Multi-objective optimization of a net-zero tiny home using resiliency, cost and energy indicators

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Abstract

Designing to improve infrastructure resiliency aims to provide essential services such as heating, cooling, lighting and plug-loads during extended power outages which may be caused from disruptive regional climate events or chronic stressors. Using a multi-objective approach (energy, cost and resiliency indicators), a methodology is presented to optimize annual operation indicators and event-specific performance indicators using a high performance building case-study. To exemplify the methodology, an ice-storm similar to the 1998 Eastern Ontario event was used leading to an electrical-grid outage for 48 hours. Results show that it is advantageous to strive for more air-tight and well insulated envelopes, beyond what is considered optimal for annual design performance, while utilizing renewable energy and storage system to ride-out events. Value of lost load calculations shows that payback of key technologies, such as electrical storage using batteries, can be reduced by over 10 years by considering climate change events in the design process. The contributions of this paper are: (i) the proposed resilience KPIs for use as an optimization objective function, (ii) the optimization methodology and visualization techniques including 2D projections of higher dimensional solution spaces as well the pathway analysis grid.

Introduction

The ability of our building stocks to adapt to climate change should be given equal due diligence as greenhouse gas mitigation. In recent years, acute and chronic events have had a significant impact on the economic and societal well-being of Canadians. For example, the 1998 Eastern Ontario ice storm caused around $1.2B in losses and over 840,000 insurance claims (Lecomte et al., 1998). Similarly, summer events, such as heat waves in Fort McMurray followed by wildfires, have caused $3.7B in in damages making it the most costly disaster in Canadian history. This event was recently superseded by the recent flooding in BC which is estimated to have caused $7.5B in damages. To address both the adaptation and mitigation aspects of climate change, a 2021 report recommends that Canadian's allocate no fewer than 2–3% of annual GDP to transition to net-zero and adapt to our changing climate by 2050 (CICC, 2021).

Building performance simulation has been recognized as a tool which can help designers explore how to improve the resiliency of buildings. Designers can gain insights by coupling resilience measures with both economic, energy, and emissions key performance indicators (KPIs).

This paper demonstrates an optimization study using energy, life-cycle cost and thermal resilience KPIs to redesign a net-zero energy tiny home. Our aim is to showcase how focusing on resilience leads to different design outcomes than only co-optimizing for energy and cost. We focus specifically on thermal resilience although several other resiliency metrics exist. An acute outage event demonstrates the methodology, however, we recommend using several outage events (roughly 5–7 events) to gain a better understanding of building performance.

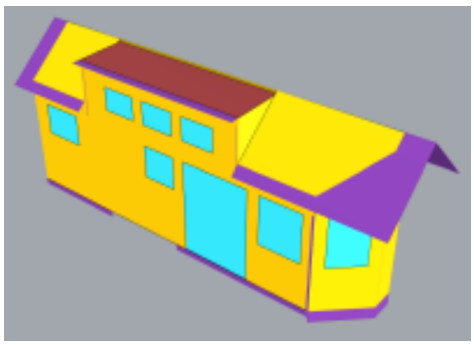
Case Study

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 water storage and optional thermal mass. 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 kinematic battery.

The Northern Nomad research home is an ideal 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

(a) The Northern Nomad (North Face)



(b) Energy Model representation

Figure 1: Case-study building

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.

Table 1 shows a sample of the 17 decision variables considered for the case-study. A total of 12 variables are shown (glazing types vary in all cardinal directions). 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 optimization results, however, they had less significance with respect to performance outcomes. The reference building is a minimal code compliant design as per Ontario Building Code Part 9 (OBC, 2021). The proposed building is the as-built design.

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 backwards compatible with EnergyPlus version 9.0 with minor changes to output variables.

Figure 2 shows the electrical configuration used by 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 summer time by using surplus renewable generation to air condition the home. Optionally, occupants can operate window during summer evenings and utilize the thermal mass in the home to take advantage of free cooling.

