Is a Generator the Only Solution When the Grid Fails? Optimizing Systems for Resiliency and Carbon Reduction

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ABSTRACT

Traditionally, buildings are dependent on utility infrastructure, and when a grid failure happens, end users rely on the closest source of energy storage to sustain operation until power is restored. For buildings, that typically means using an electric generator. This electric generator either uses on-site energy storage such as fossil fuels in a tank or a gas connection which is, in turn, tied to gas wells—also a form of energy storage. Generators are popular for their ease of implementation and low capital costs; however, they have limited value outside of disruptions, and they are a source of direct greenhouse gas emissions from sources controlled by the building owner, also referred to as scope 1 emissions.

In contrast, some power generation and storage systems, such as photovoltaic (PV) panels and battery energy storage systems (BESS), can serve the same purpose during grid disruptions while presenting advantages outside of power failure. This study explores methods for storing and converting energy on-site to increase building resiliency, focusing on solutions that minimize scope 1 emissions. We analyze the cost and carbon impacts of energy efficiency measures, PV arrays, and BESS, with and without generators, in a simulation test case. We find significant benefits can be achieved both during and outside of power failure events when designing systems that integrate the on-demand capability of generators, the low carbon energy supplied by PV, and the storage capabilities of BESS. Specifically, adding even minimal BESS and PV can result in downsizing the generator, increasing generator efficiency, and requiring less fuel.

Background

Most buildings are highly dependent on utility infrastructure to operate. Disruptions to the electric grid, and, to a lesser extent, the natural gas supply, can greatly affect the operation of a building. These disruptions in the utility grid can be caused by interruptions in power generation or byby the failure of distribution and transmission lines. In theory, for buildings or end users to be resilient against upstream disruptions, energy storage is needed as close as possible to the end use. In buildings, the most common solution is to rely on electric generators. In that case, energy is stored on-site in the form of fuel and converted to electricity when needed. An alternative is to use generators powered by a different utility infrastructure, such as natural gas, which conceptually is a large energy reserve (storage) connected to the end user by pipelines.

Building owners are increasingly interested in reducing their scope 1 emissions, i.e., direct greenhouse gas emissions from sources controlled by the owner (EPA 2022). Emissions from fuel combustion in boilers, furnaces, or generators are examples of scope 1 emissions. Although generators are popular because of their ease of implementation and low capital and maintenance costs, other solutions that reduce scope 1 emissions exist, and they can have benefits for building owners that extend beyond reducing greenhouse gas emissions.

Current Energy Resiliency Technologies

Generators

On-site electricity production typically uses internal combustion engines (ICEs). The ICE operates on a fossil fuel, either located at the unit (propane, kerosene, or diesel fuel) or is connected to a natural gas line. ICE generators are popular because of their low cost when compared to other technologies and their ease of implementation. They are available in many different load capacities, and are often a drop-in-place system that can be installed temporarily or permanently.

Generators are sized to at least 125% of a building's critical peak load, which is the power required to energize all emergency systems with a 25% safety margin (NFPA 2021a). Designers and operators must define what part of the building is part of the emergency system depending on the building function and expectations for operations in the event of a grid outage. In the United States, this rule is mandated by National Fire Protection Association (NFPA) 70, which also specifies methods for measuring building loads, and it is often applied beyond the minimal requirements specified in the standard (NFPA 2021a). To power systems beyond the emergency systems, no standard method is defined in the literature, and common practice can range from quick, back-of-the-envelope calculations to precise building load assessments.

Although generators can provide intermittent power, they are not without issues. Because they are rarely used, they are often not tested nor maintained frequently enough. This fact leads to frequent mechanical failures, that often go undetected until the generator is needed. Marqusee and Stringer (2023) report that a poorly maintained emergency diesel generator is not likely to provide power for outages that last longer than three to four days and is only 80% reliable after 12 hours of a power outage. Maintenance requirements are specified in the NFPA 110 and Unified Facility Criteria (UFC) 3-540-07 guidelines, and include semiannual, annual, and triannual inspections, each of which has to be carried out by a qualified technician (NFPA 2021b DOD 2019). In total, a building owner who operates a generator could see as little as eight service or testing visits per year, and as many as 17. In addition to routine maintenance, system designers must ensure that the ICE generator is loaded above a certain threshold, which is usually 25 to 30% of the maximum load. Underloading the generator for extended periods of time can damage it, and manufacturers recommend additional service inspections when it happens (Jabeck 2014). **Error! Reference source not found.** illustrates how, in a simulated building, the total building load during normal operation is likely to be less than 50% of the peak load. Although electrical systems must be designed for peak load, buildings rarely operate at more than 50% load.

