ARCHITECT'S GUIDE TO

Ultra-Low-Energy Buildings, Microgrids, & Direct Current

Lisa White, MSc, CPHC®
Walter Grondzik, PE

phius

30 June 2023
Developed by Phius with funding provided by the AIA Upjohn Research Initiative grant

TABLE OF CONTENTS

ACKNOWLEDGMENTS

This Guide was developed by Phius[43] under the auspices of an AIA Upjohn Research Initiative grant. The team conducted research into the grid interactions of buildings designed for high performance and reduced environmental impacts and developed an Architect's Guide to cover the coordination of high-performance buildings with microgrids. An overarching consideration of this Guide is to support the design of building groupings that can deliver owner and societal benefits greater than possible from individual buildings.

From the AIA Upjohn grant announcement[44]:

Synergies between Ultra-Low-Energy Buildings, Microgrids, and Direct Current

This study will assess the feasibility and performance benefits of linking passive building design guidelines with a city-block microgrid, simulated in Milwaukee and composed of 20-30 residential buildings. It will develop an architect's guide to analyzing and designing such blocks to manifest a resilient, low-emissions future. The goal of this project is to create a template for architects and other design professionals to incorporate both passive building strategies and microgrid design strategies into their projects to achieve optimal carbon performance.

Architect's Guide to Ultra-Low-Energy Buildings, Microgrids, & Direct Current

EXECUTIVE SUMMARY

This Guide was prepared to assist architects (and other building professionals) in navigating rapidly emerging design issues associated with decarbonization (with its companion: electrification) and resilience. Decarbonization and resilience are larger than the buildings sector–but buildings are a big player in society's efforts to accomplish both objectives. It is reasonable to state that buildings will be a powerful tool in our collective efforts to decarbonize the way we live on planet Earth. At the same time, more clients are asking that their buildings provide respite from natural and human-made incidents that would historically have made buildings unproductive and/or uninhabitable. If buildings are to be both a tool and a solution, then architects must be actively involved.

This Guide is aimed mainly at smaller-scale residential buildings but many of the concepts expand to all buildings. Specific recommendations presented herein are based upon research conducted via numerous case studies (see the associated Case Study Report) focused on a typical existing neighborhood in Milwaukee, Wisconsin. A recurring theme in these case studies is the effect of building enclosure stringency (acting as a surrogate for overall building energy efficiency) on the ability to effectively reach decarbonization and resiliency goals. A key takeaway from this research is that building enclosure is a critical first step in decarbonization and resiliency. Ultra-low-energy buildings greatly facilitate reducing carbon emissions from building operations and greatly improve the opportunity for resilience of the building electrical system and connected devices.

Two other key themes explored in this research, and discussed in this Guide, are microgrids and direct current (DC) power. Microgrids allow us to deal with big problems collectively rather than individually. There appears to be a goldilocks scale for power systems that is smaller than existing macrogrids yet larger than individual building nanogrids. Microgrids are discussed in this Guide and explored in the associated case studies. Buildings are becoming hotbeds for DC devices and equipment. The most commonly distributed renewable resource, solar PV, produces DC power. Therefore, possibilities for synergies between DERs (distributed energy resources) and DC building loads curated through microgrids are considered in this Guide and the case studies.

Read this Guide for an introduction to ultra-low-energy buildings, microgrids, and direct current. Read the Case Study Report in this document for detailed information on how these building design tools interact with each other and with other design variables (such as electric tariffs, batteries, electric vehicle charging, smart controls) on the road to resilience and reduced emissions.

1. INTRODUCTION

1.1 A Brief History of the Grid

Electrical grids have been a part of daily life for urban North Americans for over 100 years. Rural electrification efforts extended the scope of these grids to most homes about 50 years ago. When electrical grids work as intended, they are fundamental support systems that reside in the background of our regular routines. When they fail (as they occasionally do) they can become headline news or the cause of local inconvenience and economic loss—because so many of our daily activities revolve around access to dependable and affordable electric power.

Electric power is a recent addition to humankind's energy arsenal. The first commercial electric grid in North America was established in 1882 in New York City and was supplied by electricity generated by steam-powered generators located in the Pearl Street Station. This first grid, Figure 1, served around 90 customers and provided them with 110 V DC (direct current) power[1]. How things have changed.

Today, essentially all residents in the US (except in very remote locations) have access to grid-based electricity,and rely on it to carry out almost all day-to-day tasks. The 90 customers in a small part of Manhattan have grown to 140 million customers nationwide served by 1600 utility companies organized into 3 mega-grids and overlapping coordinating grids (as shown in Figure 2)[2]. As a result of the monopoly status granted to electric utilities during the early days of electrification, the "grid" is expected to provide all customers with dependable electricity 24/7/365. This is a formidable challenge that involves the orchestrating of diverse power generation resources, tracking and forecasting of consumption, and brokering of power exchanges.

This growth and success of the electric grid was made possible by the choice of an AC (alternating current) distribution standard (promoted by Nicola Tesla and George Westinghouse) instead of the original DC Edison grid. AC distribution permitted the use

Fig. 1. Extent of the First Electric Grid in the US, essentially a Microgrid.[1]

of transformers to raise and lower system voltages which was a critical feature for the distribution of energy from central power plants. Higher voltage reduces energy losses during transmission across long distances, lower voltages accommodate the building uses we've become accustomed to (such as 120 V toasters). The ability to easily change voltages has served both utilities and customers well—and AC loads came to predominate in buildings and is what is delivered by the macrogrid. But,there are still many benefits to the original DC grid which will be outlined later in this report.

1.2 What is Changing?

The electrical system in North America has worked quite well for over a century. So why worry? What is changing? And why is this an architectural concern?

The demand for electricity continues to grow with increases in population and an apparently inexorable love affair with electrical appliances, gadgets, and spending time inside in conditioned spaces. Figure 3 illustrates this growth—which has not been dampened much by improvements in energy efficiency for buildings, equipment, and

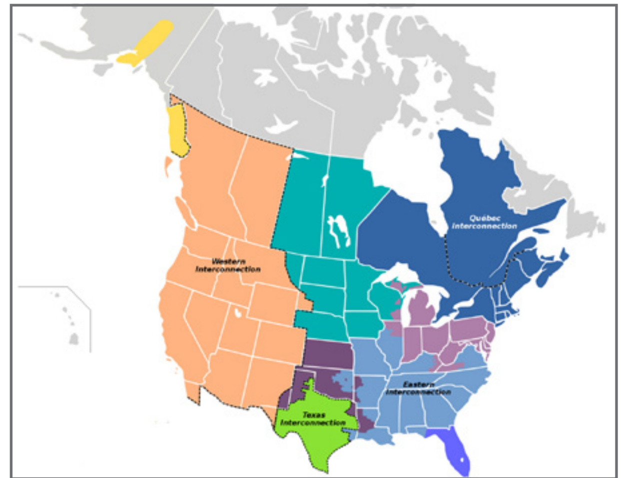


Fig. 2. North American Power Grids[2]

appliances. Although per capita use of electricity has been mitigated mainly through the intervention of energy efficiency measures (including building enclosure improvements, see Figure 4), total electricity use has continued to grow. This existing growth may be accelerated by several emerging trends—including the increasing numbers of electric vehicles and associated charging stations alongside electrification of building loads for heating and hot water. While this give and take between efficiency and new uses is happening, there is also a marked change in the fuels used to generate grid electricity—as seen in Figure 5.

The existing growth in US (and global) consumption of electricity may be further energized by several social and political trends that notably include decarbonization, electrification, and resilience. All three of these trends are recognized by the building design professions, including the AIA (American Institute of Architects), with decarbonization and resilience leading to the promulgation of official position statements and resource packages by the AIA and ASHRAE (American Society of Heating, Refrigerating, and Air-Conditioning Engineers). These trends are further described below.

Fig. 3. Patterns of Growth in Retail Electricity Sales in Three Market Sectors.[3]

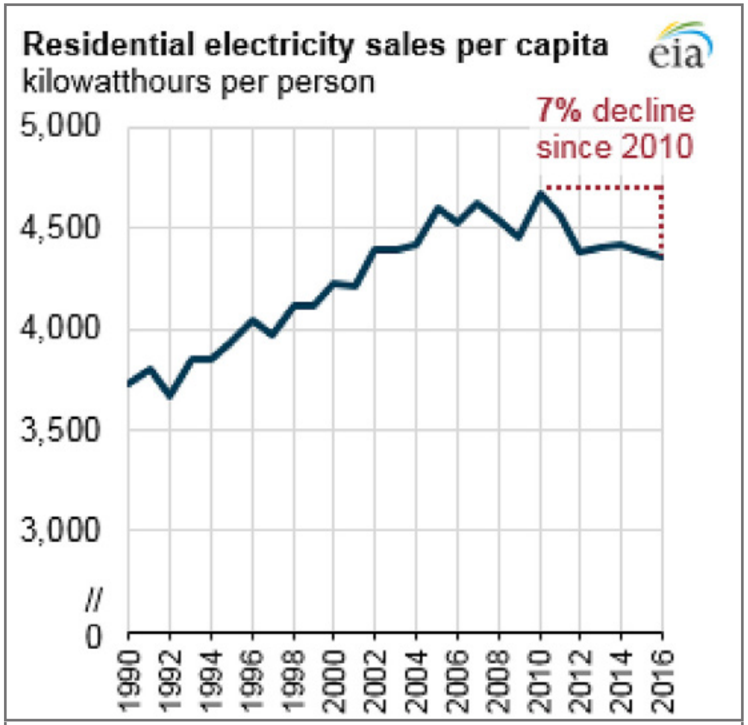


Fig. 4. Patterns of US Per Capita Electricity Use.[4]

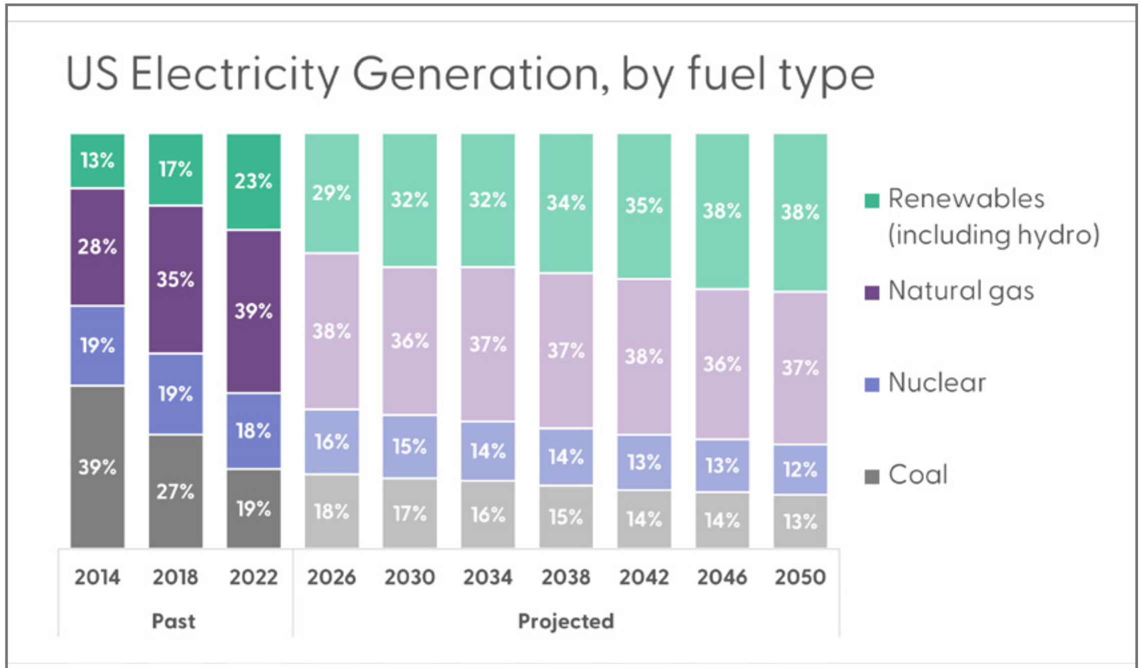


Fig. 5. Transition of US Electricity Generation Sourcing[5] by Fuel Type. Combined past data and future projected data through 2050 data. Note more than a doubling in contribution from renewable resources from 2020 to 2050. Source: Energy Information Administration (EIA)

1.2.1 Decarbonization

Decarbonization is the reduction of carbon dioxide emissions through the use of low carbon power sources, achieving a lower output of greenhouse gasses into the atmosphere[6]. The term “carbon” is usually used as a surrogate for the larger issue of greenhouse gasses. Serious decarbonization efforts must include concern for both operations-based carbon emissions (presumably to be reduced by the development of a renewable-energy-dominated grid) and also concern for the carbon emitted by the fabrication and installation of building materials and equipment[7]. The AIA has adopted a commitment to decarbonization and developed a tool kit to assist designers in doing so[8]. ASHRAE has recently engaged in decarbonization through publication of a public policy brief and establishment of a decarbonization task force[9,10]. The design professions are being challenged with the difficult task of decarbonization, and the more tools available to accomplish this task the better–including an understanding of the role that buildings can play in grid decarbonization and the transition to a clean electrical grid.

"From landmark federal electrification investment proposals, to major automakers electrifying their offerings, to utilities rolling out EV charging networks, to cities phasing out gas infrastructure while electrifying buildings, electrification became an unstoppable part of America's future in 2021."[14]

"Buildings represent nearly 40% of annual greenhouse gas emissions. We know that to reach the decarbonization targets set by the Paris Agreement, we must do more. From energy use to the materials specified, there are many opportunities for the architectural community to make a significant impact on reducing carbon emissions across the industry."[7]

"Decarbonizing the grid and electrifying everything is one of the fastest ways to reduce U.S. greenhouse gas emissions, creating compounding decarbonization impacts with every new building or vehicle running on an increasingly clean grid."[8]

1.2.2 Electrification

Electrification is defined as the conversion of a machine or system to the use of electrical power and is a tool in the quest for decarbonization. In the current context, this involves converting natural gas and fuel heating end-uses in buildings to electric such as space heating, water heating, cooking, and clothes drying. This also includes the conversion of gasoline-powered vehicles to electric vehicles.

There are clear signals from numerous U.S. entities that electricity is considered to be the future of energy and the time to start down the path to electrification is now.[11 12 13] The rationale for electrification is that electricity can be "clean" from a carbon emissions perspective by transitioning away from coal, oil, and gas power plants and internal combustion engines and toward electricity produced from solar and wind resources. Heating with natural gas/propane or driving with gasoline is and will be inherently non-renewable and carbon-laden.

This desire (becoming a policy in some jurisdictions) to shift energy sources will involve the building sector through conversion of space heating with gas (or fuel oil) to heating with electric heat pumps (which also provide cooling). The same is true for the heating of domestic hot water. Plug loads are inherently electrified; lighting loads have been electrified for the last 100 years. Energy for transportation will overlap with the design of buildings through the provisioning of electric vehicle (EV) charging stations in a range of building typologies. The more electricity we use, the more electricity that must be supplied by the existing grid (placing stress on utilities) or by buildings-based renewable resources (placing focus on designers).

"Building electrification is the ticket for entry, and where smart grids can meet smart buildings, we can decarbonize the grid, says Michael Frank, vice president of engineering and design for McKinstry. We need buildings to play a big part. We can't get there from the utility side alone."[5]

1.2.3 Resilience

Conceptually, resilience is the ability of an entity to withstand an assault from a reasonably predictable adverse event and continue operating and providing expected services and/or to recover quickly after a pause to reset. Buildings are increasingly expected to be resilient in the face of extreme events—especially those that seem to now be the norm with climate change, such as 100-year rains and record winter ice storms. We also expect our utility networks to be resilient. The resilience of the electric grid can be enhanced by appropriate building design decisions, while the resilience of buildings can be enhanced by a resilient electric grid. These issues are interrelated, as the grid was designed with the specific goal of reliably operating buildings. As with decarbonization, both the AIA and ASHRAE are on board with design for resilience.[15, 16, 17]

Resilient design places architects at the center of the solution, with particular emphasis on the private, non-governmental sectors. I would like to congratulate my fellow leaders in the design and construction sector for joining together to make sure resiliency is not viewed as just a fad but remains front and center in our efforts moving forward."[15]

- Robert Ivy, AIA EVP/CEO

Add to this list worries about the national or regional security implications of relying on large-scale grids. Such concerns about bad actors or bad weather generally lurk in the background but occasionally draw public attention.[19, 20, 21, 22]

Economic resilience can be provided during normal building and grid operations by reducing vulnerability to spikes in fuel prices passed through the macrogrid through the use of locally generated clean electricity.

1.2.4 Direct Current

On top of these trends, the very nature of electric loads is changing. In the early days of the electric grid, most loads were from alternating current devices—

explained by the fact that the grids providing electricity to the loads were AC. Building loads are changing to inherently DC loads—for LED lighting, for consumer appliances, for computers. A 2016 article in Applied Energy reported[18] that "around 50% of the energy presently used in buildings is either consumed as DC in electronic loads or passes through a transient DC state as a means of motor control..." Conversion of grid AC to DC for a majority of loads is inefficient—even more so if some of the building power is from an on-site PV (photovoltaic) system, which natively produces DC power.

Thus, we have a variety of factors that individually and collectively provide more than adequate food for thought about how we heat/cool our buildings, heat water for showers and cooking, design building enclosures, and enjoy the benefits of electrified automation of chores. How we power our daily lives, and the actions of many individuals can and will impact the transition to a resilient, decarbonized future.

1.3 The Winds of Change

Figure 6 attempts to capture a sense of the technologies and forces that are currently—and will likely in the future—influence thinking about the relationships between buildings and electric grids. These influencers can be broadly thought of as load modifiers, load disruptors, load aligners, and design priorities/outcome filters. These categories are informal and somewhat amorphous but can help assign value to the many influencers that have been and will be acting on building loads as a result of changes in building design.

A load modifier is best described as a technology or design approach that incrementally changes the magnitude of electrical loads in a building. Examples of load modifiers include LED lamps, Energy Star appliances (such as high efficiency refrigerators), better windows, the use of ERVs/HRVs (energy recovery ventilators/heat recovery ventilators) and the like. Load modifiers typically act to reduce electrical loads—and may be adopted into a building by a change in code, by a change in product availability, or by a change in culture (economic or social). Load modifiers have in recent decades allowed the U.S. per capita use of energy to remain flat (Figure 4), while the collective use has increased (Figure 3). Load modifiers have bought the grid some time; and will likely continue to do so in the near future. Modifiers included in the Milwaukee Case Study include varying building enclosure efficiency levels.

A load disruptor is a trend that substantially impacts the load profile (see section below) of a building. With widespread adoption, it also significantly

A RESTAURANT ANALOGY:

Imagine the electric grid as a small-town restaurant service that is open 24/7/365. The restaurant is built with the capacity to serve the whole town of 1000 customers at once. That "rush" typically comes on weekends at dinner time. Other times, like at 6am, they may only be serving 50 customers.

In order to plan for the dinner rush, the restaurant must have the infrastructure (space, tables, kitchen/cooktops, equipment, cooking staff, serving staff) to serve 1000 customers. When it needs to serve all 1000 customers, all staff must work, and some of those staff had already fulfilled their weekly quota so now you're paying overtime. This is similar to how the grid has to plan to meet peak demands, and this is why meeting peak demands is expensive – it requires utilization of the most expensive resources.

The introduction of high-performance buildings to that grid, that have lower peak loads, is like reducing the "peak" amount of customers that the restaurant serves. For example, if the peak number of customers the restaurant now needs to serve is 500, then the seating space can be half the size, cut down on infrastructure costs, staffing costs, kitchen space and equipment, etc to meet that same rush period. And if there are never significant steep increases of customers arriving, it's like low-load buildings that don't see significant variation in power needs throughout the day.

Removing the option for walk-ins and ONLY taking reservations, allowing up to 250 customers to dine at once, for four select, 60 minute periods (4-8pm) is like load shifting or load alignment. In this case, the restaurant now can reduce said infrastructure and staffing by a fourth compared to the baseline.

Allowing all staff (cooks, servers, etc) to schedule themselves for shifts and take breaks whenever they want is like the introduction of renewable energy resources into the electric grid. Creating "warming stations" for food once it's ready for customers is similar to implementing energy storage, for aligning supply with demand. This can allow the cooks to stage the preparation of meals for the peak customers, and allow wait staff to service more tables than if the meals needed to be delivered directly to tables with no time lag.

Allowing the customers to coordinate / share (think "family style meal" or splitting the last roll at the dinner table) between one another is like a coordination of smart loads or "DER"s (distributed energy resources). New advancements in technology are creating opportunities for bottom-up approaches to load coordination, where "smart" devices are enabled to set parameters for operational goals and coordinate between one another to adjust the timing to meet those goals based on energy availability.

impacts the electric grids that serve buildings. Electric vehicles, decarbonization (in the form of building electrification), and the growth of distributed energy resources (in the form of site-based energy production) are examples of load disruptors. The impacts of such trends can be quick, large, and system wide. Load disruptors tend to place additional stress on an already stressed grid and present significant challenges (and design opportunities). Disruptors included in the Milwaukee Case Study are electrification and on-site photovoltaic systems.

Load modifiers and load disruptors change the magnitude and/or timing of building electric loads—which may either stress the grid or relax the grid depending upon the timing and specific nature of the impactor. Because buildings today are so tightly connected to the macrogrid, a stress to the grid can easily become a limitation on the building. The expanded use of LED lamps, for example, eases the loads seen—and needing to be met—by the electric grid. The addition of buildings-based electric vehicle charging stations will increase the electrical load and potentially dramatically shift the peak, creating more challenges for utilities who are required to deliver power on-demand.

