Evaluation of the Thermal Resilience of a Community Hub
Aylin Ozkan\textsuperscript{1} and Joel Good\textsuperscript{2}
\textsuperscript{1}RWDI Consulting Engineers and Scientists, Toronto, ON, Canada
\textsuperscript{2}RWDI Consulting Engineers and Scientists, Vancouver, BC, Canada

Abstract
The frequency of power outages as a result of climate pressures are increasing and community centres are relied on as areas of refuge. Therefore, designing these buildings with passive survivability in mind is important, and challenging due to its high occupancy and fresh air requirements. This paper aims to evaluate the design measures of a community hub in the Canadian province of Ontario through the thermal resilience metric of passive survivability using building performance simulations.

This study compares the performance of design strategies from building certification programs commonly followed to achieve high-performance envelope design. These include Passive House, Zero Carbon Building and Ontario Building Code (OBC) compliance criteria. The performance indicator is defined as the duration of time that the buildings remain habitable until the arrival of help or repair in the event of an extended power outage. Using whole-building energy modeling a power outage is simulated and the building is forced to rely on passive means of maintaining comfort, the PH and ZCB cases show far improved thermal autonomy (60\% and 49\% acceptable, respectively) when compared to the code baseline (18\%). The high-performance envelopes of the PH and ZCB cases also result in greater passive survivability performance in both extreme summer and winter conditions.

Introduction
The frequency and severity of climate disasters are escalating. Often these weather events occur during periods of extreme heat and cold and can knock out power for extended periods of times. As a result, most buildings quickly get too cold or too hot, unable to deliver occupant shelter needs under these conditions. An emerging body of research has identified and evaluated passive design measures that support thermal resilience of multi-unit residential buildings (Ozkan, 2018 & O’Brien 2016), allowing residents to shelter in place for longer periods of time. However, these measures are limited and costly for most of our existing building stock. Equally as important as preparedness for the residential market, public sectors are planning for temporary and/or near-by emergency shelters to accommodate the populations that may be more at risk because of their physical location or residing in older or poorly maintained housing that may not be adequate for sheltering in place (U.S. Department of Commerce, 2020). To increase our preparedness for climate disasters widely, it is advised that larger scale community buildings should be a focus of thermally resilient design in order to provide safe, comfortable gathering spaces for people in need during a prolonged power outage. These high-occupancy buildings are expected to have unique design considerations necessary to achieve passive survivability when compared to low-occupancy residential spaces.

The objective of this study is to create a comprehensive comparison between the baseline or reference model which represents typical construction practices with no sustainability measures, versus construction of a Net Zero or Passive House building. The goals are to evaluate their performance during a prolonged power outage, and also discuss their annual performance with/out the active systems (HVAC, lighting and equipment) input. For this purpose a conceptual design for a mid-scale transit hub is modeled. It is assumed to be located in Climate Zone 6 based on the OBC SB-10, and a Cold Climate as defined by the Passive House Institute Climate Zones.

In the current paper we will briefly summarize the requirements of the standards and metrics to evaluate them for thermal resilience. After the explanation of modeling assumptions and the steps for simulations, we will discuss the results through the conventional emergy metrics of \textit{“energy use intensity”} (EUI) and \textit{“thermal energy demand intensity”} (TEDI), and \textit{“thermal}
autonomy” for their regular operation mode, and “passive survivability” for an extended period of power loss. As an additional measure, we will evaluate the impact of the density of people when the hub is used as a gathering space in an extreme winter and/or summer event.

**International Passive House Standard**

The Passive House Standard is a voluntary, rigorous standard which is committed to creating and designing buildings to the highest energy and comfort standards, while simultaneously reducing maintenance costs and fuel reliance. This standard is recognized internationally and applies to any building typology. Below are the minimum requirements to achieve Passive House certification for a Cold Climate, the selected climate zone as defined by the Passive House Institute (PHI) Climate Zones (Passive House Institute, 2016).

1. A high-performance envelope, with opaque element U-values less than or equal to 0.12 W/m²K. This ensures internal comfort and pleasant surface temperatures.

2. Triple-glazed windows as standard. The maximum U-value shall be less than 0.65 W/m²K.

3. A continuous airtight layer, with a maximum of 0.6 air changes per hour verified through testing. This ensures minimal loss of heat through air leakage, minimal ingress of moisture, humidity, pollutants or vapour. (mandatory PHI requirement).

