A Framework for Resilience and Energy Efficiency in Buildings

Mike Specian, American Council for an Energy-Efficient Economy
Dakoury Godo-Solo, American University
Nelson James, U.S. Department of Energy
Michael Reiner, U.S. Department of Energy
Karma Sawyer, U.S. Department of Energy

ABSTRACT

Modern studies of energy efficiency and load flexibility have begun to establish the benefits they provide for energy savings, emissions reductions, economic growth, enhanced productivity, and improved health outcomes. Yet resilience – the ability to predict, prepare for, withstand, and recover from major disruptions – has remained a relatively less well understood component of energy efficiency despite the effect it can have on a range of stakeholders including building occupants and owners, businesses, utilities, and communities at large. While a diverse set of building technologies can lead to the same efficiency outcome, their enabling characteristics do not necessarily have the same impact on resilience. In this paper we establish a framework that considers resilience and energy efficiency in buildings as a coupled system. We demonstrate that efficiency can either complement or conflict with resilience, and that these outcomes are a function of multiple variables including building type, climate zone, external weather conditions, and access to backup power. Through this analysis, important scenarios in which efficiency and resilience ought to be co-optimized are identified, as are key challenges in integrating the two.

1. Introduction

We expect our residential and commercial buildings to provide an array of features and services. Core among these are durable shelter, temperature and humidity management, access to light, healthy air quality, and security. We expect these to be provided in ways that are comfortable, easy to use, and accessible to all. In commercial buildings we desire effective spaces for commerce that facilitate learning, innovation, and productivity. As technology increasingly enables grid-interactive efficient buildings (GEBs) that are flexible, connected, intelligent, and cybersecure, we anticipate our buildings will become a resource to the electric grid and a financial benefit to the building owner. And ideally these features would be provided in manner that is future-proof, sustainable over the building's life cycle, produces zero emissions, and that is aesthetically pleasing and achievable at low cost.

However, typical building design and construction often involves those with specialized training in individual building systems working in relative isolation from each other. Given the diversity of features we expect in our buildings – and the fact that each may suggest conflicting solutions – it is no wonder that much of our building stock is created in ways that are suboptimal.

Yet it is encouraging that in the last two decades there has been progress in optimizing buildings at the *systems level*. In pursuit of energy efficiency, the U.S. government has defined a high-performance building as one "that integrates and optimizes on a life cycle basis all major high performance attributes" (U.S. Congress 2007). The National Institute of Building Sciences (NIBS) subsequently published a Whole Building Design Guide (WBDG) premised on an "integrated design approach" (NIBS 2019) that recognizes dependencies between building elements in order to optimize at a systems level the benefits they provide.

One benefit that has received relatively less attention even in these integrated design approaches is *operational resilience*. Many definitions of resilience exist, and most share four key elements. A resilient system is one that can prepare for, withstand, recover rapidly from, and adapt to major disruptions (NIST 2020, FEMA 2018).[1] In the building space these disruptions can include physical threats (e.g., flooding, extreme wind, fire, earthquakes), fuel disruptions (e.g., electricity, natural gas, DERs), equipment failure, and cyberattacks.

Unlike structural resilience, which deals with impacts to a building's structural integrity (e.g., framing, roof, foundation) (NIBS 2018) and are commonly addressed through building codes, operational resilience concerns a building's ability to serve critical loads during a major disruption. Most disruptions of this variety involve a loss of access to normal generation resources, as might occur during a power outage. From an integrated design perspective, it begs the questions, "How do energy efficiency in buildings and operational resilience relate to one another, can they be co-optimized, and if so, how?"[2][3]

A Paradigm Shift in Buildings

To begin, it is worth noting how building construction and operation has changed over the years. While modern buildings attempt to isolate their occupants from the exterior environment, classic vernacular and bioclimatic designs – which often needed to operate without power – embrace it. For example, one modern building type, the glass office tower, is subject to significant solar heat gain and can effectively become a dangerous greenhouse during an extended power outage.