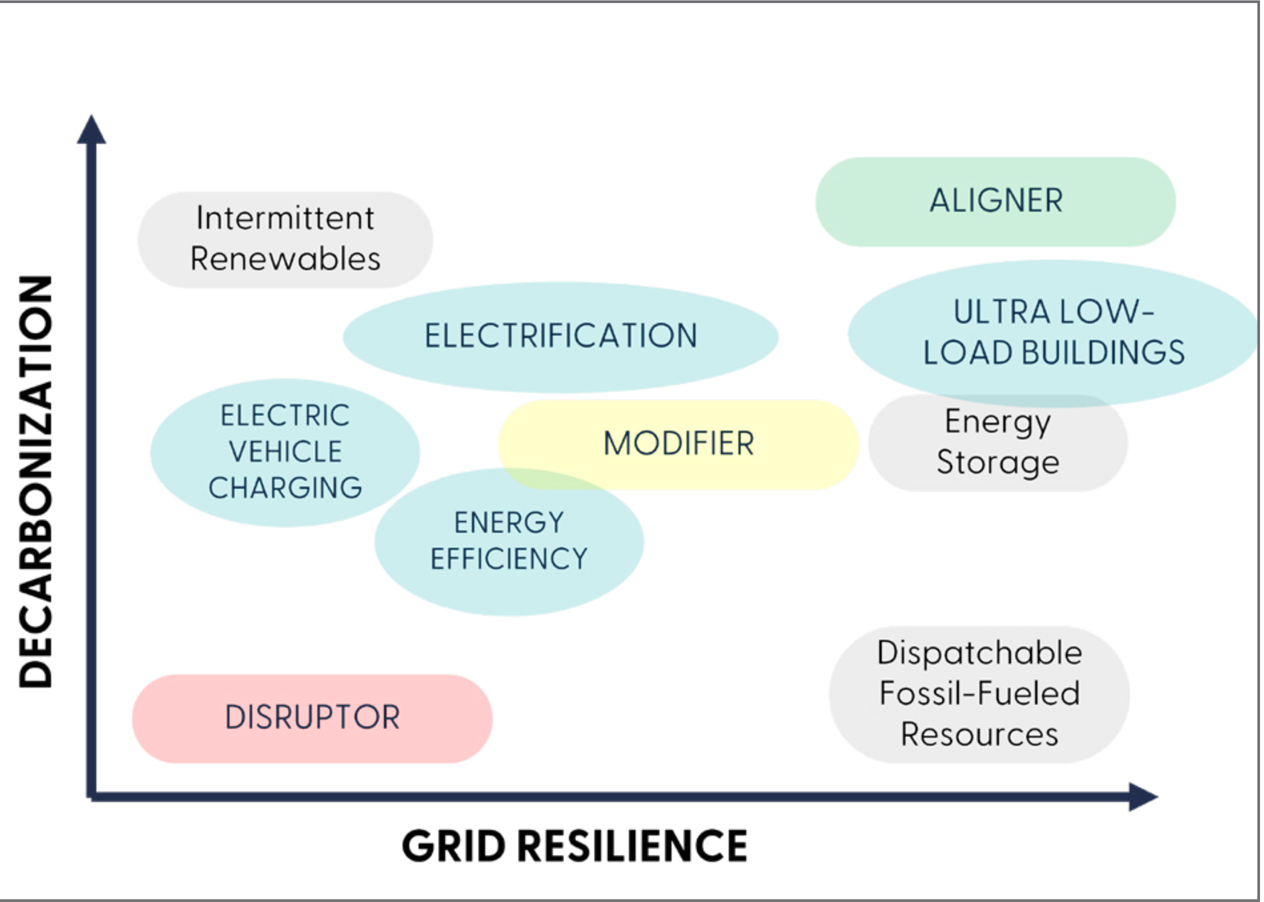


Fig. 6. Conceptual Representation of the Opportunities for Grid-Building Interactions.

Load aligners are technologies and solutions that, in response to disruption, contribute to the coordination and alignment of building loads with energy supply. Aligners take in energy during times of excess supply and export (or shed) during times of low supply. Examples include on-site battery storage, grid interactive load responses such as shifting and shedding, and native DC power. Several load aligners are explored as variables in the Milwaukee Case Study.

Design outcome filters (priorities, perspectives, viewpoints, design filters) can tilt the design playing field shown in Figure 6 by changing the relative importance of factors we use to evaluate success. For example, an increased concern for low-carbon electricity or for greater system reliability will change how we evaluate the costs and performance of the electric grid and the buildings that are attached to the grid. It is probable that the desired outcomes of running an electric grid (for example, maximizing income) will not fully align with the desired outcomes of using an electric grid (for example, minimizing expenses). Filters addressed in the Milwaukee Case Study include economics, resilience, and decarbonization.

1.4 Why Architects?

So, why an architect's guide to the evolving electric grid landscape? Mainly because many of the grid changes that will be coming will impact residential buildings—where the prime design professional is an architect and where the valuation of design outcomes is driven by the architecture profession. Secondarily, because these grid changes will also impact commercial/institutional/educational/retail buildings—where responsibility for design direction is shared with other professionals, but should not be abdicated to those who are less attuned to an owner's design objectives and less connected to the ethical aspirations of the architecture profession. Further, one of the most impactful of the available grid-betterment tools is energy efficiency, in particular efficiency harnessed by improving the building enclosure, which is a uniquely architectural responsibility.

Reliable electric grids and a decarbonized energy supply will not be developed without the active and knowledgeable participation of the design professions. Architects should and can take the lead. As will be shown in the following sections of this Guide, improved enclosure design is as powerful a grid change agent as better electrical transformers, improved lighting fixtures, and even electrical energy storage. The answer is as architectural as it is engineering.

Renewable, clean energy is decentralized by nature, and is a solution to decarbonization at the "grid edge", i.e. where the centralized power distribution connects to the building loads. Inherently, this brings building design professionals into the renewables picture and makes them a key player in the renewable energy solution. For example, the roof of a building can either be designed to act as a barrier to solar radiation–rejecting this abundant resource year-round as a means of mitigating summer cooling loads–or the roof can become a transformer–converting the solar resource into needed electricity while also reducing summer cooling loads.

Microgrids, or even just the incorporation of some of their key elements such as load shifting, present new opportunities in building design. With the microgrid as part of the design toolkit, new goals become a possibility–like sustained resilience during an outage, long-term energy affordability through self consumption of on-site energy generation, and/or significant emissions reductions.

Architects are the "jack of all trades" that coordinate the project and are responsible for coordination and implementation of project plans. They work directly with owners and clients to determine project goals and requirements. It is their professional responsibility to educate clients about the world of possibilities and different ways to achieve those, and what the societal and environmental impacts of those are. By introducing these concepts into early discussion with a client, the design professional can create a paradigm shift about what is possible through building design.

Many local and national policies are aiming to reduce carbon emissions in buildings. It is critical that design professionals understand all the tools available to them to achieve decarbonization, which includes both awareness of load disruptors as well as implementation of load aligning strategies outlined in this Guide. Additionally, in jurisdictions where tariffs or penalties are placed on carbon emissions, this Guide may support effective design strategies to meet emission reduction goals.

This information can also function as a builder's guide for residences that are designed without the input of an architectural professional.

1.5 Objectives

The goals of this Architect's Guide are to enable readers to:

- Identify common building performance and microgrid terminologies and concepts
- Interpret microgrid concepts and configurations from a buildings-based focus
- Assess the relative benefits of various microgrid configurations to individual clients and to society
- Assess the relative benefits of common microgrid features (such as PV, storage, efficiency, DC)
- Articulate the benefits of various microgrid options to clients and other stakeholders
- Knowledgeably communicate with other design professionals regarding microgrids

2. LOAD PROFILES

2.1 Load Profile Basics

A ***load profile*** is simply a plot (graph, chart) that shows a building load over time (for example, the electric load on a building as seen at the meter). This graphic represents the energy that is being consumed by the building (customer) that must be generated and supplied instantaneously by the supplier (utility grid). This interaction between the energy supplier (utility grid) and the user (customer) can be very helpful to understand the patterns for timing and magnitude of energy use - both at a daily and annual scale. These patterns can help to inform and support decisions that allow us to reach our energy-related design objectives—such as low first cost, low annual cost, reliability, low carbon emissions, and the like. Understanding patterns informs decision making. The load is not completely random but tends to cycle with two particular time periodicities - a daily cycle superimposed on an annual/seasonal cycle.

In this Guide an existing city block in Milwaukee, Wisconsin is used as a case study of grid-building interactions and microgrid possibilities. Thus, in addressing load profiles we'll start by looking at generic Milwaukee utility load profiles. Figure 7 shows the annual total energy use of residential properties in Milwaukee (as cataloged and projected by ResStock, a product of the National Renewable Energy Laboratory). The vertical axis is total energy consumption (both gas and electrical, in gigawatt-hours per day). The horizontal axis is the time of the year, starting with January. Except for the summer months, the largest use of energy is natural gas for heating (the darker green band in Figure 7). This load subsides in the summer months, leaving natural gas used for domestic water heating and electricity as baseline loads (bumped up slightly by electricity for space cooling, the pink band). In terms of magnitude, natural gas heating is the main energy consumer in this city and climate. Consider the effect of electrification on the electric load profile (Figure 8); wherein the roughly 500 gigawatt-hour peak heating load now handled by the gas grid would be switched to the electric grid (with appropriate adjustments for relative heating equipment efficiencies). This potential impact of electrification is emphasized in Figure 9.

Figure 8 is the annual cumulative electric load profile for Milwaukee County, Wisconsin (also extracted from data cataloged by ResStock[23]). This profile represents the electric load that needs to be met by the electric grid serving this collection of residential customers. Note the scale of the y-axis, which only reaches a maximum of 20G for electricity consumption , whereas the total energy consumption (Figure 7) peaks at 800G. The different colors in Figure 8 indicate different electric loads—with the main load contributors being space heating (green) and space cooling (teal). The other loads include clothes washers and dryers, lighting, fans, refrigerators, cooking ranges, and plug loads.

The annual electrical consumption profile reveals the following:

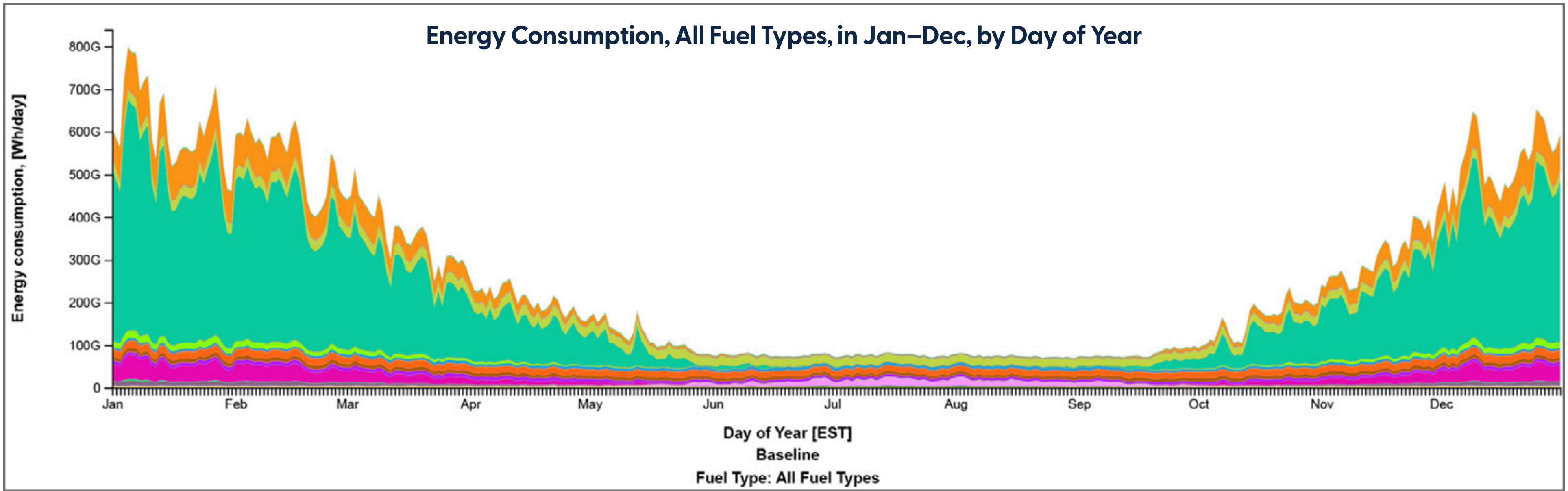
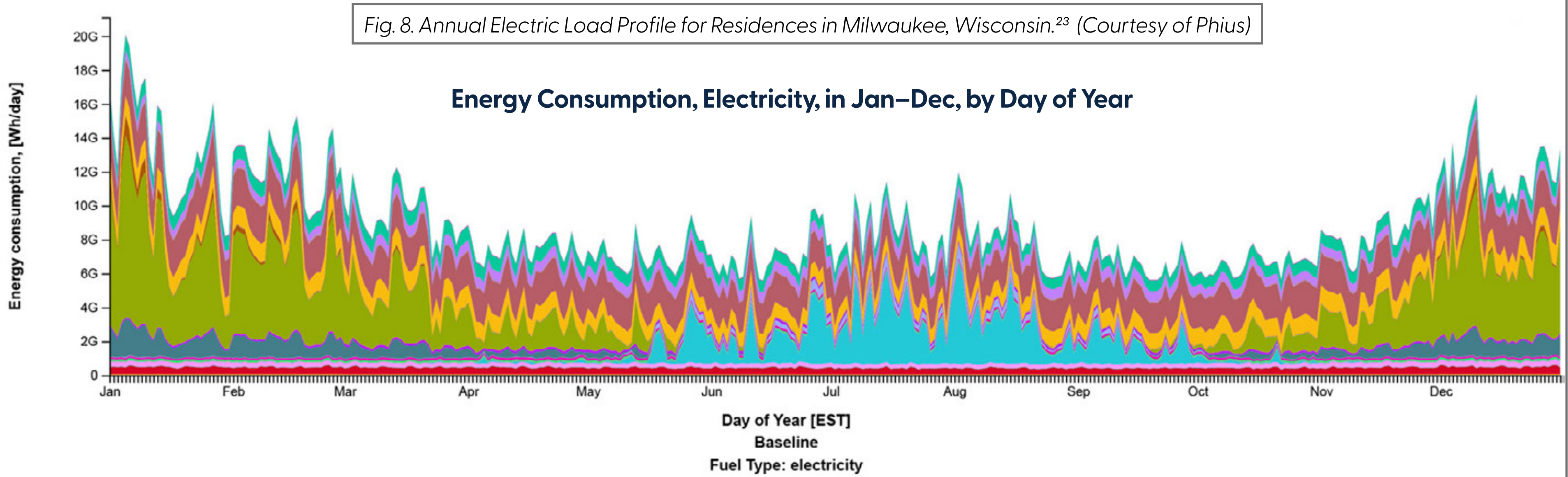


Fig. 7. Total Annual Energy Consumption Profile for Residences in Milwaukee, Wisconsin.[23]

Fig. 8. Annual Electric Load Profile for Residences in Milwaukee, Wisconsin.[23] (Courtesy of Phius)



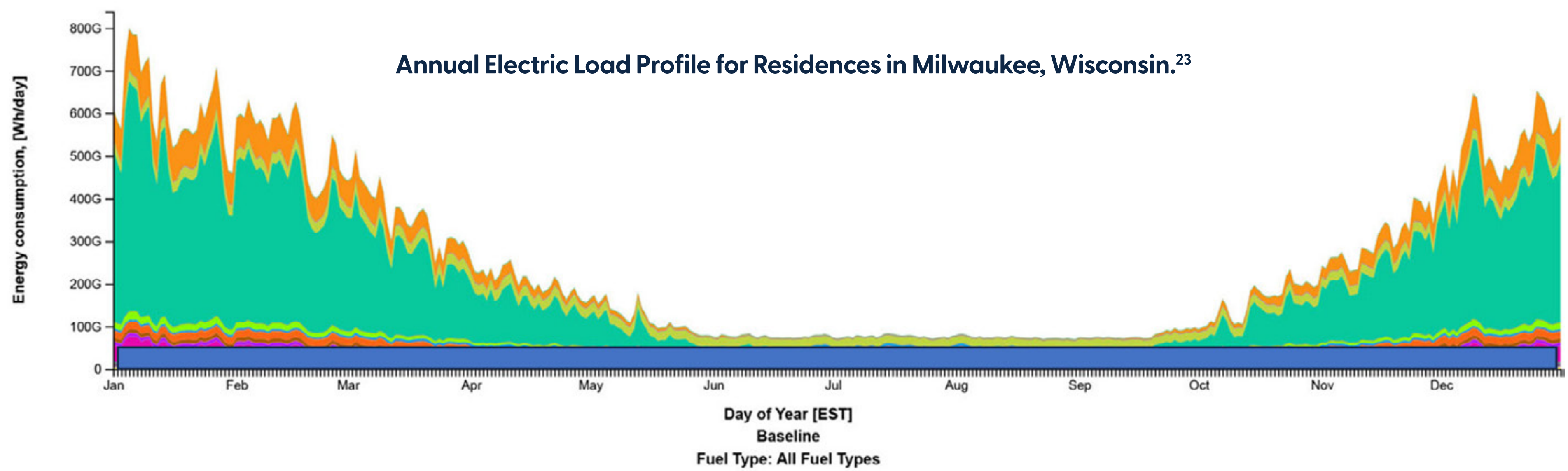


Fig. 9. This figure represents the relative scale of the residential Electric Load Profile (Fig 8) relative to the all-fuels total load profile (Fig 7). Note that the entire electricity profile fits into the outlined blue horizontal bar (peaking at 20G, while the total fuels peaks at 800G). The difference in these charts represents the potential new electric load on the grid simply through the electrification of hot water and space heating.

- Even with the high penetration of natural gas heating in Milwaukee, heating loads dominate the electric load profile in the winter months and cause the peak load (around 20 gigawatt-hours) that needs to be met by the electric grid
- This ResStock data represents homes where only a very small percentage rely on electricity as a primary heating source or even as a supplemental heating source (think, plug-in space heaters)
- Cooling loads replace heating loads in the summer, but are not as demanding (with a roughly 10 gigawatt-hour summer peak) of utility capacity as heating
- Daily loads vary substantially (as seen in the spikey plot), and track well with the magnitude of heating and cooling loads.

Figure 10 zooms in from the broader yearly profiles presented above to look at a residential daily electric load profile for a typical January day in Milwaukee. This profile is collective—for thousands of homes—but is also generally representative of the consumption pattern of a typical single customer—smoothed out by diversity. The vertical axis is energy consumption per 15-minute intervals in gigawatt-hours; the horizontal axis is time of day, starting with midnight to the left.

A grid sub-peak is seen around 8:00 am as people awaken and prepare for their daily activities. A larger peak is seen at 8:00 pm as people begin to settle in for the night. Note that this evening peak (or demand) is driven by a spike in lighting (yellow) and in plug loads (mauve) superimposed on a reasonably consistent heating load (green). Remember, however, that much of Milwaukee's space heat is currently provided by natural gas and not plotted on this profile. With the electrification of space heating, new electricity peaks will be determined by space heating loads. This will be discussed further in Section 4 Load Disruptors.

Figure 11 shows a summer daily electric profile—for a typical day in July. The grid peak demand for electricity (around 3.5 gigawatt-hours) occurs at 6:00 pm and is clearly driven by cooling load (teal). There is an obvious minimum demand for electricity at 5:00 am when cooling needs are at a minimum and people are sleeping and not yet engaging in their electric amenities. Note that the local utility must economically supply the minimum power demand as well as the maximum. The ability to do so has been part of the utility/grid scene for years. But, this balance can be affected by load modifiers, rattled by load disruptors, and dampened by load aligners as discussed later.

Today, in the majority of US electricity markets, residential consumers are charged for their use of electricity based upon a simple summing of consumption—they are billed for the total area under the profile curve in Figure 12. The units of this consumption are kilowatt-hours (kWh). This process is suggested by the gray vertical bar in Figure 12—which represents consumption during a nominal 1-hour time period.

It is common for commercial/institutional customers to also be billed for their peak demand (in kW) as

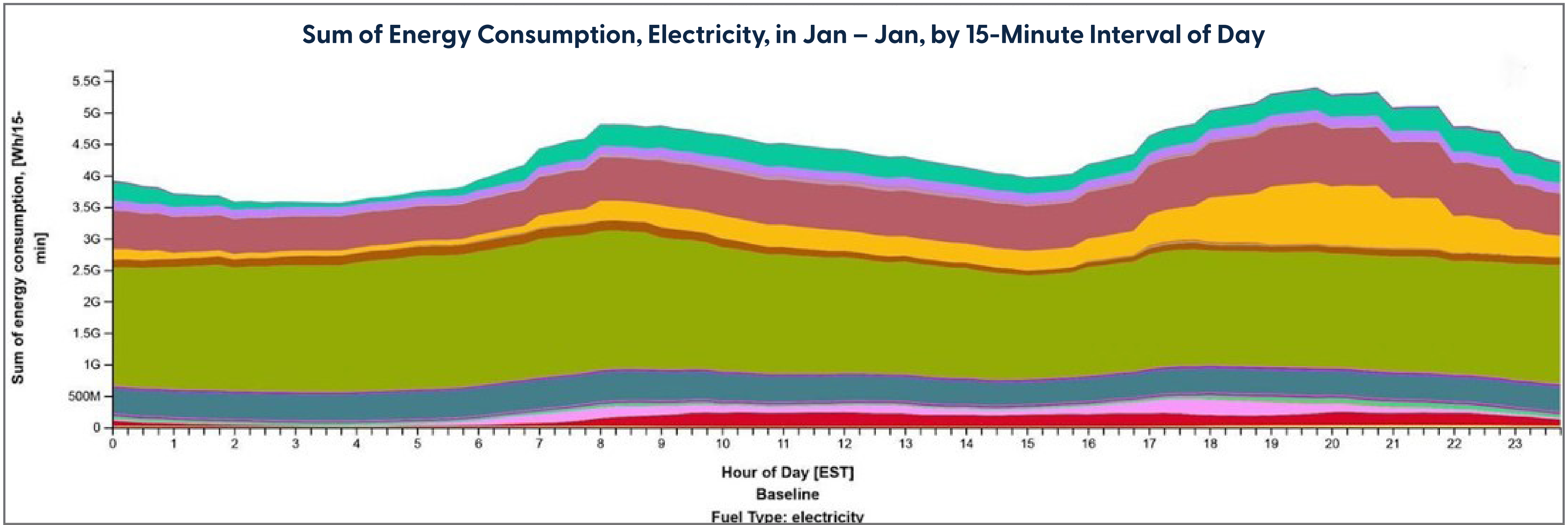


Fig. 10. Daily Winter Electric Load Profile for Residences in Milwaukee, Wisconsin.[23]

recorded by a utility-provided electric meter placed at the service entrance to the building. The basis for the demand charge is represented by the horizontal line in Figure 13. Demand charges are not yet common in residential markets, but this may be changing. For a residential customer served by an electric utility grid, life is straightforward. The customer is billed directly based upon consumption—the more electricity used the higher the electric bill. The grid-providing utility handles all else, including ensuring reliability so the customer's peak demand can be met. This simple use-pay relationship is in transition for customers in several parts of the US with the emergence of time-of-use rates, opportunities to select electricity providers, and involvement with smart grid controls which are in some residential markets already now. What was once a transaction like buying fruit by the pound in a supermarket (what's in your cart is what you pay for) is on the path to becoming more like paying for meal delivery service.

