, the Yukon Conservation Society has control over the charging times for the ETS systems in participating homes. The charging periods set for the 2021-2022 heating season are provided in Table 2. Charging times were configured to match the local power grid's off-peak periods, where the non-charging times correspond to on-peak periods.

Table 2: Charging times and dates for ETS systems, September 1 2021 – April 1 2022

ETS Manufacturer	Charging times (hrs)
1	1100 – 1600 and 2200 – 0600
2	1100 – 1500 and 2200 – 0600

The amount of power drawn by each ETS system was analyzed with respect to the system's scheduled charging times to calculate a variable for adherence to scheduled charge times. This was done by summing the power draw unit by unit with respect to on and off-peak periods, and then calculating the percentage of the total power draw each category comprises. A higher resolution for adherence to scheduled charge time was found by calculating the percentage of power draw during off-peak times and on-peak times day-by-day.

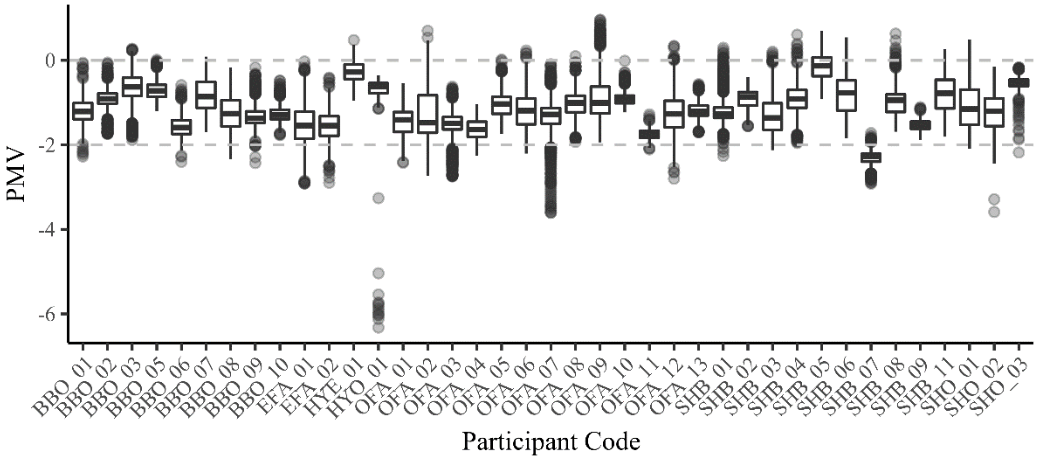
ANALYSIS

Participants were coded according to the primary heating system(s) the ETS unit(s) replaced. An explanation of the coding is given in Table 3.

Table 3: ETS coding

ETS coding	Explanation
BBO	Baseboard only
EFA	Electric furnace
HYE	Electric boiler
HYO	Oil boiler
OFA	Oil furnace
SHB	Space heater + baseboard
SHO	Space heater only

The hourly results for Fanger's PMV and the 2-Node-PMV model are given in Figure 1.



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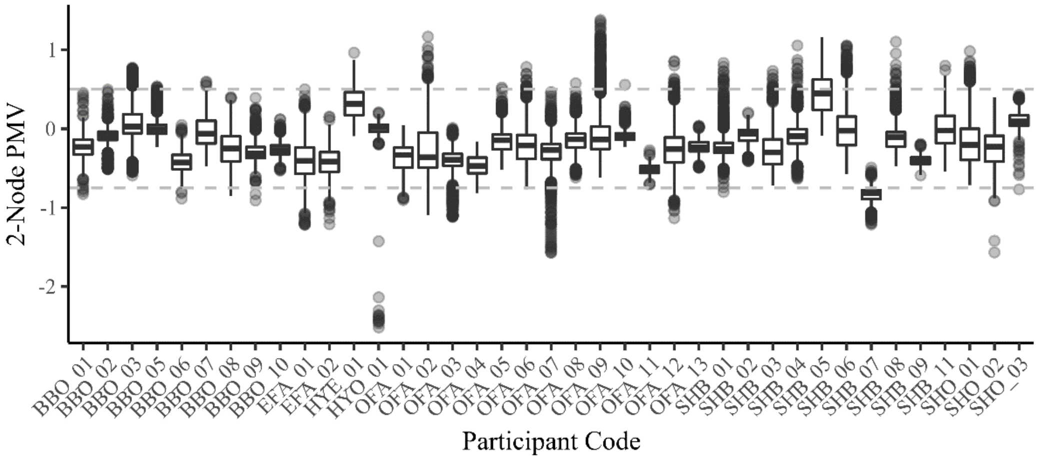

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Figure 1: Fanger's PMV (a) and Gagge's 2-Node-PMV model outputs.