4. A high-efficiency PHI Certified (minimum 75% efficiency) heat/energy recovery ventilation system, supplying 24/7 fresh air to the building, recovering heat/energy from extracted air. (mandatory PHI requirement).

**CaGBC Zero Carbon Building – Version 2**

The Canada Green Building Council (CaGBC) launched the Zero Carbon Building (ZCB) Standard to assist the industry’s transition to a zero-carbon future. The Zero Carbon Building – Design (ZCB-Design) Standard is a made-in-Canada framework for designing and retrofitting buildings to achieve zero carbon emissions. The standard is a framework for the design of low-carbon, highly efficient buildings, and ensures the best potential to achieve zero carbon once in operation. The Standard recognizes that there are many strategies for reducing carbon emissions at the design and operating stages, providing flexibility for buildings across Canada – of all sizes and uses – to achieve certification (CaGBC, 2017).

ZCB-Performance certification is awarded based on one year of operating data. It includes, in the case of projects that previously achieved ZCB-Design certification, verification of airtightness, and offsetting of the embodied carbon of the structural and envelope materials.

ZCB Design certification is broken into three options: Flexible Approach, Passive Design Approach and, Renewable Energy Approach, each with different strategies to achieve ZCB Design certification. Refer to Table 1 for a breakdown of the energy targets required for each option, established using Climate Zone 6 for Ontario.

<table>
<thead>
<tr>
<th>Table 1 Energy Targets for the Options</th>
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<tbody>
<tr>
<td><strong>Flexible Approach</strong></td>
</tr>
<tr>
<td>TEDI 34 kWh/m²/yr</td>
</tr>
<tr>
<td>Site EUI 25% better than NECB 2017</td>
</tr>
</tbody>
</table>

By utilizing TEDI and EUI targets, flexibility in design is offered for the design and construction of assemblies and building components. Assessing and modeling the impact of building components early in the design stage, such as increased insulation, air tightness, window and door performance, efficiency of HVAC systems, and implementation of renewable energy allows the designer to create a strategy which meets the certification requirements, project budget, and climate/site conditions without following a prescriptive approach.

**Metrics for Regular Operation Performance**

Total energy use intensity (TEUI) and thermal energy demand intensity (TEDI) are the most commonly used metrics to evaluate the results of energy simulations, and they both define a benchmark for both certifications and code compliance. TEUI corresponds to a combination of all fuel types used by a building in a year, normalized to building size (in square meter/feet of floor area). “All energy used on site including all end-uses, such as heating, cooling, fans, pumps, elevators, parkade lighting and fans, and exterior lighting, among others. It incorporates all site efficiencies, including the use of heat pumps or re-use of waste heat, but does not include energy generated on site,” as defined in TGS guideline (City of Toronto, 2020). TEDI corresponds to the annual heating delivered to the building for space conditioning and conditioning of ventilation air. Measured with modeling software, this is the amount of heating energy delivered to the project that is outputted from any and all types of heating equipment, per unit of modeled floor area.

Thermal autonomy is a measure of the percentage of time a building can deliver comfort passively, without...
any additional active systems. It measures “how much of the available ambient energy resources a building can harness rather than how much fuel heating and cooling systems will consume” (Levitt et al., 2013). It is correlated to the metrics TEUI and TEDI, but requires less complicated modeling and can serve as an efficient indicator of high-performance at the early stages of design (Ozkan et al., 2018).

**Metric for Power Outage Performance**

Thermal resilience is among the many aspects of overall building resilience that has the co-benefit of reducing energy demands and carbon emissions. Thermal resilience of buildings is commonly assessed using passive survivability which is a measure of the duration of time that an indoor space remains habitable following a prolonged power outage over an extended period of extreme weather. For passive survivability wider temperature thresholds are chosen since “survivability” suggests marginally acceptable, or reasonably tolerable, temperatures (i.e., habitable).

