Quantifying resilience at scale using EnergyPlus and Modelica

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ABSTRACT

Addressing the immediate and future implications of climate change requires both mitigation and adaptation upgrade measures applied to buildings and communities. While there is a proliferation of building and urban performance simulation tools aimed at annual performance indicators (e.g., energy, emissions), there is a paucity of tools designed to quantify performance during periodic extreme weather events. This paper demonstrates the steps required to modify EnergyPlus to quantify the thermal resilience of buildings during historical extreme weather events.

The outage algorithm is implemented using the Energy Management System (EMS) feature in EnergyPlus. A Python script implements the outage algorithm by modifying schedules of every zone within the building. Two shortened simulations are required: (i) without a grid outage but with the extreme weather event and (ii) with the full outage. The difference in energy meters between the no-outage and outage scenarios determines the '*loss load*' which quantifies the energy and operational cost performance indicators. Building upgrades such as improved insulation, airtightness, renewable energy generation and storage can all be quantified using this tool for any building size or archetype. Several quality assurance measures are outlined to support model outputs and outcomes.

A scalable simulation approach to communities is outlined using a combination of EnergyPlus models linked together using Modelica (modelling both thermal and electrical networks). This ongoing research is novel allowing for the consideration of mitigation to net-zero and adaptation performance indicators such as energy, cost, risk, emissions and thermal resilience. A long-term objective is to integrate optimization approaches to build roadmaps to achieve resilient net-zero communities. The simulation methodology is open-sourced using reproducible software approaches for the BPS community to use.

Keywords: Building performance simulation; thermal resiliency; climate change; adaptation.

INTRODUCTION

Climate change action in the built environment requires an equal emphasis on both GHG mitigation and adaptation to extreme weather conditions as increasingly made self-evident by events resulting in prolonged grid outages. Scaling methodologies beyond building towards clusters, districts and communities better enable the use of renewable/waste-heat resources and electrical/thermal storage while ensuring a future-friendly plug-and-play infrastructure which can accommodate new future technologies. A limiting factor in knowledge creation is the lack of modelling and simulation tools available and performance metrics suitable for buildings and communities. The paper contributes a methodology using EnergyPlus and a custom EMS algorithm to allow for consideration of extreme weather events and combines building loads to be met by a community energy system.

CASE STUDY

As a simple case-study, this paper considers four archetype tiny homes each with 12 design parameters to vary the electrical and thermal loads to be met by the shared thermal and microgrid loop. Tiny homes allowed for the quick prototyping of ideas and technologies, however, four additional energy models have undergone peer-review ranging from one to 84 thermal zones (Bucking et al., 2022; Rostami et al., 2023). Two scenarios are studied. The first is a code-compliant scenario, called the reference design, that studies the implications of typical construction on thermal loops and electrical microgrids. The second scenario is a net-zero solution, called the proposed design, that considers the implications of a prosumer model where electrical and thermal energy can be exported or imported to/from centralized resources.

Northern Nomad tiny home

Figure 1 shows the case-study considered in this paper. The Northern Nomad is a 202ft^2 tiny home that was constructed in 2018 and is located in Ottawa, Canada. The home showcases many innovative features including a thin, highly insulated enclosure using vacuum panels and a 2.34 kW south-facing, roof-integrated PV system with 21kWh of electric battery storage. A 900L tank was integrated into the conditioned space serving the dual purpose of potable water storage and optional thermal storage. The water tank affects the thermal decay of the as-built design and is not present in the code-compliant reference design. The case-study was modelled in EnergyPlus using a single thermal zone, a photovoltaic one-diode model and a kinematic battery. Four tiny home models formed the community case-study shown for this paper. This is part of an ongoing initiative to create a tiny home village which shares energy resources.

The Northern Nomad research home is a suitable case-study as it includes several technologies and design approaches that improve resiliency metrics and the magnitude of those improvements can be experimentally validated without disrupting existing occupants. Presently, the home is undergoing experimental studies to ensure it meets its original net-zero energy design goal. Experimental validation of resiliency measures is also planned and is important as design variables which improve resiliency may differ from those which reduce annual energy use.