Comparing Figure 1 (a) and Figure 1 (b), Fanger's PMV reports colder thermal sensations than the 2-Node-PMV model. The majority of Fanger's PMV outputs lie within the [0, -2] interval, contrasted with the 2-Node-PMV model which lie within the [0.5, -0.75] interval. The outliers from Fanger's PMV are also more extreme than the 2-Node-PMV. Thermal comfort related survey responses are given in Figure 2.

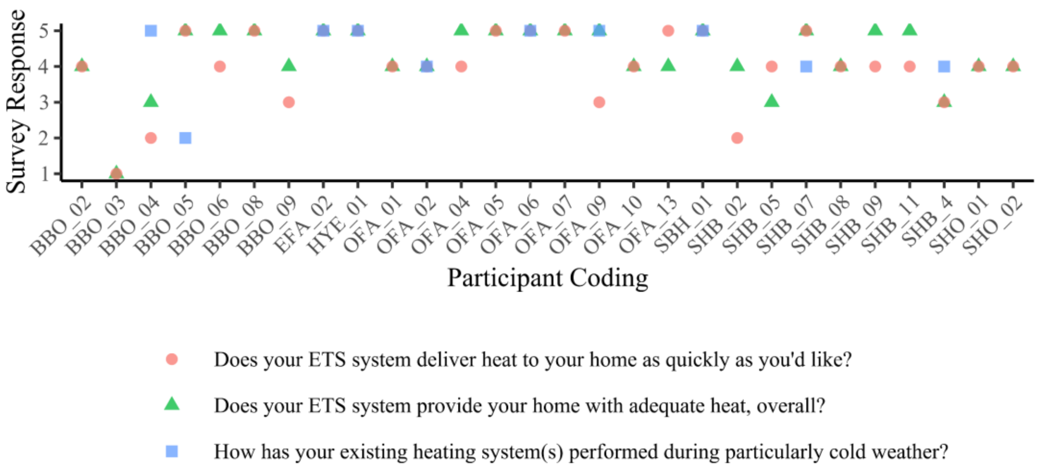
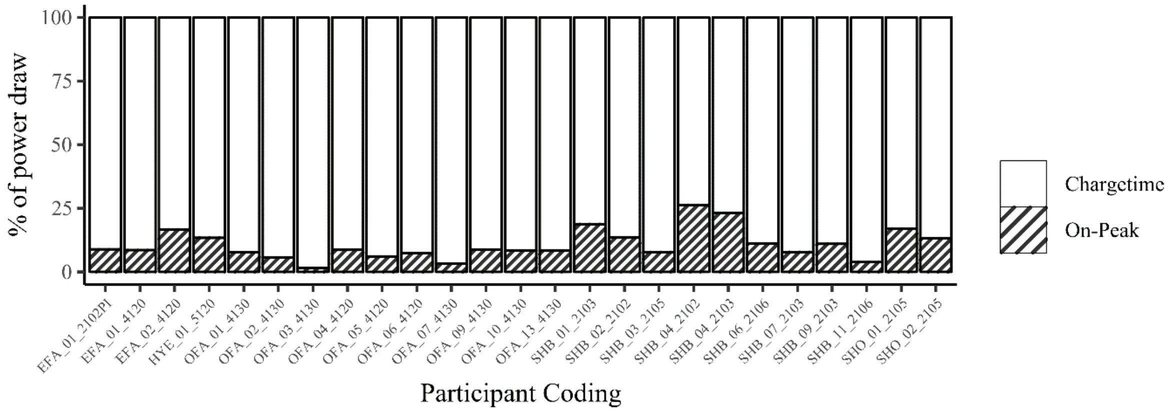


Figure 2: Responses to survey questions regarding thermal comfort.