**Methodology**

**Modeling Assumptions**

A conceptual design of a mid-scale transit hub has been selected to represent a community space in which it may be expected for large occupancies to shelter in place during a power outage. The building is modeled using the energy modeling tool DesignBuilder, powered by the energy modeling engine EnergyPlus. Three separate variations of the building model are generated to represent typical performance of an OBC Baseline, CaGBC ZCB, and Passive House designed building. Typical values for each of these designs is summarized in Table 2. For ease of comparison, the base structure remains the same across models, with only insulation requirements varying to reflect the required thermal properties of each envelope design. The building is assumed to be located in the Climate Zone 6 based on SB-1, and a Cold Climate as defined by the Passive House Institute Climate Zones. The building geometry is south-north elongated. The gross floor area is 455 m² (4898 ft²). The total window area is 139 m² (1496 ft²) with 86.5 m² on the east façade and 52.5 m² on the west. The overall window to wall ratio is 37%. With the exception of the Baseline model, all options carry 14.5% of glazed area that is to be operable. Automated ventilation systems reduce reliance on mechanical cooling. Except for the Baseline model, all options carry exterior shading on the west elevation. The occupancy density is defined as 0.066 people/m², and the area assumed to be occupied from 4 AM to 12 AM daily with a fluctuation of occupancy density.

<table>
<thead>
<tr>
<th>Table 2 Minimum envelope requirements</th>
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<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>OBC/ Baseline</td>
</tr>
<tr>
<td>Roof</td>
</tr>
<tr>
<td>Exterior Wall</td>
</tr>
<tr>
<td>Ground Floor</td>
</tr>
<tr>
<td>Window</td>
</tr>
</tbody>
</table>

**Air leakage rates (50 Pa)**

Air tightness testing is not a requirement of OBC, however 5 ACH @ 50Pa was carried in the energy model, which is reflective of Code methodology and conventional construction techniques (OBC-SB-10, 2016). Air tightness testing is a requirement of CaGBC Performance Certification and has been carried in the energy model at 2.5 ACH @ 50Pa. The PH case has 0.6 ACH @ 50Pa, the maximum allowable air change rate for a PH certified building. These values carried into the model are listed in Table 3.

<table>
<thead>
<tr>
<th>Table 3 Maximum Air Leakage Rates</th>
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<tbody>
<tr>
<td>OBC/Baseline</td>
</tr>
<tr>
<td>CaGBC ZCB</td>
</tr>
<tr>
<td>Passive House</td>
</tr>
</tbody>
</table>

ERV (Enthalpy Recovery Ventilator), is recommended in climates with high dehumidification demands. Minimum Electrical efficiency input for PHI certified units is 0.45 Wh/m³, and minimum unit efficiency is 75%. In this study both the CaGBC ZCB and Passive House models are assumed to have ERVs with 84% efficiency. The baseline model has no ERV. All the models have packaged AHU (electric heating and cooling coils), and underfloor heating system is installed for the ground floor. To achieve the criteria regarding the heating and cooling demands, the CaGBC ZCB and Passive House cases are modeled with ground source heat pumps.

**Simulations**

For annual analysis (to quantify TEUI, TEDI and thermal autonomy), the whole-year simulation is performed using the standard TMY file. However, for passive survivability, shorter simulations during simulated emergency events are performed both for winter and summer periods. The periods are chosen by running a whole-year simulation with HVAC disabled and identifying the period with the most extreme indoor
temperatures. The benefit of using real weather data is that the relationships between all parameters are physically viable. For the cold period, the seven-day period with the coldest average temperature is used, whose average daily peak direct solar radiation is no more than 50% of the peak possible values (about 50% of 1000 W/m² (317 Btuh/ft²). For the warm period, the seven-day period with the highest average wet-bulb temperature is used. And that also has an average daily peak direct solar radiation of more than 50% of the peak possible values (or approximately 500 W/m²).

For annual analysis to quantify EUI and TEDI, the occupancy, equipment and lighting densities are all kept the same across the Baseline, CaGBC ZCB, and Passive House models. All the active systems are kept on regular operation mode.

For thermal autonomy analysis, the systems for HVAC, lighting and equipment are turned off in the model. The number of hours above and below comfort levels of 18°C (64.4°F) and 26°C (78.8°F) are identified based on operative temperatures. For passive survivability analysis, all active systems are shut off during a period of extreme summer or winter weather. The time between when heating is shut off and when the indoor operative temperature reaches 15°C (59°F) from an original heating setpoint of 21°C (70°F) represents the winter threshold for passive survivability. In summer, the threshold is determined by the time until the indoor operative temperature reaches 28°C (82.4°F) from an original cooling setpoint of 25°C (77°F). This simulation methodology is consistent with the framework for thermal resilience modeling outlined by Kesik et al. (2022).

Discussion and Results Analysis

Comparison with Active Systems

Table 4 below provides an illustration between the assessed sustainability pathways. Each pathway has been compared making use of TEUI, heating demand (TEDI) and cooling demand.

