New Indices for Sustainability in the Face of Climate Change

David B. Goldstein, Natural Resources Defense Council
Theresa Weston, The Holt Weston Consultancy, LLC

ABSTRACT

Sustainability has many aspects, one of which is a building's ability to remain habitable or usable for hours to weeks or months during an interruption in energy. The interruption may be due to extreme weather events, including high winds, severe tropical or winter storms and ice storms, or even be part of a wildfire prevention plan. An aging and under-invested electrical grid is more vulnerable to unpredictable and severe weather. Climate-change-related disruptions over the last 5 years have shown the importance of this aspect of sustainability: hurricanes, wildfires, high summer temperatures, and low winter temperatures have all disrupted energy systems for diverse reasons.

This paper suggests metrics of resilience that can characterize a building's ability to remain comfortable or habitable even during once-in-100-year conditions. One of these metrics assumes that no mechanical/electrical systems are available, while others assume small amounts of on-site solar power generation and storage. Other possible metrics include the ability to address temporary but persistent outdoor air quality problems. These metrics may be usable in building codes, in above-code programs or as part of specifications that can guide building owners, tenants, and insurers to make better decisions. These metrics may be especially important in addressing the design of buildings for vulnerable populations, such as the elderly or disabled. The paper shows how better resilience performance overlaps constructively with mitigation of climate emissions.

Introduction

We define sustainability, following common practice, as "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (UN Secretary General, 1987). Sustainability is increasingly being considered in relation to resilience, because of the increase in extreme weather events due to climate change. Resilience, in turn has been defined as "the ability to reduce the magnitude and/or duration of disruptive events" (NIAC 2009).

Sustainability and resilience have many aspects. This paper focuses primarily on one: the ability of a building to remain habitable or usable for hours to weeks during an interruption in energy supply. Power outages are often secondary effects of extreme weather events or natural disasters, or war, including high wind events, severe tropical or winter storms and ice storms, tornados, or earthquakes (Massachusetts Emergency Management Agency 2010). Power outages may result from load shedding due to extreme heat or cold, or from an accident, such as the Fukushima nuclear disaster of 2011. Additionally, power disruption may be a part of a wildfire prevention plan.

This paper will discuss a key component of resilience that we define as survivability. It discusses two forms of survivability. Passive survivability has been defined as "the ability of a building to maintain critical life-support conditions for its occupants if services such as power, heating fuel, or water are lost for an extended period"(Wilson, 2005). We focus first on passive survivability, which we consider as the ability to assure health and safety without any energy inputs at all, and then on “active survivability,” which we define as the ability to stay adequately operational based on onsite or local renewable energy coupled with some level of onsite battery storage. The connection between sustainability and passive survivability is evidenced by the development of a LEED pilot credit on “Passive Survivability and Back-up Power During Disruptions" (USGBC 2019) and in the RELi Guideline Hazard Mitigation & Adaptation Requirements (USGBC 2018).

We begin the discussion by defining to what conditions a building might need to be resilient, and how they might be defined such that standards can be developed to measure success. We then develop trial metrics for what such standards might require in terms of their scores on such metrics.

The paper then discusses synergies between measures that will improve survivability while also reducing greenhouse gas emissions, particularly those associated with energy consumption. We find that many important technical and operational measures to decarbonize buildings also help improve the sustainability metrics. But some emissions reduction measures that are not widely accepted due to their marginal economics (comparing emissions reductions to measure costs) become more economically attractive when valued for sustainability.

Metrics for Sustainability

Data from the U. S. National Oceanic and Atmospheric Administration show increasing frequency of billion-dollar disaster events over the last 5 to 10 years (NOAA 2022). Moreover, the world has seen an increasing number of extreme weather events over the last two or three decades, and climate science predicts that these will become more frequent and extreme depending on the degree of climate change (IPCC 2018). But even after global society achieves a stabilization of greenhouse gas concentrations in the atmosphere, extreme weather events will get worse for decades due to time lags in the global climate system.