From the perspective of the electric utility, things are not nearly as simple, as shown conceptually in Figure 13. The electric grid must provide service during periods of low consumption as well as meeting the peak system load. To do so, different generation resources (of different cost and availability) are often employed. The specific nature of such generation resources varies geographically and historically. The base load (blue horizontal bar in Figure 9) may be met by nuclear or coal-fired baseload power plants; the next step of capacity (brown bar) by available renewables; the next step (yellow bar) by natural-gas load-following plants; the peak capacity (red bar) by natural-gas peaker plants. This complicates the job of providing electricity to a diverse group of customers. The cost to produce electricity ($ per kWh) will vary by time of day; the carbon emitted as a result of electricity generation will vary by time of day. The availability and reliability of electric generation resources may vary by time of day.

Two basic rate design responses to this complexity are shown in Figure 13.

A utility may try to control peaks on the grid (which represent expensive and stressful electricity) by imposing charges for peak demand. This is already common for non-residential building typologies, with related design responses becoming a normal aspect of the building design process. Common responses include load monitoring and load shedding, thermal energy storage, and ubiquitous use of energy management systems. There is indication that expectations for demand adjustment, and compensation for it, is moving into the residential market.

A utility can also attempt to control peak demand by imposing differential electricity rates; known as time-of-use or time-of-day rates (or tariffs). This is illustrated in Figure 13 where "Rate 2" represents a higher cost per kWh for electricity than "Rate 1." The objective

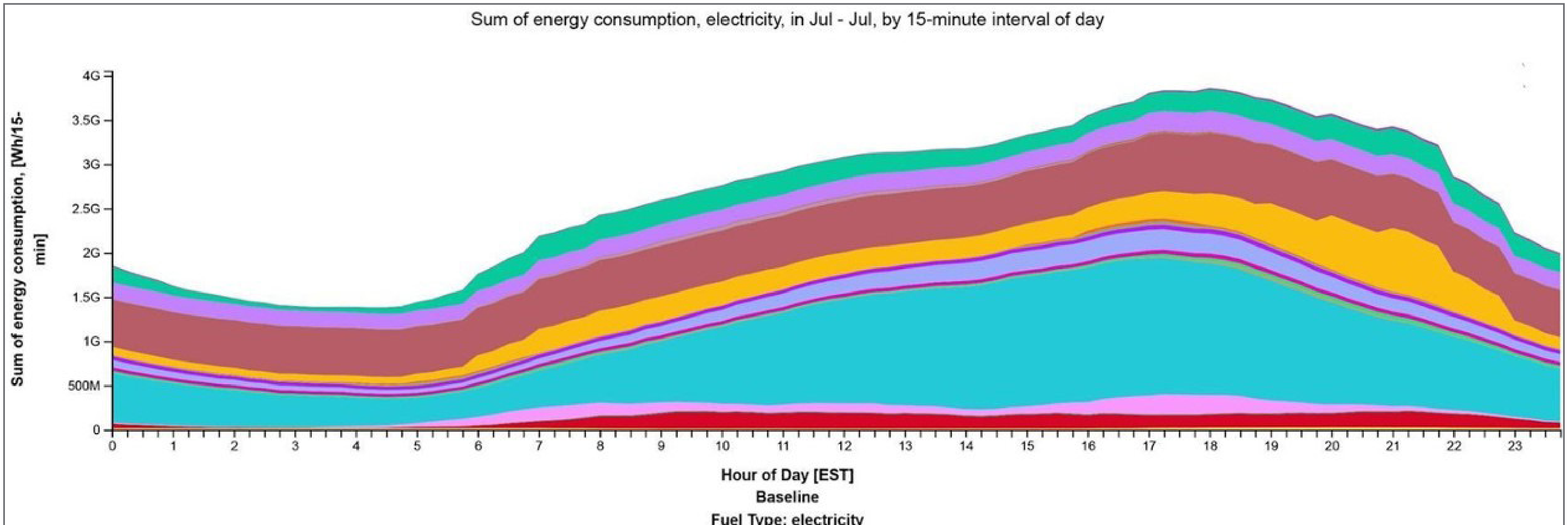


Fig. 11. Daily Summer Electric Load Profile for Residences in Milwaukee, Wisconsin.[23]

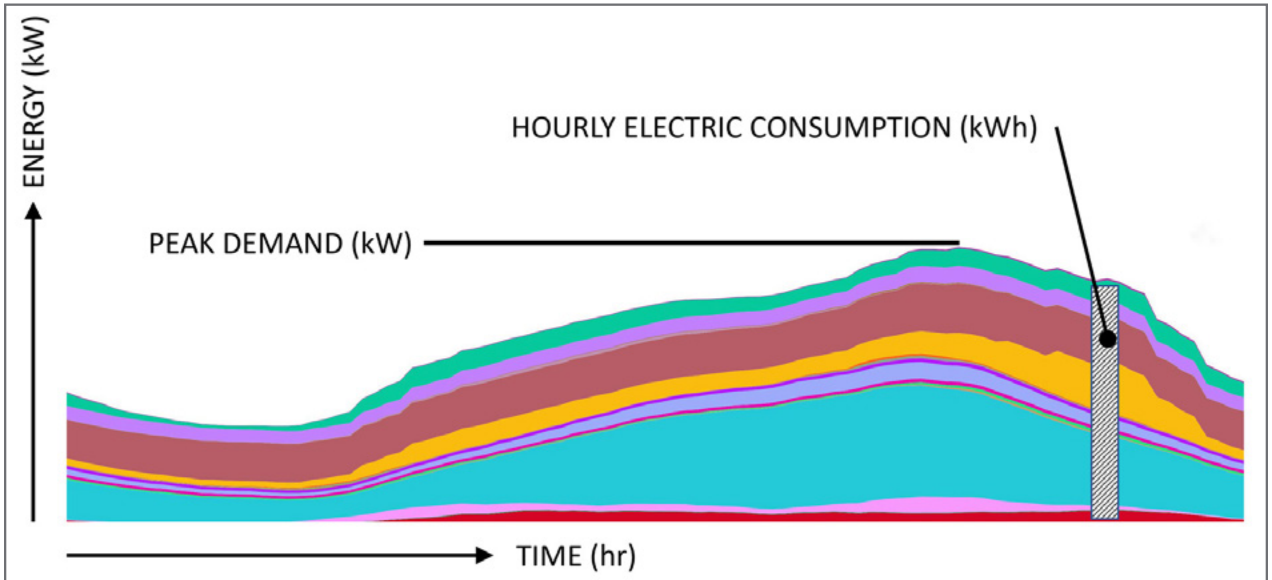


Fig. 12. Historic Implications of Load Profiles (Courtesy of Phius)

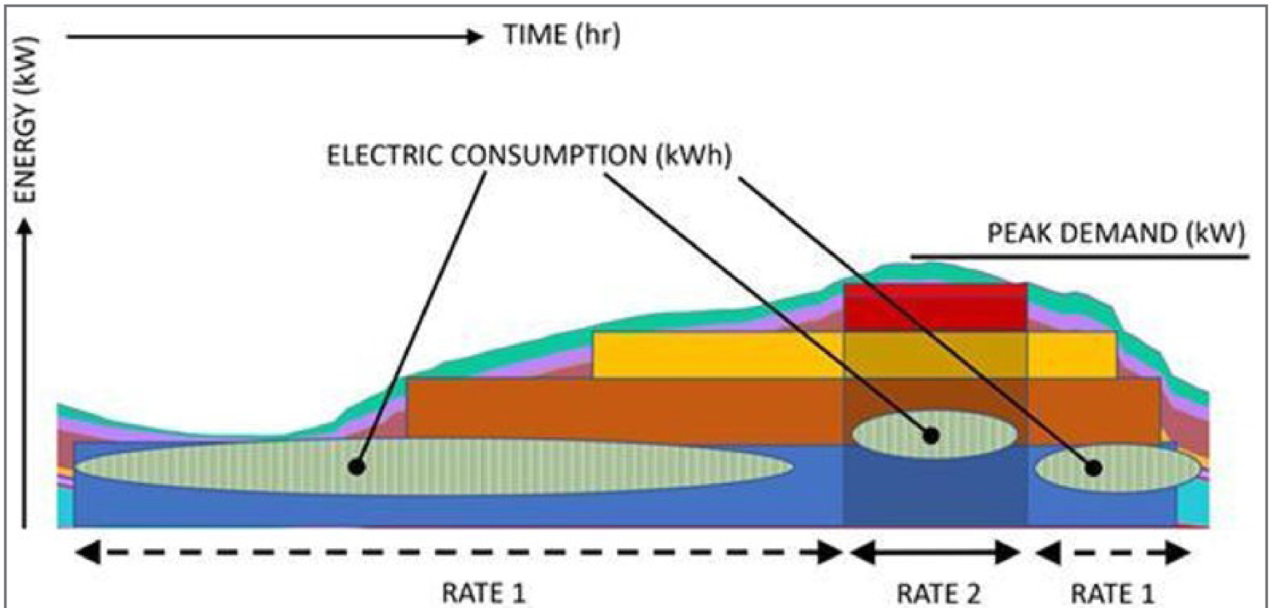
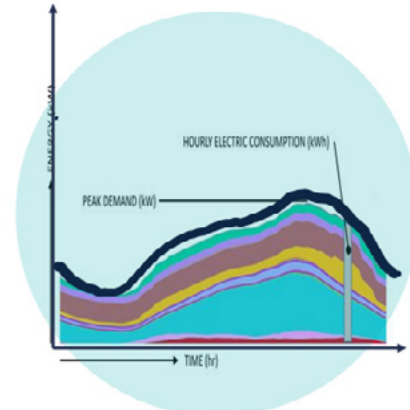


Fig. 13. Evolving Implications of Load Profiles. (Courtesy of Phius)

Simplified, Total Electric Daily Load

For a single-family home, the peak demand for a typical winter day in Milwaukee may be between 2 kW–15 kW, depending on the building enclosure design and heating equipment. More on this in the Milwaukee Case Study. (Courtesy of Phius)



of time-of-day rates is to encourage a change in behavior that leads to a change in electricity use patterns. For example, getting people to avoid running dishwashers, clothes washers/dryers, or water heaters during the most challenging hours of the day (red bar). The magnitude of these utility billing strategies is suggested in Figure 14–extracted from the tariff (rate) structure for Wisconsin Energy (WE, the electricity provider for Milwaukee). Efforts to reduce stress on the grid are further discussed in Section 3, Load Modifiers, and Section 5, Load Aligners.

2023

Electric rates

The electric service rates listed in this brochure reflect the rates authorized by the Public Service Commission of Wisconsin (PSCW) for Wisconsin Electric Power Company doing business as We Energies.

Energy *you can depend on*

Residential and Farm (Rg1, Fg1)

Customer Charge, per day:	
Single-phase/Three-phase service	$.49315
Additional meter	$.05951
Energy Charge, per kWh	$.16580
Fuel Cost Adjustment, per kWh	$0.00
Environmental Control Charge, per kWh	$.00043

Residential • Time-of-Use (Rg2)

Customer Charge, per day:	
Single-phase/Three-phase service	$.49315
Additional meter	$.05951
Energy Charge, per kWh:	
On-peak energy*	$.22827
Off-peak energy	$.10376
Fuel Cost Adjustment, per kWh	$0.00
Environmental Control Charge, per kWh	$.00043

*Customers have a choice of four on-peak periods: 7 a.m. to 7 p.m., 8 a.m. to 8 p.m., 9 a.m. to 9 p.m., or 10 a.m. to 10 p.m.

General Secondary • Demand Time-of-Use (Cg2)

329 kWh per day for the month for any three months in a 12-month period.

Customer Charge, per day	$1.32000
Additional Meter, per day	$.18542
Energy Charge, per kWh:	
On-peak energy*	$.12438
Off-peak energy	$.08884
Demand Charge, per kW:	
On-peak demand*	$7.783
Customer demand	$2.46
Fuel Cost Adjustment, per kWh	$0.00
Environmental Control Charge, per kWh	$.00040

*The on-peak period is 9 a.m. to 9 p.m.

Fig. 14. Portions of the Milwaukee Electric Tariff Showing Impacts of Time-of-Day Pricing and Demand Charges.[24]

2.2 Generation Profiles

Just as building loads can be represented through load profiles, energy generation from various resources can be represented with generation or supply profiles.

Until the advent of intermittent, renewable energy into the grid-supply mix, generation profiles weren't much to look at. The dominant generation sources on the grid today (nuclear, coal, and natural gas) have generation profiles that are mostly shaped based on the building load that they must meet. Nuclear and coal plants can't adjust output very quickly and their profiles tend to be flatter. Natural gas, however, is considered a "load-following" resource that can ramp up and down quickly, and as the name implies can be shaped to match the load. Figure 15 illustrates these generation or source profiles. Figure 13 illustrates the need for and concern over such profiles.

Renewable resources, on the other hand, are shaped based upon the availability of each particular resource. Generation profiles for photovoltaic energy track solar radiation availability – generation begins in the morning when the sun rises, peaks in the middle of the day, and ends when the sun sets (Figure 16). There may be hourly or daily interruptions of this parabolic pattern as a result of cloud cover, morning fog, or other local weather patterns.

Generation profiles for wind energy are correlated to local wind patterns. Generally wind speeds tend to be higher during the night and lower during daylight hours, and therefore the generation profiles match that pattern (Figure 16). Wind in particular can create significant spikes in output when conditions are "gusty", creating significant surges of available power followed by gaps that must be filled by other resources.The representation above is a simplification of a single day's wind profile, though day-by-day can vary from this seasonally.

Hydropower is an interesting renewable resource, driven by solar radiation acting through the hydrologic cycle.

Naturally occurring hydropower varies in output seasonally, based upon rainfall and subsequent stream or river flow tempered by water storage behind dams. It is also often reported that many of the suitable sites are exploited, so a significant increase in capacity from this resource is not expected.

Pumped-storage hydro is used as a "load aligner" that takes in energy during times of excess supply and exports during times of low supply – think of it like "gap-filling" between the other renewable generation profiles.

The electricity placed into the grid comes from a variety of sources operated to provide stability while serving peak loads and being reasonably economical. Figure 17 illustrates the source (or generation) mix expected to be seen in Wisconsin in the year 2024 (from Cambium25). The bottom line

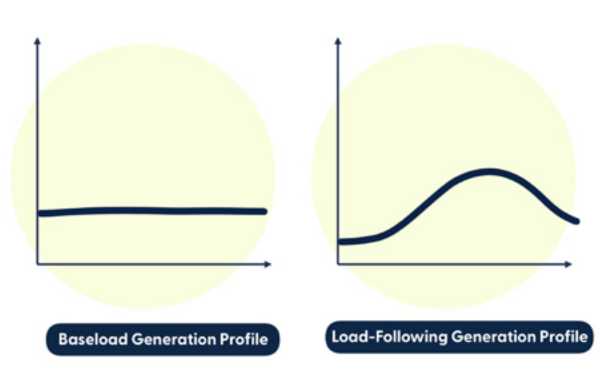


Fig. 15. Two Key Types of Electricity Source Profiles. (Courtesy of Phius)

The generation resource capacity on the electric grid now is sized to meet the peak load, with a significant safety factor in order to ensure reliability. In many regions of the US, that peak occurs in the summer. The electrification of heating loads will create winter peaks significantly higher than exist now.

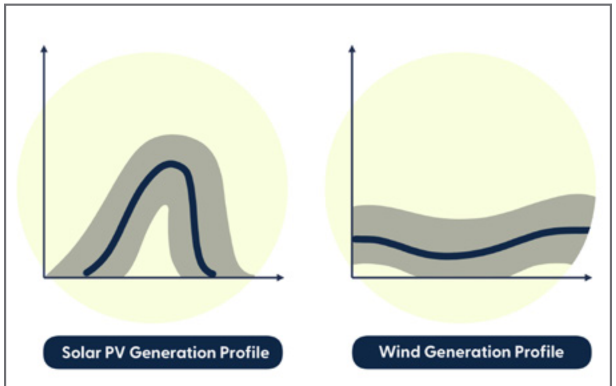


Fig. 16. Sample Generation Profiles for Solar Power and Wind Power. (Courtesy of Phius)

in the mix (red) is nuclear power which provides an essentially constant baseline source of electricity. The next line (black) is electricity from coal-fired power plants. The purple line represents electricity generated by natural gas plants; the yellow and blue lines are the production from PC and wind respectively. The most dispatchable (i.e., quickly operator controllable) of these sources are natural gas plants, and it is predicted that these types of plants will need to be utilized to help facilitate the transition to a renewable future, filling the gaps between spikey supply sources.

2.2 Load Profile Patterns

Let's look conceptually at how several load modifiers, disruptors, and aligners change electrical load patterns for small-scale residential buildings. These effects and their implications will be further explored via discussion of the Milwaukee Case Study in Section 7.

a. Energy Efficiency. Building energy efficiency, which has evolved steadily since ASHRAE Standard 90 was first published in 1970, is a tried-and-true load modifier that is now part of most US codes. The impact of energy efficiency, in whatever form it is applied to a building (enclosure, equipment, appliances), is to depress the load profile (see Figure 18 part a). This reduces both overall electricity consumption and peak demand. Utilities have historically used efficiency incentives as a viable tool to control the growth of electricity consumption. Beyond-code efficiency, as represented by ultra-low energy building design, seriously flattens load profiles. Section 4 of the Milwaukee Case Study for an example of this effect. Code efficiency is a load modifier; ultra low energy buildings are a load disruptor. Energy efficiency resides with building design.

b. Electrification. Many locations in the US are served by both natural gas and electric utilities. Where this is the case, as in Milwaukee, a substantial percentage of the total building energy load is borne by natural gas, including typically space heating, hot water heating, and cooking. Electrification–the switching from gas to electricity for such key loads–would dramatically impact electric load profiles as shown in Figure 18 part b. For many utilities this would be catastrophic. For some buildings this will be a serious challenge requiring an upgrade to the electric service (panel) and distribution (wiring) components. Electrification will be accomplished through building equipment modifications.

c. Distributed Energy Resources (DERs)–typically PV (photovoltaics). The International Energy Agency defines distributed energy resources as: "small scale energy resources usually situated near sites of electricity use, such as rooftop solar panels..."[27] Although these resources may be located off-site as well as on-site, usage trends in the US favor on-site applications. Building-based PV systems are by far the most common on-site DER. Such resources are a source of electricity and, as such, offset the need for grid electricity to meet a building's electrical loads. This is illustrated in Figure 18 part c. On-site DERs (say photovoltaics) should be incorporated through building design for best results.

d. Electrical Storage (batteries). Buildings-based battery storage is often lumped in with other DERs, but this seems unwise as the effects produced by the storage of electricity are quite different from the effects produced by the generation of electricity. Storage allows electricity to be shifted in time, as seen in Figure 18 part d. This is a powerful effect, especially in connection with solar generation of electricity. Battery storage is a technology solution, with minimal direct impact on building design. As will be seen below, however, the availability of storage impacts the sizing of on-site production, which does have architectural implications.

e. Electric Vehicles (EVs). Uni-directional (charge only) electric vehicles are basically just another load to be handled by the building electrical system and then by the grid. A close-to-capacity building electrical system may be stressed[28] by the addition of EV charging–although negative impacts can be mitigated by careful control of the times when charging is permitted. Some existing buildings may be pushed too far by an EV charging load, requiring upsizing of electrical service and distribution elements. Some grids may be able to take the addition of substantial EV charging loads in stride–others may be stressed.

Bi-directional EV charging, though, has the potential to be a serious load aligner. In a bidirectional arrangement, electricity can flow from the building to the vehicle as a means of charging the vehicle battery–but electricity may also flow from the vehicle battery to the building as a means of supporting building loads during a power outage.