Results show that it is possible to reduce TEUI by 74.5% with Passive House and 72.7% with Net Zero design criteria, compared to a code compliant building over a typical year.

TEUI and TEDI metrics provide useful ways to compare the conceptual massing with the different envelope and building systems identified for each pathway. But, since this approach needs active system inputs, it usually requires more time and expertise to model the systems. It can be considered as an appropriate analysis metric for later phases of design, and less suitable for early phases.

### Table 4 Comparison of pathways using energy metrics

<table>
<thead>
<tr>
<th></th>
<th>TEUI kWh/m²/yr</th>
<th>Heating Demand kWh/m²/yr</th>
<th>Cooling Demand kWh/m²/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>OBC Baseline</td>
<td>220.7</td>
<td>165.8</td>
<td>12.7</td>
</tr>
<tr>
<td>CaGBC ZCB</td>
<td>60.3</td>
<td>8.1</td>
<td>7.7</td>
</tr>
<tr>
<td>Passive House</td>
<td>56.2</td>
<td>5.3</td>
<td>8.0</td>
</tr>
</tbody>
</table>

Comparison without Active Systems

Table 5 provides an illustration for the comparison of each pathway with the thermal autonomy metric. This metric provides a relatively simple, fast, accurate and intuitive simulation results for the early design stages (Ozkan et al., 2017).

As shown above, if the acceptable operative temperature ranges from 18°C (64°F) to 26°C (79°F) is used to define the thermal autonomy (TA) threshold, then the baseline model has the lowest TA of 18%, while the CaGBC ZCB model is at 49%, and the Passive House model is the best at 60%.

### Table 5 Comparison using Thermal Autonomy

<table>
<thead>
<tr>
<th></th>
<th>Too Hot &gt;26°C</th>
<th>Acceptable 26°C&gt; x&gt;18°C</th>
<th>Too Cold &lt;18°C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% hours</td>
<td>% hours</td>
<td>% hours</td>
</tr>
<tr>
<td>OBC Baseline</td>
<td>31</td>
<td>18</td>
<td>51</td>
</tr>
<tr>
<td>CaGBC ZCB</td>
<td>13</td>
<td>49</td>
<td>38</td>
</tr>
<tr>
<td>Passive House</td>
<td>14</td>
<td>60</td>
<td>26</td>
</tr>
</tbody>
</table>

Figure 1: Thermal Autonomy Comparison
Figure 1 above depicts a graphic representation of thermal autonomy for the common public area. The graph shows the temporal variability of performance in a very dense format with continuous annual data. So Thermal Autonomy of the space is visualized with the periods that are too cold, acceptable, and too hot indicated for each hour of the year. It shows that during summer months the hot hours are slightly higher for the Passive House case compared to the ZCB case. This can be explained with higher airtightness and insulation requirements of the Passive House standard, which is causing higher accumulation of heat over summer.

Comparison During a Power Outage
Table 6 below provides a comparison of standards using the Passive survivability metric indicated as consecutive hours before habitability thresholds are exceeded.

During a winter power outage, the operative temperature of the waiting area never drops below 15°C (59°F) for a Passive House design, while it only takes 2 hours for a minimum code compliant building, and 6 hours for a Zero Carbon Building. Although the OBC baseline and CaGBC ZCB cases seems to be performing similarly, the operative temperature drops down to 1.8 °C (35.2°F) for the minimum code compliant design, whereas the Zero Carbon design stays above 10.3 °C (50.5°F) for the whole power outage period. So, it is important to note that survivability analysis requires effective visualizations to inform the design process as exemplified in Figures 2, Figure 3, Figure 6 and Figure 7 below.
Table 6: Comparison using Passive Survivability

<table>
<thead>
<tr>
<th></th>
<th>Winter PS</th>
<th>Summer PS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>hours</td>
<td>hours</td>
</tr>
<tr>
<td>OBC Baseline</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>CaGBC ZCB</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>Passive House</td>
<td>n/a</td>
<td>9</td>
</tr>
</tbody>
</table>

Another note on the performance of the CaGBC ZCB case is that, when the occupancy density is increased during the power outage time, the operative temperatures also do not drop below 15°C (59°F) as in the Passive House case. Whereas the OBC Baseline case drops below the threshold in 5 hours. The impact of increased occupant density on Passive Survivability is discussed in detail under the following heading.