In contrast, buildings that intentionally leverage passive measures, responsive to their exterior environments, can become both more energy efficient and resilient. (For a review of passive measures and their effectiveness, see Oropeza-Perez (2019) and references therein.) In climates with large diurnal temperature swings, adobe walls can act as a heat sink, keeping interiors cool during the day, and releasing heat into them at night. Traditional Persian buildings employ windcatchers that utilize prevailing winds or solar-induced convection for cooling, refrigeration, and ventilation. Crescent-shaped structures in desert environments can capture moisture from winds and fog and use it for evaporative cooling. Following Hurricane Katrina, buildings with passive architectural elements like window shadings, deep wraparound porches, and ceilings that allowed thermal stratification of air proved to be more resilient. Eastgate Centre, a modern commercial building in Zimbabwe, saves energy and stays cool in a region with frequent power outages by leveraging cooling and ventilation insights from termite mounds (Pearce 2016), an approach known as biomimicry.

[1] Some definitions also consider a system's response to "chronic stressors". We conclude that reacting to a chronic stressor aligns more closely with the concept of *reliability*, or the capacity for a system to perform as intended under less extreme "blue sky" conditions.

[2] For brevity, references to energy efficiency in the context of its intersection with resilience should be interpreted to refer to both "energy efficiency" and "load flexibility" that can "shape, shift, shed, and shimmy" load, often through some form of demand response (Alstone et al. 2016).

[3] To the extent that energy efficiency reduces greenhouse gas emissions, it can mitigate the impacts of climate change that make resilience more necessary (e.g., Nadel & Ungar, 2019). In this paper, we avoid this connection and focus exclusively on efficiency's relationship with disaster mitigation and climate adaptation.

In addition to design, the paradigm of building operation – particularly with respect to providing critical services – has changed significantly with the advent of electricity. It is primed to change further still with the expansion of energy storage (thermal, electric, and chemical) and connectivity.[4] Whether a building has these will influence its response pathway during a disruption (see Table 1). A study investigating single-family detached homes during a 2012 Chicago heat wave found in homes with air conditioning (AC) running at the time of a simulated power outage, those with leakier envelopes saw their thermal resilience compromised more quickly than in buildings with more airtight envelopes. In buildings without AC, though, airtightness had a mixed impact on resilience (Wilson et al. 2019). In other words, otherwise identical buildings exhibited different resilience responses depending on whether they were thermally preconditioned.

Table 1. Resilience scenarios for different knowledge and storage conditions

	Knowledge of impending outage	No knowledge of impending outage
Backup power onsite	• Maximum resilience scenario • Ability to charge storage devices and thermally precondition space • Maximum ability to service critical energy efficient loads using backup power • Advanced deployment of all operable efficiency measures (e.g., solar shades, natural ventilation) • Reduced need for passive efficiency measures and obtaining energy from environment	• Back-up power limited to whatever is available at time of outage, plus that which can be obtained from the environment • No ability to thermally precondition space • Ability to service critical energy efficient loads using backup power • Operable passive measures remain deployable after onset of disruption
No backup power onsite	• Ability to thermally precondition space • Energy efficient electrical and gas equipment rendered inoperable • Advanced deployment of all operable passive efficiency measures possible • Fully reliant on passive efficiency measures • Time to safely power down sensitive equipment • Prep time exists to meet critical needs (e.g., food, light) in advance of outage	• Minimum resilience scenario • No ability to thermally precondition space • Energy efficient electrical and gas equipment rendered inoperable • Fully reliant on passive efficiency measures, likely deployed after onset of disruption • Abrupt power outage could damage sensitive equipment

[4] In this context, *connectivity* is the capacity for a building to send and receive information relevant to its operations. This information can take forms including weather forecasts, price signals from the electric grid, or signals from a local micro district.

The Intersection of Energy Efficiency in Buildings and Resilience

Energy efficiency and resilience are increasingly being considered in tandem, though outcomes are often less than ideal. Federal agencies like the Department of Defense and FEMA have pursued resilience with an efficiency component, but their purview generally extends behind-the-meter only for municipal buildings and critical facilities. Programs like Commercial Property Assessed Clean Energy (C-PACE), the pre-disaster mitigation component of the Disaster Recovery Reform Act (DRRA), and even Vice President Joe Biden's housing plan have both resilience and energy efficiency as stated goals, but do not consider them in combination.