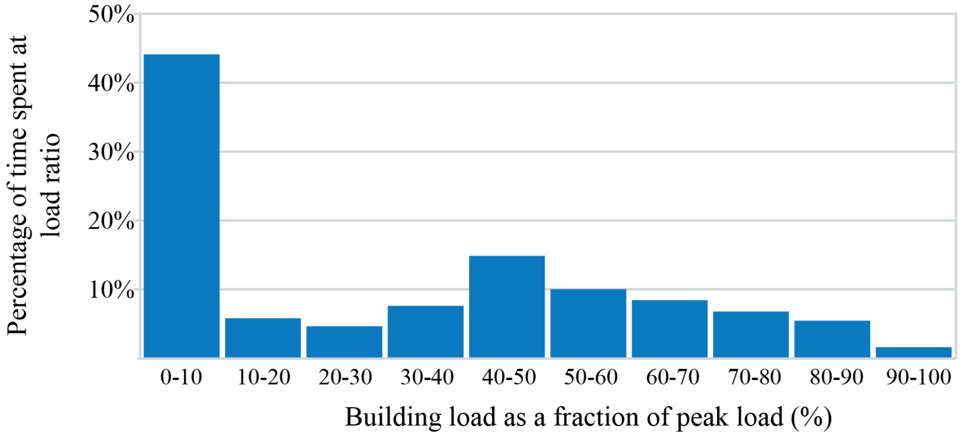

Figure 1. Plot showing the percentage of time spent at a given building load, expressed as a percentage of the peak load. These data are from simulation of a U.S. Department of Energy prototype retail building in climate zone 3B.

The efficiency of ICEs is not linear, and peak efficiency is around 75 to 80% of the maximum load. An example is shown in Figure 2, where the efficiency of a commercially available diesel-powered backup generator peaks at around 33%, when the generator is loaded at 75% of its rated power. Operating the generator inefficiently can have consequences for the amount of time a generator can run with on-site fuel storage and can also impact the maintenance interval. The building much ofis usually at loads that, if operated bya generator, are very inefficient compared to the peak efficiency of the generator.

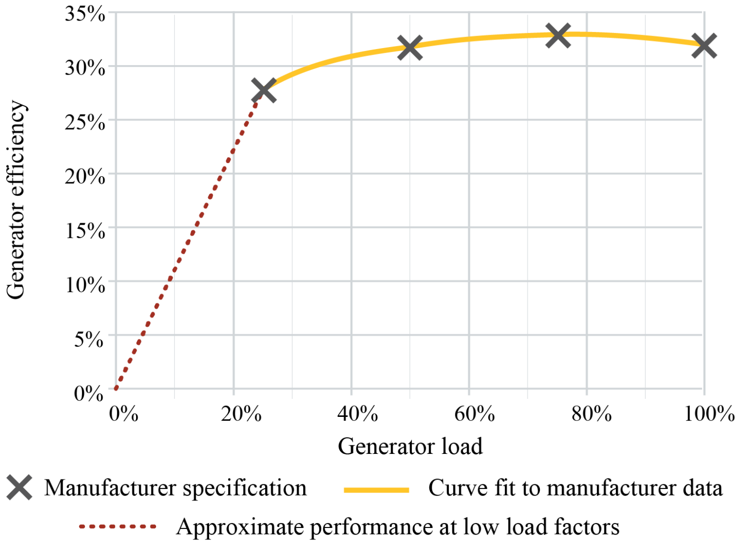

Figure 2. Manufacturer provided generator efficiencies at various load percentages as a fraction of total generator capacity for a Cummins 6BTA5.9-G5 Diesel backup generator.

Energy Storage Systems

Energy storage systems, for the purpose of this analysis, are systems located at buildings that can store energy by charging and discharging. Among the types of building-level storage systems are thermal mass in the building structure and interiors, hot water and cold-water tanks, ice storage systems, and batteries. Energy storage can be used to absorb demand peaks, resulting in lower energy bills, or it can be used to store electricity purchased from the grid during off-peak periods. Once the case for storage is established, the optimum type of storage can be determined and is often dependent on the building loads. Determination of the best form of energy storage is beyond the scope of this analysis. This determination is also dependent on how energy efficiency is deployed as part of the holistic solution.