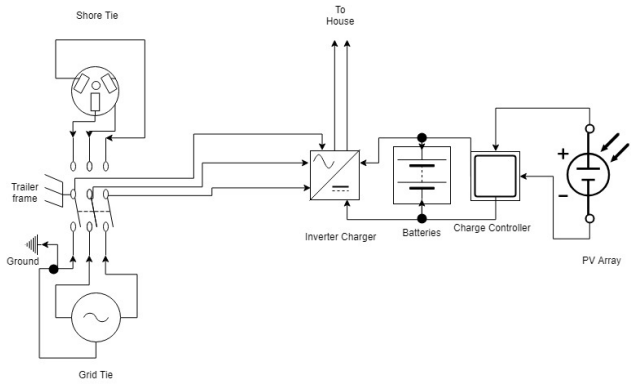


Figure 2: Electrical single line diagram of the Northern Nomad's renewable energy system

Selected Resiliency Event

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., 2016). Emphasis in this paper is placed on frequently reoccurring events, 1:10 – 1:30 year events, and not extreme outliers such a 1:100 or 1:200 year event.

This paper uses the 1998 Eastern Ontario ice-storm (January 5–10$^{\text{th}}$, 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 and Morgan, 2015). This paper conservatively uses an outage period of 48 hours with an average outdoor temperature of $-1\,^{\circ}\text{C}$ based on actual meteorological data. For reference, the typical January monthly average in Ottawa is $-10\,^{\circ}\text{C}$ (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:

Table 1: Influential Model Variables for Case-Study

Variable	Description	Units	Reference	As Built	Start	Stop
wall_ins	Effective resistance of wall insulation	m^2K/W	3.5	6.51	2.0	9.0
ceil_ins	Effective resistance of ceiling insulation	m^2K/W	4.23	6.51	2.0	10.0
floor_ins	Effective resistance of floor insulation	m^2K/W	5.46	6.51	2.0	9.0
infil	Natural infiltration rate @50Pa	$L/s/m^2$	0.302	0.076	0.302	0.076
pv_eff	PV efficiency	%	–	15.8	–	24.0
GT_s	Glazing type, south (also N,E,W)	–	DGLowE	TGLowE	DGLowE	TGLowE
hvac_sys	HVAC system configuration	–	Elec. Baseboard	CC ASHP	Elec. Baseboard	CC ASHP
use_tank	Use 900L water tank as thermal mass?	–	False	True	False	True
batt_size	Battery size for DC-coupled system	kWh	–	21.12	–	40.0

(i) the outage event lasted from Jan. 5–7$^{\text{th}}$, (ii) historical weather data was translated from NRCan website into EPW format (NRCan, 2021), (iii) the frequency of the event was set to every 10 years which, regionally, is how often these events occur (Lecomte et al., 1998). Other comparative events include the Houston TX Winter Storm (Feb 10–20$^{\text{th}}$, 2021) and the 2009 North American Ice Storm (Jan. 25–30$^{\text{th}}$, 2009) (NASA, 2021).

Methods

The proposed methodology for modelling resiliency events alongside other annual indicators is described in Figure 3. A detailed explaination of the resilience implementation is described in Bucking et al. (2022). Major steps include: (i) problem definition, (ii) defining resilience KPIs, (iii) creating event-specific energy model, (iv) defining cost model parameters, and (v) calculating annual KPIs: net-electricity use and 25 year life-cycle outcomes.