Of the studies that do investigate efficiency and resilience in an integrated fashion, many suggest that the former is universally beneficial for the latter. This can take the form of explaining how they are mutually beneficial (Baechler and Gilbride 2018), or how individual efficiency measures map to distinct resilience benefits (Williamson, Indvik, and Martin 2018). It has been argued that energy efficiency in buildings can improve energy system reliability (Golden, Scheer, and Best 2019; Ribeiro et al. 2015), make generation more valuable by enabling buildings to deliver critical services with less energy (Agan, Holleman, and Gheewala 2019; NASEO 2015; Office of Energy Efficiency and Renewable Energy 2019), and reduce risk to extreme heat and other events (Enterprise Green Communities 2016; Hoverter 2012; Santamouris et al. 2007; Singh et al. 2019).

While efficient buildings are almost certainly more resilient than inefficient buildings on the whole, measures that yield similar energy savings may not necessarily offer the same net resilience benefit, especially given the variety of hazards buildings face and the critical services that must be maintained. For example, consider quantifying the number of hours an occupant can shelter-in-place during a power outage. A first-order analysis might take the envelope properties of the building, and through modeling measure the amount of time the building can maintain a survivable temperature given exterior conditions. Studies taking this approach have concluded that efficient envelopes are positively correlated with hours-of-safety (Ayyagari, Gartman, and Corvidae 2020; Leigh et al. 2014; White and Wright 2019; Wilson et al. 2019).

Yet complications can arise when efficient envelope measures intersect other resilience goals. A building in the wildland-urban interface experiencing a power outage induced by a summer wildfire might benefit from passive ventilation to lower indoor temperatures. However, that approach can also expose residents to reduced indoor air quality and ember intrusion. Separately, Britain's deadly Grenfell Tower fire in 2017 has been partially attributed to a thermal cladding retrofit that was particularly susceptible to fire (Guillaume et al. 2020; Laban et al. 2017).

Stakeholders and Value Streams

For practitioners who abide by the "do no harm" principle, understanding how efficiency maps to resilience is critical, less represented in the literature (Baniassadi, Heusinger, and Sailor 2018; Fisk 2015), and one of the aims of this paper. The value capture can be significant. Notwithstanding the previous example, by allowing occupants to shelter-in-place during extreme events, their health – both physical and mental – can be protected, and the costs of evacuation and relocation can be avoided. Businesses will be able to preserve inventory longer and, if backup generation is available, suffer fewer business interruptions and at lower cost. Insurance premiums can decline. Utilities can utilize load flexibility enabled by GEBs to make the electric and natural gas grids more resilient to disruptions (Wang et al. 2017), and utilize pure efficiency to lower system load, “fail gracefully”, and enable softer restarts after a power outage. These potential value streams are relevant for a variety of stakeholders including:

- the scientific research community and equipment manufacturers who will adapt and improve upon existing technologies to better deliver resilience as a component of performance;
- utility operators who will recognize and utilize the benefits GEBs can provide through demand response and DERs;
- municipal resilience and sustainability officers who must prioritize how to best protect their communities;
- governments that assist those officers in performing that role and who often bear the costs of recovery;
- codes officials who will identify what an energy resilient building code looks like, and those who must enforce them;
- designers and architects who will consider buildings as a system;
- financiers and insurers who will value those buildings; real estate professionals who will market them and tout their benefits;
- facilities managers who must decide how to best invest in energy efficiency, renewable energy, and resilience; and
- occupants themselves who depend on those buildings for their lives and livelihoods.

However, we must remember that what constitutes resilience for one actor may not for another, e.g., a utility that sheds load of a vulnerable residential customer in service of grid reliability.

Answering all these questions is beyond the scope of this paper. Rather, we intend to provide a foundation from which deeper explorations of these issues may commence. We accomplish this through a combination of our own research with the output of the 2019 Oak Ridge National Laboratory *Workshop on the Nexus of Resilience and Energy Efficiency in Buildings* (Ott, Morgan, and Antes 2019). In Section 2 we summarize some hazards buildings must be resilient against, and present ways that buildings can fail to provide resilience for occupants, owners, utilities, communities, and other stakeholders. In Section 3 we discuss which factors influence how resilience is affected by energy conservation measures, then present complements and conflicts between them for set of technologies. We identify some challenges and opportunities for co-optimizing resilience and energy efficiency in buildings in Section 4, and offer brief concluding remarks in Section 5.