Thus, it makes sense to define the types of weather events that we can try to be resilient against and then evaluate metrics of sustainability that increase this resilience. This list should be as broad as possible because it is likely that we will fail to list some events since we have not yet seen anything like them. Some of the events we need to become resilient against include:

- Short or mid-term events of extreme heat (a few days to a few months)
- Short events of extreme cold (typically a few days)
- Wildfires that both threaten thousands of buildings through fire risk as well as millions more buildings through the generation of persistently high levels of air pollutants that harm human health
- High winds that cause damage to utility infrastructure that may cause power outages that last for a few days to a few months
- Extremes of rainfall and consequent flooding or water shortages

This paper prioritizes the first four of these metrics, as the literature and practice on energy efficiency allows us to make faster progress on establishing the metrics and standards and installing the measures or establishing the procedures that will improve survivability performance. First, we hypothesize what some of the direct and indirect temperature-related metrics could be.

Temperature Metrics

Extremes in outdoor temperatures have led to significant excess deaths throughout the world over the last two decades. Heat spells in Europe, India, and in the U.S. Pacific Northwest, with temperatures 10 C above regional normal hot weather episodes, led to hundreds and even tens of thousands of excess deaths, to say nothing about discomfort and loss of productivity, due to overheated buildings (Lu and Cox 2021; Popovich and Choi-Schagrin 2021). Cold snaps and storms have also led to deaths when they result in disruptions to energy supply such that buildings can no longer be kept warm. In some cases, buildings became so cold that the water pipes froze, adding an economic loss to the health losses. One example was the series of winter storms and cold snap in Texas in February 2021, which was estimated to have resulted in 700 deaths (Aldous, Lee, and Hirji 2022).

But efficient buildings can greatly reduce the degree of discomfort. Better insulation in conjunction with improved air sealing reduces heat gains and losses, and, coupled with the thermal mass already in the building, potentially enhanced by additional mass provided to improve temperature stability, allows the building to take much longer to overheat or overcool (Goldstein 1978; Urban Green Council 2014; White and Graham 2012). In the case of cooling, increasing ventilation (naturally or mechanically) when the temperatures are relatively milder compared to the rest of the day can produce average interior temperatures below the average ambient temperature. In the case of heating, solar radiation through windows will produce a thermal balance in which the average indoor temperature is warmer than the average outdoor temperature on average over a day. With sufficient insulation, even the body heat of the occupants and their pets can provide significant increases in indoor temperatures.

These simple observations suggest that a good sustainability metric would measure the ability of a house to stay within safe temperature limits for a period of days or weeks without external power or fuel. Most calculations of indoor temperature assume that the variable of interest is air temperature. But comfort depends more heavily on mean radiant temperature, which is more comfortable when insulation levels are higher. The best measures of comfort under these conditions may not be air temperature alone.

The metric could be *the highest and lowest temperature that the building would experience when modeled in response to extreme weathe*r *compared to the temperatures at which humans can survive or maintain adequate levels of comfort.*

What type of weather would be used to model these extremes, and how long would the simulation be for? A readily available approximation would be to use a full year of typical weather and to take the very hottest and coldest indoor temperature that the model predicts at any hour of the year. From the building science perspective, this metric can be derived repeatably for any building, using standard inputs that are already part of the energy modeling infrastructure used for energy code compliance, such as EnergyPlus™

From a policy perspective, the metric creates several sources of error. The first error is that an extreme weather event in a changed climate is unpredictable, but certainly more extreme than anything that can be simulated based on data. This error underestimates the discomfort of the most extreme hours. The second error is that health and comfort problems that only last an hour or two are not as serious as those that last all day or for several days. Looking at the worst hour is a much more stringent requirement than looking that the worst 0.5 percentile hour, and also less arbitrary. A question to ask is, do we want the worst .5 percentile, which happens about 40 hours of the year, or the worst 0.1 percentile, or a even lower percentile?

The reason to select a full year for the metric is this: the time that a crisis will occur is unpredictable, as is the length of the crisis. Rather than selecting an arbitrary choice for times of onset and duration, standardizing on a year means that the outcome is invariant as to starting date and also to the length of time of the crisis.