This effort focuses on battery energy storage systems (BESS), but the analysis applies across different types of storage. For example, if there is need for a hot water load, hot water storage can be used in place of BESS, often more effectively. Differentiating between different types of energy storage makes the overall analysis complex in determining the impact of storage, renewable energy, and efficiency. For simplicity, all the storage considered herein this study is battery storage, but using a mix of storage solutions would achieve the same results, often more efficiently and for less cost.

At the building scale, batteries can be used outside of the emergency of a power outage Looking at the larger picture, BESS can help in reducing carbon emissions from the grid by reducing the requirement for carbon-based power generation, because it can be used to store energy when renewable power is available and release it when it is not. Aligning renewable power with building power is critical for reducing carbon emissions.This alignment on the building side can include building level storage to help shape loads to match renewable supplies both on-site and off-site.

Barriers to BESS adoption are capital cost and safety concerns about the current lithium-ion technology. The potentially game-changing technology of lithium ferrophosphate ($LiFePO_4$) is close to commercialization and is acquiring customers in large industrial sectors, such as the automotive sector. $LiFePO_4$ batteries are cheaper to produce than other high energy density batteries and eliminate most of the safety hazards associated with lithium-ion batteries. Their principal disadvantage when compared to lithium-ion batteries is that are heavier for the same capacity, but the lower energy density has minimal impact in buildings.

Photovoltaics With Battery Energy Storage Systems

Photovoltaic (PV) power systems have become widespread in recent years due to a price point that makes on-site electricity generation competitive with grid-supplied electricity. Nowadays, with decreasing battery costs and utility rates that promote using batteries to reduce grid peaks, PV can be installed in conjunction with an energy storage system. Energy can be stored when not needed by the facility or can respond to grid needs. This strategy can help decarbonization by better using renewable energy sources and minimizing the need for fossil fuel peaking power plants. Conversely, subsidies from state, local, and federal programs make this solution financially viable. For example, for smaller buildings (8-kW PV and 12.5-kWh storage) the installation cost is approximately $40,000, while for larger buildings (500-kW PV and 1200-kWh storage) it can reach up to $1.5 million (Ramasamy et al. 2022). These systems provide a levelized cost of electricity of 8.7 to 11.1¢/kWh, which is lower than many utility rates. These systems also provide an opportunity to save on demand charges, although demand control strategies are needed to realize these savings. PV with BESS can reduce the buildings emissions if deployed with grid power that has a high emission factor.

Combining Photovoltaics, Battery Energy Storage Systems, and Internal Combustion Engine Generators

As noted previously, ICE generators can suffer from low load factors, which result in poor energy efficiency performance; they also can be unreliable if poorly maintained. One solution is to use ICE generators in conjunction with energy storage such as BESS, so that the generator is used to generate and store energy at peak efficiency—in optimal conditions and independently from the immediate energy use. The storage system, in turn, supplies the energy when needed and acts as a buffer to absorb demand peaks. The ICE generator can therefore be sized for the average building demand rather than the peak demand. Increasing the overall ICE generator efficiency also means longer running times for a given fuel reserve and improved overall system reliability.

Additional benefits can be obtained when combining PV and BESS with ICE generators. Even when there are no power failure events, the PV and BESS retain their advantages in terms of potential energy cost savings and carbon impact. Generators are an asset that has a very specific limited use while PV and BESS, if configured to do so, can be used both in a grid failure mode as well as providing services when the grid is available.

Utilities, Code, and External Factors

External factors affect the design of an emergency power system. The expected impact of the power outage informs system sizing, utilities affects cost through ancillary revenue and incentives, and code dictates minimum requirements or limitations. It is important to consider the technical, economic, and regulatory aspects together to ensure that a system is properly designed and benefits building owners and operators.

First, designers should consider opportunities for savings or the ability to generate revenue with the system. Whenever electricity can be produced and stored on-site, there are opportunities to generate revenue depending on the utility's rate structure. For example, if net metering is available, on-site power generation becomes a stable source of revenue for the system owner at any time. If time-of-use tariffs are in place, energy storage offsets the purchase of electricity to less-expensive off-peak times, resulting in additional savings. Even a small BESS can help shave demand charges and participate in demand response programs, which offer discounts if building operators can curtail power demand when required. In some cases, utilities can incentivize technologies through rebate programs; some have programs that incentivize batteries for energy storage to be available to the utility for grid-level power quality management. There are many opportunities for generating ancillary revenue and leveraging local utility programs. It is important to include ancillary revenue in cost projections, as it can have a notable impact on the levelized cost of a system.