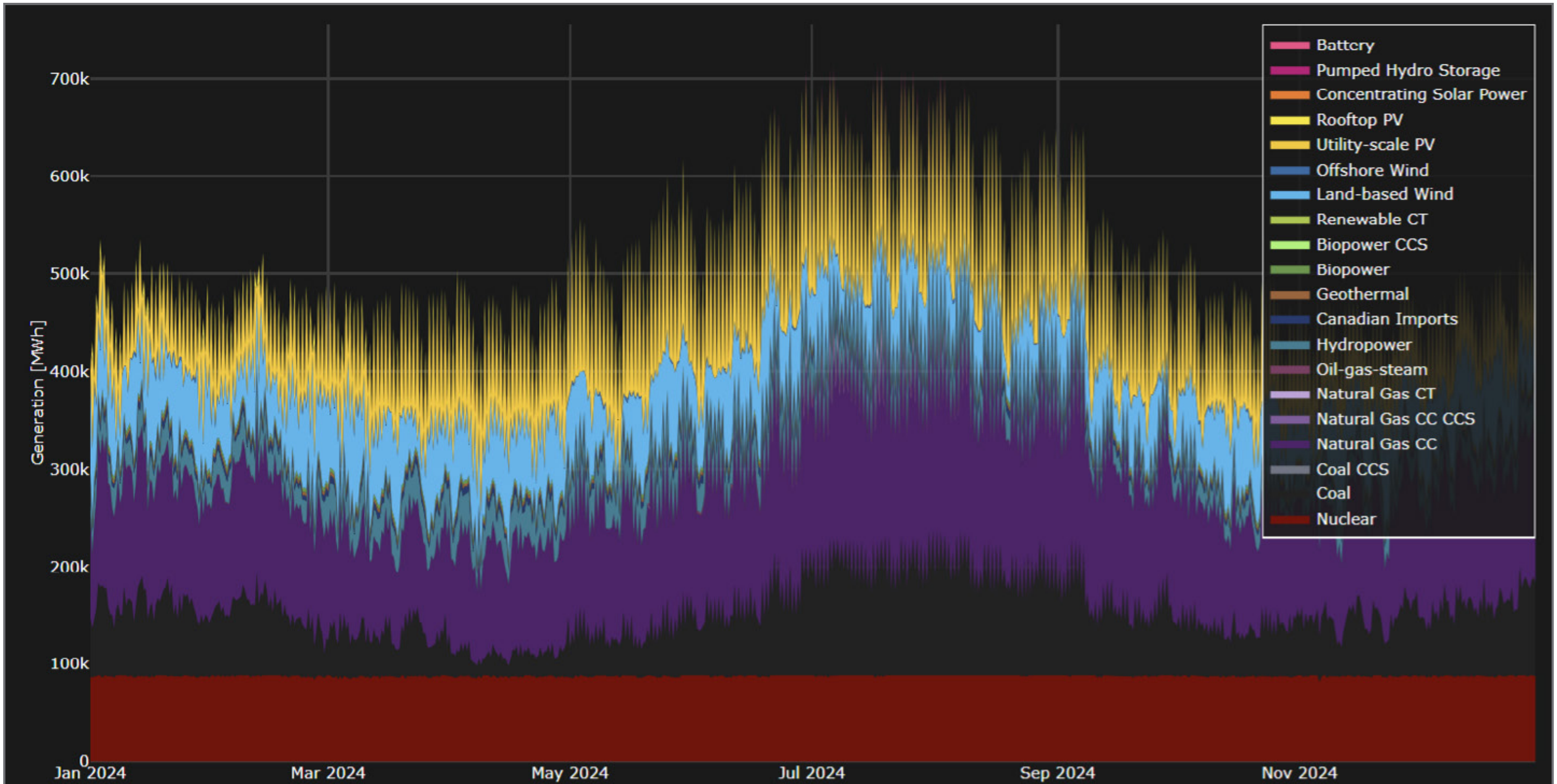


Fig. 17. Typical Mix of Generation Sources in the State of Wisconsin.[26]

Daily Load Profile Shifts

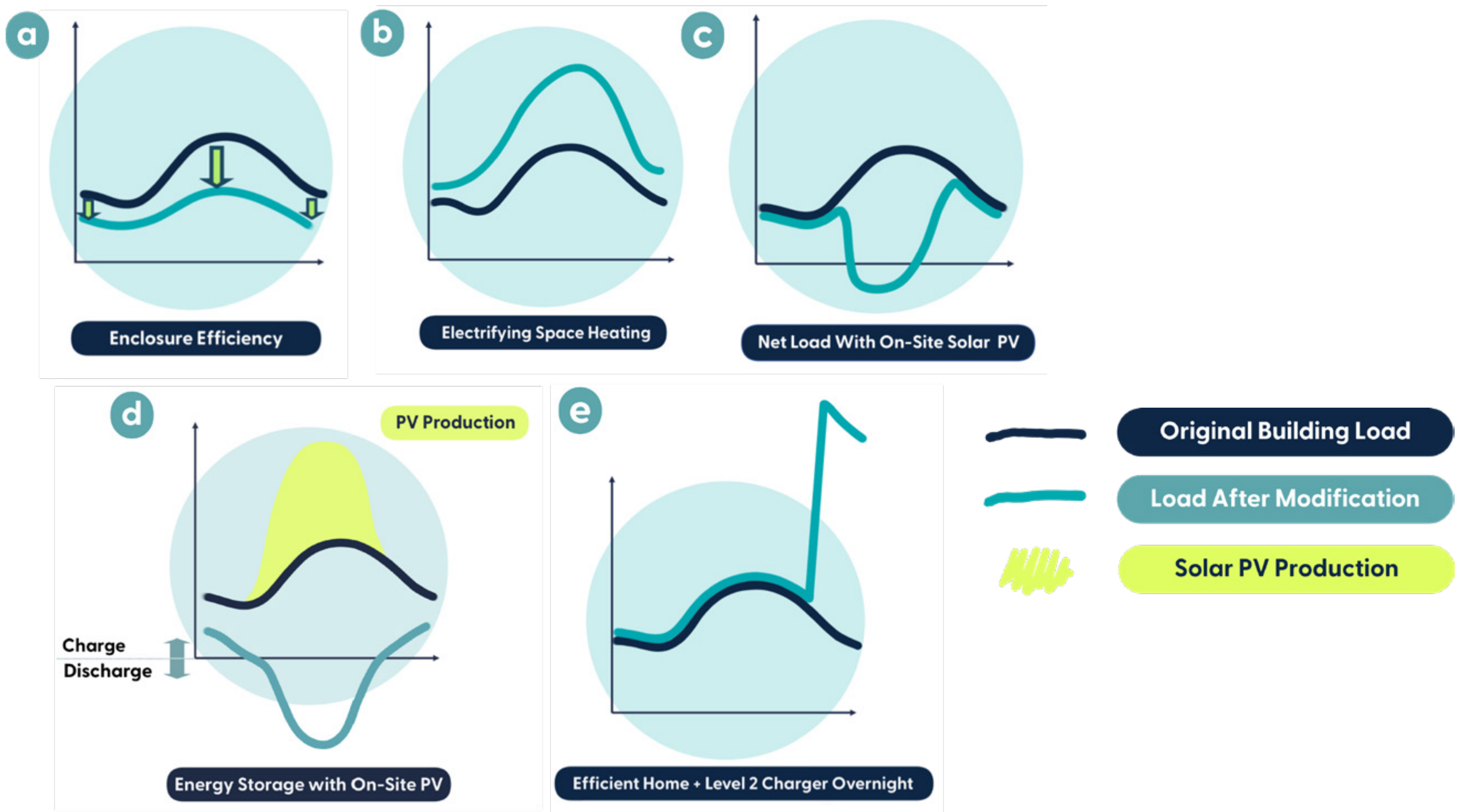


Fig. 18. Daily Load Profile Shifts for Selected Grid Impactors. (Courtesy of Phius)

3. LOAD MODIFIERS

Load 'modifiers' are described as incremental changes in building load that have occurred over the past few decades and are typically achieved through efficiency. These modifiers don't substantially change the building load, but collectively may have dampened the requirements for total supply on the grid, or at least dampened the effect of an increasing population relative to service on the grid. With only the presence of these modifiers, our existing, centralized electric grid has been generally able to operate with a "business as usual" attitude.

In this section we will discuss energy efficiency from the perspective of equipment and appliance efficiency, efficiency driven by the building enclosure, and ultra low-load passive buildings.

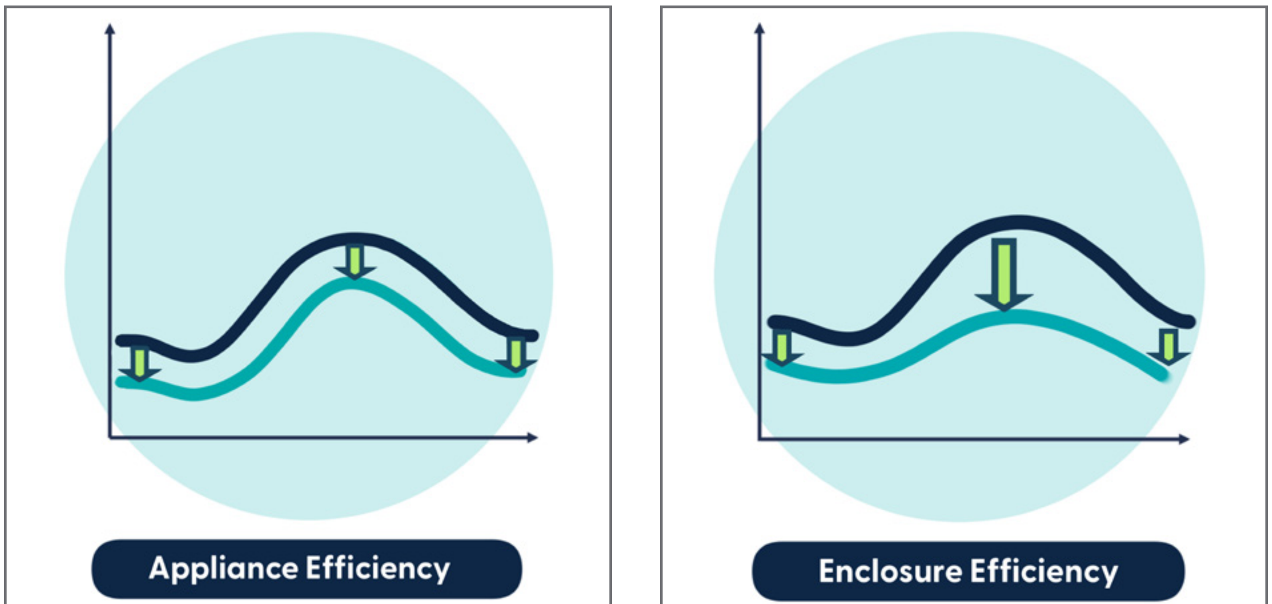


Fig. 19. The Effects of Efficiency on Building Load Profiles.

3.1 Energy Efficiency of Appliances and Equipment

Equipment efficiency, also referred to as "active" efficiency, refers to improving the operational efficiency of individual electrical devices. This may be achieved through a more efficient clothes washer, lighting, or any device that consumes electricity. These measures provide steady, linear efficiency gains, such as a 5% reduction in energy consumption year-round for baseline electrical loads (as seen in Figure 19). While many appliances and equipment have gotten more "efficient" over the years, the complexity of demands for the functionality of the devices has also increased (for example, refrigerator technology has gotten more efficient, but the average refrigerator size has also grown due to market and societal influences). In the US, the US DOE Energy Star program[29] is responsible for driving much of this efficiency evolution.

3.2 Energy Efficiency Driven by Enclosure Upgrades

Enclosure efficiency, also referred to as "passive" efficiency, is harnessed through investment in enclosure measures such as improved insulation in the walls, roof, floors, double-pane windows, and air-tightness. These measures specifically target a reduction in heating and cooling loads, and therefore provide more efficiency gains in some times of the day (and year) than others, specifically when space conditioning is needed. When considering the driving forces of daily and seasonal "peak demand", widespread reductions in heating and cooling loads can make a profound effect on the grid capacity required to support that load (as per Figure 19).

As seen in Figure 20, the stringency of US residential energy codes (as represented by the IECC, International Energy Efficiency Code) has improved incrementally—although quite spottily—over the past three decades. There is reason to believe that such improvements in stringency (including enclosure efficiency) will continue to be incremental—thus landing codes in the category of load modifier.

3.2.1 Ultra Low-Load Passive Buildings.

Buildings that incorporate significant (beyond code) passive design strategies, referred to as "passive buildings," flatten the building load profile even more than mainstream efficiency, and remove the need for space conditioning during many times of the year.

Passive design strategies can be applied to all building typologies—from single-family homes to multifamily apartment buildings, offices, and skyscrapers. Three concepts shape these design principles[31]: thermal control, radiation control, and air control.

Thermal Control is achieved by continuous insulation, or thermal resistance, in the building envelope. Typically, this is increased thermal performance resistance relative to code construction, as well as attention to detail at connection points to avoid thermal bridging.

Radiation Control is achieved through climate optimal glazing selection, considering glazing size, solar heat gain, and appropriate shading strategies.

Air Control is achieved by creating an airtight boundary in the building envelope and then employing balanced, fresh air ventilation with filtration. Heat or energy recovery is often also employed as an energy-saving or load-reduction strategy.

It is important here to distinguish between two types of "passive" building design. The focus here is on passive house or passive building as promoted by Phius, which is a holistic approach to reducing heating and cooling loads. This is not to be confused with the more dated "passive solar" concept which was promoted heavily during the 1970s and 80s, and focused primarily on reducing heating needs with a lot of south-facing glazing and thermal mass.

To reiterate and distinguish passive building from passive solar heating, the basic passive building design principles disseminated by Phius and incorporated in this Guide and the exploratory case studies create a high quality building with:

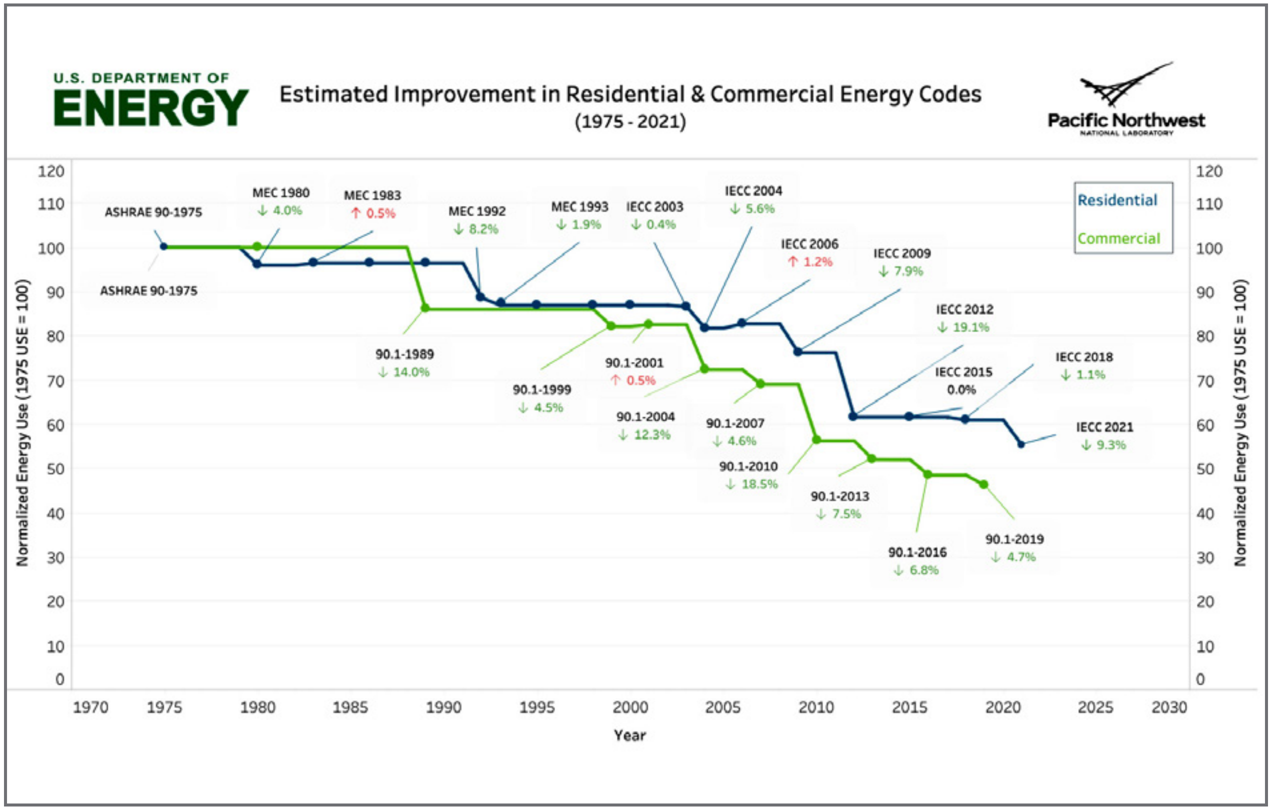


Fig. 20. Progression of Residential Energy Efficiency Stringency.[30]

- **High performance walls, roof, and floor**–with specific thermal performance requirements being determined by climate (project geographic location), building size, and typology.
- **Reduced thermal bridging in the building enclosure**–accomplished through awareness, detailing, and analysis.
- **High performance windows and doors** (fenestration)–with climate-specific requirements for U-factor (thermal performance) and SHGC (solar heat gain) values
- **Airtightness** (reduced infiltration)–as a means of improving envelope durability while reducing energy consumption, based upon leakage rate per surface area of building enclosure
- **A balanced ventilation system** with heat recovery and fresh air filtration system–to ensure superior indoor air quality while reducing energy use
- **High-efficiency mechanical, electrical, and plumbing systems**–to reduce pass-through energy use as service systems respond to reduced building heating and cooling loads
- **Quality assurance throughout the design and construction process**, achieved through a comprehensive on-site inspection and testing process. For applicable building types in the US, compliance with co-requisite high performance building programs ENERGY STAR, DOE Zero Energy Ready Homes (ZERH) and Indoor airPLUS is required.

Passive building certification through Phius may be achieved through one of two paths: performance certification or prescriptive certification. Performance certification requires computer simulated compliance with five performance targets as well as a list of required elements (such as balanced ventilation and a defined airtightness level).

The five energy targets are:

1. Peak heating load
2. Peak cooling load
3. Annual energy consumption for heating
4. Annual energy consumption for cooling
5. Annual source (primary) energy use.

Prescriptive certification, which is currently only available for single-family and duplex residences, requires compliance with a substantive list of benchmarks for factors such as wall R-value, window SHGC, airtightness via blower door testing, domestic water heater energy factor (among others) and is intended to serve as a streamlined compliance path that will produce a similar design as the performance path.

In the Milwaukee Case Study, we look at the impact such an ultra low-load building profile has on the electrical system infrastructure and its performance at the scale of a building + PV + electric storage, and at the scale of a neighborhood microgrid.

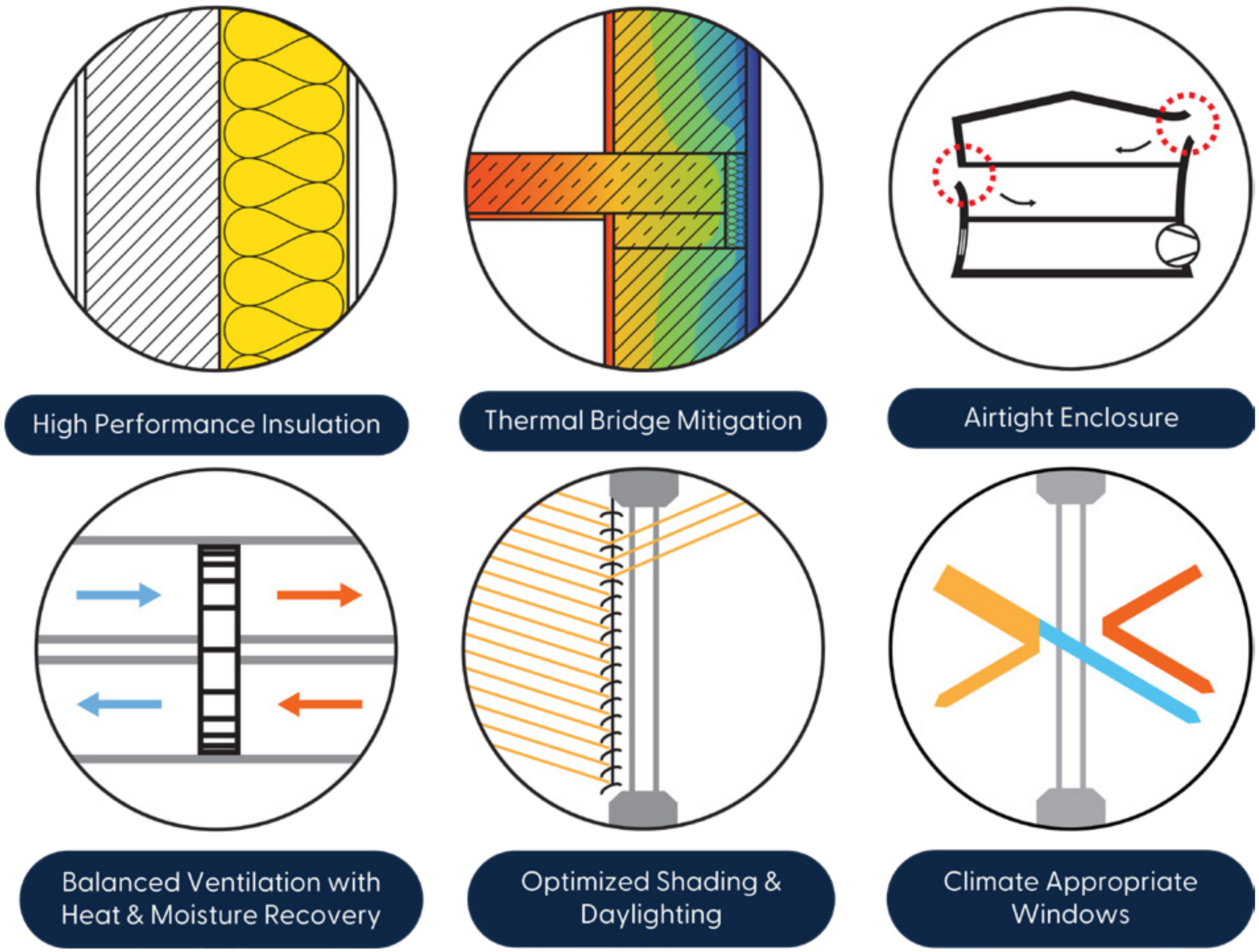


Fig. 21. Fundamental Passive Building Principles. (Courtesy of Phius)

4. LOAD DISRUPTORS

Load disruptors are the significant, rapid changes we are seeing to the energy industry today. These are characterized by dramatic changes to building electric loads, so much that the loads are doubling, tripling, or even zeroing out from the perspective of a utility grid. These disruptors not only change the building peak but also significantly change the timing of the building peak, from stable, predictable, and dealt-with to unstable, unpredictable and challenging. Together, disruptors are creating cascading effects to the supply side, causing significant challenges for grid operators, and creating new opportunities for load alignment and coordination strategies. The loads that utilities must meet that are created by disruptors may be referred to as "bursty", or "spikey".