There are several possible variants of this metric. The broad distinction between them is whether they refer to *passive survivability*—the resilience to lack of power and fuel entirely, or *active survivability*—the resilience to lack of *external* power supply from off-site fuels (meaning the ability to continue to use on-site generation with or without storage). The discussion below will illustrate why the concept of active survivability better fulfills the high-level goals of resilience of buildings in the face of disasters.

Within the class of passive survivability, to what extent should active energy management by occupants be considered, and how should it be modeled? Important management activities include opening windows in summer when outdoor temperatures drop sufficiently and managing draperies or electrically controlled window transmissivity (assuming this can be done with stored electricity) to admit or exclude the desired amount of solar radiation.

The concept of active survivability has not been addressed much in the literature; however, it can be important in the context of renewable-energy-based grid that relies on demand flexibility and storage. Demand flexibility will work more optimally if demand can automatically be delayed or advanced in time based on real-time grid conditions. Once major end uses are automatically controlled, whether by a building specific energy management information system (EMIS) or through the Internet, these controls can be programmed to respond to a weather-induced constraint. Uses of energy would have to be prioritized by the occupants or owners in terms of importance and energy consumption for each end use.

Determining load criticality, along with the percentage of the total building load that needs to be served, is a key step. For example, a user might prioritize the use of power for computers and modems first, refrigeration and fresh air ventilation next, and space conditioning near the bottom of the list. In the case where occupants are elderly or chronically ill, medical equipment such as oxygen concentrators and refrigeration of medicines (e.g., insulin requires refrigeration) would likely be prioritized. The energy consumption and its timing could be balanced against the amount of stored electricity, fuel, or thermal energy, and the predicted change over the next day or week. If there is renewable energy and energy storage systems connected to the building or its microgrid, then the building could be modeled as self-sufficient for longer periods of time, when compared to a conventional system, by using the same sustainability metric as suggested above (e.g., the extreme temperatures in a typical year with additional modifications to describe what end uses would be powered, and to what extent, during the test year). Note that the extreme temperatures could be moderated by using the triage algorithms for the use of mechanical space conditioning under worst-case conditions.

For example, the controls could be configured to allow temperatures to float down to ~10 C indoors, but no further, or to allow one shower per person per week with an emergency 0.5 gallons per minute (1.9 liters per minute) showerhead. Water systems may need to be designed to operate without energy, through passive measures such as gravity fed systems, assuming water is able to be treated and is potable.

Both active and passive indices have broader applicability than solely for conditions where power is unavailable due to extreme weather directly. Increasingly, many utility grids have to shut down in areas prone to wildfires where power lines have been implicated in starting fires. These shutdowns have lasted for days at a time in some places. While utilities have been able to target areas within their service territory that are shut off more finely over time, we also know that the risk of wildfires will increase due to climate change. Some grids have remained nonfunctional for many months following hurricanes or other natural disasters, such as in Puerto Rico following hurricanes Irma and Maria. This observation supports our hypothesis that full-year simulation is the best metric compared to selected shorter periods.

Calculating the Metrics

Energy simulation models were developed with the purpose of predicting thermal energy needs for maintaining a constant temperature indoors. Solving the equations for heat flow in this manner produces results that differ from those obtained when the indoor temperature (and therefore the temperature profile of the envelope materials) varies over time. In particular, the effectiveness of thermal mass is higher. These issues have been addressed in the current versions of the U.S. Department of Energy's EnergyPlus™ software. One study has used the WUFI® Passive Simulation engine to model 5-day blackouts in both winter and summer conditions (White 2019), but it may still need to be determined the simulation tool characteristics which are sufficient to accurately determine meaningful metrics.

Broader Comfort and Health Metrics

Discussions of thermal stress begin with the issue of sensible heat and are measured by looking at temperatures, ideally both radiant temperature and air temperature but more commonly, air temperature only (For very efficient/sustainable buildings, the difference between these parameters' values is inconsequential.). Human comfort also depends on humidity. Particularly at the upper end of the range of relative humidity, the sustainability metrics will have to consider avoiding excessive humidity when the building is unconditioned during a survivability period. This concern is amplified when one considers the health impacts of mold, which could become established during a period of high heat and humidity when no power is available, especially if the power outage has resulted from a storm or flooding event. If mold turns out to be a big problem in some climates, it suggests a strong value to active survivability in which dehumidification is one of the high priority uses of energy.