Figure 1b shows an image of the energy model as constructed in EnergyPlus version 9.6 (viewer shown as per OpenStudio SketchUp plugin). The energy modelling approach is backward compatible with EnergyPlus version 9.0 with minor changes to output variables.

Table 1 shows 12 variables, a sample of the 17 total decision variables, considered for the case-study. The remaining five decision variables include orientation, DHW system type and waste heat recovery, and lighting and plug-load reductions. These variables were included in reported results, however, they had less significance with respect to performance outcomes and thus are not formally reported in this paper. The reference building is a minimal code-compliant design as per Ontario Building Code Part 9 (OBC, 2021).

(a) The Northern Nomad (North Face) **(b) Energy model representation**

Figure 1: Case-study building

Figure 2 shows the electrical configuration used by the Northern Nomad tiny house. A DC-coupled configuration was selected to use AC-based loads in the home and enable on-grid/off-grid capabilities via a microgrid-compatible inverter. These components allowed for the as-built design to grid-disconnect and self-power where as the code-compliant design experienced a complete loss of power during the outage event. The microgrid capabilities allowed the well-insulated and air-sealed Northern Nomad to avoid overheating in the summertime by using surplus renewable generation to air condition the home. Optionally, occupants can operate windows during summer evenings and utilize the thermal mass in the home to take advantage of free cooling.

Selected resiliency events

This paper considers an acute event to quantify building performance using a historical outage. The IPCC anticipates that future events will be more severe and longer than historical events (Parry et al., 2007). The emphasis in this paper is placed on frequently reoccurring events, 1:10 – 1:30 year events, and not extreme outliers such as a 1:100 or 1:200 year event.

Table 1: Influential model variables for case-study.

Variable	Descriptive	Units	Reference	As-built
Wall-ins	Effective resistance of wall insulation	m^2 K/W	3.50	6.51
Ceil-ins	Effective resistance of ceiling insulation	m^2 K/W	4.23	6.51
Floor-ins	Effective resistance of floor insulation	m^2 K/W	5.46	6.51
Infill	Natural infiltration rate	L/s/m^2	0.302	0.07
pv-eff	PV efficiency	%	-	15.8
GT_s	Glazing type, south (also N,E,W)	-	DGLowE	TGLowE
hvac_sys	HVAC system configuration	-	Elec. Baseboard	CC ASHP
use_tank	Use a 900L water tank as thermal mass	-	False	True
Batt-size	Battery size for DC-coupled system	kWh	-	21.12

