
# The Future of Zero Energy Buildings: Produce, Respond, Regenerate

## Preprint

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*National Renewable Energy Laboratory*

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**The Future of Zero Energy Buildings: Produce, Respond, Regenerate**

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# ABSTRACT

The zero energy buildings concept is more than 20 years old, and the paradigm shift from buildings as energy consumers to buildings as energy producers is underway. Buildings also consume land and material resources, however, with additional environmental impacts. Another paradigm is emerging: a built environment that produces energy and is environmentally responsive and regenerative. This paper investigates an updated framework for thinking about zero energy buildings that includes discussions of prioritizing renewables; determining on-site versus off-site generation; exploring how and when buildings should use energy; and balancing renewables, storage, and energy efficiency.

Buildings are typically connected to the utility grid and the utility grid develops largely in response to the built environment. If more buildings' real time electricity use aligned with renewable generation, more renewables would be added to the grid. Ultimately, a key goal for zero energy buildings will be to use 100% renewables, 100% of the time, matching loads with energy storage and renewable generation at each discrete timestep over a year. This target is beyond the current zero energy definitions, which focus on an annual balance of renewable supply and energy demand and use the grid to "store" excess production to make up for hours without sufficient on-site renewable generation. This paper looks at simple metrics to evaluate the alignment of renewable sources and storage with building loads. This process can provide insights on building design considerations, including the use of flexible loads and optimal resource management and will improve with better data and analysis techniques.

# Background

Today's buildings are much more energy-efficient than those of 40 years ago, thanks to improvements in high performance heating, ventilating, and air-conditioning (HVAC) systems; lighting systems; and electrical equipment combined with tighter, better-insulated thermal envelopes with advanced glazing. Even though energy efficiency has improved, greater overall energy consumption reductions are needed as the number of buildings continues to increase.

In other words, the rate of deployment of energy efficiency and on-site renewable energy is being closely matched with addition of new conventional buildings (EIA 2020). The utility grid responds to the needs of the buildings adding and subtracting generation capacity and as buildings demand resources at different times of day—particularly in the late afternoon. This, largely driven by air-conditioning, has reduced the capacity factor of the grid over the last 50 years from 70 percent to near 40 percent—in other words, buildings produce higher peaks for shorter periods of time (EIA 2019).

Buildings have impacts beyond energy consumption. They use land and material resources for construction and ongoing maintenance and occupants use transportation, material, and food resources, all of which have a substantial impact.

The concept of a net-zero, zero-net, or zero energy (ZE) building that can fulfill its intended purpose without negative environmental impacts—and perhaps have a positive environmental impact—is compelling. Energy efficiency has its roots in the notion that using energy resources to power buildings has negative environmental impact. Energy has long been a surrogate for environmental impacts ranging from water and air quality, mercury and sulfur release, nuclear radiation and waste production, habitat destruction, and, more recently, carbon emissions ($CO_2e$). The idea is that if less energy is consumed, the environmental impact because of building operations can be reduced.

The thought experiment of imagining a building with no or minimal energy impact yielded the concept of a balance—extremely energy-efficient buildings could produce as much energy as they consume by adding on-site renewable energy sources, usually solar photovoltaics (PV). To validate this ZE concept at scale, Griffith et al. (2006, 2007, 2008) examined the entire commercial sector with a comprehensive energy model to determine which building types could achieve ZE and what levels of energy efficiency were needed to achieve that goal. The study found that the concept was technically feasible for significant portions of the commercial sector, including educational buildings. The study also determined that with moderate levels of efficiency, there are enough rooftops to power the built environment.

A framework emerged around the effort to define these ZE buildings and included the development of calculation methods, led by the U.S. Department of Energy, with the goal of achieving consistent and widespread industry adoption (DOE 2015; Torcellini et. al. 2006; Pless and Torcellini 2010; Torcellini et al. 2016; Peterson et al. 2016). This common version 1.0 definition states that a ZE building is "An energy-efficient building where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy" (DOE 2015). This definition is not limited to buildings; it can also apply to campuses, communities, portfolios, or any other specified boundary as discussed further by Polly et al. (Polly 2016). In locations where on-site renewables installations are limited by utilities, policies, or economics, the building can be designed to be ZE Ready—that is, it is highly energy-efficient and ready to accept a solar system when circumstances allow. These definitions have been the foundation of the industry and are still very relevant as a vast majority of buildings are not zero—somewhere in the order of 2000 for commercial buildings and 22,000 for residential buildings (NBI 2019; TeamZero 2020).