2. How Buildings Fail

Most residential and commercial buildings require reliable delivery of power to operate successfully. Yet the U.S. has experienced a steady increase in the annual number of electrical system disturbances (see Figure 1). While routine factors like local weather, squirrels, and equipment failures account for the majority of these instances, high-magnitude events account for the bulk of outage minutes. With respect to resilience, these long-duration outages are of greatest concern.

Over the past two decades the number of billion-dollar disaster events attributed to weather events has trended upwards (NCEI 2020a, Silverstein, Gramlich, and Goggin 2018), as shown in Figure 2. In one crucial example, some locations in Puerto Rico were left without power for a full year in the wake of Hurricane Maria (Mazzei, Penn, and Robles 2020). Models project that changing climate conditions will continue to drive growth in the frequency and magnitude of these events. This includes more extreme heat days (Dahl et al. 2019), increased snowfall (NCEI 2020b), and higher wind speeds and precipitation. These are projected to increase the average duration of power outages (Larsen et al. 2016).

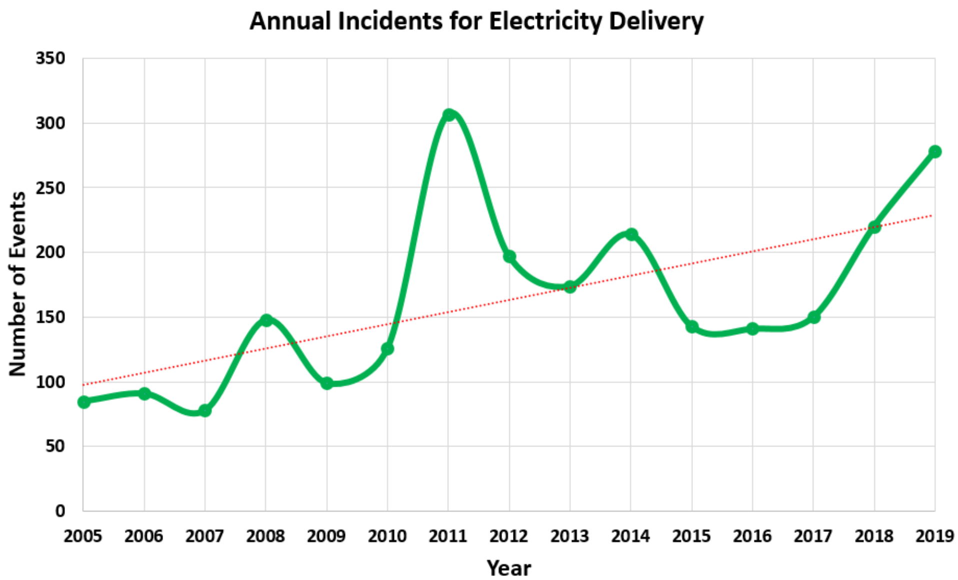

Figure 1. Reported annual number of electrical disruption events. *Source:* DOE, OE-417.