A similar issue arises with ventilation: higher levels of indoor air quality increasingly are related to mechanical ventilation becoming a priority energy use. This problem becomes more significant as we tighten the building against air leakage, which helps significantly with resilience to temperature extremes, especially in cold climates. A building that remains thermally comfortable for two weeks without power is not adequate if the air quality degenerates, for example, if the fans cannot operate.

Indoor air quality is also affected by wildfires. In September 2020, much of Oregon and Northern California were subject to the worst air quality in the world for over two weeks: levels of PM 2.5 between 300 and 600 affecting tens of millions of people. Buildings were not designed to act as HEPA filters on the infiltration of polluted air and are unreliable for this purpose. A sustainable building would have to provide healthy indoor air, provided by balanced ventilation and the use of an appropriately fine filter. The filter might not be utilized during normal weather, but rather as a component of active survivability.

Another parameter of interest is lighting. For residential buildings, adequate lighting during the daytime is not an issue: most homes hardly use artificial lighting during the day and portable lanterns which are battery powered can be used in the evening. But commercial buildings often have significant spaces that are not designed for daylighting, and lighting during the day is a major source of energy consumption. This is fatal for the concept of passive survivability and makes the achievement of active survivability more difficult.

Lighting would also need to be a part of an active survivability metric, as the intensity of light would need to be part of the test procedure, much as temperature limits are part of the thermal metric. Unlike thermal requirements, however, which can be defined quantitatively by human physiological needs, lighting intensities for commercial buildings are based on an attempt to optimize productivity. The amount of light needed for basic performance of tasks, especially when visual tasks are dominated by screen viewing, is at least an order of magnitude lower--significantly below the generally selected levels of 200-750 lux. However, there are few standards to suggest what an appropriate level of emergency lighting for a passively survivable building should be. The LEED Pilot credit references “a minimum of three (3) foot candles (32 lux) in all building spaces to define a path of egress but this may be as much a consequence of maintain an appropriate contrast level between daylight normal artificial light as an absolute requirement for safe visual quality. At any rate it is an order of magnitude below normal lighting practice with full access to power (USGBC 2019).

Regardless of what lighting intensity is chosen, a survivable building would allow the potential of dimming by an order of magnitude or more to respond to an emergency event. This is not hard to do, as California's Title 24 energy code already requires dimming controls that can reduce lighting levels to 10 percent of full-on illumination, which results in nearly 90% reduction in electricity needs.

Another part of sustainability in a crisis is access to potable water or at least grey water. It would be hard to call a building in which the toilets no longer work (or only work for a few days) survivable. Water use for low-rise buildings that are on municipal water supply, would likely not be an issue unless the municipal water supply is affected by the power outage. However, water supply that rely on power for pumping from a well or for supplying higher floors with water would need to prioritize the power for water pumping. This provides another reason why active survivability is an important concept. Some green buildings collect rainwater for this use; however, this would only provide for a finite period of usability for climates that can go for months without rain.

Integration with Resilience Mitigation

State and local jurisdictions are adopting resilience planning which focuses on mitigating the effect of future extreme weather events. These plans are responsive to the local extreme weather events. Infrastructure improvement to manage flooding is prioritized in areas where high intensity rainfall or the overwhelming of stormwater management systems is expected. The adoption of the most current building codes, including energy codes, has been shown to be an important aspect of achieving resilience (ICC 2019). Metrics to assess the passive and/or active survivability could be used by jurisdictions to assess their building portfolio for determination of community resilience.

Synergies with Decarbonization

Decarbonization can be achieved by increasing energy efficiency, which has been the major thrust of energy/environmental policy worldwide for some 50 years. It can also be achieved by switching to energy sources that involve lower CO2 emissions than those currently in use, and by adding solar panels or other renewable energy sources to the building or its site. It can also be accomplished by changing the time of use of energy.