In this section, we will discuss the electrification of space heating, water heating and cooking, EV charging, and on-site solar PV generation systems.

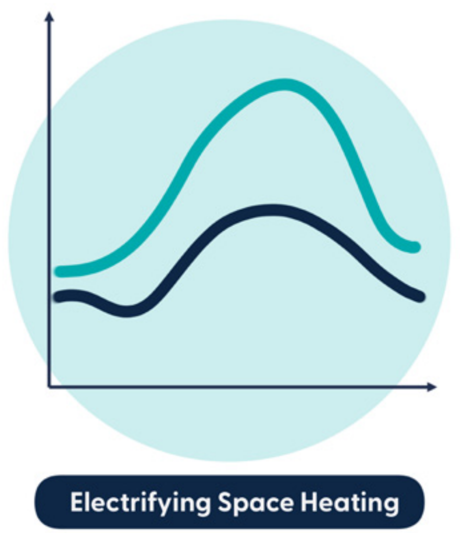


Fig. 22. The Effect of Switching from Natural Gas Heating to Electric Heating.

4.1 Building Electrification

As described above, building electrification involves converting the operation of space heating, water heating, cooking, and clothes drying from natural gas (or other fossil-fuels) to electricity. Typically, electricity was not used to meet these loads previously, so all instances of electrification add a new electric load to the grid.

4.1.1 Electrifying Space Heating

The electrification of space heating creates seasonal, climate-specific, and weather-based spikes in building load profiles (Figure 22). In some climates, the load from heating may be significantly higher (5-10x) than the load for cooling, which presents a significant increase in that building's peak demand for the utility to provide.

4.1.2 Electrifying Water Heating

The electrification of water heating creates a more year-round increase in electrical demand than the electrification of space heat. The increase may be slightly seasonal based on varying incoming water temperatures. On a daily basis (Figure 23), this load can be spikey during times of day with high demand, and during water heat-up cycles. In high-performing efficient buildings with low heating and cooling loads, the load for water heating typically becomes the most significant load, and the electrification of this load can create significant changes to the building's overall load pattern.

4.1.3 Electrifying Cooking

The electrification of cooking loads doesn't add a significant total load for the grid to supply, but can definitely contribute to peak loads and create "spikey" loads during peak cooking periods.

In existing buildings, electrification of cooktops and ovens often leads to a peak power draw higher than the kitchen was originally configured for. For this reason, electrical services (breakers and circuits) may need to be upgraded, or novel solutions introduced–such as induction stoves with built-in batteries to

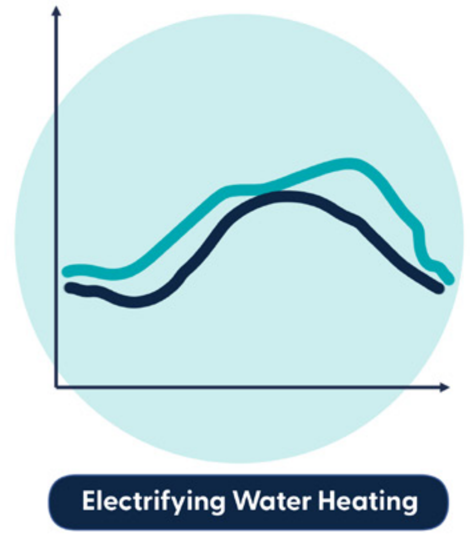


Fig. 23. Sample Effect of Switching from Natural Gas Domestic Water Heating to Electric Heating.

provide that peak power (think: double ovens and three burners coincidentally running on Thanksgiving) and avoid a service upgrade. This peak sizing instance is conceptually similar to other electrical infrastructure upgrades that can be mitigated through thoughtful avoidance of peaks, such as at individual building electrical panels all the way out to neighborhood substations, as will be discussed later.

4.2 Electric Vehicle Charging

Electric vehicles (EVs) are increasing in market share nationwide, and policies point toward accelerated adoption over the next decade. Electrically powered vehicles are another element of the "electrification" movement. When buildings integrate EV charging infrastructure on site, the EV loads are then coupled with building loads and create new load patterns that the utility must satisfy.

The electrification of transportation loads through EVs presents significant challenges to the electric grid, similar to the electrification of heating and hot water loads in buildings. But, given that EVs are mobile, and charging needs are not constant, they may be even less predictable and when aggregated at a multi-building scale, more coincident, than typical building loads.

Additionally, the power required to charge an EV may be the equal to, or even significantly greater than the typical power required for a home. For homes that start with low-loads, EV charging stations have a greater relative impact on the total load.

There are various types of EV charging stations that may be deployed on a building site, with different power draw levels and different technology[32]. Chargers are categorized as 'Level 1' or 'Level 2' depending upon their peak power draw and power capacity requirements:

- **Level 1** draws a lower power and can take more than a full day to charge a car battery.
- **Level 2** draws more power and requires less time to charge a battery.

Figure 24 illustrates the load patterns (in isolation) of Level 1 and Level 2 EV chargers that begin their work in the evening. With no responsiveness or smart charging features enabled, Level 1 charges at a lower power for a longer period of time, while Level 2 charges at a higher level for a shorter period of time. When these device profiles are superimposed on overall building load profiles the patterns seen in Figure 25 result. The relative impact of adding an EV charger is higher when building loads start lower and flatter. The relative impact of a Level 2 charger is greater than that of a Level 1 charger.

EV charger technology, in terms of load control and direction of power flow, also varies between chargers.

Some chargers introduce untimed, unmanaged 1-way power flow (from building to charger to car) – these are the most disruptive. Chargers that introduce "smart" 1-way power flow are referred to as V1G, and although they may be able to be timed, they may still cause disruptive loads.

Level 1 Chargers pull between 1.3 - 2.4 kW

Level 2 Chargers pull between 3 - 19 kW

An average, all-electric single family home in Milwaukee may have a daily peak demand between 2-15 kW. The incorporation of these charging stations can create exponentially higher loads.

Currently, there is significant research and technology being deployed to manage and control EV charging loads. An EV battery may even be able to help support the building load depending on the technology and infrastructure, which is discussed under 'Load Aligners'.

4.3 On-Site Photovoltaic (PV) Systems

On-site renewable energy systems may also be referred to as DERs, or distributed energy resources. Like EVs, distributed energy resources can be either load disruptors or load aligners, depending upon their usage and dispatch.

On-site, rooftop PV systems are becoming increasingly common as a strategy for customers to reduce their utility bills, to provide building-level resilience, as well as a means to meet 'Net Zero Energy' goals. "Net Zero" is becoming an increasingly popular goal for high-performance buildings.

Many rooftop solar systems are installed "behind-the-meter," and the energy production from the PV system is first used to satisfy any building load occurring while it is being produced. If the building load is met, any extra PV power is sold back to the grid. Because the production is "behind-the-meter," the utility is only able to see the 'net load' of the building energy use, that is, the remaining load "net of" renewable energy production at each moment in time.

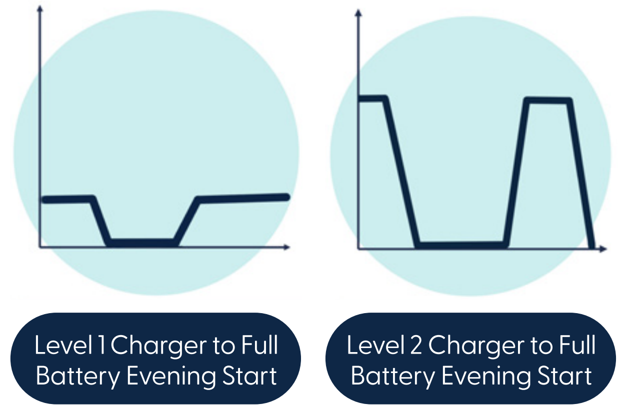


Fig. 24. Generic Stand-Alone Load Profiles of Level 1 and Level 2 EV Chargers.

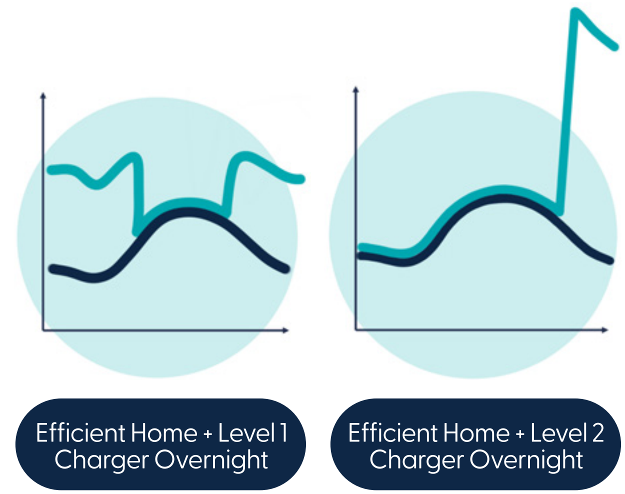
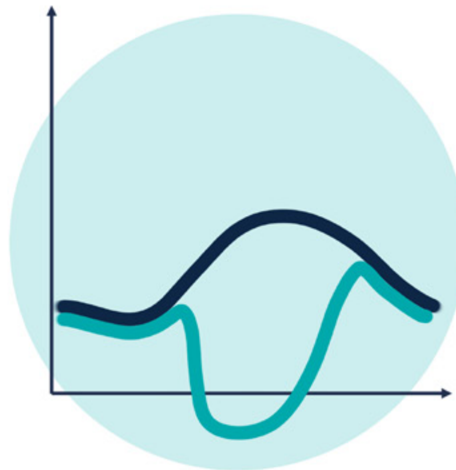


Fig. 25. Total Building Load with Level 1 and Level 2 Chargers Incorporated into an Efficient Building.

PV creates a steep decline in 'net load' when the sun comes out, a dip in the middle of the building load during daylight hours, and a steep incline when the sun goes down.

When considered at scale, and considering the resource availability to meet the steep adjustments in load, this becomes a significant challenge to meet. This phenomenon is often referred to as the "Duck Curve" (squint your eyes and apply some imagination to Figure 26), where the "belly of the duck" drops low in the middle of the day[33].

For "net zero" buildings, typically only about a third of the renewable energy that is generated on site is actually consumed on-site. The remaining two-thirds is sent to the main electrical grid, which acts as an outlet for necessary overproduction. For this reason, "Solar + Storage" is becoming a more common design concept–which increases on-site consumption of renewable power and also provides some energy reserves in case of grid outages. Energy storage is discussed further under 'Load Aligners'.



Net Load with On-Site Solar PV

Fig. 26. Net Load Profile with On-Site PV (also known as The Duck Curve).

NET ZERO BUILDING *refers to a concept where the total amount of energy used by the building on an annual basis is equal to or less than the amount of renewable energy produced (or procured) over the year.*

In a net zero building, the renewable energy that is applied to "net" out the energy use isn't required to align with when the building is using energy.

But, over the course of the year, it is required to net out to zero.

V1G *is the term used to describe one-way "smart charging". This is referred to as "smart" because it uses a data connection to allow the EV and EV user to optimize charging time based on electricity rates and availability.*

5. LOAD ALIGNERS

There is a significant challenge in addressing load disruptors while also addressing the fact that grid decarbonization requires integrating more intermittent, renewable energy resources into the existing, centralized electric grid.

Many technologies have come to market to address the alignment of energy supply (generation) and energy demand (load) to more wholly utilize the intermittent supplies. These are often referred to as "grid-Interactive" technologies and strategies, which are capable of addressing the timing of energy use and harnessing load flexibility. ***They utilize capability provided by on-site distributed energy resources (DERs) to reduce, shed, shift, modulate, or generate electricity.***

Distributed energy resources (DERs) is a generic industry term that refers to anything that:

- stores, consumes or generates electricity
- is located in the distribution grid, and
- may be able to respond to a grid signal.

Buildings that harness these technologies may be referred to as "grid-interactive efficient buildings"[35] (GEB). GEBs must be smart, connected, and efficient. They have flexible loads and are able to share that flexibility as a service to help support grid reliability.

In this section, we will discuss energy storage, demand response (flexibility, shedding, shifting), smart loads, electric vehicle charging, and direct current.

5.1 Energy Storage

Energy storage devices are a classic example of load aligners. For the most part, they are utilized to store excess energy when supply is greater than demand, and feed it back when demand is greater than supply. By definition, energy storage devices or systems directly help align and coordinate available supply with demand. Storage may also be used to provide resilience by maintaining critical loads when power generation is not available (either local generation isn't available in the case of rooftop solar, like at night, or during a main grid power outage). Storage may happen in large, utility-scale installations, at the individual building level in the form of modestly sized batteries (Figure 27), or (as discussed later in this report) thermal storage utilizing the building enclosure like a battery.

5.2 Demand Response

Demand response is generally defined as a building's ability to change load, manually or automatically, based upon a grid signal. Historically, demand response has been thought of as reducing load but can also refer to an increase in load.

Demand response programs have been around for awhile, often targeted at large power consumers, such as manufacturing plants. In these programs, customers are paid to reduce their energy consumption during peak times; it is less expensive for a utility to pay the consumer to use less than it would be for the utility to ramp up to ensure more

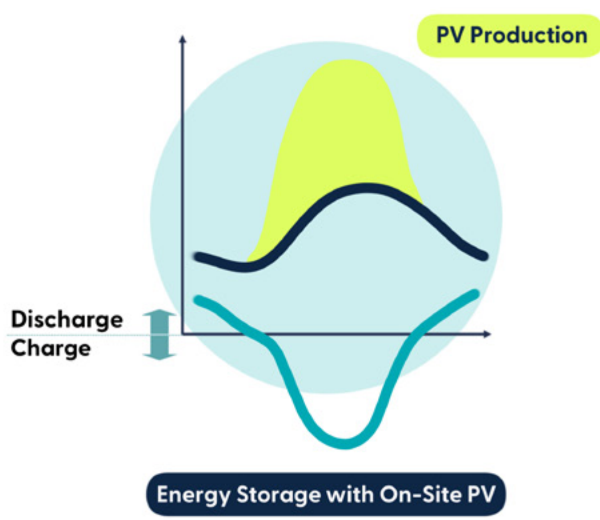


Fig. 27. Example of Charging Scenario in a Building with On-Site PV and Where On-Site Consumption of Renewable Energy is a Priority for the Owner.

> **"Buildings consume power indifferent to grid conditions, blind to the high costs and threats to reliability posed by high peak demand and grid stress; inflexible to opportunities offered by variable, carbon-free renewable power sources; and senselessly missing the smart and connected technology revolution.**
>
> **Grid-interactive efficient buildings (GEBs) can remake buildings into a major new clean and flexible energy resource. GEBs combine energy efficiency and demand flexibility with smart technologies and communications to inexpensively deliver greater affordability, comfort, productivity and high performance to America's homes and commercial buildings."[34]**
>
> **– David Nemtzow**
>
> Director, DOE Building Technologies Office

The term demand response should not suggest outcome deprivation or adjustment. *Many loads are flexible, and timing can be adjusted and still achieve the same outcome. For example, when you plug your computer in, you know that you want it to remain charged, at least in the time period predicted ("45 minutes until fully charged"). However, an occupant may not care if it is mostly charged in the first 15 minutes, and then steadily charged for the remaining 30 minutes, or quickly charged for 5 and then paused for 5, as long as the outcome is met. The same is true of devices like a refrigerator - it must maintain an interior setpoint to keep the food fresh, but the timing of the compressor is not important, as long as that outcome is met. Same with interior spaces.*

generation. Similar, but less direct, programs are targeted at smaller buildings – sometimes in the form of notifying customers to reduce energy use to avoid spiking prices or in the form of "time-of-use" rates that are generally simplified to "on-peak" and "off-peak" pricing.

5.2.1 Demand Flexibility

Demand flexibility is the capability of load profiles to be shaped – up and down, earlier or later – typically in response to pre-established price changes (tariffs) or direct real-time utility signals, to provide benefits to building owners, occupants, and/or to the grid.

5.2.1 Flexible vs. Non-Flexible Loads

There are two basic categories of loads suited for demand response:

Non-Flexible, Timing-Based: A load where the timing influences an occupant's experience (the person cares). This may be an appliance like a cooking device (you want to cook a burrito when you are hungry) or a stereo or TV.

Flexible, Outcome-Based: A load where the timing of operation may not influence an occupant's experience (the person simply seeks an outcome). Space heating and cooling are examples – as long as the comfort setpoint is met, the occupant is not really concerned about when the device itself is running.

5.2.2 Load Shedding

Shedding can occur for loads that are non-critical and, thus, can be shed altogether. These are most often space-conditioning loads. When you set your heating setpoint down from 74F to 70F, the "load shed" is the difference between the effort required to maintain the higher versus the lower setpoint. Such shedding is generally a temporary adjustment (Figure 28), for a short period of time, and may be called upon on short notice. This is different from efficiency measures, which provide a sustained avoidance to some peaks.

5.2.3 Load Shifting

Load shifting (Figure 29) can occur with loads necessary to provide some service but where the timing of operation can be adjusted with no hindrance to the outcome. This most commonly involves adjusting the time when large appliances are run, preheating or pre-cooling a space, preheating hot water tanks, or adjusting temperature levels in water heaters.

Passive buildings inherently provide the potential for load flexibility with space-conditioning loads. Passive building enclosures create a thermal (heat) storage system that can be tapped into easily and deeply. Essentially, a passive building can defer or mitigate heat flows which effect is then passed along to the electric loads that handle such thermal loads.

Through outage and resilience studies, it has become clear that passive buildings can completely cut space-conditioning system output for significant periods of time (in many cases for multiple hours, depending on the desired indoor condition and the setpoint before if any pre-conditioning was used) with little to no impact on the interior temperatures, especially when load shifting is used to slightly pre-condition a space before the load is shed.

5.3 Smart Loads

To facilitate automated load shifting, load shedding, and demand response, devices can be enabled to receive signals and manipulate their load based on that signal. Some new devices, such as heat pump water heaters and thermostats, are being sold with smart technologies embedded. There are also options for integrating new technologies into existing equipment. These controls allow for quick, automated

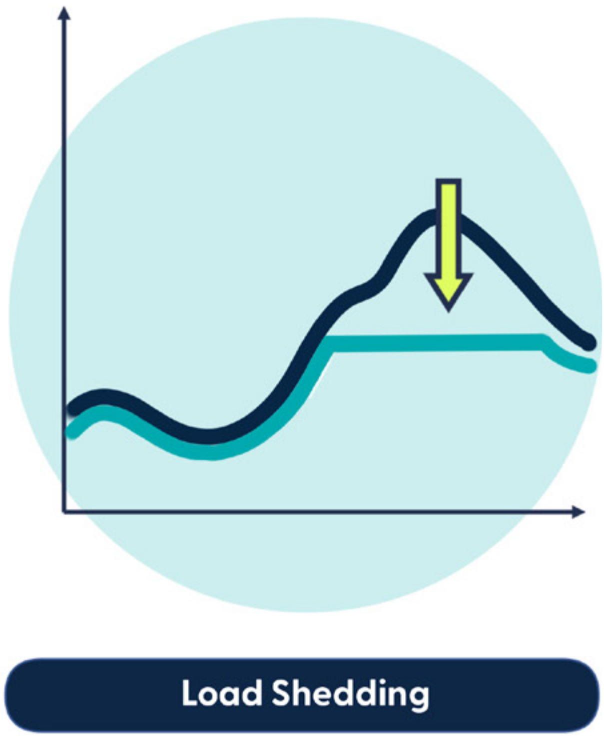


Fig. 28. Impact of Load Shedding on Peak Demand.

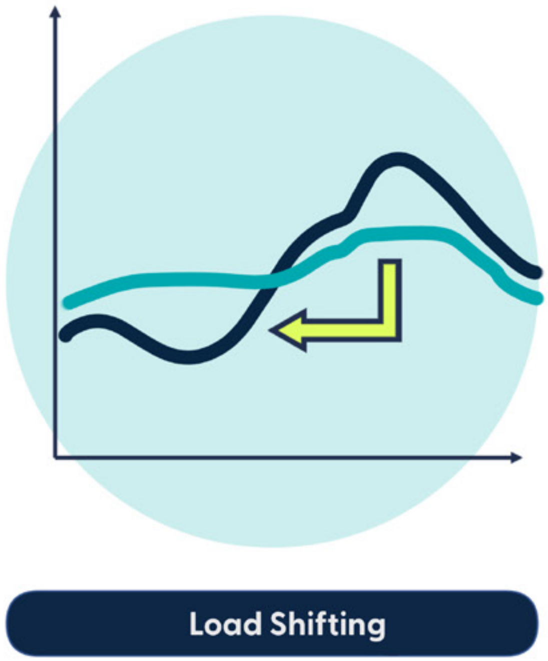


Fig. 29. Impact of Load Shifting on Peak Demand.

responses to signals that do not hinder outcomes for occupants. Often these signals are seen as a top-down approach, where signals are being sent from a central utility to orchestrate the other end.