The interest in very low energy buildings and ZE buildings is growing. For example, California adopted ZE targets for 50% of the floor area of existing state-owned buildings by 2025 and for all new or renovated state buildings beginning design after 2025 (SAM 2017). California has also set a target of making all new commercial buildings ZE by 2030 (CPUC 2011). Several other states are thinking along the same lines and have established task forces that are working on the issue. Much has been written about what ZE buildings are, and the idea of a measurable, achievable ZE goal is taking hold in the marketplace (Liu et al. 2017; Torcellini et al. 2016). The zero energy building concept is simple and easy to understand and the version 1.0 definition is valued across the high-performance buildings sector.

## Zero Energy Buildings Version 2.0

An end goal is to create buildings that are environmentally benign, which may require giving back such that a building's net operational impact is environmentally positive. This regenerative state represents buildings that can improve the environment rather than be neutral (sustainable) or cause resource depletion or environmental damage. This long-term goal has manifested itself in different goals and concepts over the last 40 years, including reducing the consumption of fossil fuels (for air and water pollution concerns as well as economic and energy security) to comfortable, healthy, high-performance buildings to climate change mitigation strategies, including carbon and refrigerants. More recently, DOE has expanded the understanding of Grid-interactive Efficient Buildings (GEB)[1] as an energy-efficient building that uses smart technologies and on-site distributed energy resources to provide demand flexibility while co-optimizing for energy cost, grid services, and occupant needs and preferences in a continuous and integrated way.[2] The GEB initiative focuses on buildings becoming smarter about the amount and timing of energy use, but ZEB 2.0 expands on these concepts and focuses on stakeholders that choose off-site and on-site renewable generation and shifting from ZEB 1.0 accounting that nets out over the course of a year to a goal that aligns available renewables with building loads during a full year, which can be simplified to:

*100% renewable energy, 100% of the time*

provided that the renewable resources do not create additional issues related to the environmental goals.

Although 100% renewable energy, 100% of the time is a difficult goal to achieve today, the process of achieving this goal provides the foundation for the next 20 years of ZE buildings, much like the current static balance definitions defined the last 20 years. Some organizations have expressed interest in this goal, including working through storage issues.[3]

ZEB 2.0 requires buildings to be designed and operated, and their equipment selected, so that a ZE building's demand profile closely matches renewable supply profiles. In other words, buildings should focus on demand side management, but also address when energy is consumed and not just how much energy is consumed. Note that in this ZEB 2.0 future, the goal is not for every building to be "off-grid." In this future, the grid would provide critical backup for individual buildings as well as a way for a building to back-feed renewables to offset the hours that the sun is not shining and the wind is not blowing, as well as providing additional grid services and utility cost reduction operations.

## Development of Effective Metrics, Boundaries, and Zero Energy Definitions

All building design decisions influence energy use and can have environmental impacts. Building design has a profound impact on how much energy a building requires to operate. The goals established and the metrics used to evaluate the progress toward a goal need to influence those that make decisions that impact the environmental outcomes. This is done with the span and control of all decision makers, which can be anyone who has interacted with a building project. This includes designers, occupants and building users, contractors, and building owners, at a minimum. Fundamentally, the creation of an energy definition (including a zero energy definition) has two parts—establishing a boundary and establishing energy metrics that are measured as they cross that boundary. Some rules include:

[1] https://www.energy.gov/eere/buildings/grid-interactive-efficient-buildings

[2] https://www.nrel.gov/docs/fy20osti/75478.pdf

[3] https://storage.googleapis.com/gweb-sustainability.appspot.com/pdf/24x7-carbon-free-energy-data-centers.pdf; https://www.pv-magazine.com/2019/01/04/off-grid-swedish-housing-block-to-be-supplied-100-by-pv-hydrogen/

- Energy flows of interest are measured as they cross the boundary. In general, these energy flows of interest are the commoditized energy sources such as electricity to and from the utility grid and fossil and other fuels delivered (such as wood chips). Energy at the point of delivery is a common energy metric that can be measured effectively with conventional metering technologies.
- Other metrics, such as $CO_2e$, source energy, and primary energy are calculated using methodologies based on the site energy measurements. These metrics are based on models relating site energy to that metric.
- Boundaries are most easily established at the point of metering. This is typically the utility electric meter, the gas meter, or the delivery point of fuels such as propane and oil. For the last two, the storage tank can represent an issue for the balance depending on its size and the variation of the level of the fuel in the tank, in which case an alternative is to measure the fuel leaving the tank.

ZEB 2.0 metrics should:

- Influence design decisions such that the building has the potential to move towards the metric of interest, such as "save as much energy as possible"
- Result in a well-designed building such that operators can more easily operate the building to its energy savings potential and understand how the ongoing operations align with the design metrics
- Move towards 100% renewables, 100% of the time.