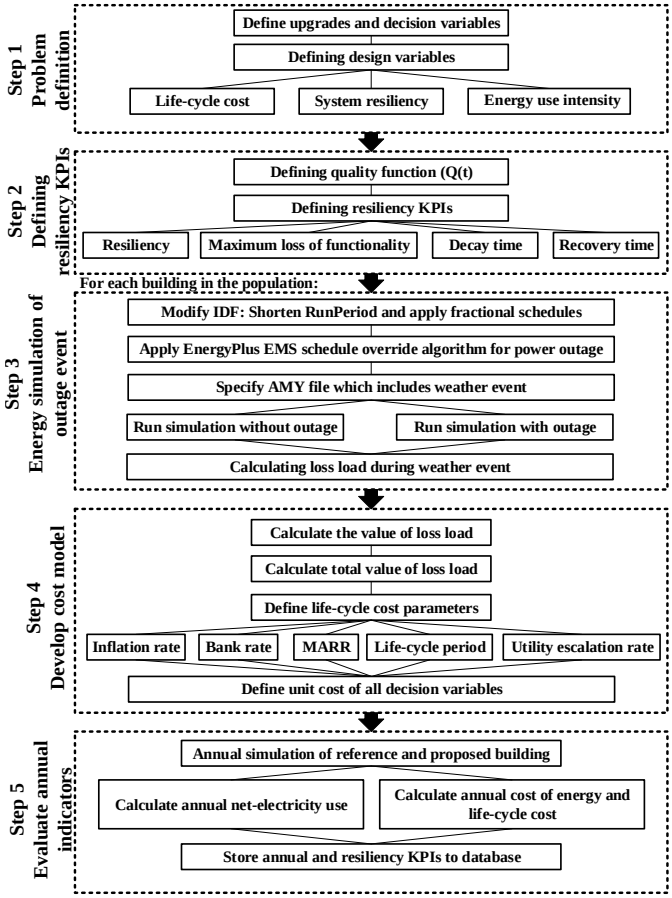


Figure 3: Research framework for multi-objective resiliency studies

Resiliency Indicators

Quality functions, denoted as $Q(t)$, allow for the quantification of infrastructure resilience. For this paper, we mathematically defined the quality of interior environments using equation 1.

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

Where: $T_\alpha = 0\,^\circ\text{C}$, and $T_\gamma = 20\,^\circ\text{C}$ and Q(t) is a linear interpolation between acceptable values when $T_\alpha < T(t) < T_\gamma$. In this paper, Q(t) is only applicable to winter outages (heating mode), however, all season outages can be handled by expanding equation 1 definition to include higher temperatures.

Using this quality function, a failure occurs when $\alpha =$

$Q(T(t) \leq T_\alpha) = 0$, and an acceptable recovery is defined as $\gamma = Q(T(t) \geq T_\gamma) = 1$. Thus, α, γ define failures and acceptable recoveries respectively while taking on values between zero to one constained to $\alpha < \gamma$.

Thermal resiliency is defined as the area under the Q(t) curve as shown by equation 2.

$$\text{Res}(t) = 1 - \sum_{i=1}^{n} \frac{\int_{t_{1',i}}^{t_{2',i}} \gamma(t) \cdot dt - \int_{t_{1',i}}^{t_{2',i}} Q(t) \cdot dt}{t_{2',i} - t_{1',i}} \quad (2)$$

Visually, this is the area under the quality function curve where $Q(t) \leq \gamma$ as shown in Figure 4. Since the acceptable recovery rate is $\gamma = Q(T(t) \geq T_\gamma) = 1$, we can simplify equations such that $t_{1',i} = t_s$ and $t_{2',i} = t_f$ which are the start and stop times of the outage event(s).

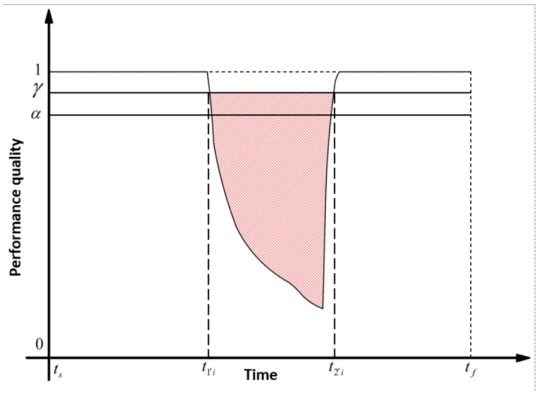


Figure 4: Visual Definition of Resiliency

The maximum loss of function, equation 3, describes the maximum vulnerability of the interior environment. Recall that $Q(t)$ is defined by equation 1.

$$LoF_{max} = 1 - min(Q(t)) \quad (3)$$

The decay and recovery times (t_{decay}, t_{recov}) are defined with respect to LoF_{max} for the event as shown in Figure 5. 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 are quantified.