There are also new, bottom-up solutions where smart devices are able to collaborate with one-another based on a signal (price or similar) which provides information about energy availability, etc. In these cases, devices are programmed with operational requirements and can take different paths to meet those requirements based on the signals. For more detailed information on smart loads see the Smart Grid Application Guide.[36]

5.4 Electric Vehicle Charging

As discussed above, electric vehicle charging can create a grid-disruptive load. But, with the correct technology, may also be able to support alignment between supply and demand at both the building level and the grid level.

V2H, "vehicle-to-home", or V2B "vehicle-to-building" refers to technology that allows for bi-directional power flow[37]. This is helpful for buildings with excess renewable production (such as with rooftop solar PV), that can receive power and then give it back to the building. It helps create a locally balanced energy environment and can be thought of as mobile electricity storage that provides services similar to stationary electricity storage.

V2G, "vehicle-to-grid" refers to technology that allows for bi-directional power flow to and from the charger directly into the electric grid (such as in a parking lot, rather than through a building). This is beneficial for the grid, especially those with intermittent renewables, and can help balance supply and demand.

5.5 Direct Current (DC) Distribution Networks

DC distribution networks are load aligners that rather than adjusting the timing of building loads with available energy supply, align the "type" of load to the power supply. These distribution networks can exist at a building level or even neighborhood (microgrid) level.

Power can be transmitted two ways, via AC (alternating current) or via DC (direct current). See Section 1.1 for some historical background. The primary technical difference between AC and DC is the pattern of current flow as shown schematically in Figure 30. The primary useful distinguisher between the AC and DC is what devices operate on each.

The existing electric grid transmits AC electricity, but buildings and equipment within buildings use both AC and DC electricity.

Fig. 30. AC versus DC Electricity (the Vertical Axis is Voltage, the Horizontal Axis is Time).

Solar photovoltaic panels (PV) are a common distributed energy resource, serving both the main grid (macrogrid) and microgrids. PV systems natively output DC power. In a typical AC distribution network, the DC electricity produced by a PV array is converted to AC by inverters that enable its use in buildings.

The use of DC distribution networks can be advantageous when combined with on-site PV to reduce inefficiencies caused by conversion losses. The DC power produced by PV can be fed directly to DC loads in a building or stored locally in batteries reducing conversion losses and reducing the need for conversion equipment. Many current electrical loads can be served directly with DC power and the number of devices that can be fed is increasing. For this reason, among others, there is increasing interest in utilizing a DC power (or hybrid AC/DC) distribution networks in buildings. It is estimated that DC distribution within buildings can improve electrical system efficiency on the order of +/- 10%.[38]

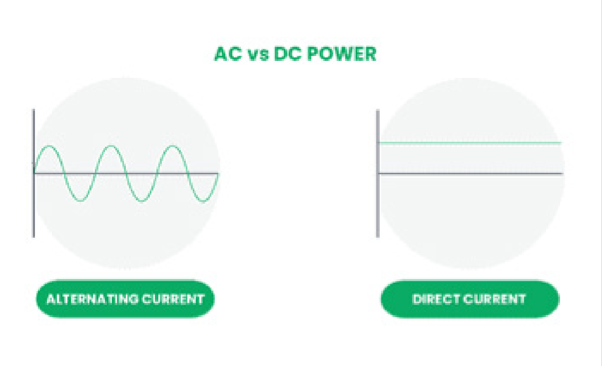


Fig. 30. With AC power, the Direction of the Current Reverses and Concurrently the Voltage Changes. With DC Power, the Direction of the Current and Voltage is Always Constant.

6. MICROGRIDS

6.1 What is a Microgrid?

A microgrid is one technical solution to many of the challenges and opportunities that were introduced above. Numerous definitions of "microgrids" have been developed by various organizations. The fundamental characteristic of a microgrid is conveyed by the prefix "micro" meaning small (either absolutely or relatively small). A microgrid is particularly small compared to a macrogrid. Macro implies large—typically a grid that is community-wide, statewide, or multi-state in scale (as per Figure 2). Typical microgrids serve neighborhoods (Figure 31), campuses, military bases, but can be as small as two homes. The scale of interest in this Guide is the neighborhood. The building type of focus is smaller-scale residential (single-family, duplex, and six-flat homes). The principles in this Guide, however, work equally well for other building typologies—in fact, mixed-use typologies with load diversity may be ideal for microgrids.

The US Department of Energy (DOE) defines a microgrid[39] as "a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island mode." Key characteristics under this definition include loads, energy resources, interconnections, a clear system boundary, and a connection to the larger grid.

Another definition[40] states that "microgrids are small-scale, low-voltage power systems with distributed energy sources, storage devices and controllable loads. They are operated connected to the main power network or "islanded" in a controlled, coordinated way." Low voltage here implies typical residential/commercial service voltages (120-480V), not the lower voltages (12-24V) typical of control systems. Both definitions are fairly vague about the DERs (distributed energy resources) that are part of this system; this definition adds storage and control of loads to the DOE list of characteristics. The ability to "island," or disconnect from the larger grid when desirable, is part of both definitions.

Figure 32 illustrates a residential microgrid in the context of this Guide. Key elements of this type of microgrid are discussed below—these include some features that would historically be considered building-related and features that are more likely to have been seen as grid-related. The boundaries between buildings and grid, however, start to blur in the realm of microgrids. The relationships between the various components and their relative sizing will be discussed in the Milwaukee Case Study.

6.1.1 Key Components of a Microgrid

A discussion of the key components of a residential microgrid is provided here. These components, and their characteristics, can substantively affect the performance of a microgrid—and are modeled in the research that underlies this Guide. This discussion defines these components and explains their role in the operation and success of a microgrid. Measurement units and terminology are also presented as appropriate.

Generally, a microgrid is a local energy system within a clear boundary and controlled network that contains, at a minimum, four main components:

1. Energy **generation** (supply),
2. Energy **consumption** (demand)
3. Energy **storage**, and
4. Energy **control** objectives or operating system

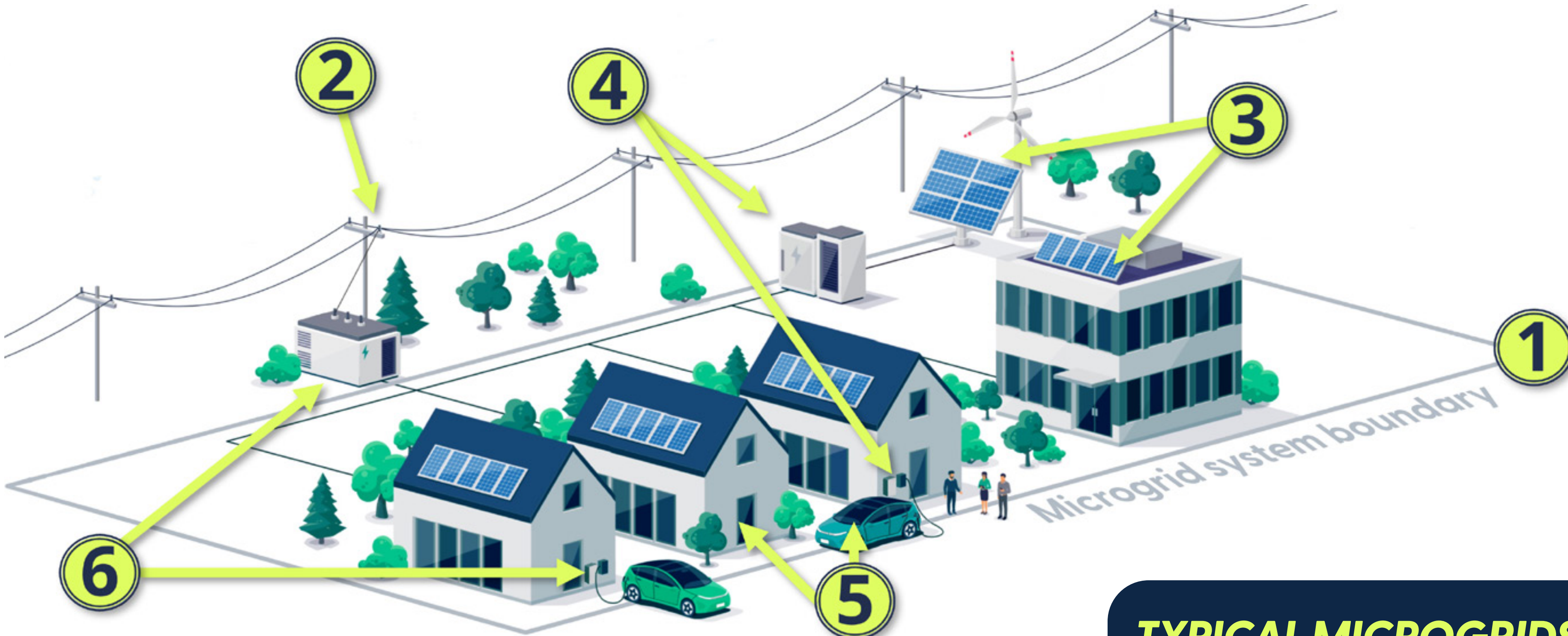
Each of the basic building blocks of a microgrid (Figure 33) is discussed in greater detail below.

Energy Generation/Supply: A source of power (or energy) is required for any scale electrical grid. In a conventional grid, as discussed above, this source is typically a large-scale fossil-fueled power plant, nuclear power plant, or a hydropower installation. Photovoltaic (solar PV) panels are the most common distributed renewable energy resource used in microgrids. Wind is also sometimes used as a renewable source of electricity in larger capacity installations (typically remote from a building). PV exhibits greater architectural flexibility than wind. By definition, a microgrid must have access to both grid and local electricity sources.

Energy Consumption/Loads: Traditional building occupancy drives residential electrical loads—generated as occupants use heating, cooling, hot water, appliances, and lighting. As discussed above, there are many ways to transform the shape of these loads – from appliance and enclosure efficiency, to load shifting and shedding. These traditional loads are starting to be supplemented by the charging of electric vehicles (EVs) and morphed by electrification policies.

Energy Storage: The storage of electricity allows a system to match customer needs (building loads) with desirable supply resources (generation); thus electricity generated at noon by a PV module can be used to charge an electric vehicle in the late evening. Batteries are the most common electrical storage approach in microgrids.

Load Control: This feature of a microgrid acts as an internal dispatcher to match electricity supply with electricity load within the system boundary. Electricity from a PV array on the roof of 'Building One' can be sent to loads in 'Building Two' or to a battery near 'Building Three' as best serves the microgrid. Successfully and economically satisfying the needs and priorities of the microgrid is the key purpose of load controls. A clear understanding of an owner's priorities (low cost, resilience, decarbonization) defines the control objectives.



1 Microgrid System Boundary

2 Point of Connection to Main Grid

3 Stand-Alone and/or Building-Mounted Energy Supply

4 Stand-Alone and/or Building-Mounted Energy Storage

5 Loads from Buildings (and sometimes EV Chargers)

6 Microgrid and/or Building-Focused Control Systems

Fig. 31. Isometric Diagram of a Prototypical Microgrid.
Adapted from Electricity Networks Aotearoa (ENA) Microgrids graphic[46]

TYPICAL MICROGRIDS

serve neighborhoods (Figure 31), campuses, military bases, but can be as small as two homes. The scale of interest in this Guide is the neighborhood.

The building type of focus is smaller-scale residential (single-family, duplex, and six-flat homes). The principles in this Guide, however, work equally well for other building typologies... *[Section 6.1]*

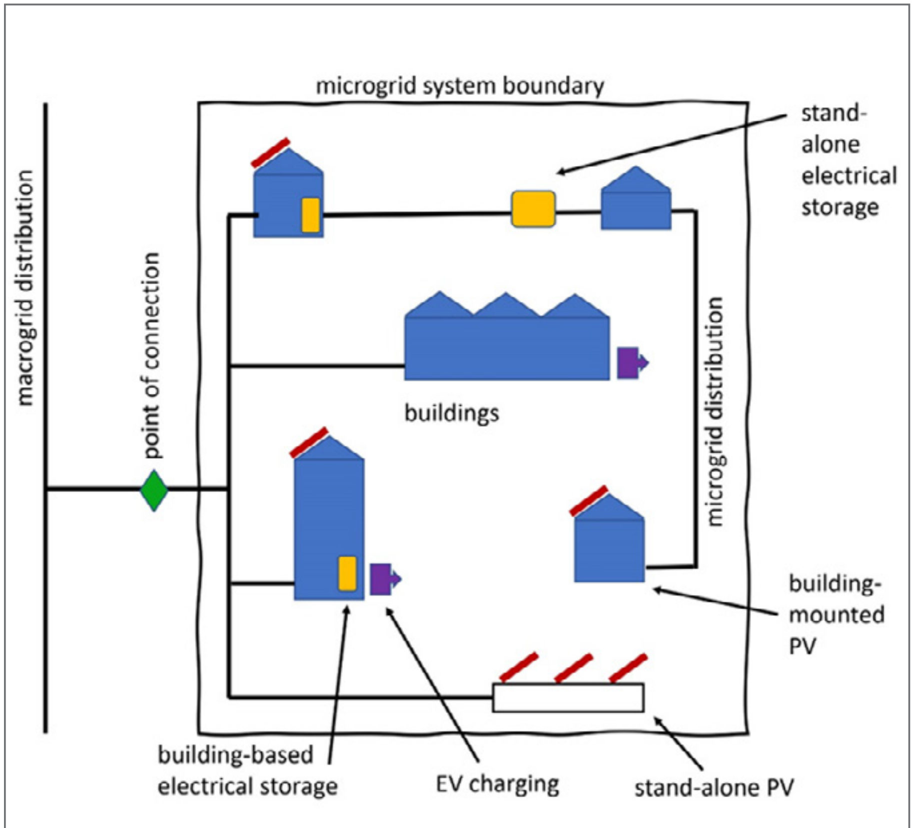


Fig. 32. Schematic Diagram of a Neighborhood Microgrid. [Courtesy Phius]

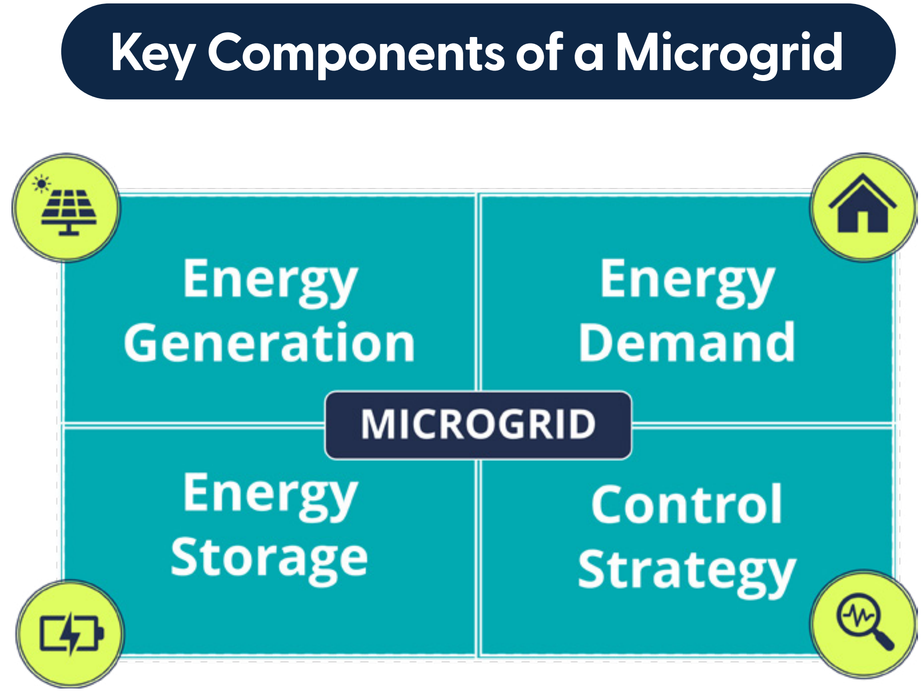


Fig. 33 Fundamental Components of a Microgrid. [Courtesy Phius]

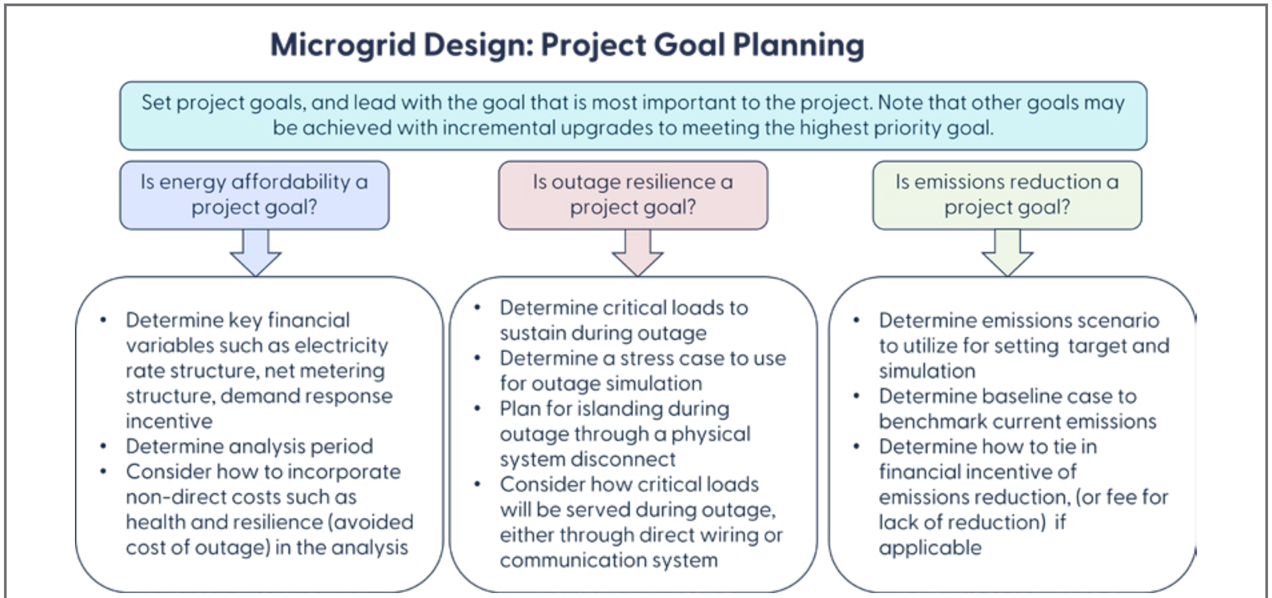


Fig. 34. Microgrid Design Initial Thought Map: Determining Project Goals.

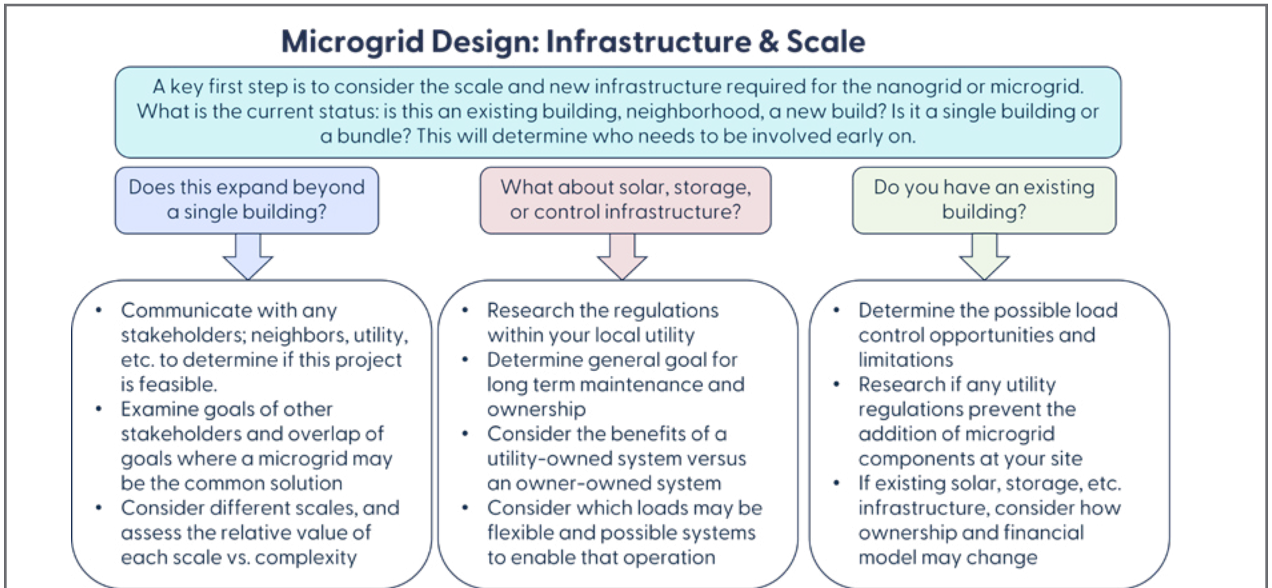


Fig. 35 Microgrid Design Initial Thought Map: Determining Scale and Infrastructure.

Beyond the core components that create a microgrid, the elements below support the identity of a microgrid as a distinct physical and logical entity.

System Boundary: the system boundary in a microgrid is somewhat arbitrary (usually established for convenience in management or scale or cost), but must be clearly defined for a viable microgrid. Buildings in a microgrid need not be contiguous but must (at least today) be close enough to be connected by power wiring. A microgrid can have buildings added or removed if necessary through revision of the wiring connections.

Connection to Macrogrid: a connection between the microgrid and the macrogrid is a defining feature of microgrid design. This is referred to as a “point of common coupling” or PCC. Without an interconnection, the smaller grid would be a standalone grid that cannot benefit the larger grid or benefit from the larger grid.