Boundaries need to be well established as a measurement point of the metric. Although this paper will generically refer to the building as the boundary location, it can be described a number of ways, including:

- At the building site—typically at a point of metering
- A building portion that operates autonomously, e.g., a store within a retail strip mall
- A group of buildings that has logical interconnections and adjacency, in other words, a development district or a campus
- A community of buildings including subdivisions and neighborhoods
- Larger boundaries including towns, cities, and even states or utility balancing regions
- A portfolio of buildings owned by a single entity such as a chain retail store.

The boundary chosen is often a function of the "span and control" of the building or collection of buildings. A building owner or tenant may be interested in just their space while a larger corporation or governmental authority may have a corporate commitment to purchase renewables for all their buildings. All levels are critical to achieve scale. Metrics that struggle at a building level will face similar struggles at multibuilding scales. Solutions that do not work at a building level can benefit from multibuilding scales and the metrics must recognize this. Independent of the boundary selected, the measurement techniques and metrics are the same.

Many of these secondary metrics require models that change independently of what is happening in the building (both in design and operation). Care must be exercised in metrics when externalities can influence the ability to meet a metric over time. For example, if the calculation methodology changes or a boundary changes, then a building may fall in or out of "compliance" with no adverse action of the design team or the building operators. Examples might include changing the utility balancing regions for a carbon metric or changing from a fossil fuel equivalency to a captured energy equivalency for site to source calculations.

The first generation of energy flow diagrams for ZE buildings did not account for electric vehicles or storage within the building. Figure 1 shows the current accounting for energy flows. Although transportation within the boundary was considered—elevators, forklifts, etc.—the notion of a large number of electric vehicles was not considered. Vehicles used exclusively within the boundary should be considered a building load, and vehicles that can leave the boundary are external to the boundary. Note that there is a provision for charging and discharging electric vehicles as well as an indication of on-site fixed storage, which is inside the boundary, much like on-site transportation. After electric vehicles, buildings can interact with the "grid" through the electric utility, delivery of fuels (including natural gas and oil), and delivered renewable fuels including biogas and wood products. Electricity exported to the utility grid should be from a renewable energy source.

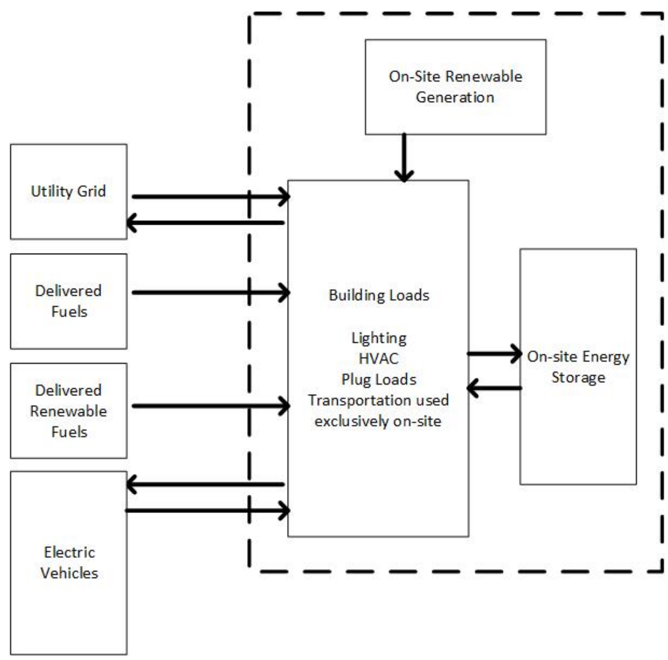


Figure 1. Energy flows across and within a boundary for an accounting system for a zero energy building.

Each energy flow can have an associated conversion ratio to alter the site energy to another metric. Historically these metrics have been source energy, $CO_2e$, and energy costs (Pless 2009; DOE 2015). Expressing the energy balance in Figure 1:

$$E_{net} = \sum_{i}^{n} \left[ \sum_{j=1}^{T/\Delta t} \left( E(t_j)_{del,i} r(t_j)_{del,i} \right) - \sum_{j=1}^{T/\Delta t} \left( E(t_j)_{export,i} r(t_j)_{export,i} \right) \right] \quad \text{Eq 1}$$

Where

$E_{net}$ is the net delivery of energy or another metric through the conversion ratio $r$.