Cost Model

The Value of Lost Load (VoLL) was calculated by multiplying the lost load at every timestep to the values shown in Figure 6 (which is based on the hourly zone-averaged dry-bulb temperature). The quantification of lost load and value of lost load was developed based on Bucking et al. (2022). The VoLL, divided by the frequency of the event in question, was applied to the annual utility costs. Although it is not immediately intuitive, this approach implies that a consumer is indirectly spending more to operate their building if it performs poorly during an outage event. As such, VoLL should ideally be event specific and determined from repair costs to damaged components and services. An

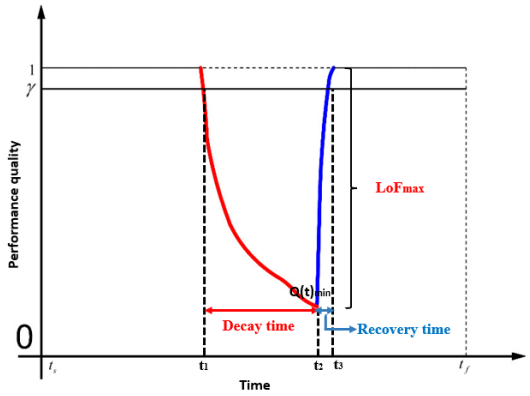


Figure 5: Visual Definition of LoF_{max} and t_{decay}–t_{recov}

end-user can also consider health and well-being implications and subsequent actions to condition spaces in the event of an emergency. This proposed approach allows for resiliency design features to carry a cost benefit for improving performance and accelerates the payback of technology packages. Studying multiple outage events (for example 3–5 events in the life-cycle of the building) is recommended to better capture a full spectrum of outage events and should further accelerate paybacks.

For resiliency studies, the peak value of lost load should be specific to the outage event. For this event, we are particularly concerned about occupant health and the replacement cost to repair the home given a burst frozen pipe (major failure). As such, Figure 6 shows an extreme value of $\$250/kWh$ (at freezing temperatures). This peak value is based on the estimated repair costs due to flooding in the case-study of approximately $5,000 (3% of initial cost). Also implicated in this plot is the health and well-being of the occupant as the probability of hypothermia increases as a core body temperature dips below 37 °C. An exponential relationship demonstrated the occupant's willingness towards action as the average temperature in the occupied space decays towards zero.

This approach suggests that economic value can be reinvested back into the system making it more resilient to future outage events.

For the life-cycle economic analysis, it was assumed that a long-term inflation target of 2% is met over the 25 year period studied. An expected marginal rate of return (MARR) of 2.8% takes into consideration a guaranteed investment alternative with a 0.8% growth rate (Bank of Canada, 2021). Utility prices are expected to increase annually over the life-cycle at a rate of 3%.

The utility rates are shown in Table 2 Hydro-Ottawa (2021). The battery system was not controlled to

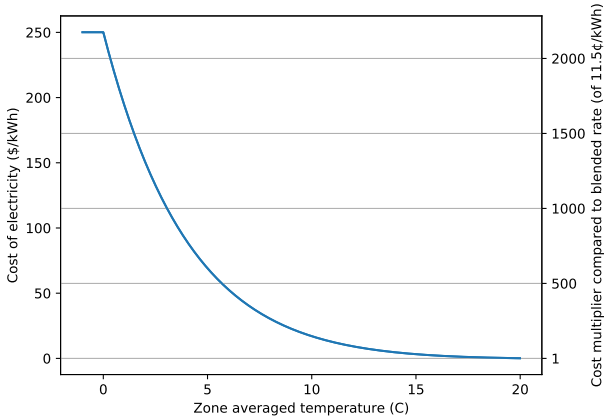


Figure 6: Relationship between VoLL and Zone-Averaged Indoor Air Dry-Bulb Temperature

take advantage of reduced overnight rates. The battery is programmed to charge the module if a surplus of electricity is available, otherwise any stored charge is used at the following timestep. The battery module could be programmed to charge overnight and discharge during the day when peak rates occur resulting in 8.8¢/kWh of savings. This simplification ensured that we are studying accelerated paybacks from modelling resiliency events in isolation and not the savings from a difference in overnight utility rates.