The graph below shows how clean or dirty electricity is–depending on the month of the year (x axis) and time of day (y axis). It is for the California grid, which is one of the first to have incorporated high levels of renewable generation with requirements for more to come. Thus, it is typical of what most electric grids worldwide will look like in the future as the whole world turns to renewables to meet climate goals.

It shows considerable variation today and much more intense variation along the same pattern for 2030. Controlling demand so that it moves from the redder hours to the greener ones reduces carbon emission by taking advantage of abundant renewable energy during the green hours and avoiding electricity use in the red hours when more fossil fuels power the system.

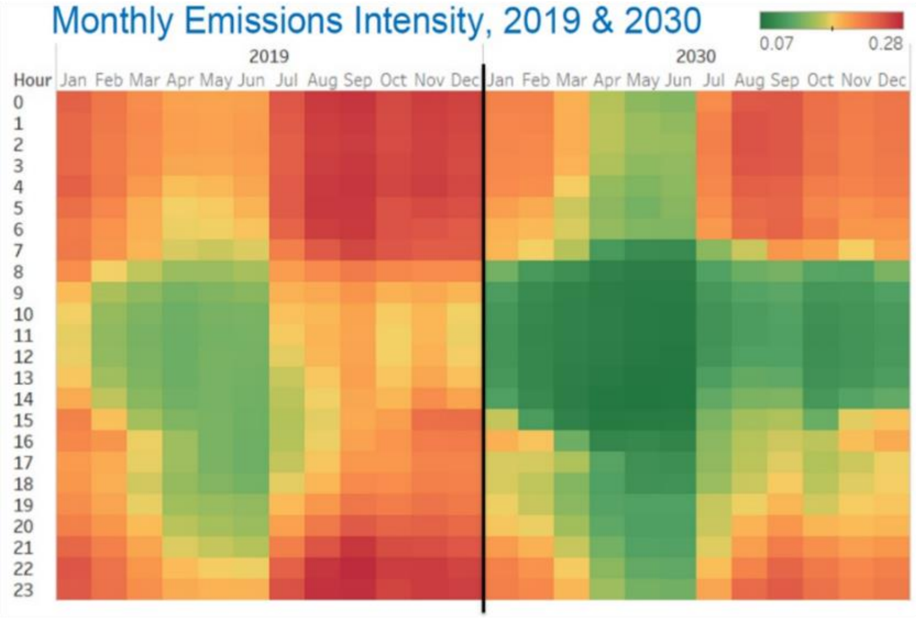

Figure 1: Average Hourly Grid Emissions Profile, Full Year; Source: Brook, M. 2018. *Building Decarbonization.* Docket 18-IEPR-09. Sacramento, CA: California Energy Commission.

As we take advantage of the increasing amount of renewable energy on the grid, we will see that heat pumps are an attractive decarbonization strategy, but that there is a consequence we must avoid: the potential to create new, or exacerbate existing, winter peaks in electric power consumption. The projected results for the New England region are presented below:

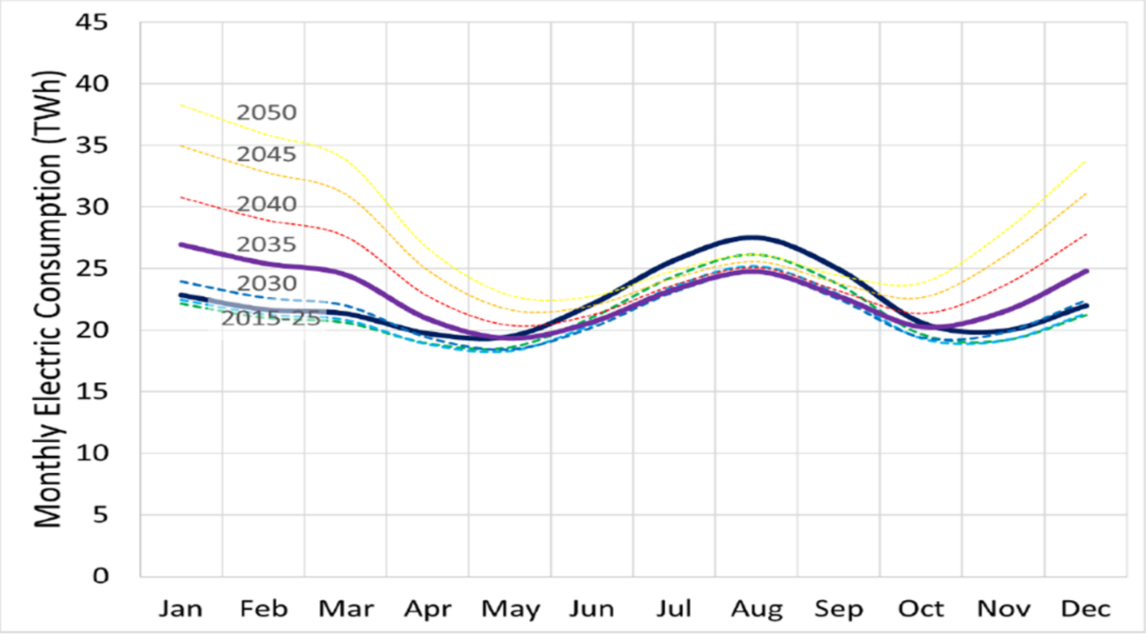

Figure 2: Northeastern Regional Assessment of Strategic Electrification. Source: NEEP 2017. https://neep.org/strategic-electrification-regional-assessment

The largest elements of the cost of electricity are the cost of transmission, distribution, and generation, all of which are sized to meet peak power demands. If we add electric equipment indiscriminately, we will risk adding to those costs. As an example of risks, high peak demands for gas power plants drove the Texas energy shortages of 2021 during Winter Storm Uri.

We can mitigate this growth in peak by increasing building survivability features, and by continuing to improve the engineering of heat pumps to boost their cold-weather performance. Thermal storage, in the shape of pre-heated water and spaces, can also help.

Developing a carbon metric that can evaluate these and other options is straightforward, and one carbon emissions calculation standard is already available, with other efforts underway. Current energy codes already rely on 8760-hour year computer models of energy consumption: it is a simple software exercise to multiply the energy consumption for each hour by an emissions factor to generate an estimate of annual carbon emissions. RESNET and ASHRAE are already working on this.

Typically, these models are used mainly for new construction, but climate goals are likely to expand their use for retrofits as well (Urbanek and Goldstein 2020). RESNET issued its first standard on how to calculate a carbon index based on time of use considerations in March 2022 (RESNET 2022) and expects to make steady incremental improvements through addenda that will be available for public review. The other piece of the solution is creating standard algorithms for crediting storage and demand controls. These are being developed in collaboration by RESNET and the California Energy Commission, and the first set of them should have completed public review late as of this paper's publication date in 2022.

Implementing both passive and active survivability will improve the sustainability of the building, although different types of control algorithms will be needed for the EMIS when the building is within the sustainability mode compared to the normal operational mode and optimizing for reduced emissions or low utility bills. Buildings that can shift the major loads—HVAC and water heating—will depend on improving insulation and thermal mass, which will also increase the level of passive sustainability, and the controls themselves can serve to improve passive sustainability even more.

Summary and Conclusions

There is a clear link between resilience and sustainability, especially when building energy use is considered. Improving the energy efficiency of buildings reduces those buildings' contribution to climate-change and climate-change-related extreme weather events. Improving the energy efficiency of buildings also improves the capability of building occupants to manage through power loss that result from extreme weather events. Developing metrics to evaluate passive and active survivability of buildings can aid communities in understanding and creating a holistic approach to resilience and sustainability. New metrics would include those that would maintain the indoor environmental conditions for safety and comfort, including temperature, ventilation and filtration for air quality and lighting. Additional metrics would maintain services necessary for health, hygiene, and accessibility, e.g., water supply, operation of necessary medical devices and elevator/lift operation.

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