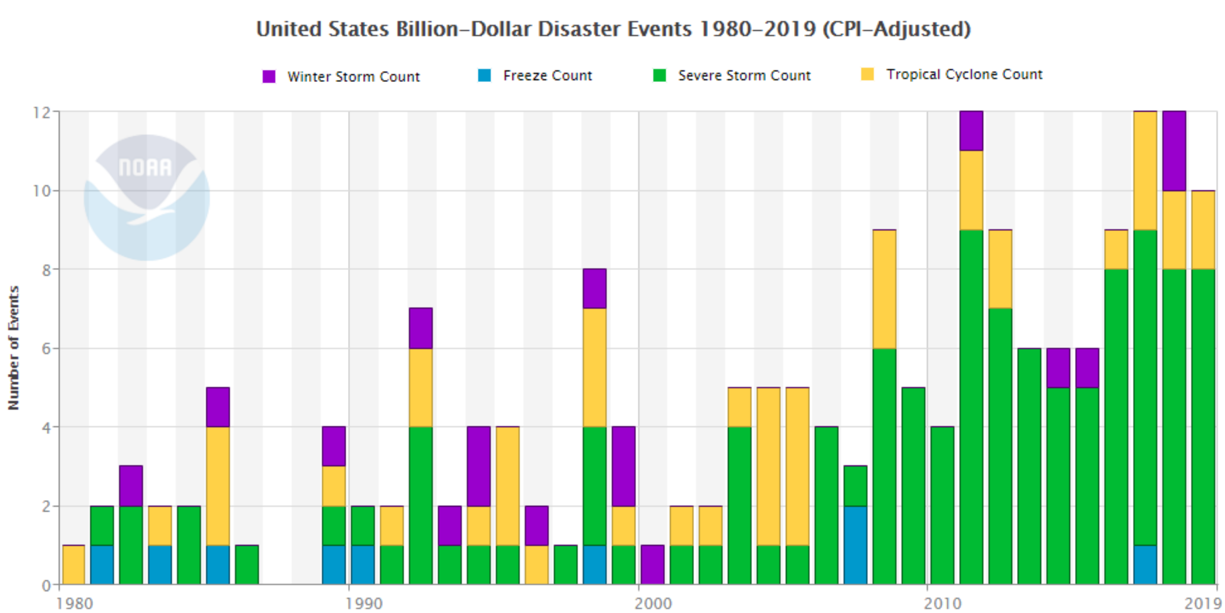

Figure 2. Storm and temperature related billion-dollar disaster events within the United States. *Source:* NOAA 2020.

In Table 2, we offer some of the ways in which these disruptions are felt within buildings. Health and safety can be compromised by loss of temperature regulation, ventilation, lighting, refrigeration, clean water, and capacity to service electrical medical equipment (Klinger, Landeg, and Murray 2014; Shapiro and Robinson 2019). While extreme temperatures garner much attention, critical conditions can emerge outside of that window. An extended cooling outage in a Florida nursing home in 2017 proved deadly despite exterior temperatures being mostly in the 80s (Sun, Specian, and Hong 2020). Flooding from Hurricane Harvey in the same year impeded the evacuations of millions of people who were advised to shelter-in-place (Jonkman et al. 2018). Open flames used for interior heating, lighting, and cooking have led to fatalities due to fire and carbon monoxide build up (Rappaport et al. 2016).

Commercial buildings can fail in ways linked to their particular mode of operations. Inability to service critical loads can lead to a loss of inventory; inability to contain hazardous materials; loss of business continuity; shutdown and startup costs; and more. Critical facilities like hospitals, police stations, and communication centers have additional unique challenges.

Table 2. Examples of how buildings can fail when power is disrupted

<table>
<tr><th>Residential Buildings</th></tr>
<tr><td>
Refrigerated food and medication spoilage
Compromised capacity to prepare food
Thermal safety (heat stroke/hypothermia)
Carbon-monoxide poisoning from improper generator/grill/kerosene use
Medical equipment outage
Lighting loss (hazardous navigation)
Elevator outage in high-rises
Water delivery in high-rises
Compromised ventilation
</td></tr>
<tr><th>Commercial Buildings</th></tr>
<tr><td>
Hospitals
Inability to access electronic records
Inability to transport patients/equipment between floors
Inability to sterilize instruments
Food spoilage and preparation
Refrigerated medication spoilage
Diagnostic equipment loss

Retail/Office
Lost revenue from idle resources
Shutdown and restart cost
Computer data loss

Data Center/Telecommunications
Temperature regulation challenges if backup power not also available for HVAC
Degradation of storage media if temperatures rise
Downstream losses to firms that require connectivity for business
Backup batteries not designed to fully drain in cases of long-term power outage

</td></tr>
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3. Intersections

Energy efficiency and load flexibility can be realized through a variety of mechanisms that each map to unique resilience outcomes. A common metric used to capture the value of resilience as we are describing it is through the "value of lost load" (VoLL), or the cost to consumers of being unable to take power from the system (Office of the Assistant Secretary of Defense for Sustainment 2019; Synapse Energy Economics et al. 2018). This value can be a function of multiple factors that can vary with time, location, and circumstance.