$E(t_j)_{del,i}$ is the delivery of energy type $i$ at time step $j$

| | |
|---|---|
| $E(t_j)_{export,i}$ | is the export of renewable energy type *i* at time step *j* |
| $r(t_j)_{del,i}$ | is the delivered conversion ratio of energy type *i* at time step *j* |
| $r(t_j)_{export,i}$ | is the exported conversion ratio of renewable energy type *i* at time step *j* |
| $n$ | is the number of fuel sources that are measurable crossing the boundary. |

Table 1 compares the original concepts of ZE buildings as being strictly a balance of energy flows over a one-year period or longer. To align renewable resources with consumption, the renewable energy and storage must be valued as part of the consumption. Ironically, in a typical measurement of building energy, storage is often a drain on energy performance even though it will help align the renewable energy with the consumption. Version 1.0 represents the concepts of Pless (2010) where energy flows in and out of the boundary are not dependent on time or direction. Through application of this framework others have established time-fixed discount factors based whether is entering or leaving boundary and based on the proximity of the renewable resource to the building.[4] This accounts for direction through the utility meter and at a simplistic view can potentially represent the losses in the utility transformer and the distribution losses associated with moving the renewable energy to another consumer. To scale ZE for large markets and better align building energy consumption with renewable production, renewable energy must be valued at least at the building scale and, if data are available, at a grid scale. This provides the mechanism to measure whether a grid-connected building is 100% renewable, 100% of the time.

### *Evaluation Metrics*

ZEB 1.0 buildings represent the current state of the art. Although they are still a niche market, the values of r assume energy balance over a long period of time. There are three areas of focus in moving ZE to the mainstream: (1) ability to scale the concept; (2) ability to achieve 100% renewables, 100% of the time; and (3) ability to maintain a simple concept of balance to maintain market acceptance. Note that these metrics are not an overall evaluation tool to assess a building, but a framework to examine the ability to balance and align consumption to renewable generation. The metrics are foundational to balancing building energy and not determined by market factors. Voss (2010) examined several metrics and the alignment of renewable resources to match the load. Two metrics, solar use index and load coverage factor, are used in this paper to help describe the relationship of generation to consumption.

*Solar Use Index (SUI)*: Percentage of on-site solar energy that is used at the time of generation for direct use in the building.

$$SUI = \frac{\sum_{i=1}^{T/\Delta t} P_{i,osr}\Delta t}{\sum_{i=1}^{T/\Delta t} L(i)} \qquad \text{Eq 2}$$

or

[4] ASHRAE Standard 189.1 (https://www.ashrae.org/technical-resources/standards-and-guidelines/standards-addenda/addenda-to-standard-189-1-2017), LEED Zero (https://www.usgbc.org/programs/leed-zero) and International Living Future Institute (https://living-future.org/zero-energy/) have all looked at ways of valuing renewable resources based on location.

$$SUI = \frac{\sum_{i=1}^{T/\Delta t} P_{i,osr}\Delta t}{\sum_{i=1}^{T/\Delta t}(P_{i,import}\Delta t + P_{i,osr}\Delta t - P_{i,export}\Delta t)} \quad \text{Eq 3}$$

Where

$P_{i,osr}$= the power from the on-site renewables at time step $i$,

$P_{i,import}$= the power imported from outside the energy boundary at time step $i$,

$P_{i,export}$= the power exported from inside the energy boundary to outside at time step $i$,

$L$ = Energy Load for timestep $i$ or $L(i) = P_{i,import}\Delta t + P_{i,osr}\Delta t - P_{i,export}\Delta t$

$\Delta t$ = the length of time of the time step $i$.

$T$ = the total time of the evaluation.

Equation 3 is useful as most electronic utility meters integrate the power to energy by tracking the flow of the power, either receiving electricity from the grid ("buy") or sending electricity to the grid ("sell"). Equation 3 is easy to implement with monthly meter bills and the amount of renewable energy produced during the same period as the utility meter bills. A larger SUI indicates that on-site renewables are better used in the building versus exporting the excess. Low SUI, combined with net metering, indicates that the grid is being used as a virtual battery. A high SUI can also be achieved with small renewable systems indicating full use of the solar but will not meet the building's energy needs in the context of a ZE building. Therefore, the load coverage factor (LCF) is an effective metric to complement the SUI.