The responses are on a five-point scale, with a "1" corresponding to the most negative response, and "5" corresponding to the most positive response. It is clear most participants felt their ETS systems met their thermal comfort needs, which the 2-Node-PMV model in Figure 1 (b) also suggests. Of the total responses to the questions in Figure 2, 55 of 66, or 83%, answered with a 4 or a 5. The high proportion of positive responses contrast with the results from Fanger's PMV in Figure 1 (a), which indicate cooler temperatures consistently across all participants. The survey responses indicate the 2-Node-PMV is the more accurate predictor of participant thermal comfort for the ETS demonstration project and provides outputs closer to the ASHRAE standard for thermal comfort. The 2-Node-PMV is used going forward.

The percentage of all power draw during on and off-peak times is given for manufacturers 1 and 2 in Figure 3. The model number is provided in the x-axis labels, with larger numbers corresponding to larger units. Comparing Figure 3 (a), (b), and (c), the units from manufacturer 1 generally draw less power during on-peak times than the units from manufacturer 2. While the majority of manufacturer 2 units have levels of power draw during on-peak times closer to manufacturer 1 units, a noticeable minority of manufacturer 2 units have around 50% of their power draw occurring during on-peak times. 15 of 25 manufacturer 1 units draw over 90% of their power during scheduled charge times, whereas 33 of 45 manufacturer 2 units draw over 90% of their power during scheduled charge times. Generally, the fleet of ETS units in the ETS Project demonstrate an ability to draw power during scheduled charging periods.



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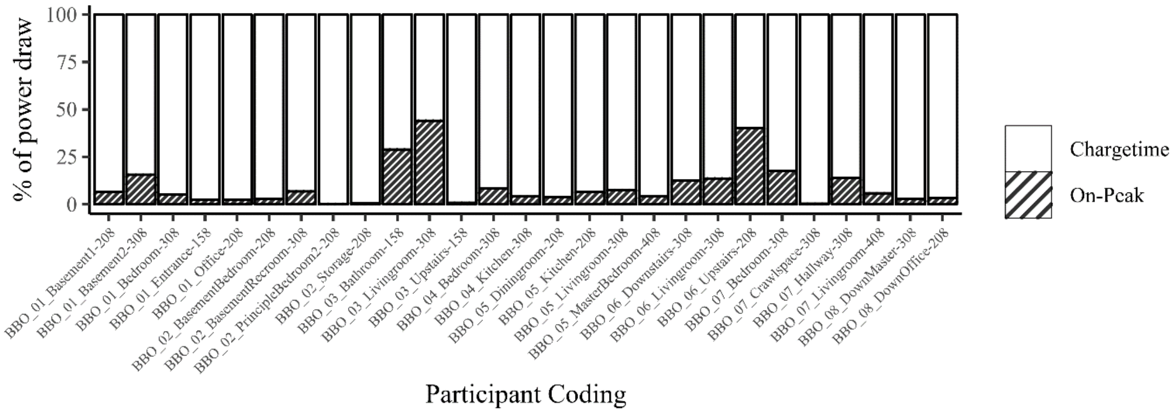