Table 2: Time of use billing schedule (Winter 2021) Hydro-Ottawa (2021)

Pricing Schedule	Hours	TOU	Price (¢/kWh)
Summer Weekdays	19:00–07:00	off-peak	8.2
	07:00–11:00	mid-peak	11.3
	11:00–17:00	on-peak	17.0
	17:00–19:00	mid-peak	11.3
Winter Weekdays	19:00–07:00	off-peak	8.2
	07:00–11:00	on-peak	17.0
	11:00–17:00	mid-peak	11.3
	17:00–19:00	on-peak	17.0
Weekends and Holidays	00:00–24:00	off-peak	8.2

A microgrid compatible inverter and an automatic transfer switch allowed the home to disconnect from the grid and self-power during an outage. This configuration enabled the home to import and export electricity throughout the year while still maintaining off-grid capabilities. Microgrid compatible configurations do carry significant cost premiums. For this paper, it was assumed that PV was roof integrated (ie. replacing a finished surface) for $1.5/W and microgrid compatible components carried a 25% total cost premium (applied to PV, inverter and battery capital expenditures). The 21kWh battery back was purchased for $9,000 CAD ($425/kWh). As microgrid compatible components become more common, this cost premium may decrease in the future.

To explore a policy implication of improved resiliency, the proposed cost methodology explores reductions in insurance payments to further accelerate payback. Naturally, buildings that can withstand outage events are less likely to make claims on their insurance policies. As such, we assumed a 10% reduction in annual insurance premiums (savings of $100/year for the case-study). The policy implications of this assumption will be explored in future research.

Optimization

Decisions variables included 17 continuous variables (many noted in Table 1). The analysis used an NSGA-II algorithm from the *Platypus* package (`https://platypus.readthedocs.io`). Three objective functions were specified: net-electricity use intensity (kWh/m^2), life-cycle payback and LoF_{max}. Figure 3 describes the steps taken to analyze each population of buildings. The algorithm was run for 2500 fitness evaluations using three separate runs to ensure convergence.

Results

Figure 7 shows the energy and temperature/Q(t) profiles for reference and proposed/as-built designs.

The performance metrics of the study are summarized in Table 3.

Figure 8 shows a 2D projection of the 3D Pareto front (ie. three objectives). Two independent y-axis displaying a resilience indicators (LoF_{max}) and a life-cycle performance indicator (payback) are compare to the x-axis energy use intensity. The optimization algorithm is minimizing each of the three objective functions. Each projected line includes all of the optimal solutions in the Pareto front (as such, solutions are technically displayed twice in this plot using different KPIs). The energy optimized design also yielded near optimal solutions for resiliency outcomes, however, optimal outcomes of both objectives were not consistent. However, we do not suggest that the aim of the analysis should be to eliminate the impacts of an outage event (by minimizing resilience KPIs) as the paybacks of such designs are clearly not feasible (paybacks approach 20 years as shown in Figure 8). We anticipate that good design practices will favour trade-off solutions which offer attractive energy, resilience and cost performance. The point where the payback-vs-EUI line and the LoF_{max}-vs-EUI lines cross can be considered as a balanced trade-off of all three objective functions and is likely where the most desirable solutions reside. Regardless, all proposed solutions from the Pareto front demonstrated a factor of two, or larger, for all resilience KPIs relative to the code-compliant design. The cost methodology used includes the VoLL applied to the operational costs of the design so acceptable resilience is also reflected in the payback values.