Among them are seasonality and climate zone. Measures effective in one set of climate conditions (e.g., tight envelope in a cold climate) could be liabilities in another (e.g., tight envelope without air conditioning during a heat wave). Occupant demographics are also relevant. The VoLL is generally higher when buildings are occupied, serving vulnerable populations (e.g., children, elderly, disabled, infirmed), or meeting a critical need like an emergency shelter.

Another important concern is determining which loads are of highest priority for a given circumstance. In general, commercial buildings may have greater need to preserve inventory, while residential buildings are more likely to value meeting thermal loads. Even then, the preferred method of meeting that critical service – whether through active or passive measures – can differ based on ambient environmental circumstances like proximity to the ocean or the wildland-urban interface.

The characteristics of a building's storage and generation properties play a key role as well. Resilience outcomes can differ based on whether the storage can be recharged (e.g., solar-plus-storage), versus being finite (e.g., diesel generator). Whether stored energy can be converted to electricity (e.g., electrochemical batteries) or not (e.g., thermal storage) is relevant, as is whether the building is part of a local microdistrict. Energy efficient loads will be more valuable when generation is limited, as this can allow some loads to be powered longer, more loads to be powered per unit time, or something in between.

Envelope

The energy efficiency of a building's envelope depends on multiple, mostly-passive elements including the R-value of wall insulation; U-factor and solar heat gain coefficient of windows; wall-to-window ratio; window attachments; thermal bridging; roof type; air tightness, and local topography and vegetation. High performance buildings may further reduce thermal loads by incorporating passive measures like large, south-facing windows with solar shades that increase solar heat gain in winter and reduce it in summer; high ceilings that enable thermal stratification; vented attics that expel hot air; and operable windows optimized for passive ventilation.

Resilience is most important during periods of extreme heat or cold when occupants need to *shelter-in-place*. This concept is closely connected to that of *passive survivability*, or the ability to maintain critical life-support conditions during a loss of power (Wilson 2005). This connection was demonstrated in the Belfast Ecovillage in Belfast, Maine where buildings built to the Passive House standard were able to maintain safe thermal conditions during an ice storm-induced power outage in December 2013. Outside temperatures dropped to -4°F, yet interior temperatures were recorded at 58°F four and a half days later.

Because each envelope element influences efficiency through a different mechanism, its connection to resilience outcomes will similarly differ. Envelopes can be made more resilient to windborne debris if windows are covered with anti-shatter films, and the wall-to-window ratio is large. Green roofs improve resilience to extreme precipitation events by capturing water that could otherwise inundate the sewer system.

However, both open and airtight envelopes can compromise resilience under certain circumstances. The absence of natural ventilation can cause an airtight building to heat up more quickly than a less airtight one (Sun, Specian, and Hong 2020), provided the exterior temperature is lower than the interior temperature. Airtightness can also lead to humidity build up, increasing the indoor heat index and worsening thermal survivability. On the other hand, passive thermal and ventilation measures can also compromise resilience. Soffit vents can permit ember intrusion during wildfires. Passive ventilation can admit smoke, water, and windborne projectiles. Open windows can be a security risk, while open upper story windows increase defenestration risk. If the wall-to-window ratio is too high, critical daylighting can be compromised.

High R-value insulation and fire resistance do not necessarily go hand-in-hand, as illustrated in Table 3. Even cool roofs, which in aggregate reduce the urban heat island effect, can worsen air quality in a waterside city by lowering the temperature and pressure gradients between land and water that drive cleansing winds. Conversely, lowering the urban heat island effect brings thermal benefits and mitigates the formation of ground-level ozone.

Table 3. Flammability based on two tests for surface burning characteristics

Envelope Insulation Technology	R-value	Thermal Stability	Toxic Smoke	Ignition Risk
EPS (Expanded Polystyrene)	Medium	Low	High	High
XPS (Extruded Polystyrene)	Medium	Low	High	High
PIR Foam (polyurethane)	Medium	High	High	High
Phenolic foam	High	High	Medium	Low
Silica Aerogels	Medium	Medium	Low	Low
Polymeric nano-foams (aerogels)	High	High	High	High
Vacuum-insulated panels	High	Medium	Medium	Medium

Source: Flame spread (ASTM E84 test) and room fire growth (NFPA 286 test). Assessments of flammability characteristics from personal communications (K. Sawyer and S. Mumme, Emerging Technologies, DOE Building Technologies Office, February 2018).