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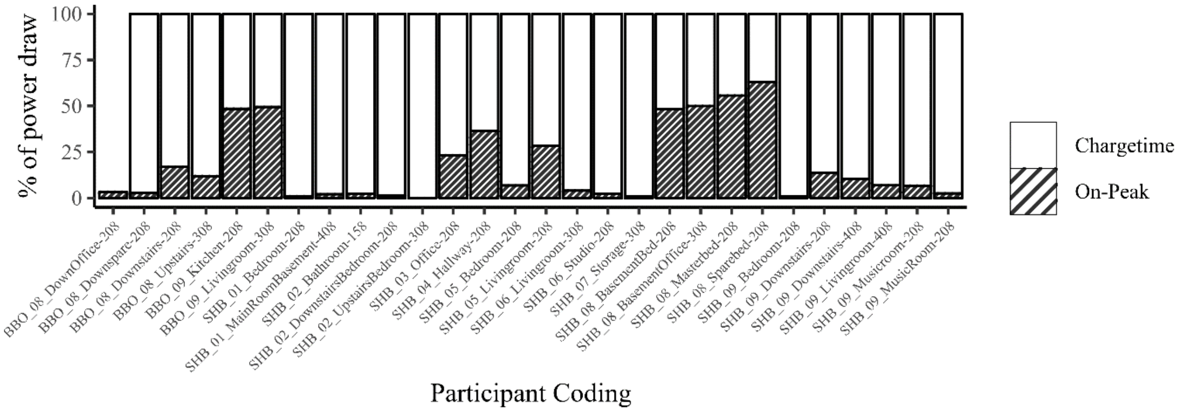
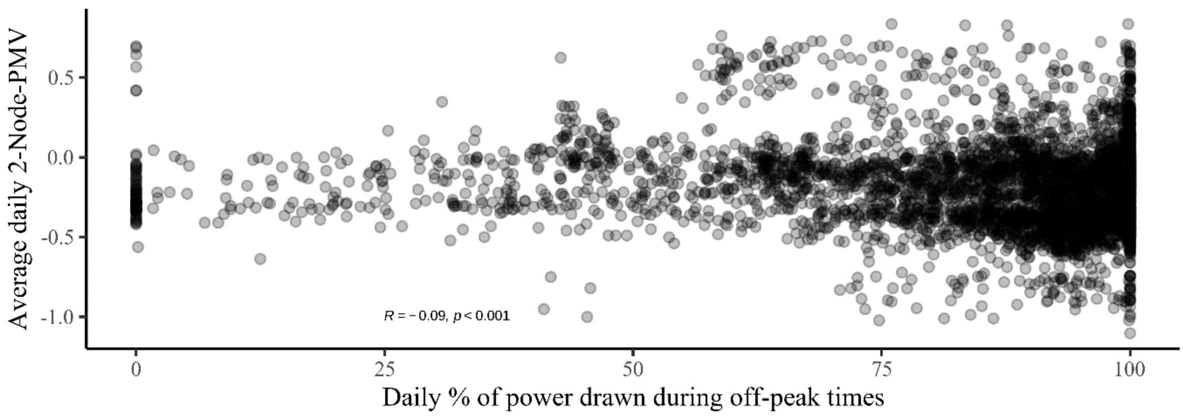


(c)

Figure 3: Percentage of power draw during scheduled charging times and assumed on-peak periods for manufacturer 1 (a) ETS units and manufacturer 2 (b) (c) ETS units.

Overall, Figure 1, Figure 2, and Figure 3 show that ETS units have demonstrated an ability to meet occupant's thermal comfort needs while adhering to a set charging schedule. The relationship between thermal comfort and charging schedule adherence is investigated to identify any correlation between the two variables. As well, the role outdoor temperature may have with respect to thermal comfort and charging schedule adherence in investigated. It is important to assess how freezing outdoor temperatures could affect thermal comfort or charging adherence due to the Yukon's continually harsh winters.



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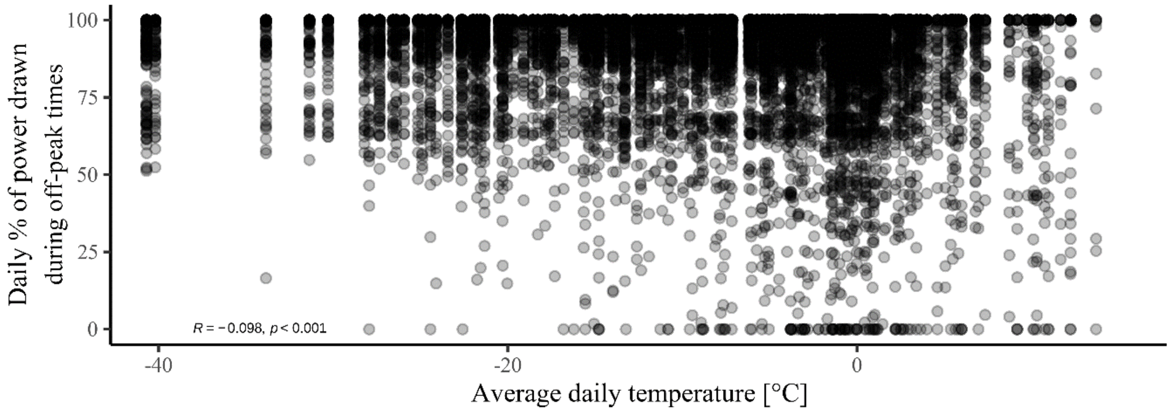