Islanding: this concept refers to the ability of a microgrid to disconnect from the marcogrid and function solely within its own boundary when it is advantageous to do so. Such disconnection typically occurs when the macrogrid shuts down, often as a result of an adverse weather event; perhaps because of problems with transmission or generation capacity. Islanding provides resilience, allowing a microgrid to continue providing electricity to the loads within the microgrid system—either at full or reduced capacity depending upon system design.

Interconnections: a grid is a network that requires interconnections in order to function, through the exchange of data and/or power. In an electrical grid, interconnections are currently established through wiring between the various buildings that constitute the grid and associated power sources. All elements in a microgrid will be connected (directly or indirectly) to all other elements in the microgrid.

6.2 MICROGRID BENEFITS

Microgrids present an exciting opportunity because they can address many different challenges at once. The combination of all of the benefits of the main electric grid joined with a local energy source and storage allows for greater optimization of supply and demand. Several benefits simply not possible with only a macrogrid also arise.

6.2.1 Resilience and Reliability

Resilience to outages is a primary design driver for many of the microgrids that exist today. Many were configured to prioritize and maintain uninterrupted power supply for buildings and campuses where a shut-down in operation is costly or damaging. By nature of their design principles, microgrids are self-contained systems, capable of disconnecting from the main grid. This removes vulnerability to large-scale grid outages and reliance on exposed transmission and distribution infrastructure to carry power to the buildings. True reliability, however, can only be accomplished through a microgrid with battery storage capabilities.

Local resilience of electricity is only possible with a microgrid. Any building connected solely to a macrogrid is subject to power outages whenever the utility grid goes down. Islanding and appropriately sized site-based DER (storage in particular) are necessary to accomplish the extent of resilience desired by the client. Bridging a 1-hour grid outage is simpler and cheaper than bridging a 5-day outage. Powering half the loads in a building during a grid outage is easier and cheaper than powering all building loads.

A microgrid will not necessarily be more reliable than a macrogrid, in fact the opposite may be true. But with a macrogrid-interconnected microgrid in place, overall reliability will increase because both grids now have a backup system in place.

6.2.2 Energy Independence and Affordability

Microgrids that harness local renewable energy generation reduce dependence on external fuel sources and costs, providing security through renewable resources and harnessing excess supply to use energy cost-effectively. The "fuel cost" for renewable resources is free, but that free renewable energy isn't always available so additional investment in storage to align supply with demand is required.

The financial case for on-site energy generation and storage can vary widely between projects due to variances in utility allowances, macrogrid electricity rate structures (flat-rate versus time of use), incentives for decarbonizations, or fines for carbon emissions. A handful of financial factors are studied in the Milwaukee Case Study, which provides insight into financial feasibility for "business as usual" cases, as well as a general range of costs associated with meeting various resilience and decarbonization goals.

On top of this, depending on the buildings serviced by the microgrid, there is a benefit (or avoided cost) known as the the value of lost load (VoLL), which essentially represents the costs of an electrical outage. The avoided blackout or service interruption could help support the financial analysis for investment in microgrid systems, and seems to be the motivation for many of the microgrids which exist in the U.S. today.

6.2.3 Increased Utilization of Renewables

Optimization of the balance between generation, storage, and orchestrated demand through the microgrid control objectives allows for greater alignment of building load with intermittent, clean energy resource availability.

This concept is often referred to as the "hardening" of renewable resources, i.e. increasing their utilization factors. As more renewable resources are integrated into the grid, ensuring the resources that are utilized as efficiently and effectively as possible is very important. This includes avoiding transmission congestion and curtailment in order to realize the financial gains and make the case for more renewable energy.

Large scale, centralized renewable energy projects take a lot of time, planning and coordination to execute – they have to tie into the existing grid.

> **"The process of approving projects for interconnection is so complicated and expensive that it's forcing developers to abandon the projects they were planning to build."**
>
> **– Shayle Kann**
>
> CATALYST Podcast
> "Understanding the Transmission Bottleneck"

6.2.4 Avoided Transmission and Distribution Infrastructure Upgrades

By creating a local energy system (microgrid) and bringing renewable energy generation closer to the load, the network capacity required to deliver power to a building is decreased. With today's existing electric grid, there are many challenges related to transmission and distribution line congestion where renewable power is available on one end, but the wires physically cannot handle the load and the utilization of renewable energy is therefore curtailed. This will likely continue to be an issue in areas with large-scale renewable systems until infrastructure is upgraded.

Similarly, there are significant challenges related to interconnection of new renewable generation systems to the existing transmission network. There is a queue, and each potential new solar farm, wind farm, etc. requires significant analysis and approval to connect to the existing grid. This is predicted to be one of the largest hurdles to more renewable energy integration at the macrogrid scale. Microgrids can be deployed quicker than the planning horizon for new transmission lines and as a result have the potential to offset investment in new infrastructure and accelerate decarbonization.

6.2.5 Services to the Macrogrid/Society

Microgrids can offer significant benefits to the macrogrid. The single 'point of common connection' with the main grid decreases the unpredictability of the building loads served by the microgrid, which in a typical macrogrid would be treated as individual loads each with their own level of "risk" and requirement for generation capacity (+safety factors) to meet their load. Capturing the 'net balance' of that series of buildings, through the single connection point can decrease capacity requirements at the macgrorid level.

Microgrids can also deliver grid resilience back to the macrogrid through other services such as demand response (shifting, shedding, and alignment of loads) and voltage regulation, which is becoming a larger challenge with increased renewable energy penetration into the grid-mix.

6.3. Microgrid Design Process

To a large extent the design of an electric microgrid is similar to the design of other building infrastructure systems (such as roadways, storm drainage, communications). Design steps that are common to such multi-building efforts are summarized in Table 1–with emphasis on what is important relative to a microgrid. There are several big-picture concerns, however, worth highlighting:

- A microgrid will most likely involve multiple building owners; thus details of ownership, maintenance, and stewardship need to explored prior to embarking on design work; development of a condominium may be a reasonable parallel;
- It is highly likely that a microgrid will interact with state regulations for electric utilities; these constraints and implications must be understood before beginning design work;
- Because some of the benefits of a microgrid may be hard to quantify (such as peace of mind regarding security or resilience), the true objectives underlying such considerations must be explored and understood prior to design;
- Microgrids are not business as usual and may involve proprietary components (especially for controls), thus turnkey projects–relative to the electrical elements–may be common.

The microgrid design process is a multi-variable, multi-objective design problem. The nature of this situation is suggested by the thought-mapping diagrams seen in Figures 34 and 35. This is not at all unique to microgrids, and is in fact common to many aspects of building design (such as designing a wall assembly, an HVAC system, a comfortable and healthful indoor environment). What is different about microgrid design is that there are no conventional design codes or standards to help bound the initial design variables and only a small body of examples to suggest a logical starting point for initial analysis. Designers often use some form of trial and error to reach a successful design conclusion, but lots of variables (load profiles, PC capacity, battery size, control schemes) and many possible outcomes (reduced carbon, reduced energy costs, increased reliability) can make for lots of trials (and dead ends). The Milwaukee Case Study provides some assistance in navigating this complex territory. **The following recommendations are provided as initial and generic design guidance:**

- Consider building efficiency as the starting point for a successful microgrid–the more efficiency the better (within the constraints of individual building budgets and practicality); code-minimum is not adequately efficient.
- Clearly and rationally identify critical loads to be met under resilience criteria; higher loads and greater duration may rapidly increase the cost of microgrids for resilience.
- Consider future scenarios even if statistically uncertain–what is certain is that historical data on temperature, humidity, storm frequency and severity are not going to prevail in the near future.
- Remember that there isn't a one-size-fits all solution, the microgrid design will be specifically shaped based on the priorities of the owner.
- Understand that a microgrid is essentially a series of connected components. Even if your building system cannot get all of the way to microgrid level, there are benefits that can be harnessed through load control, energy generation and energy storage on site. The full potential is harnessed through orchestration of all of these in a nanogrid/microgrid setting.
- Even though there isn't a common packaged "microgrid solution", utilize incentives and guidelines that may target the individual components of a microgrid.
- Research other successful microgrid designs, they're out there.

MICROGRID DESIGN PROCESS

STEP 1 Decide to Develop a Microgrid

Either as a self-justified entity or as a means toward meeting building objectives. In some cases a microgrid will be the desired project outcome; in other cases a microgrid will be the most rational way to accomplish desired building-level objectives.

EXAMPLE

A microgrid might be the development objective (as a demonstration project or power provider); or, a microgrid might be the most logical way to accomplish a building outcome such as decarbonization

INVOLVE

Development Team (Developer, Owner, Architect, Engineers, Contractor)

STEP 2 Establish Project Goals

This involves the owner's project requirements (OPR) relative to a microgrid, which involves setting design intent and design criteria:

Design Intent: *a verbal narrative of what is to be accomplished (does not include methods).*

Design Criteria: *specific measures of success in meeting intent (does not include methods); criteria are design targets.*

EXAMPLE

Intent: *Allow building to function when utility grid goes down.*

Criteria: *Power a defined subset of building loads for no less than 24 hours in the event of macrogrid failure.*

INVOLVE

Architect and Owner–with assistance from subject matter experts (Utility Representatives, Electrical Engineers, Contractors)

STEP 3 Create a Plan for Success

Engage the design commissioning process, an owner's quality assurance process engaged to assure that an owner gets the outcomes they anticipate.

EXAMPLE

The commissioning provider will confirm that the OPR (relative to a microgrid) are conceptually doable and develop a quality assurance plan to ensure success in meeting those goals.

INVOLVE

Commissioning Provider, Design Team, Owner, Contractor, Speciality Equipment Suppliers

STEP 4 Research

Investigate possible means of achieving design intent within the criteria constraints to establish whether a microgrid can deliver the project design criteria and whether a microgrid is the most logical means of doing so.

EXAMPLE

Review precedents and case studies, catalog local resource data (utility tariffs and reliability; solar energy potential), conduct back of the envelope analysis.

INVOLVE

Architect, Consulting Engineer (mainly electrical)

STEP 5 Establish Budget

For both design and for construction. Consider a microgrid as an investment versus an expense; look at cost-benefit analysis, risk mitigation, and externalities; a microgrid will typically include multiple buildings and costs at the residential scale may be shared amongst participants.

EXAMPLE

Typical construction estimating sources may be useful for developing an initial budget; REOpt software may also assist in developing a rough estimate using default system values for key components.

INVOLVE

Owner, for funds; Architect, for design;
Contractor, for construction

STEP 6 Develop Conceptual Design & Logical Feasibility Study

Evaluate likelihood of success. The conceptual design of a system can often be a sketch showing proposed system components and how they are interconnected and arranged; this is usually adequate to allow for a logical analysis of success potential–does it look like it will work without violating the laws of physics?

EXAMPLE

A one-line diagram of the proposed system with labeled components and a non-technical narrative of how the thing works under likely operational scenarios–avoid wishful thinking and fiction; commissioning provider will evaluate from OPR perspective.

INVOLVE

Architect, Engineer, Specialist Consultant, Commissioning Provider

STEP 7 Identify Critical Design Variables

These are inputs associated with the proposed solution– there will be many. Moving from conceptual to schematic design requires preliminary sizing of system components, which requires knowledge of design variables for input into analytical calculations.

EXAMPLE

Cost of energy (time of day, demand, escalation, inflation); definition of critical loads (what and how long); identification of carbon emissions parameters; estimated cost of components–building efficiency, battery, PV, controls.

INVOLVE

Architect, Owner, Engineers, Contractor, Specialty Consultants and Equipment Suppliers

STEP 8 Develop Schematic Design & Practical Feasibility Study

Develop solution and evaluate extent of success. This evolution of the design solution will be grounded to the project (site- and building- specific) and responsive to project constraints and aspirations expressed in the OPR.

EXAMPLE

To-scale plans, sections, details, and outline specifications of the system in the context of the associated buildings; draft construction documents will confirm physical "fit," updated estimate will confirm economic "fit".

INVOLVE

Architect, Engineer, Consultant, Manufacturer's Representatives

STEP 9 Iterate and Optimize

Consider optimization studies on the proposed solution to determine the best combination of elements that will meet design criteria. Run appropriate analyses to improve the proposed solution—most likely using software because of the large number of variables and their interactions.

EXAMPLE

BEOpt, REOpt, PVWatts; use sensitivity analysis to determine relative impact of various components and tweak solution to improve results and/or reduce costs.

INVOLVE

Architect, Engineer, Specialist Consultant, Commissioning Provider

STEP 10 Engage Design Development

Produce construction drawings and specifications; finalize cost estimate. Quality for innovative systems will reside in explicit specifications; commissioning provider will complete a final OPR review of proposed solution.

EXAMPLE

This stage of the microgrid design process is not much different from the conventional design process—although commissioning is highly recommended.

INVOLVE

Architect, Engineer, Specialist Consultant, Commissioning Provider

STEP 11 Engage Contractor & Install System Components

Work to ensure system objectives are understood. Pre-bid and post-bid conferences are recommended to ensure that the owner's project requirements are clear. Contractor to carry out installation of the microgrid components according to specifications provided.

EXAMPLE

This step is typical of design-construction handovers where the systems involved are unusual or specialized.

INVOLVE

Architect, Engineer, Specialist Consultant, Commissioning Provider, Contractor

STEP 12 Commission the System

Complete tests to confirm that system meets the design criteria -- this is highly encouraged to ensure success. This stage also includes training appropriate personnel and transferring the systems manual to owner.

EXAMPLE

See ASHRAE Guideline 0 or Standard 202 for details on the commissioning process and its implementation

INVOLVE

Architect, Engineer, Specialist Consultant, Commissioning Provider, Contractor, Speciality Equipment Suppliers, Owner's O&M Personnel or Provider

STEP 13 Project Closeout

Close out design and construction, benchmark performance, and operate project. Provide the microgrid owner/operator with readily available information that will allow most beneficial use of the system over its lifetime.

EXAMPLE

Accessible data on design criteria and measured operating parameters will allow the owner/operator to track in-use system performance and identify areas where performance is degrading.

INVOLVE

Architect, Engineer, Specialist Consultant, Commissioning Provider, Contractor, Specialty Equipment Suppliers, Owner's O&M Personnel or Provider

7. MILWAUKEE CASE STUDY

7.1 Overview

This section of the Guide provides summary results of a pilot study exploring the interactions of design variables in a neighborhood microgrid setting. The purpose of the study was to explore patterns of performance that result from combinations of building energy performance targets, on-site renewable distributed energy generation, energy storage, and building-grid interactions. This research looks only at small-scale residential buildings assembled into a neighborhood block (Figure 36) typical of Milwaukee, Wisconsin (climate zone 5A). The climate examined is also that of Milwaukee—and conventional climate data sources were used (versus future climate projections).

This detailed case study builds upon the concepts outlined above and focuses on simulating all-electric buildings of varying typology and enclosure levels in order to understand the impact of the enclosure on estimated annual energy use, carbon dioxide emissions, peak loads and critical loads. These building-level results were used to then assess the feasibility of meeting project goals that extended beyond the building enclosure design with the incorporation of on-site renewable energy and energy storage systems. Such goals might include decarbonization in the form of on-site emissions reduction, or resilience in the form of sustaining a critical load at the building or neighborhood level during a macrogrid outage.

The report outlines the simulation setup, modeling process diagrams, detailed inputs for the simulations and results. You will find a comprehensive list of simulations completed at the building-scale and neighborhood scale (with and without the energy generation and storage elements), and 28 "case-level" results, which group similar simulation objectives to study the impact of the enclosure or other variables on the infrastructure required to meet the defined simulation objective.

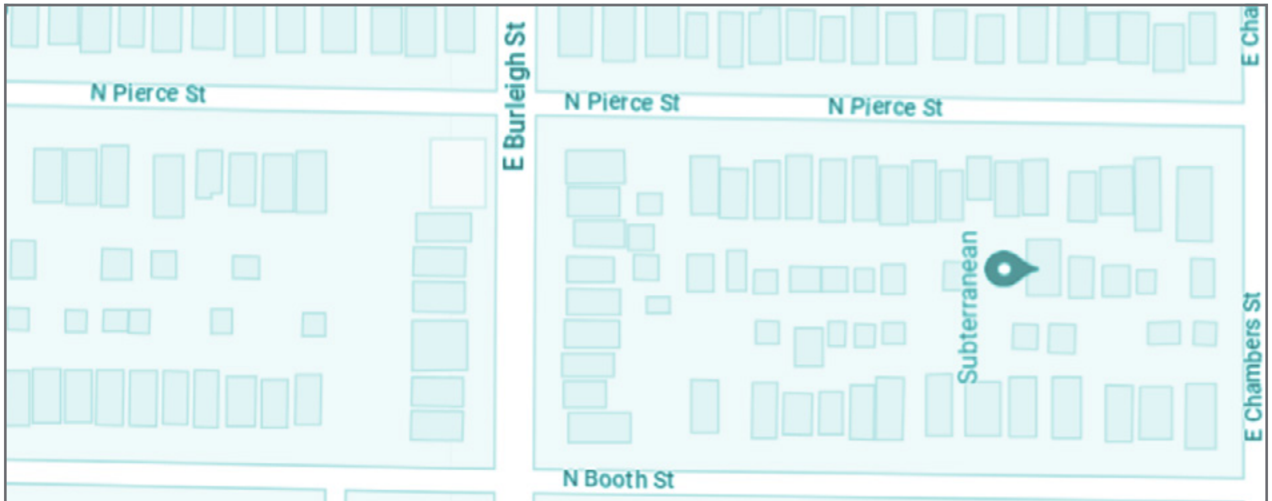


Fig. 36. Typical Neighborhood Block Layout in Milwaukee, WI. [Source: Google Maps]

Neighborhood Makeup	Units per Building	Number of	Total Dwelling	Enclosure Variants		
Single Family	1	15	15	Existing Building	IECC 2021 Compliant	Phius CORE 2021 Compliant
Duplex	2	5	10			
6-Flat	6	5	30			
Neighborhood	-	**25**	**55**			

Table 2. Matrix Showing Building Types within Typical Study Block with Building Efficiency Level Variants.

7.2 Summary of Key Findings from Case Study

7.2.1 Building Load Results

The buildings studied varied in enclosure performance but used identical all-electric mechanical systems for heating, cooling, and hot water, identical large appliance models, and consistent assumptions for lighting and plug loads.

In discussing the results, we will refer to these building enclosures as follows:

- Existing/Baseline Building Stock Enclosure = **existing**
- IECC 2021 Compliant Enclosure Building = **code**
- Phius CORE 2021 Compliant Enclosure Building = **passive**

On average:

- An **existing** building used **1.8x** more annual energy and had a peak load **2.5x** higher than a **code** building.
- An **existing** building used **2.6x** more annual energy and had a peak load **5.5x** higher than a **passive** building.
- A **code** building used **1.5x** more annual energy than a passive building and had a peak load **2.2x** higher than the **passive** building.