*Load Cover Factor (LCF):* Percentage of the building load that is powered by renewable energy.

$$LCF = \frac{\sum_{i=1}^{T/\Delta t} min\{[P_{i,osr}\Delta t], L(i)\}}{\sum_{i=1}^{T/\Delta t} L(i)} \quad \text{Eq 4}$$

This equation can be expanded to account for off-site renewable energy on the utility grid to:

$$LCF = \frac{\sum_{i=1}^{T/\Delta t} min\left\{\left[P_{i,osr}\Delta t + abs(L(i) - P_{i,osr}\Delta t)\left(\frac{\%RE_{Grid}(i)}{100}\right)\right], L(i)\right\}}{\sum_{i=1}^{T/\Delta t} L(i)} \quad \text{Eq 5}$$

Where:

$\%RE_{Grid}$ = Percent of energy from grid-supplied renewable energy

$T$ = Total Time Under Consideration

$\Delta t$ = Time Step

Table 1. Comparison of the development of zero energy definitions moving towards 100% renewables 100% of the time where r is a conversion ratio of the fuel source

| | ZEB 1.0<br>(limited market scale) | ZEB 2.0<br>(large market scale with the ability for full market adoption) |
|---|---|---|
| On-building renewable energy | *r*=constant<br>*r*=same for import and export<br>Classification A.[5]<br>A+ is no import, only export | *r(import)>r(export)*<br>Renewable energy valued if it can be used within the building at the time of generation. Building loads, including storage, can shift to use this resource.<br>Note that values of *r* can account for inefficiencies of transformer/distribution losses of selling and buying back power or provide benefits of a system level optimization on efficiency, dispatch, or other metrics such as emissions. In this case is it possible for *r(import)>r(export)*. |
| Renewable Resources not directly on a building or multiple buildings | Full credit to site (Classification B)<br>*r*=constant | *r(import)>r(export)*<br>Renewable energy valued if it can be used within the building at the time of generation. Building loads, including storage, can shift to use this resource.<br>Note that values of *r* can account for inefficiencies of transformer/distribution losses of selling and buying back power or provide benefits of a system level optimization on efficiency, dispatch, or other metrics such as emissions. In this case is it possible for *r(import)>r(export)* |
| Grid level renewable energy | Full credit to site (Classification D)<br>=constant | Remainder of building load can shift to use available renewable energy resource. *r* is time dependent based on grid renewable availability—numbers based on long term renewable energy profile for planning or real-time data for actual performance. |
| Electric vehicles | *r*=constant | Can provide additional load shifting capabilities based on the balance between the building needs and renewable availability. |

The LCF equations indicate the percentage of the load that is met by renewable energy, either on-site or off-site. High values of LCF indicate large contributions of renewable energy to meet the load and that the building load matches the renewable resources available. Note that while the optional %REGrid term brings in externalities not in the designer's control, it can enable better use of renewable grid resources encouraging designs to increase energy consumption when renewable energy is available shifting that load from times when renewable energy is not available. Energy efficiency is a key part of making a high load coverage factor possible. The concept of 100% renewables, 100% of the time equates to an LCF of 100%. For buildings that are exactly "zero" or for grid independent buildings, the two factors are identical. Although the SUI can use information readily available on utility bills and renewable consumption, the LCF requires that data in small time intervals in order to account for the branching of how renewables are used during that time period. In addition, both electricity imports and exports can apply to % RE from the Grid if a project is seeking to balance the impacts from both imports and exports.

A key component of the LCF metric and ZEB 2.0 is the consideration of hourly renewable energy contribution from the grid. To enable building designers to consider this

[5] Classifications are adapted from (Torcellini 2006 and Pless 2009)

contribution over the lifetime of the building, regional grid planning hourly multipliers are needed. One future source of projected renewable energy data is expected to be available through the NREL Cambium project. The Cambium project is aiming to produce grid price and emissions data sets through 2050 based on the NREL Standard Scenarios across each region of the U.S. power grid (Hale 2019). An alternative is to have a mechanism to guarantee the purchase of off-site renewable energy based on both quantity and time. As ZEB 2.0 projects are designed and built, measuring success towards the 100% renewables, 100% of the time goal will require alignment and measurement of the renewable energy on the utility grid or the ability to only export energy from the building, either to the grid or other resources such as electric vehicles. This last concept is consistent with the highest classification of ZE in earlier frameworks (Pless 2010). Emerging operational metric and evaluation systems such as GridOptimal[6] can provide approaches to consistently measure a building's progress toward ZEB 2.0.