Secondly, designers should consider externally imposed limitations. Utilities may impose restrictions on how and whether electricity can be produced and stored on-site. Some programs, for example, might regulate on-site PV production by setting limits on installed power. This determines how much can be used to participate in net metering and savings opportunities. Local building codes too can dictate how power systems are designed, including considerations such as the definition of "critical" systems, the ability to use the power systems for demand response programs, minimum ratings, allowable technologies, etc. State government websites provide resources for local building codes and standards. In certain U.S. states (AL, AZ, CO, DE, IL, MS, MO, ND, TN, TX, WV, WY) (NIST 2022), designers need to consult county governments, which are responsible for applying building codes.

It is also advisable to consult local statistics on electric grid stability. Some regions suffer frequent but short power failures, while others face longer, rarer failures. Statistics on the frequency and duration of power failures in recent years are available for the United States, organized by state and grid region for historical and recent events. An example of such statistics is presented in Figure 3, where the United States in 2021 have helped characterize the average duration and frequency of power outages per customer, per state. As an example of design choice, in a region where short power failures occur most of the time, a small BESS system would supply energy during most of the outages and adding a generator backup would cover longer power outages and meet any code requirements for backup generation. This arrangement would minimize carbon emissions while making a BESS available for ancillary revenue as well as significantly downsizing the generator. Considering local grid conditions can help in better designing and sizing an emergency power system.

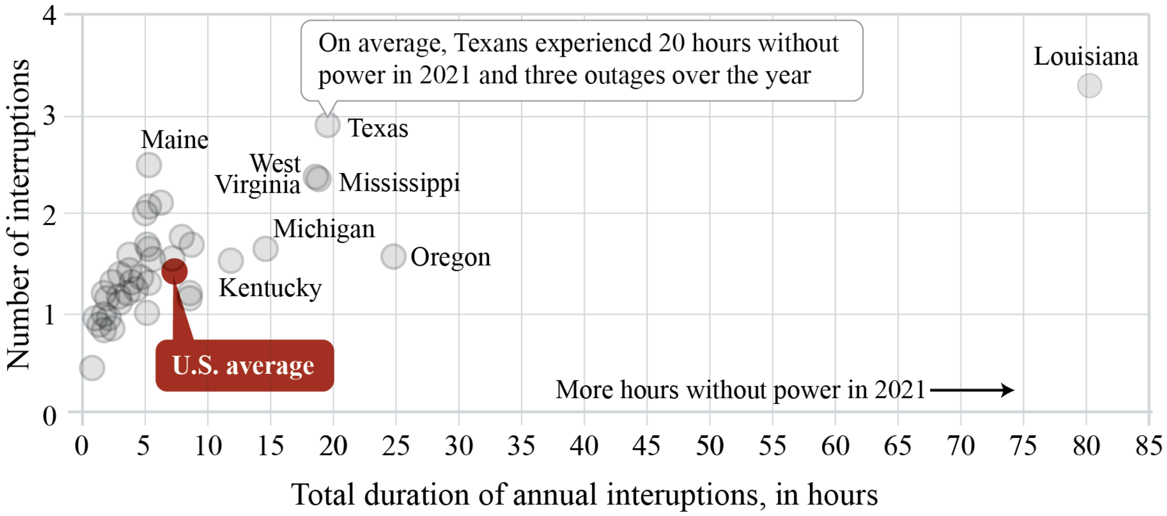

Figure 3. Average total annual electric power interruption duration and frequency per customer, by U.S. state, in 2021. *Source:* EIA 2022

By considering these external factors, designers can ensure that an emergency power system design optimally balances operation and maintenance costs and performance while increasing a building's resilience and grid-interactivity.

Role of Energy Efficiency Measures

Energy efficiency measures can reduce the required load and, thus, the size of the generator and BESS. Energy efficiency measures can be categorized by end use and have different energy use reduction impacts. Reductions in energy use for space conditioning, ventilation, and lighting reduce demand and can result in smaller generators or batteries for resiliency purposes.

Although energy efficiency generally presents an opportunity to downsize all those systems, some measures make the building more robust. Adding insulation can reduce the heating and cooling load, thus reducing the peak load and reducing the size of the generator and run time of the generation, and it can also add other value, such as preventing the building from freezing. Daylighting can reduce the lighting load and also provides direct and indirect lighting.