HVAC

Electric heat pumps offer considerable energy savings compared to more traditional HVAC technologies. Systems that decouple sensible and latent cooling such that dehumidification can be facilitated through non-electric (e.g., thermal) sources will be more resilient. Ground source heat pumps are more resilient to surface level disruptions by virtue of their undergrounding (BuroHappold Engineering 2019). However, any HVAC components located outside the building exposes the equipment to airborne debris and standing water.

Components can corrode, and damaged systems pose a fire hazard. Debris can also affect fins and coils in ways that compromise performance. Equipment placed in basements and lower levels may be susceptible to flooding.

Combined heat and power (CHP) systems are both highly energy efficient and resilient by co-locating generation and load. In addition to utilizing waste heat, CHP systems bypass issues impacting utility-scale generation and problems on the transmission and distribution system. Most CHP systems are fueled by natural gas, enhancing resilience by being operable using a non-electric fuel source.

Grid-Interactive Efficient Buildings

GEBs enable efficiency and load flexibility through a combination of sensing, measurement, data analytics, modeling, smart controls, and connectivity with outside signals. Smart thermostats and zone controls adjust thermal loads to co-optimize energy efficiency and occupant comfort. Smart lighting can save energy by operating only when occupants are present. Intelligent ventilation can optimize the relationship between indoor and outdoor temperatures to ventilate during the most favorable energy scenarios. Two-way communication with the grid, including through Wi-Fi and advanced metering infrastructure (AMI), enable demand flexibility to provide grid services (including reducing peak) while also enabling utility energy efficiency programs, like pay-for-performance M&V.

If onsite generation – including that offered through microgrids – is available, smart controls can enhance resilience by prioritizing critical loads. Connectivity enables utilities to execute demand-side management (DSM), including instances when extreme levels of demand threaten grid reliability (Wang et al. 2017). It can also induce buildings to shift into "safe" mode when necessary by, for example, preconditioning spaces through charging electric and chemical battery storage. Connectivity provides utilities visibility into power outages, enabling repairs to be made more quickly. Flexible loads may also aid in soft restarts of the grid post-outage.

Conversely, connectivity and controls increase the complexity of building operations. They may become too relied upon, or leave building operators unaccustomed to offline access less capable of handling adverse conditions than if dealing with more conventional "dumb" building systems. Utilities that rely too heavily on DSM and visibility may be unduly compromised if disconnected from their network. Connected devices also carry the risk of cyber intrusions and attacks.

Energy Storage

While self-discharge compromises the efficiency of energy storage, the capacity to load shift enables nighttime charging when temperatures, and thus line losses, are lower. Shifting enhances resilience by reducing grid stress, either by lowering demand or absorbing excess renewable energy. Storage serves as a resilient source of backup generation during an outage. Efficient end-uses can make better use of potentially limited generation, thereby increase storage's value. If portable (e.g., EV batteries), storage may also be able to escape harm's way during a weather disaster. However, electrochemical batteries, including lithium-ion and flow batteries, can compromise resilience by carrying an increased risk of explosion, fire, or contamination in the event of a physical impact.

Construction

Certain construction practices have both efficiency and resilience benefits. Cross-laminated timber has higher thickness than traditional wood construction, offering greater insulation. Insulating concrete panels (ICPs) offer similar efficiency savings. The structural integrity of both offer enhanced projectile resilience and blast performance. ICPs are more resilient than traditional construction to fire, earthquakes, wind, and floods (Portland Cement Association 2019). The details of construction matter, however. For example, steel roof fasteners may enhance high wind resilience (FORTIFIED Home 2020), but compromise efficiency if they create an additional thermal bridge.

4. Opportunities and Challenges

There are both tremendous opportunities and challenges with respect to co-optimizing energy efficiency in buildings and resilience. We have grouped these into 8 categories and discuss them in this section.