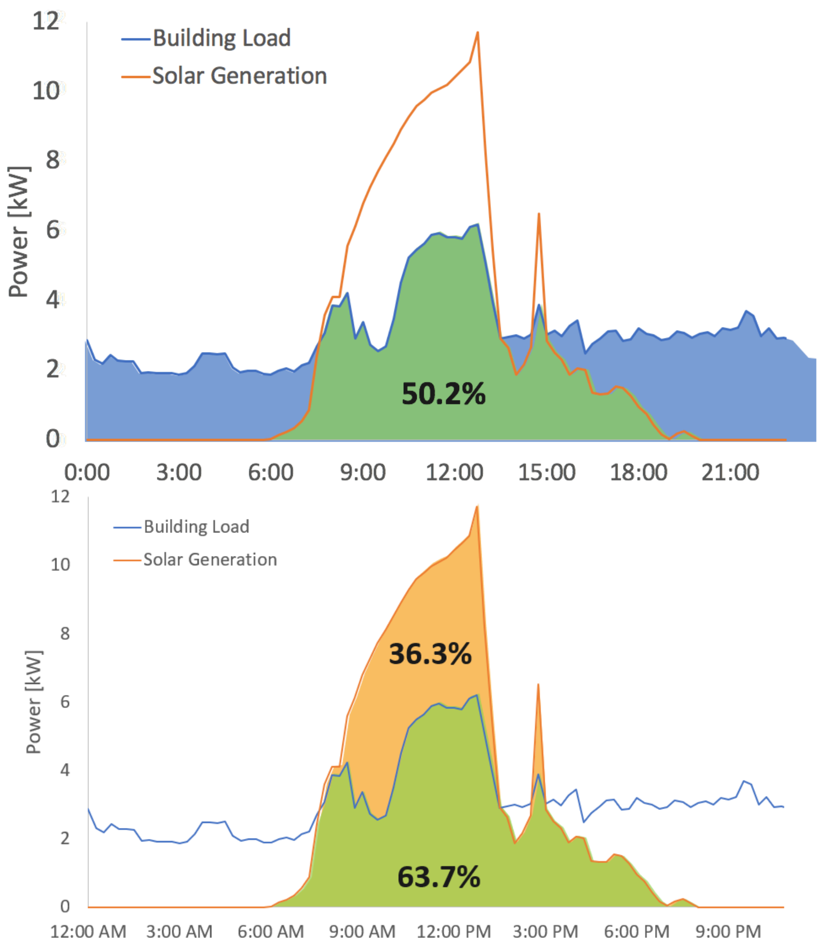


Figure 2. Example data for the load coverage factor (top) and the solar use index (bottom). (Figures created by Amanda Farthing, NREL)

### *Examples of Metrics Applied to Zero Energy*

[6] https://newbuildings.org/gridoptimal-metrics-offer-guidance-on-optimizing-building-grid-interaction/

Figure 2 shows a one-day example of the LCF and the SUI. The LCF focuses on the percentage of the load that is provided by solar while the SUI focuses on the percentage of solar energy that is used. In this one-day data set, 63.7% of the PV renewable energy is used in the building at the time of generation, the rest is exported to the grid, presumably to be purchased later through a net meter. During this day, only half the energy is produced by the renewable resource, indicating a poor alignment of the building load with the renewable resource.

Using data from a ZE house with a 9 kW PV array, Figure 3 shows the cumulative house consumption is shown as the blue line and the cumulative energy produced by the PV system is indicated by the orange line. The difference is either the net energy flow to the utility with the utility acting as a "virtual" battery for the net meter or, if the house was "off-grid," it would represent the home's storage requirement. In the past, this type of analysis has been used to size PV and battery systems for "off-grid" houses. For this all-electric house, the maximum delta seen by the utility is 2250 kWh. The amount of storage needed peaks on October 15, when the balance shifts from overproduction of the PV panels to the need to provide heat for the house coupled with less solar availability. As the lines do not cross, the storage is needed for the entire year due to the exact match of production and consumption. For this house, the SUI is 17% meaning that only 17% of the energy produced is used in the house at the moment it is generated. In other words, 83% of the power is exported to the grid and then purchased back at a later time. If the grid cannot accept the power or it has limited value, then additional storage may be warranted. The storage is 22.5% of the total energy consumption of the building for this example.

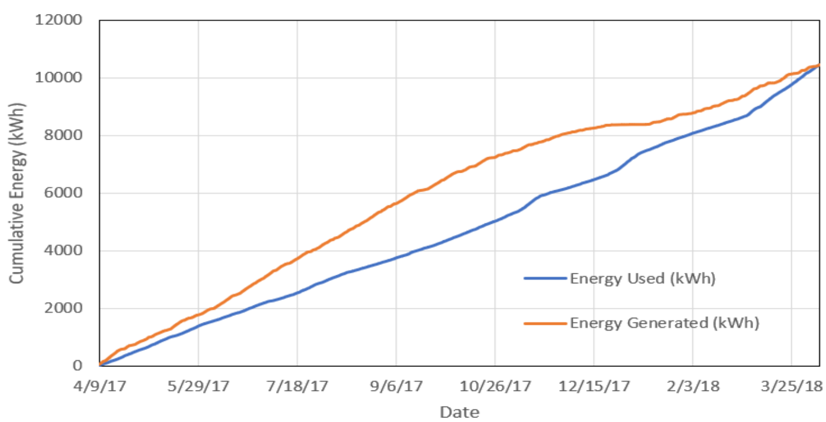


Figure 3. Energy used and energy generated for a zero energy house over a 1-year period cumulatively summed.