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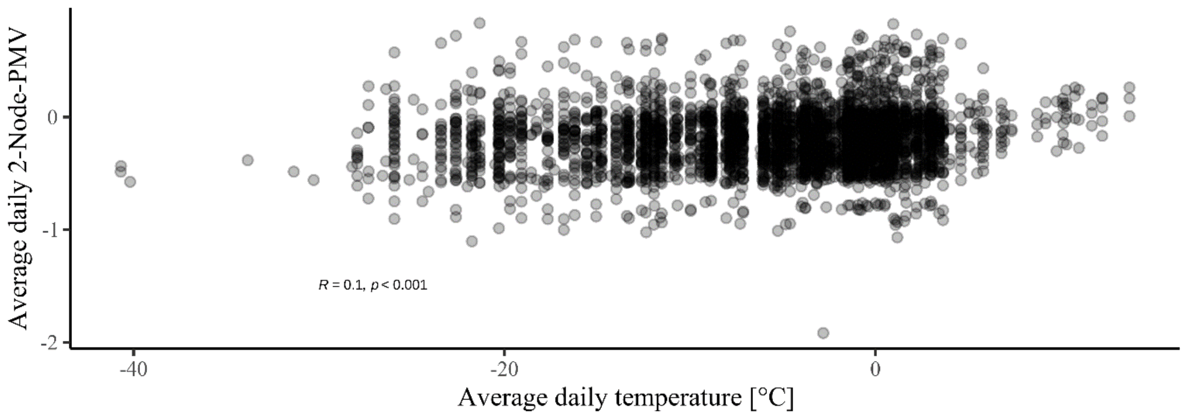

(c)

Figure 4: Relationships between thermal comfort and percentage of total power drawn during charge times (a). Relationship between outdoor temperature and percentage of total power drawn during charge times (b). Relationship between outdoor temperature and thermal comfort (c).

In Figure 4 (a) there is a slightly negative relationship between the percentage of power draw during scheduled charging times and the 2-Node-PMV outputs. However, the 2-Node-PMV outputs are reasonably distributed about the neutral sensation, with only a small proportion of values approaching "slightly cool", that is -1 on the seven-point scale. The effect of any small correlation is negligible on the thermal comfort. In Figure 4 (b) there is a slightly negative relationship between the percentage of power draw during scheduled charging times and the average outdoor temperature. In Figure 4 (c) there is a slightly positive relationship between average outdoor temperature and the 2-Node-PMV outputs. A possible cause underlying these relationships could be colder temperatures influencing occupants to demand more heat, in turn requiring more frequent charging from ETS units, which could reduce the amount of heat provided on certain days as systems work to meet increased demand.

However, all the above relationships are weak. Pearson correlation coefficients are given in Figure 4 with corresponding ρ-values, and all correlations are less than or equal to 0.1. The weak dependency between thermal comfort and charging adherence with outdoor temperature, even at the lowest temperatures, is encouraging. ETS implementation in northern jurisdictions is far more likely to be successful if cold temperatures do not affect occupant thermal comfort or peak-shifting capabilities.

CONCLUSIONS

An analysis of ETS demonstration project data has found compelling evidence the ETS technology can reliably adhere to scheduled charging times while maintaining a satisfactory level of thermal comfort across a large sample of occupants and ETS units. The majority of ETS systems drew over 90% of their total power consumption during scheduled periods. The majority of ETS project participants gave strong positive responses to survey questions regarding their ETS system's ability to provide adequate thermal comfort. An empirical thermal comfort model, partially informed by real-time sensor data, agreed with the survey responses and indicated reasonable thermal comfort for all participants. An analysis of the relationship between thermal comfort, scheduled charging adherence, and outdoor temperature found evidence of minor correlations between the three variables. The lack of a strong correlation between adherence to scheduled charging times and thermal comfort, with outdoor temperature, is an important result. The Yukon's cold winter conditions have a negligible role in ETS system's ability to store heat and provide thermal comfort. The results from the 2021-2022 heating season show ETS has potential to shift peaks in electricity demand by adhering to a predetermined charging schedule, while still maintaining thermal comfort for occupants.

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