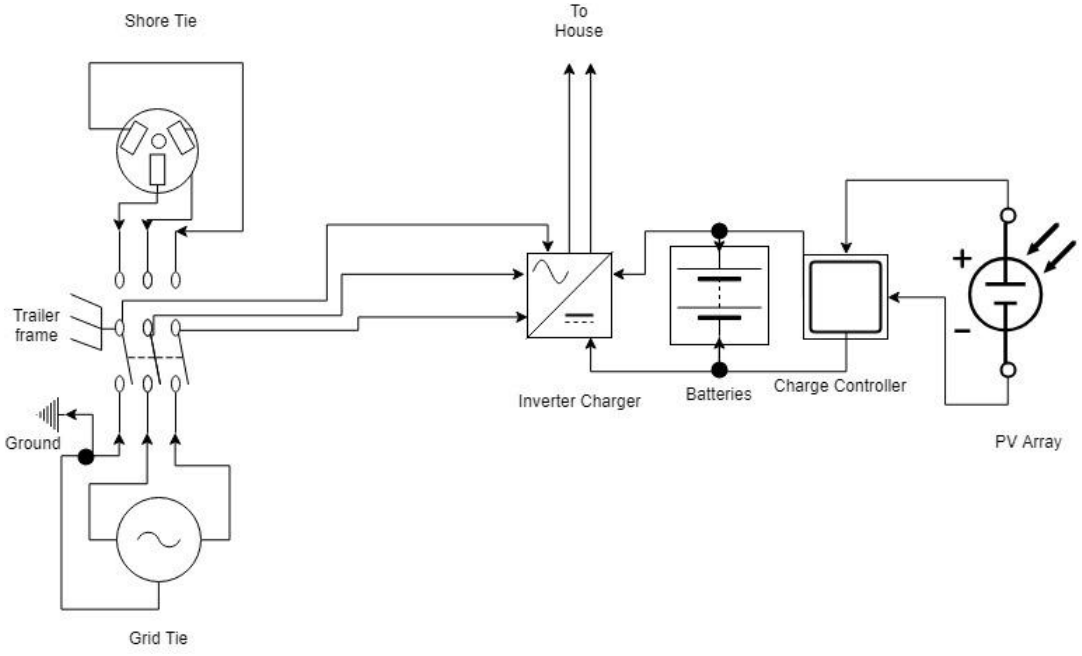

Figure 2: Electrical single-line diagram of the Northern Nomad's renewable energy system

This paper uses the 1998 Eastern Ontario ice storm (January 5‑10th, 1998) as an outage event. During the storm, nearly four million utility customers lost power due to an accumulation of up to 7-11cm of ice on trees and power lines. Although the majority of utilities were restored in a matter of days, several rural communities lost power for up to three weeks. This event was selected based on predictions that ice storm events in Northern climates will occur more frequently due to warmer and more favourable conditions (Klima & Morgan, 2015). This paper conservatively uses an outage period of 48 hours with an average outdoor temperature of −1 ◦C based on actual meteorological data. For reference, the typical January monthly average in Ottawa is −10 ◦C (NRCan, 2021). This is expected as ice storms are associated with warm, moist air-masses so the 48-hour average temperature is higher than the seasonal temperature.

The following details were specified for the simulation: (i) the outage event lasted from Jan. 5‑7th, (ii) historical weather data was translated from the NRCan website into EPW format (NRCan, 2021), Other comparative events include the Houston TX Winter Storm (Feb 10‑20th, 2021) and the 2009 North American Ice Storm (Jan. 25‑30th, 2009) (NASA, 2021).

METHODOLOGY

A detailed explanation of the resilience implementation is described in (Bucking et al., 2022). Major steps include: (i) defining resilience KPIs, (ii) modifying the existing energy model using resilience outage algorithm Bucking et al. (2022), (iii) satisfying building loads using thermal and microgrid loops, (iv) simulating buildings to define loads and then loops.

Resiliency indicators

Quality functions, denoted as Q(t), allow for the quantification of infrastructure resilience under extreme cold and hot conditions. For this paper, we mathematically defined the quality of interior dry bulb temperatures using equation 1.

$$Q(t) = \begin{cases} 1 & if\ T(t) \geq T_\gamma \\ 0 & if\ T(t) \leq T_\alpha \\ \frac{T(t)-T\alpha}{T_\gamma - T\alpha} & Otherwise \end{cases} \quad (1)$$

Where: Tα = 0 ℃, and Tγ = 20 ℃ and Q(t) is a linear interpolation between acceptable values when Tα < T(t) < Tγ. In this paper, Q(t) is only applicable to winter outages (heating mode) where there is the potential of water freezing in pipes, however, all types of outages can be handled by broadening the definition of equation 1. Moreover, the definition is sufficiently flexible to allow direct comparisons of differing performance metrics that may have different units.

Using this quality function, a failure occurs when α = Q(T(t) ≤ Tα) = 0, and an acceptable recovery is defined as γ = Q(T(t) ≥ Tγ) = 1. Thus, α, γ define failures and acceptable being constrained to α ≤ Q(T(t)) ≤ γ. Thermal resiliency, or '*Res*', is defined as the normalized area under the Q(t) curve as shown by equation 2.

$$Res = 1 - \sum_{i=1}^{n} \frac{\int_{t1,i}^{t2,i} (\gamma(t) - Q(t)).dt}{t2,i - t1,i} \quad (2)$$

Visually, this is the fraction of area under the quality function curve where Q(t) ≤ γ (shaded orange) normalized by the maximum possible loss of functionality (shaded yellow) as shown in Figure 3.