The LCF metric provides a different viewpoint of achieved success in ZEB 2.0 buildings. An example analysis outlined in Figure 4 illustrates the potential of using thermal energy storage (TES) to meet various end-use loads for various example building models. The building models have enough on-site solar PV generation to meet ZE requirements on an annual basis, and TES is used to move towards meeting loads 100% of the time. The TES model is based on a daily predictive method, where the anticipated evening/nighttime end-use energy is predicted, in addition to peak solar generation times during each day. The algorithm stores peak surplus solar power during the day and meets the corresponding end-use loads during insufficient or no solar production periods. The modeled TES ultimately maximizes the LCF metric.

One immediate observation from this example analysis is the relatively high potential for TES in aligning water heating loads with generation in the multifamily and single-family building types. In addition, the cumulative TES potential for increasing the LCF across the different building types varies and has the least impact on building types with inherently coincident temporal operations with solar generation, such as offices (~ 6% increase in on-site LCF) and malls (~6% increase in on-site LCF). In contrast, building types with higher occupancies during low or no solar generation periods typically exhibit a stronger potential, such as lodging (~20% increase in on-site LCF), food sales (~15% increase in on-site LCF), and multifamily (~12% increase in on-site LCF) buildings. A similar analysis can be performed to understand the technical potential and requirements for batteries to maximize the LCF metric. Figure 5 illustrates load duration curves of an example office building model with a battery and associated control scheme that stores any surplus on-site power and discharges the battery to meet the load. The battery model dedicates a portion of the total battery capacity towards load shifting (75%), and the remaining portion (25%) towards peak demand management. Transitioning from the baseline model to ZE V1.0 drastically reduces the peak import power (positive power values in Figure 5 indicate a power import) and introduces a high number of export power durations and amplitudes. Transitioning towards ZEB 2.0 by increasing battery size results in more hours of the year being balanced with on-site assets. Figure 5 demonstrates the nonlinear relationship between LCF and battery size, and the reduction in peak demand associated with ZE, TES, and increased battery size.

The influence of energy storage and load to renewable generation mismatch shows the issue that buildings, especially ZEB 1.0 buildings, have low SUI and LCF. ZEB 1.0 benefited from using the utility grid as an infinite storage mechanism to create a balance. The result is limitations on the ability to scale ZE buildings and increase renewable penetration. Tools exist today to move towards an alignment of loads. The typical utility meter has the ability to segregate total values for energy delivered and energy exported over a billing cycle. Although it is called a net meter, meters log imports and exports separately and a subtraction is done at the billing cycle. This provides a level of complexity in aggregating values that is transparent to the user of the metrics. It also provides an easy way to create incentives to better use on-site generation by changing the buy and sell rates (the value of $r$ in and out) to provide market drivers for design strategies that better align renewables with storage.

In addition, delivery of fuels also provides an energy value. A complexity arises with propane and oil as that energy is often stored in a tank, which acts as a storage element within the boundary. Either the assumption is made that the storage levels in the fuel tanks and battery storage are the same at the beginning and end of the period, or these need to be factored into the equation. Typically, battery storage has not been significant compared to the total throughput of energy and tanks are limited to buildings with significant oil tanks. Propane tanks typically are not as large and are insignificant to the total energy flows.

For electricity, the impact of storage is at the time that the storage is charged both on an energy and an emissions level. From this perspective, values of $r$ are dependent on the time a load occurs, including the storage elements. Charging storage when on-site renewable energy is available (reducing the export), the energy value and the emissions value is high. This high value energy can be used at a time when on-site energy is not available. The time of discharge is not needed in the accounting system. Today, renewables from buildings can be exported to the grid, although in some locations excess instantaneous renewable energy is not allowed, and this energy must be curtailed (lost) or stored. The idea of the next generation building is to reduce the dependence on the "net" at some boundary scale, which is probably larger than the building to maximize flexibility and diversity of the load. The LCF allows this to be measured. Ultimately, this is what building designers can control today as buildings are designed for the future.