Example Benefits of Combining Photovoltaics, Battery Energy Storage Systems, and Internal Combustion Engine Generators

To evaluate the application of combining efficiency, BESS, on-site renewable generation, and ICE generators, we created a fictional retail building based on the DOE prototype retail standalone building. We chose a retail building for this test case to provide a conceptual discussion for resiliency in an emergency. Neighborhood stores are often a critical community resource that can provide dry goods and limited refrigerated food in the case of an emergency. Keeping these types of stores operational during a power outage is important. However, the concept of improving the envelope and adding PV with batteries and a generator is applicable to various building types. We used this test case to support a discussion on emergency power systems that have low carbon emissions and help reduce emissions when the utility grid is available. The scenarios analyzed in this section are depicted in Figure 4, and the system sizing is reported in Table 1**.** The design choices are described in more detail in the following sections.

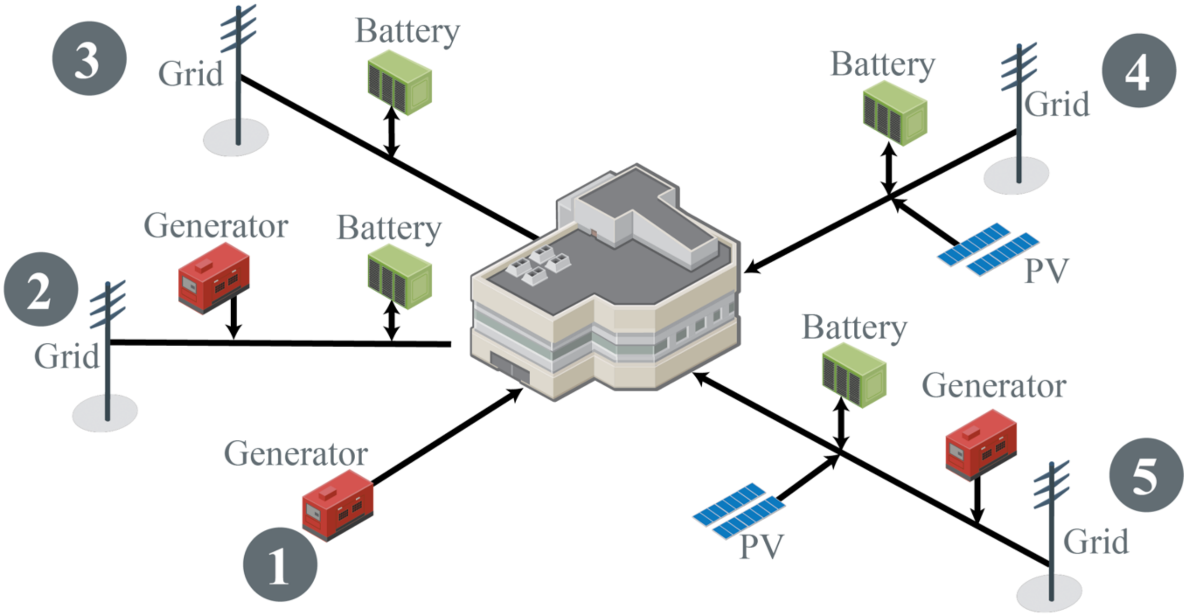

Figure 4. This study considered the following configurations: (1) a fossil fuel generator, (2) a generator with battery energy storage, (3) a battery energy storage system, (4) a photovoltaic and battery system, and (5) a photovoltaic and battery system with a generator backup.

The retail building is 25,000 ft^2 and uses an all-electric heat pump for space conditioning. The HVAC system is designed to maintain a temperature of 70°F during normal business hours of 9 am to 7 pm. During the unoccupied periods, the temperature is allowed to float between 61°F and 86°F. The shell of the building is designed to meet ASHRAE 90.1-2019 (ASHRAE 2019) and varies based on the minimum requirements of each climate zone.

To establish a baseline, we simulated the building for a year for each U.S. climate zone using the OpenStudio® Parametric Analysis Tool (NREL 2023). For this study, we selected a building situated in climate zone 4C. The whole-building energy use was reported at 10-minute time steps. Because typical resiliency systems are designed for 4-hour outages, we have aggregated these data into 4-hour windows of time. Preliminary simulations show that the same retail building, across all U.S. climate zones, has a maximum energy use of 368 kWh for a 4-hour window in a typical meteorological year.