For this paper, we define the acceptable recovery rate as γ = Q(T(t) ≥ Tγ) = 1, so we can simplify equations such that $t_{1,i} = t_s$ and $t_{2,i} = t_f$ which are the start and stop/finish times of the outage event(s).

The maximum loss of function, equation 3, describes the maximum vulnerability of the interior environment. LoF_{max} is a scaler value that by definition ranges from 0 to 1 taking a maximal value of one when a failure occurs.

$$LoF_{Max} = 1 - Q(t)min,\ Where: LoF_{Max} \in [0,1] \quad (3)$$

The decay and recovery times (t_{decay}, t_{recov}) are defined with respect to LoFmax for the event as shown in Figure 3. Although several thermal decays and recoveries may

occur during an outage, only the decay and recovery times from LoF_{max} are recorded. This ensured that the longest decay and recovery times were quantified.

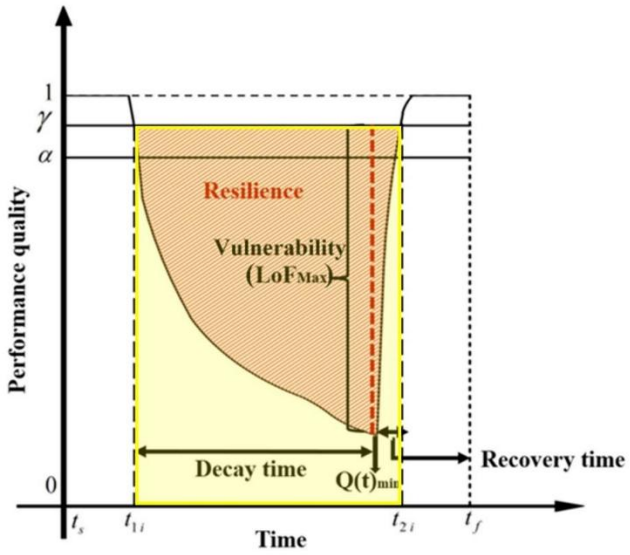

Figure 3: Visual definition of Resilience, LoF_{Max}, t_{decay}, and t_{recov}

Determining load met by microgrid/thermal loop

To determine the community load, we first define and combine the building load(s) which require both thermal (heat/cooling) and electrical meters. Because we are dealing with a loss of power and utilities, we define the building load as the energy that would have been required to meet setpoints and schedules. As such, two simulations are required to quantify energy demands: with and without the grid outage. We define the loss load as the energy difference between a building that meets its specified end-use loads and setpoints and the actual performance during an outage event, see Figure 4. An advantage of this approach is that it abstracts away the consideration of energy-saving measures onto the modelling tool and considers just the difference in energy meters.

There is no inherent capability to consider utility outage events or resilience KPIs in EnergyPlus. A custom outage algorithm, described by Bucking et al., (2022), overrides the temperature and availability schedules of equipment to simulate a mock grid outage. Furthermore, EnergyPlus behaviour was modified also self-power the building if sufficient renewables and/or a battery charge is present. The loss load estimates the energy implications of improved technology and can be used to determine the value of loss load in life-cycle cost analysis. During an outage event, the energy difference between these two scenarios would be zero if the building had sufficient generation and storage to meet all loads.

Although it is not demonstrated in this paper, we recommend studying multiple outage events (for example 3–5 events in the life-cycle of the building) to better capture the impacts of outage events on building performance. Our previous research conducts variations of historical extreme weather events causing a grid outage (e.g., hotter, colder, longer) as they identify a vulnerability in pre-existing infrastructure (Rostami et al., 2023). The use of synthetic or modelled future weather data may not fully capture the site boundary conditions and frequency of historical vulnerabilities. However, this is sufficient evidence that utility outage events caused by extreme weather events are becoming more frequent and severe.