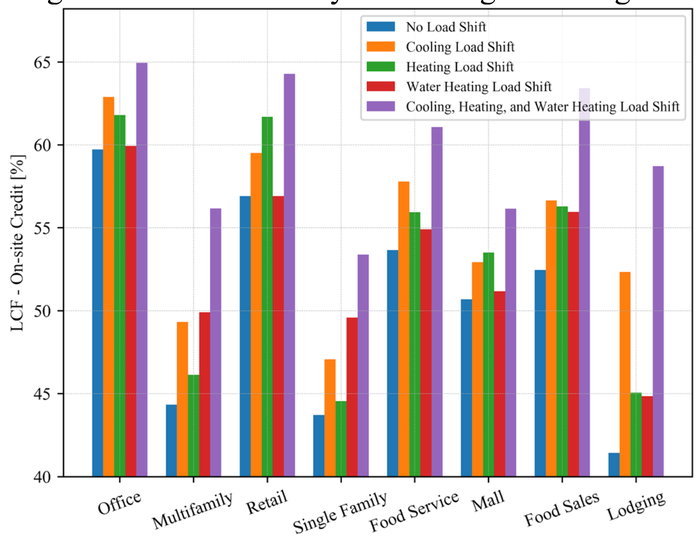


Figure 4: Example analysis of the calculated load cover factor metric as thermal storage is added to store excess solar power to meet cooling, heating, and water heating end uses (note LCF is displayed from 40 to 70 do visualize detailed differences)

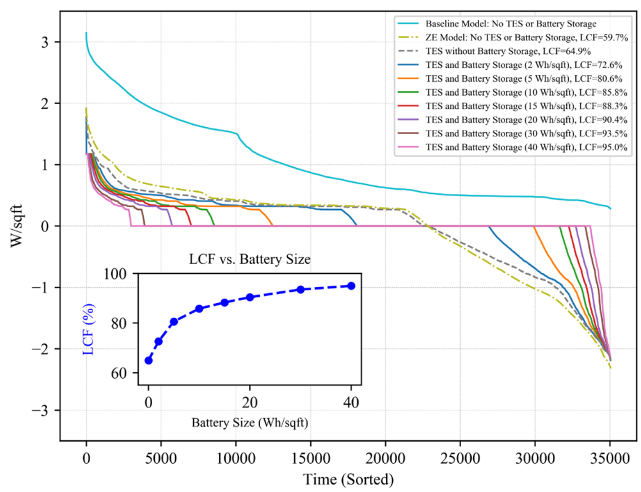


Figure 5. Net load duration curves (positive power indicates a power import) of an example office building model for the following cases: 1) Baseline model without on-site generation or storage 2) ZE office model without storage, 2) ZE office model with TES for heating, cooling, and water heating end uses, and 3) ZE model with both TES and battery storage of various sizes

## Conclusion

With the advent of inexpensive renewables and the ability to create very low energy buildings, ZE buildings are gaining market traction largely based on definitions that have been used for 10 to 20 years. These equations conceptually looked at balancing the renewable energy supply with the demand. Many of the current generation of ZE buildings have a large mismatch between the renewable generation and the building consumption, which limits the effectiveness of the balance. A key ZEB 2.0 goal is to create buildings that use 100% renewables, 100% of the time, which is a step beyond the current ZE metrics of site energy, source energy, or carbon. For market acceptance to persist and grow, ZE must be easy to measure. Successfully meeting the ZE goal must be dependent on the design and operational characteristics of the building. Although complexities can be introduced that attempt to evaluate the building with respect to the utility grid, simple metrics can address the need to evaluate the alignment of the renewable resource with the building. Two such metrics, renewable use index and load coverage factor, help address the need. As consistent hourly marginal and average grid site to source multipliers and off-site renewable energy accounting are developed for both operational use and long-term building design planning, ZEB 2.0 buildings can be designed and operated at scale and balance loads with both on-site and grid-scale renewables.

With technology advancement, cost reductions and innovative business model development, on-site and off-site advantages will continue to evolve. Stakeholders will pursue all renewable generation locations that fit their needs. This paper is focused on circumstances where stakeholders mainly have a preference for on-site scenarios, because of various reasons, such as improving resilience. It also provides methods for recognizing off-site renewable contributions. At minimum, it is important to consider on-site scenarios for establishing aggressive, but achievable building performance goals based on local renewable potentials.

Ultimately long-term market signals that are stable and trustworthy will make investments in ZE buildings a reality. Using this framework, we can use the built environment to regenerate and transition buildings from consumers to producers that can respond to available renewable resources.

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