Value Proposition: Energy efficiency will continue to be systematically undervalued until we can quantify the benefit it offers for resilience. Quantification can help businesses and homeowners better understand from a monetary perspective how valuable an efficiency improvement can be. This knowledge can guide investment decisions, allow for a return on investment at point of sale (thereby incentivizing those investments), and offset the need for more expensive interventions (e.g., oversized generators). It can also assist efficiency and resilience program managers in determining which technology and policy interventions would deliver the best net outcome per taxpayer dollar invested. While this kind of valuation is no small task, a 2018 NIBS report on the value of structural resilience provides an excellent template for how such analysis can be conducted (NIBS 2018). Case studies can also be useful, including one that assessed how energy conservation and storage methods could have improved the thermal survivability of a Florida nursing home, and at what cost. (Sun, Specian, and Hong 2020).

Resilience Assessment: Standardized metrics to assess the resilience impacts of a building's efficiency could improve safety and reshape the market. Convenient tools to measure those metrics will be needed, including determining the impact of building codes and standards on resilience. However, the massive number of combinations of building properties, local conditions, and resilience goals makes these assessments and subsequent pathways for co-optimization a complex undertaking. New modeling tools capable of accounting for both simultaneously should be developed.

Education and Awareness: More effort is needed to communicate the benefits efficiency provides for resilience, and guide customers on how to realize it. For building operators and program managers, talking points, case studies, and design guides could spur change. When buildings are being renovated, or equipment upgraded or replaced, customers should be guided toward solutions that improve both efficiency and resilience. As more resilient building designs make it to market, customers should be adequately informed on how to use their passive energy measures. All of this will require better educational curricula and training programs for retailers, contractors, building inspectors, and others.

Financing and Incentives: Building owners interested in making either efficiency or resilience upgrades should be empowered to do so through financing mechanisms that realize both sets of benefits. Public utility commissions should ensure that buildings that provide resilience through grid-interactivity should be appropriately compensated for their grid services. Because the costs for building improvements can be daunting, and intervention points are limited, particular attention should be paid to utilizing post-disaster rebuilds as opportunities to deploy affordable solutions at scale.

Technology and Design: Advanced research can identify opportunities to deliver efficiency and resilience in an integrated fashion. This includes next-generation CHP and HVAC systems, storage, sensor and IoT devices, and controls. Buildings should be able to identify their critical loads and possess the intelligence to prioritize them in low- and no-power situations. Existing resilient designs and practices should be reexamined for opportunities to integrate efficiency including structural hardening, stormwater management, fire retardation, and quick-drying envelopes. New advanced building construction techniques that combine the best elements of modern and vernacular designs should be explored as a way to maximize comfort and safety, including when buildings are operating without power. Technologies that better integrate renewable energy into exterior-facing building elements should be developed.

Zoning and Codes: Because a building's location, orientation, and relationship with its neighbors impacts both resilience and efficiency, zoning ordinances should be reexamined to ensure both are being considered in tandem. Advanced designs should occur in coordination with the codes development process to ensure best practices are being standardized.

Collaborations: Because energy and resilience have so many stakeholders, traditional siloes must be broken down and new collaborations formed. This includes designers, technologists, manufacturers, lenders, insurers, and government energy and resilience officers. Programming and funding agencies like DOE, HUD, FEMA, and EPA should coordinate their efforts. Best lessons must be disseminated and adopted. However, this presents a high level of complexity, in part because organizations have different definitions, goals, budgets, leadership, and purviews.

5. Conclusion

In this paper we have presented a framework through which to better understand resilience and energy efficiency in buildings as interconnected issues, and argued that they are best approached from a systems perspective. We identified the factors that can cause resilience to differ even between very similar – if not identical – buildings. We explored building components by categories, reporting where resilience and efficiency goals complement each other, and where they conflict. We concluded by laying out areas where progress in co-optimizing the two could be made, while recognizing the challenges to doing so.

We propose that durable solutions be pursued through four pathways: 1) improve building technologies and designs to co-optimize for efficiency and resilience, 2) create standardized valuation and assessment mechanisms, 3) explore the social science to learn the extent to which resilience is a driver of efficiency investments, and 4) develop new programs, policies, and regulations that drive holistic solutions. In combination, these strategies can add yet another valuable value stream to energy efficiency and accelerate its adoption as one of the best approaches we have to addressing our climate and energy goals.

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