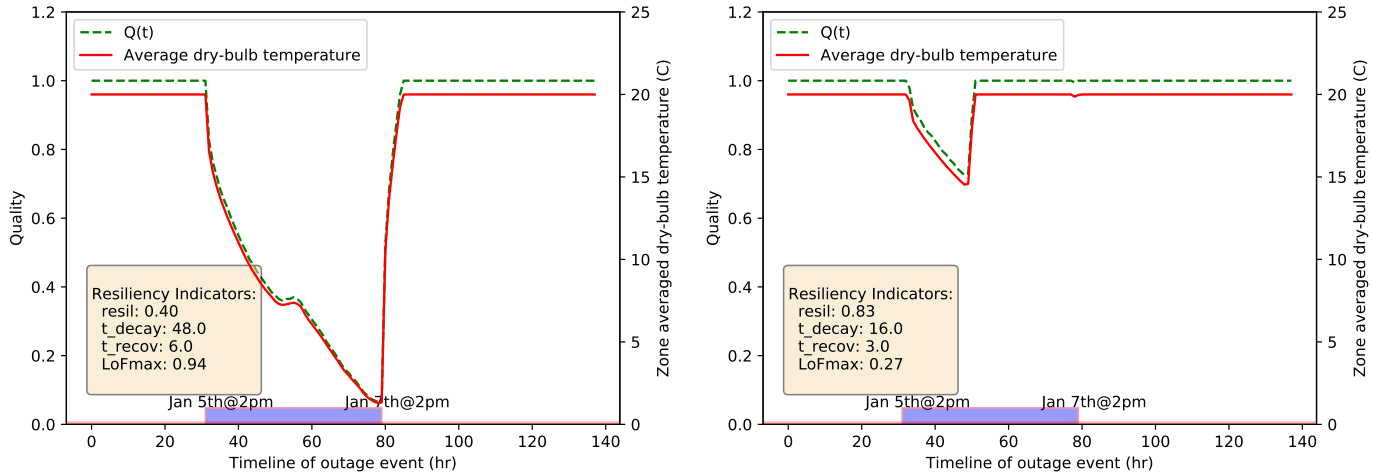


Figure 7: Comparison of Resilience KPIs for Reference and As-Built Designs

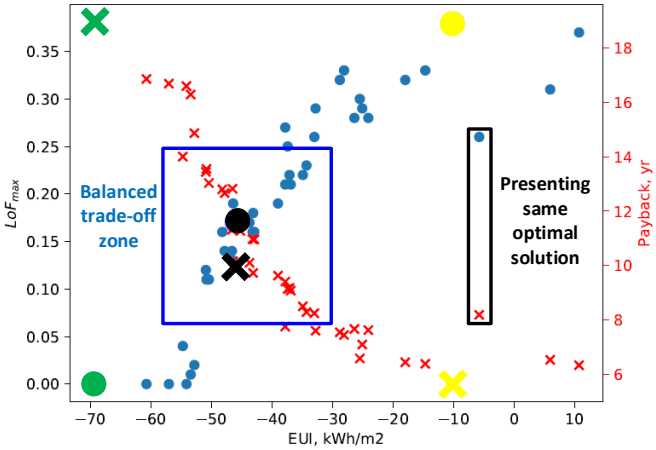


Figure 8: 2D projection of Pareto Front (missing Payback vs Lof_{max}). Green marker showing EUI optimized, yellow marker showing cost optimized and black marker showing 50-50-50 balanced trade-off.

Further analysis was conducted on the three individuals from the Pareto front: the energy optimization solution, the cost optimized solution and a solution with a balance of energy/cost/resilience KPIs. Circular markers indicate Lof_{max} vs EUI projections and 'X' markers represent payback vs EUI projections. Markers located on the same position on the x-axis represent the identical solution projected separately from the Pareto front. A pathway analysis was conducted from the reference/-code minimum design to the three optimized outcomes to better understand the relative importance of design variables on performance metrics.

A pathway analysis was conducted to understand the relative importance of each of the 17 decision variables using several KPIs. Figure 9 shows each incremental upgrade applied to the reference design resulting in the optimized design. To ensure that upgrades are ordered by significance, all options were analyzed starting with the reference design, and the design variable with the largest improvement was selected. After eliminating the selected variable, this process was repeated until each parameter from the reference design were changed to match the proposed design. The magnitude of each incremental improvement is inherently non-linear and cannot be determined as a superposition of each incremental improvement.