Further analysis has shown that if an emergency backup system were sized to satisfy the building's energy use 80% of the time, instead of 100%, then in the most demanding climate zone it could be downsized to 270 kWh. This represents a 26% reduction in energy storage. To provide a relevant case study, we assumed that our building was in climate zone 4C, and that resiliency systems should be designed to provide the building's energy needs for at least 80% of all possible 4-hour power outages. We simulated the building in normal conditions, with normal occupancy and building loads patterns. The Seattle city government defines the building code, and we assume that the building conforms to the 2018 Seattle Building Code (City of Seattle 2018). Puget Sound Energy is the main utility in the Seattle region, and we use their Schedule 25 tariff structure for Small Demand General Service (50- to 350-kW demand), as well as Schedule 150 for net metering.

Next, this case study describes different approaches to energy resiliency and propose solutions that maximize reliability and minimize carbon emissions.

Table 1. Summary of emergency power systems modeled in this study

Design choice	Generator rating (kW)		Battery capacity (kWh)		Installed PV (kW)
	No EE*	EE	No EE	EE	
1: Generator only	80	55	-	-	-
2a: Large generator and small BESS	80	55	10	10	-
2b: Small generator and large BESS	55	42	50	45	-
3: BESS only	-	-	300	240	-
4a: Small PV and small BESS	80	55	90	50	25
4b: Small PV and large BESS	80	55	300	240	25
4c: Large PV and small BESS	80	55	90	50	100

**EE: Energy Efficiency Measures*

Fossil Fuel Generation

The first approach to meet energy use described in this paper is to use a fossil fuel generator as shown in Figure 4. This approach is the most common, given the availability of proven ICE technology, its cost-effectiveness, and the system's flexibility. These backup generators can be purchased or rented if grid instability is anticipated, such as during a weather event. Typically, these systems are sized for 125% of the peak power demand, which in this case amounts to 96 kW. We therefore modeled a diesel generator set rated for 80 kW of standby power and 90 kW of prime power, which was modeled after a commercial system using manufacturer specification sheets.

As this generator is sized for peak demand, it can provide power for any length of time if it has the fuel capacity to sustain itself. For a 4-hour outage event in the retail building, we estimate that about 13 gallons of diesel fuel are needed to sustain the building, which translates to about 313 lb of CO_2 equivalent emissions during that window of time and 4.5 lb of CO_2 equivalent emissions per kWh of energy on average.

In that configuration, although the building is theoretically "off-grid" for as long as the fuel storage allows, it also operates at loads that are smaller than the minimum recommended load for that diesel generator set. This greatly increases the probability that the generator will fail during operation or start-up, which impacts the usefulness of such a system.

By adding a battery storage system that acts as a buffer between the generator and the building, we not only ensure that the generator operates within the conditions recommended by the manufacturer, but also ensure that it operates at optimal fuel efficiency (Figure 4 (2)). For example, in this case, a battery as small as 10 kWh can decrease the emissions to 2.19 lbs of CO_2 equivalent emissions per kWh on average, which is half that of the same generator without a battery. The benefits of this system would be the most obvious during outages that happen at times when the building load is too low to operate the ICE generator exclusively at peak efficiency.

This approach uses a relatively small battery with a generator that has been sized for 125% of the building's peak demand, so it would be applicable to cases where a power backup system already exists and is being retrofitted. Another approach would be to use the buffering capabilities of the battery storage system to downsize the generator. We estimated that increasing the battery capacity from 10 to 50 kWh would allow us to downsize the generator from 80 kW to 55 kW of standby power. These ratings were based on commercially-available units. This approach has all the advantages of the previous one and reduces the CO_2 equivalent emissions by 15%. However, an additional benefit of using a larger battery capacity is that it can be used outside of power failure events for other purposes, such as demand shaving. In this scenario, a 50-kWh battery would allow the system to shave a minimum of 10 kW off the peak demand all year long.

This scenario shows how including energy storage in systems based on generators can greatly improve the system's resiliency. First, it improves reliability because the generator is guaranteed to operate at the optimal design conditions, while also improving energy efficiency. It also offers opportunities for savings on utility bills, as demand-response programs have incentives that are favorable to owners and operators of such grid-interactive systems.

On-Site Battery Energy Storage

Should the designer decide against a generator, they could design a system that uses battery storage only (Figure 4(3)). In this case, the battery should have a capacity of 300 kWh to account for charging and discharging efficiency. With that capacity, the building could sustain a 4-hour outage, then use electricity from the grid to recharge the batteries after the outage. On average in the United States, the electricity from the grid used to recharge the battery has equivalent CO_2 emissions of 0.818 lbs/kWh, which is lower than the above solutions based on low-power fossil fuel generation. With the same strategy as in the scenario above, a 300-kWh battery can be used the rest of the year to shave up to 25 kW off the peak building demand or to participate in demand response programs. A challenge inwith this system is that there is risk in using the battery with demand response programs while maintaining the ability to meet the needs of an unexpected power outage. The generator provides this assurance, even if it is rarely, if ever, used. Its value is allowing the battery to be fully available for demand management.