High vs Regular Occupancy

An aim of this study was to understand the important factors impacting passive survivability for higher occupancy spaces that would be relied on for occupancy during power outage scenarios. As such, power outages were modeled for high (0.3 p/m²) and regular (0.066 p/m²) occupancy spaces and passive survivability compared.

For the hottest week of the year, it can be seen in Figure 2 and Figure 3 that the PH and ZCB designs show great improvement over the OBC case. Indoor temperatures are maintained at a few degrees above the outdoor dry bulb temperature while the OBC spaces are up to 10°C hotter. The moderating effects of the PH and ZCB cases...
is primarily due to operable windows allowing cooling through passive natural ventilation. The difference in indoor temperatures between the high and low occupancy cases are minor, as the passive cooling is capable of offsetting the increased occupancy heat gains. Additional emergency solar shading (i.e. exterior black out blinds), would also be beneficial to minimize solar gains and moderate indoor temperatures but would result in a sacrifice to daylight, views, and potential occupant well-being.

Natural ventilation has additional benefits in that it also supplies fresh air to the spaces when mechanical ventilation cannot. The CO2 levels in the spaces were tracked (Figures 4 and 5) and it can be seen that the PH and ZCB cases are able to maintain CO2 levels well below 1000 ppm even for the high occupancy case. Conversely, for a code building (fixed windows) the CO2 levels in the high occupancy scenario are quickly in excess of 5000 ppm, the permissible exposure limit for CO2 levels (DHHS-NIOSH, 1981) that can lead to headache, dizziness, nausea and other symptoms and should not be exposed to beyond 8 hrs.

For the coldest week of the year, it can be seen in Figures 6 and 7 that the improved thermal performance of the PH and ZCB (over 20°C for the high occupancy case, and over 15°C for the regular occupancy case). The code building, particularly for the regular occupancy case, fails to uncomfortable temperatures, below 10°C. Considering the high occupancy case the indoor temperatures are maintained through the week at levels that exceed the setpoint of the space. The importance of this finding is made evident when considering the CO2 levels in the space (Figures 8 and 9). CO2 levels are high in all cases as a result of the enclosed spaces (without mechanical ventilation). In this instance, the “leakiness” of the code building actually serves as a benefit by allowing some fresh air and moderating CO2 levels. The exceedence of setpoint temperatures in the high occupancy PH and ZCB cases makes it possible for occasional openings of operable windows to allow some natural ventilation, without sacrificing thermal comfort, even in the cold winter temperatures. The code or lower occupancy cases do not have this thermal buffer available, and therefore are not able to take advantage of ventilation from outside air.

**Conclusion**

When assessing pathways for carbon reduction, the International Passive House Standard (PHI) and CaGBC Zero Carbon Building (CaGBC ZCB) are the main sustainability pathways in Canada, with validation for performance targets and construction methodology. This study shows that high-performance, passive envelope design (like those outlines in PH and ZCB guidelines) improve both energy, comfort, and passive survivability of a community space.

When a power outage is simulated and the building is forced to rely on passive means of maintaining comfort, the PH and ZCB cases show far improved thermal autonomy (60% and 49% acceptable, respectively) when compared to the code baseline (18%). The high-performance envelopes of the PH and ZCB cases also result in greater passive survivability performance in both extreme summer and winter conditions. Although the high insulation values are critical to maintaining comfortable temperatures in the winter, operable windows and the resulting natural ventilation and cooling of the PH and ZCB cases are crucial to controlling overheating and supplying improved indoor air quality. For high-occupancy spaces, where internal gains are high, there is an added opportunity in the winter of replenishing fresh air through natural ventilation even during the coldest week of the year.

Assessing passive survivability by only using “hours to exceedence” of a temperature threshold does not provide full context on the success/failure of resilient design. By considering hourly temperature and CO2 plots, far more information is available to designers to achieve successful thermal comfort and indoor air quality outcomes.

From this work, the need for further research efforts has been identified to answer the following questions:

1. How can design for passive survivability be encouraged? (Not many buildings follow PH/NZ standards.)
2. How to overcome the challenges for designing for passive survivability? (i.e., currently there is no consensus on fresh air requirements and comfort thresholds for survivability.)
3. How does future climate impact passive survivability decisions?
4. How can we expand our assessment of passive survivability to standardize metrics (hourly temperatures, deadbands rather than fixed temperature thresholds, indoor air quality, etc.)?

**References**