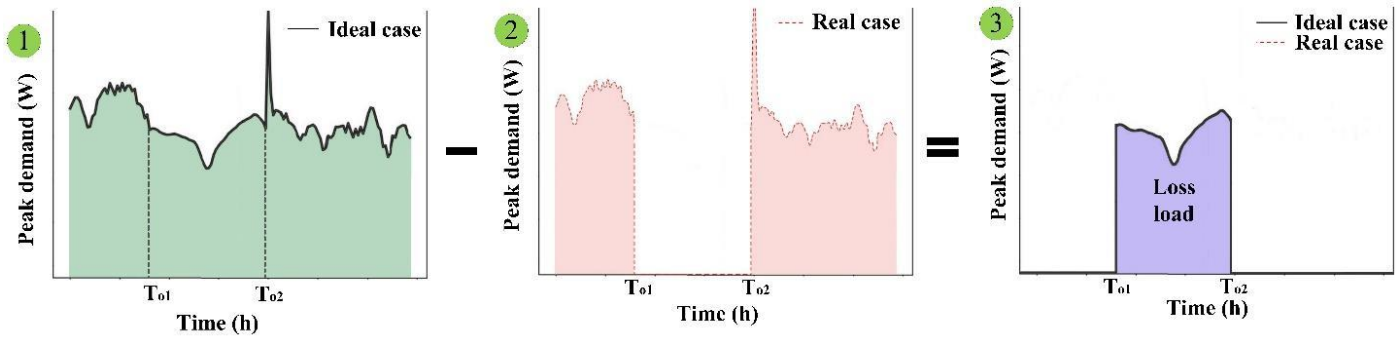

Figure 4: Visual definition of loss load

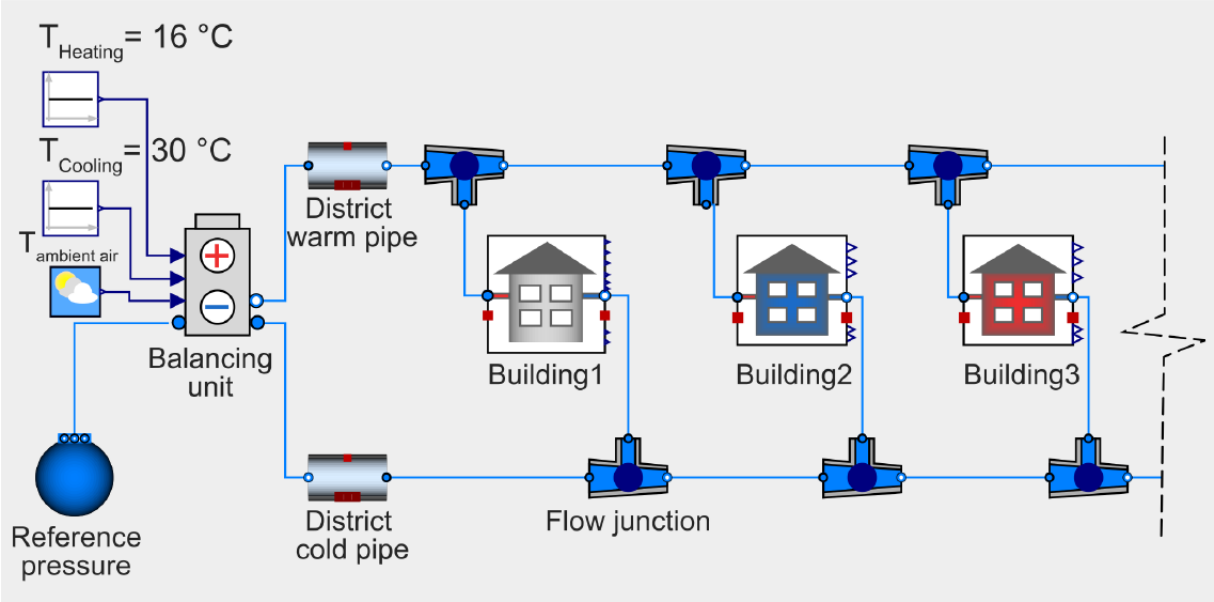

Figure 5: District thermal loop configuration (Abugabbara, 2021)