Solar Photovoltaics

Building on the previous solution for energy storage, we demonstrate additional configurations that include PV panels (Figure 4 (4)). In the first configuration, we modeled 25 kW of PV panels to the 300 -kWh BESS system described in the previous section. In this case, the system could sustain the building during a 4-hour event, but also generate 43,415 kWh of electricity annually. Additionally, if this system were used for demand shaving the rest of the year, it could help shave as much as 42 kW off the building's peak demand.

The second configuration considers a smaller battery that has been downsized to account for PV production. The same 25-kW PV array would allow downsizing the battery to 90 kWh instead of 300 kWh, which represents a major reduction in costs. In this case, due to the smaller battery, the system's demand shaving capability is reduced from 42 kW to 27 kW.

Finally, we assume that the PV system is not limited to 25 kW, but to the maximum that the building could sustain given the available surface and power transmission limitations. We simulate the same battery as above, with 90 kWh of capacity and a 100-kW PV system. In that case, the demand could be shaved by 37 kW, and the PV array could produce 173,660 kWh each year.

Energy Efficiency

Designing efficient power systems can render the building more resilient and its energy source cleaner while providing advantages all year long. A complementary approach is to improve the energy efficiency of a building by implementing passive energy efficiency measures.

We simulated the same power systems as those described above on a version of the same building model that had received an energy retrofit. Energy efficiency measures included improving the envelope and roof's thermal performance, reducing the nighttime lights and equipment schedules, and including better lighting and equipment efficiencies. Combining these measures resulted in an energy use reduction of 21% and a peak demand reduction of 24%. **Error! Reference source not found.** shows how power demand and energy use change when energy efficiency measures are implemented. This example uses simulated data from the DOE prototype retail standalone building.

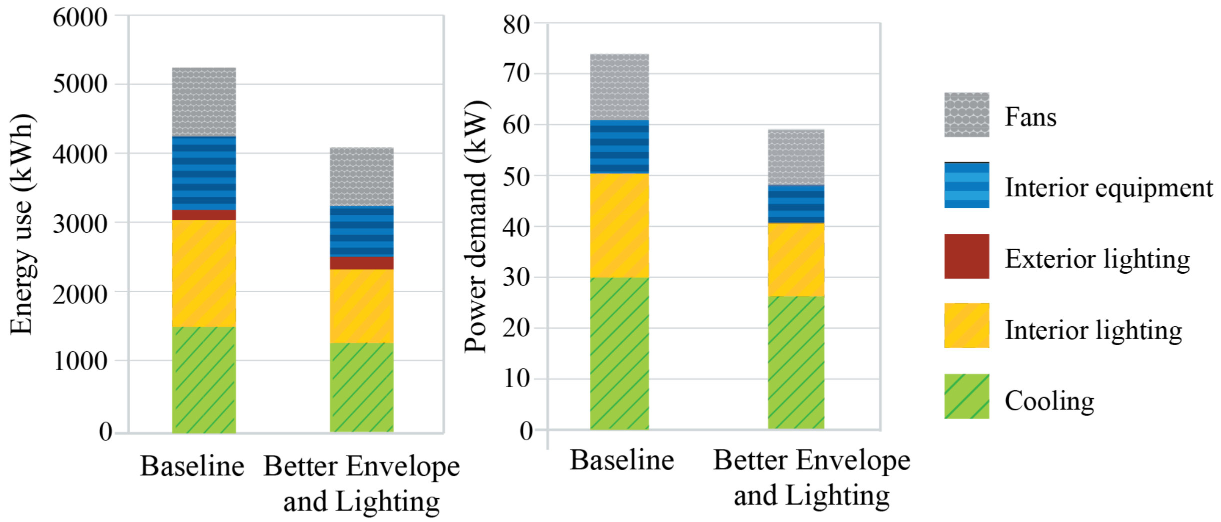

Figure 5. Energy use and power demand are reduced when energy efficiency measures are applied. Here, energy use decreases by 21% (left), while peak power demand decreases by 24% (right).

Naturally, this reduction in energy use and power demand results in the downsizing of most of the systems described above:

- The generator alone can be downsized from 80 kW to 55 kW.
- The generator and battery combination can be downsized from 55-kW to 42-kW rating and from 50-kWh to 45-kWh capacity, respectively, with the same performance and demand response capabilities.
- The system based only on BESS can be downsized from 300-kWh to 240-kWh capacity with the same performance.