Figure 9 clearly shows that the pathway changes depending on what objective function is selected. Upgrades that are optimized for energy efficiency may not necessarily have good payback or lead to good thermal resilience. However, there are some recommendations that are consistent between all three scenarios: (i) the most efficiency PV panel available should always be selected, (ii) batteries have payback, but only if outage events are considered, and (iii) the air-tightness of the tiny home is a highly influential variable (which is to be expected given the building's large surface area to volume ratio).

The incremental energy pathway emphasizes the importance of on-site generation and a well-sealed/insulated envelope. Mechanical and ventilation system upgrades appeared in the top-5 of upgrades for all scenarios. DHW waste heat recovery and reducing lighting and appliances demands were also prevalant.

The payback pathways are compared to the reference building payback of zero years (as $NPV \equiv 0$). Upgrades that were high-ranking in payback pathways include reducing lighting, plug and DHW loads. PV upgrades (without battery) and air-sealing strategies also offerred good payback. We believe there is an error in our cost analysis to decrease wall, floor and ceiling insulation values below code. This will be further investigated and corrected for in a later publication.

The resilience pathways demonstrates that different

Table 3: Performance metrics for Reference, As-Built and Optimized Designs

KPI	Description	Units	Reference	As Built	EUI Opti	Cost Opti	50-50-50 Opti
Annual: Net-EUI	Net Energy use Intensity	kWh/m^2	368	11	-69.3	-10.1	-46
Annual: LCC Payback	Life-cycle payback of upgrade packages	years	–	9.4	19.0	5.6	10.0
Initial Cost Premium	Initial cost premium relative to reference	$	–	15,260	86,500	56,700	66,200
Event 1: Energy Deficit	Unmet energy demand during outage (determines VoLL)	kWh	48	5	0	8.2	10
Event 1: VoLL Cost	Value of Lost Load during outage	$	4,600	20	0	50	5
Event 1: Resiliency	Resiliency KPI, see equation 2	–	0.40	0.83	0.0	0.77	0.89
Event 1: $\text{LoF}_{\max}$	Maximum Loss of Function, see equation 3	–	0.94	0.27	0.0	0.38	0.17
Event 1: t_{decay}	Decay time to $\text{LoF}_{\max}$	hours	48	16	0	14	6
Event 1: t_{recov}	Recovery time from $\text{LoF}_{\max}$ to $Q(t) = 1$	hours	6.0	3.0	0	3	2

thinking is needed to condition environments during acute/chronic outages. As mentioned previously the building could not self-power without a micro-grid compatible electrical equipment. A battery size of 25 kWh was 'good enough' to maintain building operations during the ice-storm. PV/batteries upgrades were combined as the full benefits of islanding was not realized unless both upgrades were present This cost-burden previously hindered the economic payback (as grid-connected equipment is far less expensive). Strategies such as envelope air-tightness and thermal insulation are significant (as with the energy pathway), however, thermal mass as a form of heat storage is pivotal in maintaining comfort in interior environments. Upgrades to improve thermal/internal mass appeared in no other pathway figure. Triple-glazing upgrades contributed three times more to resiliency patways when compared to EUI pathways and did not rank for payback pathways. Similarly, increasing insulation values in walls, floors and ceilings were pivotal in EUI/resiliency pathways for the EUI-optimized however, they were decreased in the optimal cost and balanced pathways.

Conclusion

This paper demonstrates how energy, cost and resilience KPIs can be co-optimized using annual energy simulations coupled with a series of acute/chronic outage scenarios. We demonstrate for the first time how resilience KPIs can be quantified and added as an additional objective function in optimization studies. Designing for resilience leads to different thinking regarding optimal building design. For example, maintaining comfortable and productive environments requires for micro-grid compatibility at the building, cluster, community or sub-station 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 lost 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 is 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 will extend the methodology to multiple outage events and consider how resilience KPIs can be quantitatively combined. Additionally, we will applied the methodology to larger buildings and clusters/communities to show how quantification of resilience KPIs can scale.