Table 2: Performance metrics for resiliency and proposed design

KPI	Description	Units	Reference	As built
Annual: Net-EUI	Net energy use intensity	kWh/m^2	368	11
Event: energy deficit	Unmet energy demand during outage (VoLL)	kWh	48	5
Event: resiliency	Resilience KPI	-	0.48	0.39
Event: LoF$_{Max}$	Maximum loss of function	-	0.84	0.46
Event: t$_{decay}$	Decay time of LoF$_{max}$	hours	47	14
Event: t$_{recov}$	Recovery time	hours	7.0	2.0

After conducting building simulations, the combination of loss loads is used to determine the demands on the thermal loop and community microgrid. An early prototype is under development similar to the district loop shown in Figure 5 based on work by Abugabbara, (2021). As such, we limit the scope of our results to how loads are determined which will be met by ongoing research of microgrid and thermal loop configurations. The buildings shared a microgrid with an undefined 100% efficient generator to meet building electrical loads.

A limitation of decoupling building and community loads is that a specified loop temperature is required to ensure a stable temperature difference is present across the energy transfer station (ETS)/sub-station. This erodes some of the potential benefits of thermal loops in allowing free-floating temperatures. It may be possible to resolve this limitation by calibrating simplified RCR models based on the more detailed EnergyPlus model to examine the interactions between energy exchanges and building air temperatures.

The inclusion of a thermal loop shown in Figure 5 is part of our ongoing research, however, only the electrical loads are modelled as part of this paper.

RESULTS AND DISCUSSION

The annual and resilience performance metrics of the study are summarized in Table 2.

Figure 6 shows the energy and temperature and Q(t) profiles for reference/code-compliant and proposed/as-built designs.

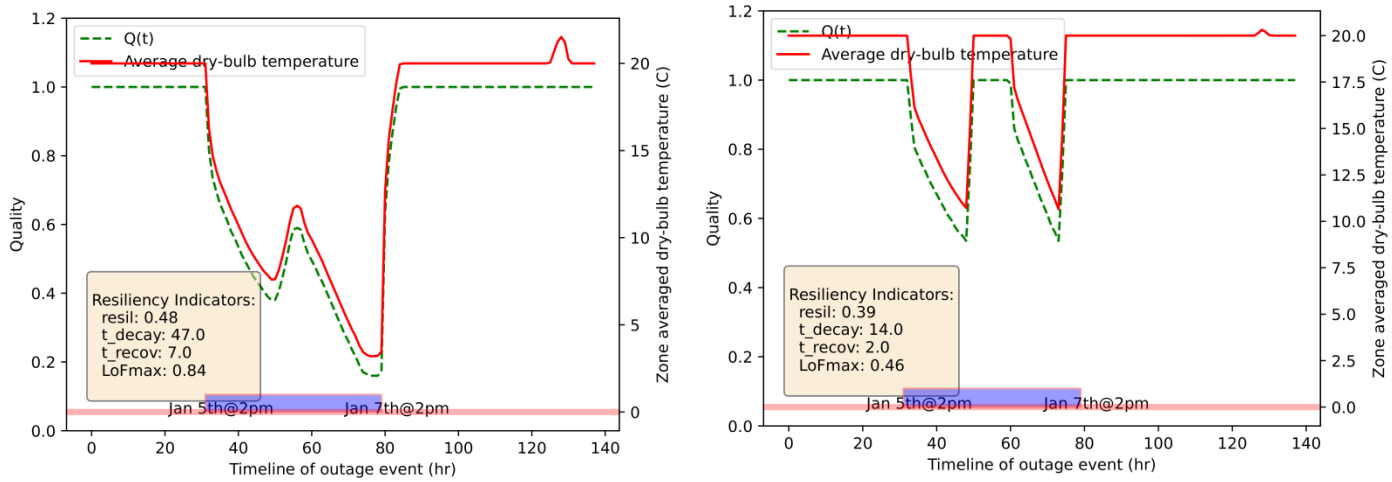

Figure 6: Comparison of resiliency KPIs for reference and as-built designs (single tiny home)