In the 25-kW and 100-kW PV systems, the BESS can be downsized from 90- to 50-kWh capacity with the same performance.

Figure 6 shows the average emissions for all the system configurations presented in this example.

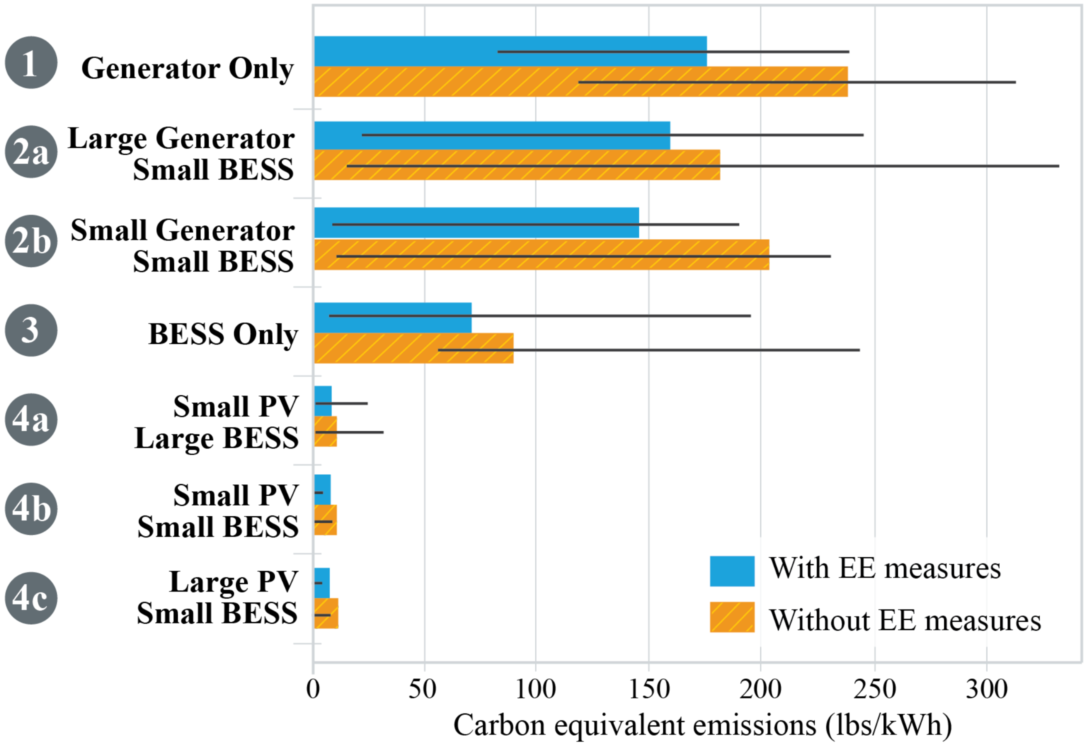

Figure 6. Average emissions for different system configurations. Error bars show the lowest and highest levels of emissions during a typical meteorological year.

Conclusion

This study uses simulation to illustrate the various opportunities offered by new technologies to either retrofit or redesign resilient energy systems with lower carbon emissions. These recommendations are based on modeling assumptions such as simplified battery dynamics, typical meteorological conditions, and fixed building schedules. Backup generation systems make a building more resilient. By combining a traditional generator systems with batteries, on-site renewables, and efficiency, energy and emissions can be reduced with or without the utility grid. They should be an integral part of building system design, both for retrofits and new construction.

For this work, we used a standalone retail prototype building in Seattle, Washington, to explore various solutions for buildingfor the building's resiliency during a power outage. Although on-site power generation using fossil fuel, like diesel generators, is a simple solution, its reliability can suffer if measures are not taken to ensure that the right operating conditions are met. This test case has shown how improvements such as battery energy storage can mitigate this weakness while reducing carbon emissions.

The greatest benefits, however, are achieved when on-site power is provided by BESS or PV power generation, or, especially, both. Emissions for these systems come mostly from purchased electricity from the grid and are lower than those from on-site fossil fuel power generation. When these systems are not being actively used in an emergency, they can enable energy cost savings and revenue opportunities. The only caveat is that using these systems regularly for generating revenue means that the power needed during a grid failure might not be entirely available, as the BESS might not always be kept at 100% charge. Designers can factor this consideration into the process of specifying the components for their system.

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