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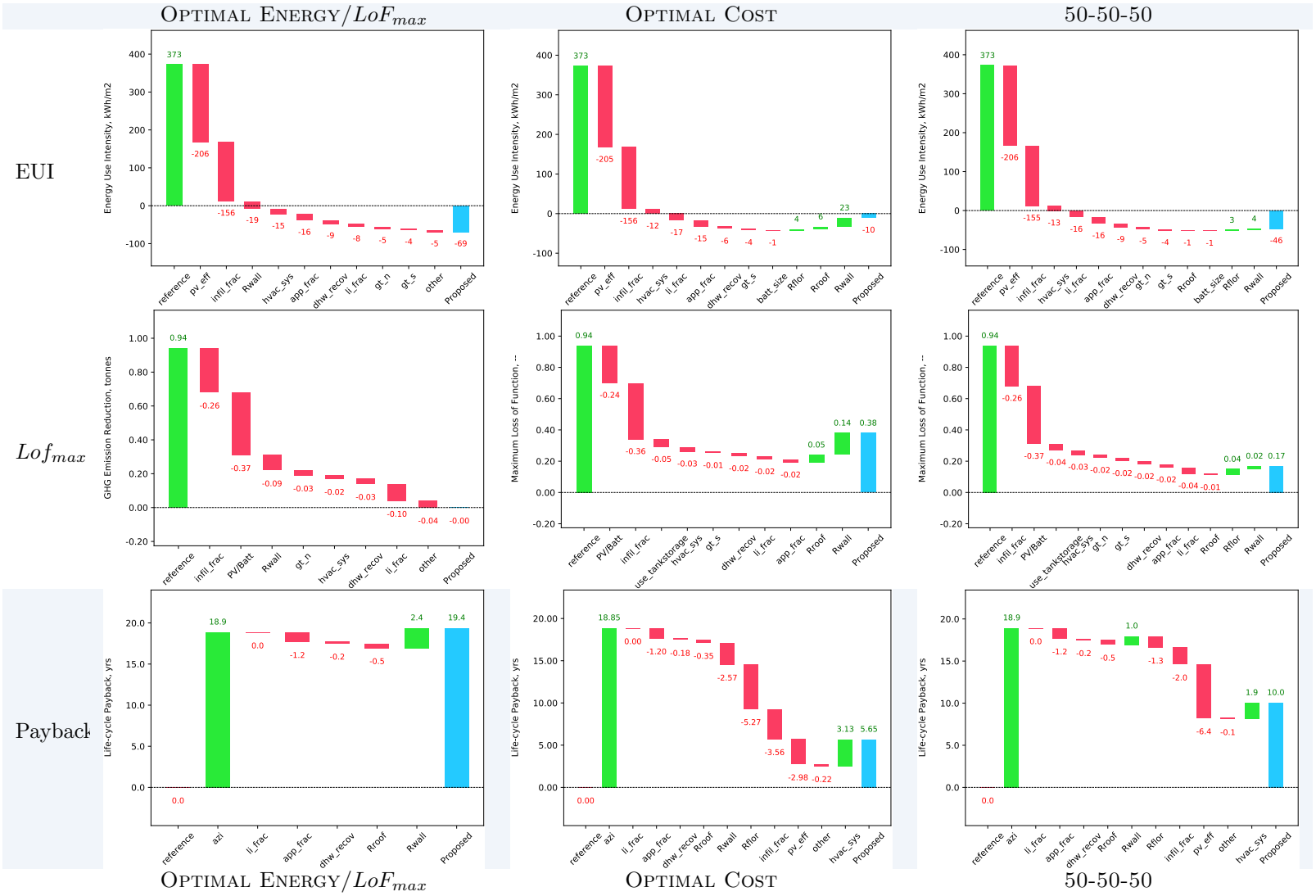

Figure 9: Reference Building Resilience KPIs

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