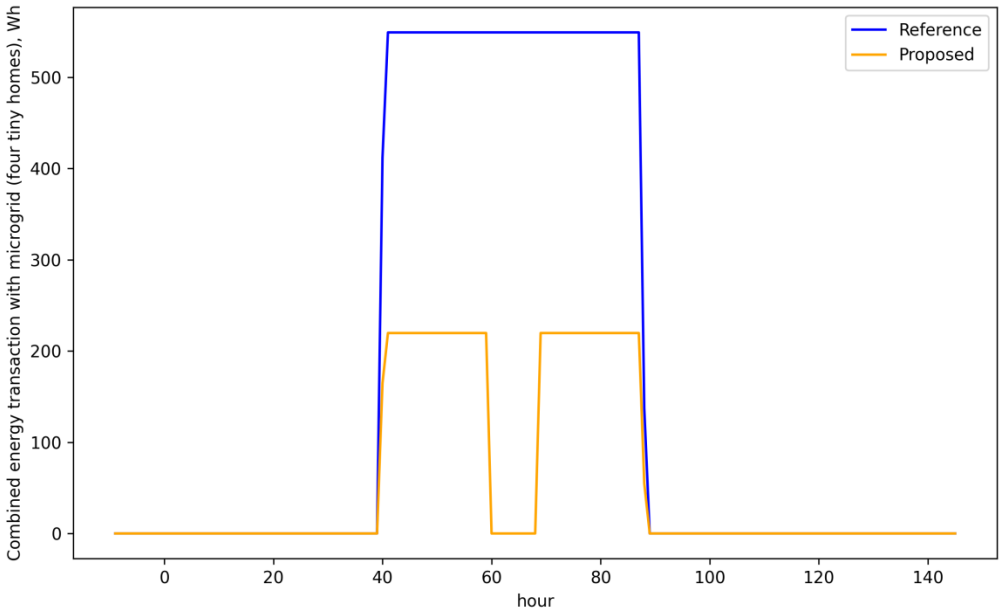

Figure 7: Comparison of power draw from microgrid of a four-home tiny homes community

Figure 6 demonstrates the impact of building upgrades on interior temperatures. The reference design approaches freezing conditions (defined as a failure) whereas the improved proposed design has temperatures drop to only drop to 15 ◦C. The building energy demands at the tail end of the outage event were met by integrated PV generation and electrical storage greatly reducing the demands on centralized infrastructure. This also highlights a possible design trade-off where building energy demands can be shaped to be more compatible with shared energy systems which can be explored by future optimization research.

Figure 7 shows the energy draw from the microgrid of the four tiny homes. There are several notable results when comparing the reference or code-compliant design to the proposed or as-built design. First, the proposed design can export energy to the microgrid due to surplus renewable energy generation and storage even during a grid outage. For similar reasons, there is a diurnal cycling of microgrid transactions in the proposed design. Notable the total energy

extracted is 60% less, however, the peak draw was reduced by 70%. This result differs for other case studies (on-going research) where the peak reduction is substantially less than the total energy reduction. This highlights a possible peak management issue commonly found in demand response research if net-zero energy buildings are connected via a microgrid and/or a thermal loop.

CONCLUSIONS

This paper demonstrates how resilience studies can be conducted on clusters of buildings connected to centralized resources. A novel simulation methodology is proposed to quantify the resilience of building clusters using open-source software and validated BPS tools. Although the case-study and results were limited to a tiny home village with an electrical microgrid, the concepts apply to any building or community.

Designing for resilience leads to different thinking regarding optimal building design. For example, maintaining comfortable and productive environments requires microgrid compatibility at the building, cluster, community or energy transfer/substation level. This electrical infrastructure carries a cost burden which is paid back if one considers the damage that may occur during outage events using the value of loss load. Furthermore, striving for a more airtight and better insulated envelope aids in allowing mechanical systems to better regulate indoor environments. Thermal mass plays a significant role in slowing the thermal decay of a building which is sometimes viewed as being detrimental to annual energy performance as it requires specialized controls to optimally use.

FUTURE WORK

There are several areas for future work: (i) trade-off analysis of building and district upgrades using optimization analysis considering both annual and resilience KPIs, (ii) consideration of additional extreme weather events (e.g., hot, wind, flood), (iii) life-cycle cost analysis, and (iv) research expansion to consider thermal loop configurations (4th generation vs 5th generation loop temperatures/technologies).

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