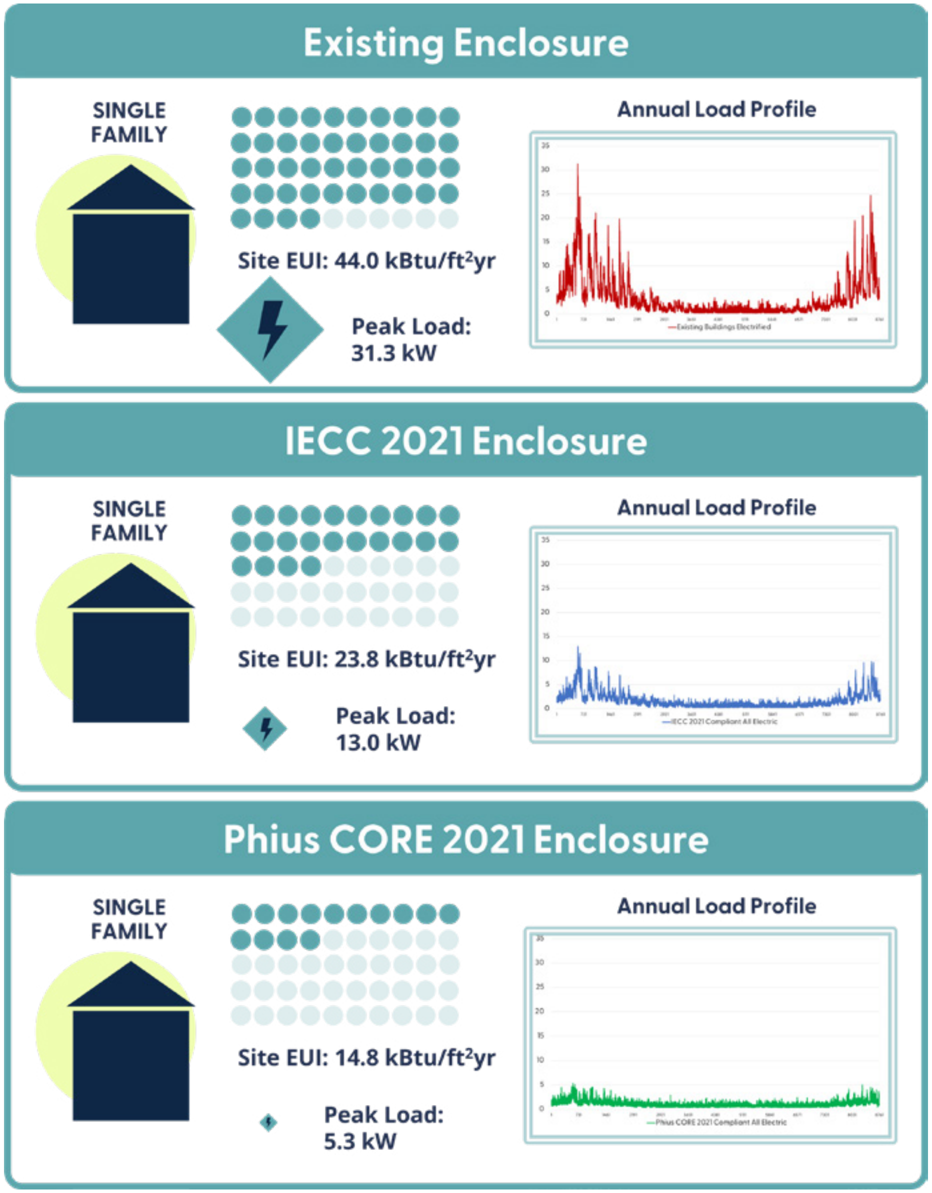


Fig 37a. Summary Results (EUI, Peak Electrical Load, and Electrical Load Profile) for Three Single-Family Buildings, Varying Enclosure Levels. (Courtesy of Phius)

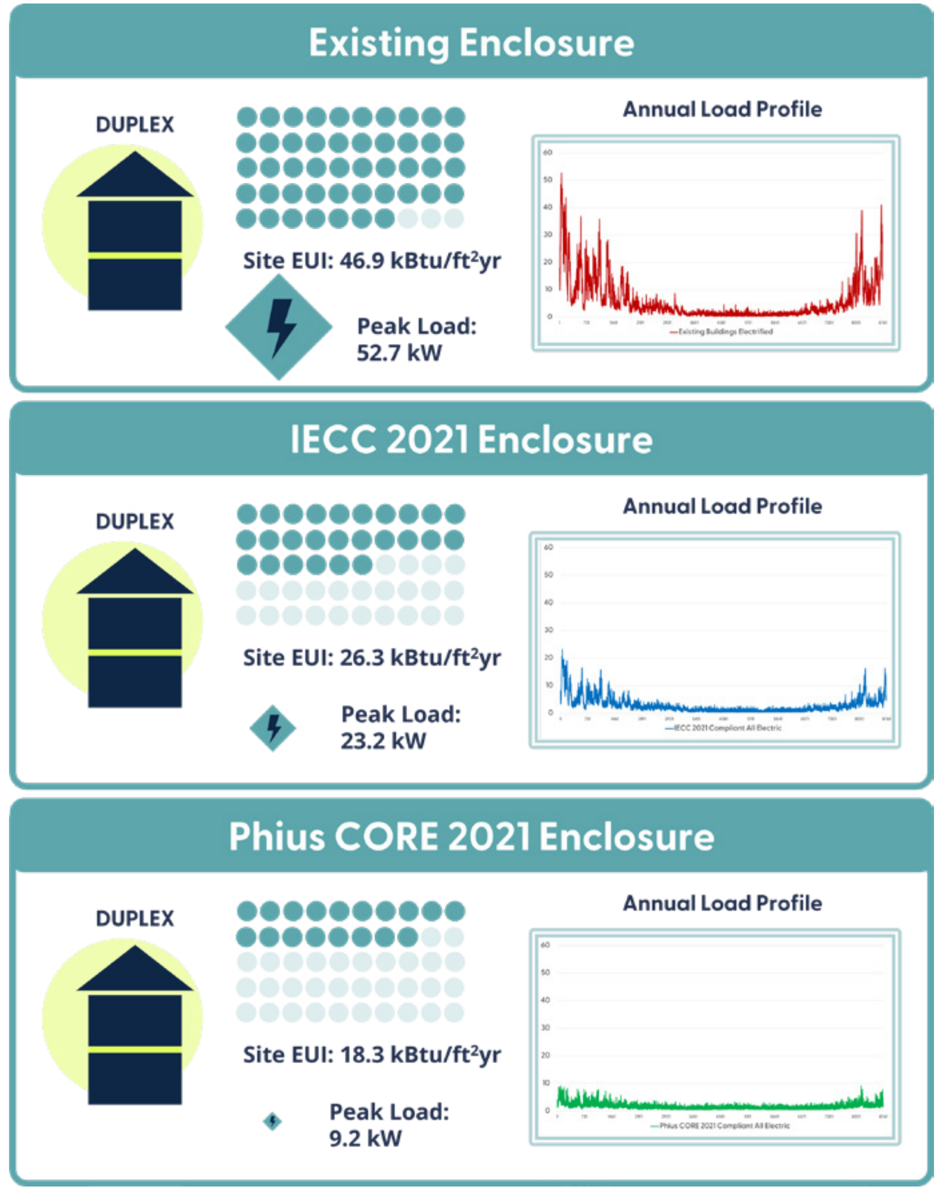


Fig 37b. Summary Results (EUI, Peak Electrical Load, and Electrical Load Profile) for Three Duplex Buildings, Varying Enclosure Levels. (Courtesy of Phius)

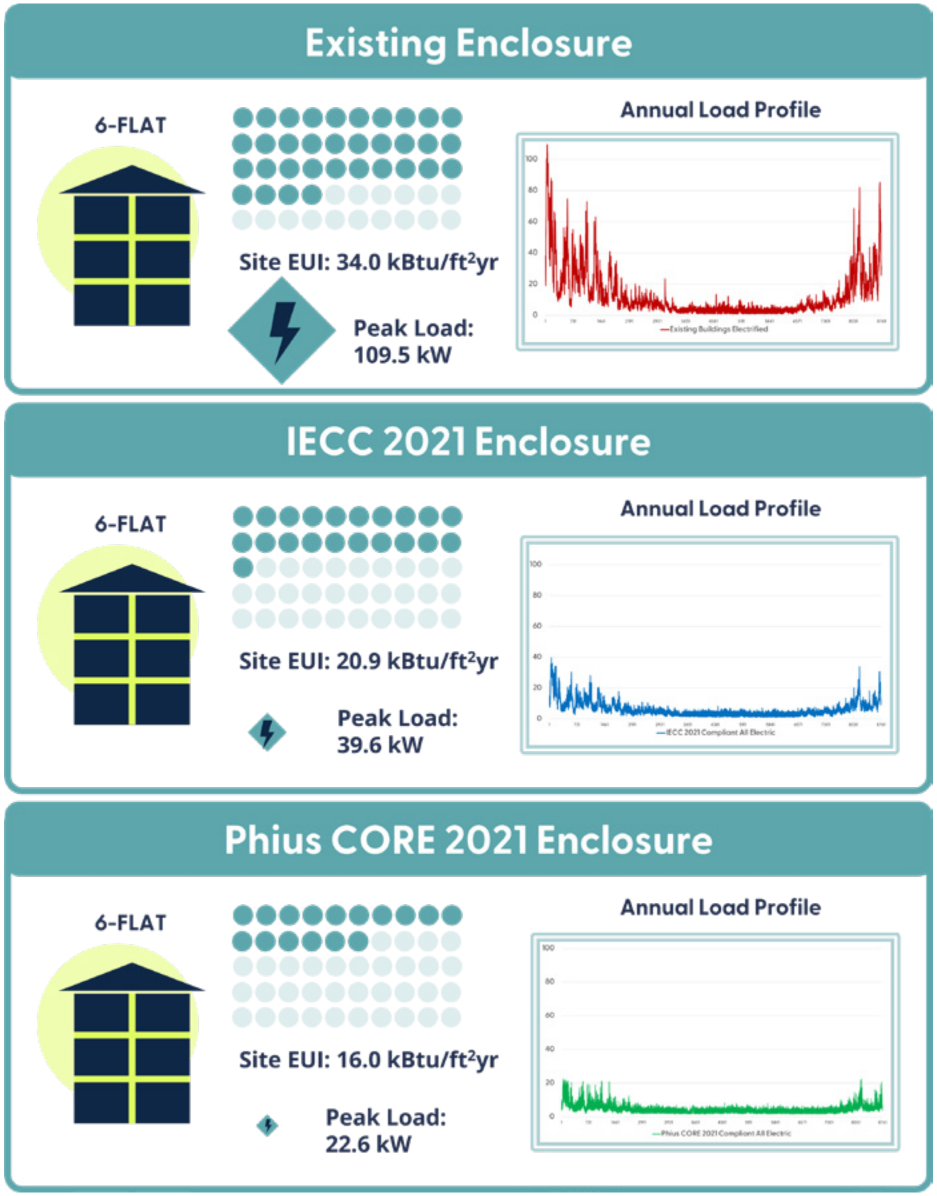


Fig 37c. Summary Results (EUI, Peak Electrical Load, and Electrical Load Profile) for Three 6-Flat Buildings, Varying Enclosure Levels. (Courtesy of Phius)

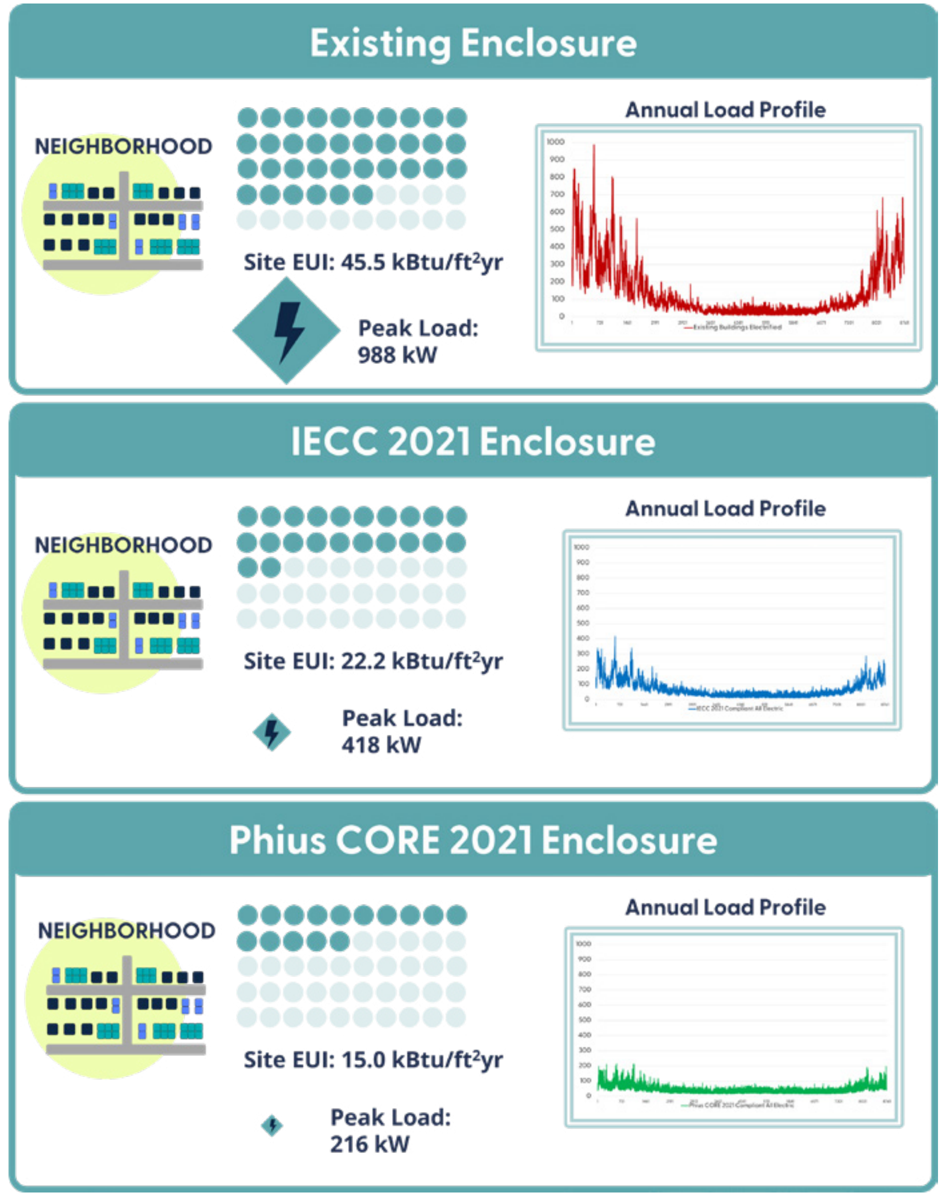


Fig 37d. Summary Results (EUI, Peak Electrical Load, and Electrical Load Profile) for Three Neighborhood Loads, Varying Enclosure Levels. (Courtesy of Phius)

Single Family	Typical Load				Flexible Load		
	Gas	All Electric			All Electric		
	Existing*	Existing	Code	Passive	Existing	Code	Passive
Annual Energy Consumption (kWh/yr)	70,124	28,392	14,110	8,726	23,102	12,370	8,197
Site EUI (kBTU/ft^2yr)	112.4	45.5	22.6	14.0	37.0	19.8	13.1
Peak Electric Load (kW)**	3.1	31.3	13.0	5.3	31.3	13.0	5.1
Peak Critical Electric Load (kW)***	N/A	24.4	9.9	7.2	N/A	N/A	N/A

Duplex	Typical Load				Flexible Load		
	Gas	All Electric			All Electric		
	Existing*	Existing	Code	Passive	Existing	Code	Passive
Annual Energy Consumption (kWh/yr)	117,463	49,564	23,321	14,151	41,481	20,278	13,368
Site EUI (kBTU/ft^2yr)	143.8	60.7	28.5	17.3	50.8	24.8	16.4
Peak Electric Load (kW)**	4.4	52.7	23.2	9.2	52.7	23.2	9.2
Peak Critical Electric Load (kW)***	N/A	37.5	13.5	6.0	N/A	N/A	N/A

6-Flat	Typical Load				Flexible Load		
	Gas	All Electric			All Electric		
	Existing*	Existing	Code	Passive	Existing	Code	Passive
Annual Energy Consumption (kWh/yr)	256,090	109,723	53,748	40,121	93,268	48,003	38,140
Site EUI (kBTU/ft^2yr)	95.2	40.8	20.0	14.9	34.7	17.8	14.2
Peak Electric Load (kW)**	14.0	109.5	39.6	22.6	109.5	39.6	22.6
Peak Critical Electric Load (kW)***	N/A	80.0	24.3	16.9	N/A	N/A	N/A

Neighborhood	Typical Load				Flexible Load		
	Gas	All Electric			All Electric		
	Existing*	Existing	Code	Passive	Existing	Code	Passive
Annual Energy Consumption (kWh/yr)	2,919,624	1,222,316	596,998	402,250	1,020,278	526,954	380,498
Site EUI (kBTU/ft^2yr)	108.6	45.5	22.2	15.0	37.9	19.6	14.2
Annual Carbon Dioxide Emissions (kg CO_2/yr)		927,702	452,330	303,839	730,293	383,854	282,594
Peak Electric Load (kW)**	96.3	987.7	417.7	216.1	960.2	417.7	212.8
Peak Critical Electric Load (kW)***	N/A	743.3	319.3	221.7	N/A	N/A	N/A

*For the baseline case, the existing enclosure with natural gas fired equipment for space heating, water heating, and cooking. The total energy includes gas energy use, converted to kWh equivalent as needed.

**The Peak Electric Load (kW) only includes the peak driven by electrical energy use. For the baseline, gas-equipment case, this does not include the power required for space heating or water heating. This serves as a proxy for the scale of electrical service currenly provided to the building.

***The Peak Critical Electric Load (kW) is the peak of the electrical energy usage required for the defined critical (outage) load profile.

Table 3. Building Level Results, Energy Consumption & Peak Loads for Typical Building Loads and Flexible Building Loads.

`Annual CO2 emissions were estimated by multiplying hourly energy use (kWh) by a dynamic hourly CO2 emissions profile (kg CO2/kWh) based on today's emissions (more details on emissions profiles can be found in the Case Study). For the baseline case, hourly gas use (kBTU) was multiplied by a flat emissions rate.

In all instances, the electrified cases (see Table 4) had a lower estimated annual carbon dioxide emissions.

On average:

- An **existing** building with natural gas equipment creates **40-50% more carbon emissions annually** than the same building with the existing enclosure and high performance all-electric space heating and water heating equipment.
- An **existing** building with natural gas equipment creates **200% more carbon emissions annually** than the same building with the **code** enclosure + high performance all-electric space heating and water heating equipment.
- An **existing** building with natural gas equipment creates **500% more carbon emissions annually** than the same building with the **passive** enclosure + high performance all-electric space heating and water heating equipment.
- A **existing** all electric building produces **200%+ more carbon emissions annually** than the same building with the **code** enclosure
- A **existing** all electric building produces **300%+ more carbon emissions annually** than the same building with the **passive** enclosure
- A **code** all electric building produces **40-60% more carbon emissions annually** than the same building with the **passive** enclosure

	Typical Load			
	Annual Carbon Dioxide Emissions (kg CO_2/yr)			
	Gas	All Electric		
	Existing	Existing	Code	Passive
Single Family	31,896	21,610	10,724	6,603
Duplex	53,156	37,578	17,656	10,686
6-Flat	117,656	83,131	40,638	30,273
Neighborhood	1,332,505	927,702	452,330	303,839

	Flexible Load			
	Annual Carbon Dioxide Emissions (kg CO_2/yr)			
	Gas	All Electric		
	Existing	Existing	Code	Passive
Single Family	N/A	16,441	9,007	6,083
Duplex	N/A	29,682	14,696	9,925
6-Flat	N/A	67,053	35,054	28,346
Neighborhood	N/A	730,293	383,854	282,594

*Table 4. Building Level Results, Estimated Annual CO2 Emissions for Typical and Flexible Building Loads, including Baseline Gas Cases *Note: 0.127 kg CO2/kBtu assumed for the use of natural gas on-site*

All in all, given the role of architects in the design of the enclosure, architects can play a large role in slashing emissions reductions at the forefront through the design of high performance enclosures beyond code minimums.

The flexible loads (those that incorporated shedding heating/cooling load based on high grid emissions), show great potential in reducing emissions even further, with:

- **25-30% annual emissions reductions** from typical loads for the **existing enclosure**;
- **15-20% annual emissions reduction** from typical loads for the **code enclosure**, and;
- **5-10% annual emissions reduction** from typical loads for the **passive enclosure.**

As the total load decreases, the amount of load to shed also decreases and therefore results in lower overall impact.

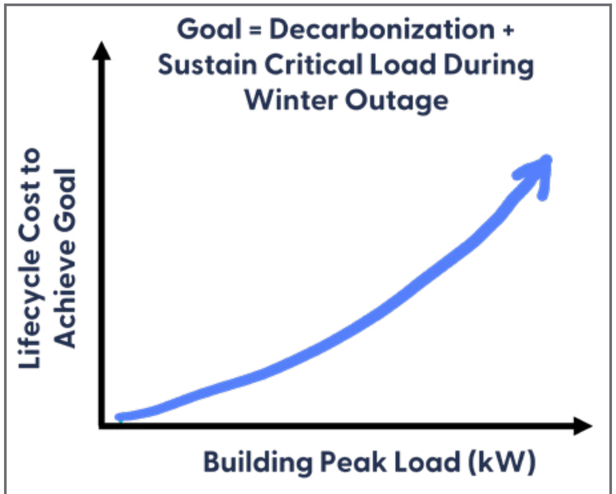


Fig. 38. Pattern of Building Peak Load vs. Lifecycle Cost of Meeting Combined Decarbonization and Resilience Goals.

7.2.2 Microgrid Level Results

- The lower the building load, the less the other variables impacted the results – creating less uncertainty or a smaller "range" of possible results. **In other words, the low load profile (passive enclosure) provides more certainty in the range of results despite the many possible simulation variables.**
- The path to building and microgrid decarbonization is not linear. As the electricity supply decarbonizes, each incremental increase in emissions reductions will require more investment than the last (see Case 13).
- When considering decarbonization goals, the emissions factors used in the simulation make an impact. Future emissions factors tend to have greater variation between hours (as more renewable energy is integrated into the grid-mix) and therefore typically more energy storage is required to meet decarbonization goals using future emissions factors versus today's (see Case 2).
- Load flexibility, in the form of shedding space conditioning loads based on high grid emissions factors, has significant potential to reduce on-site emissions and meet emissions reductions goals with less solar PV and storage (see Case 4).
- The cost, solar generation capacity and storage requirements to achieve resilience depend heavily on the critical load assigned as well as the outage duration and severity of the weather during the outage (see Case 12). Sustaining a survivable interior condition during a 3-day summer outage is far different than a 3-day winter outage in Milwaukee, Wisconsin (climate zone 5). During severe weather conditions, the impact of the enclosure is more profound on the critical load – i.e. the load on the HVAC system to meet a relaxed setpoint (see Case 9). Therefore, with the low-load passive enclosure, the duration and severity of the outage had less of an impact on the results.
- When aiming for 100% emissions reduction goals, there are significant diminishing returns when only utilizing renewable generation and storage to achieve that goal. (See Cases 5 and 18). A solution that pairs building enclosure improvements and load flexibility with a more modest emissions reduction using renewable generation and storage may be the least costly holistic solution to decarbonization, rather than attempting to decarbonize with generation and storage alone.
- **For the same life cycle cost, one all-electric existing-enclosure neighborhood could be 100% decarbonized, or six Phius-enclosure neighborhoods could be 100% decarbonized (see Case 18).**
- Electricity rate structures can make a large impact on the financial feasibility of on-site generations and storage projects. Time of use rates encourage the use of more on-site energy storage, which can help avoid purchasing electricity from the macrogrid during peak hours and align purchasing for building operation and energy storage charging during low-cost hours (see Cases 10 and 25)
- There is a significant difference in the solar PV (and storage) required to meet a typical "Net Zero" goal versus a 100% renewable electricity goal (see Cases 8 and 21).
- When using only solar + battery storage to decarbonize the electricity supply of the neighborhood, **the last 10% of emissions reduction will require more infrastructure and cost more than the first 90%** (see Case 27). What that first 90% requires is highly variable based on the electrified building load, which is a product of the building enclosure performance (see Case 18).

7.3 Microgrid Scale Patterns

As mentioned above, the enclosure level had the largest impact on the microgrid infrastructure requirements required to meet the project goal, regardless of the project goal details. Below are key patterns from those results, while detailed results graphs can be found in the Milwaukee Case Study results.

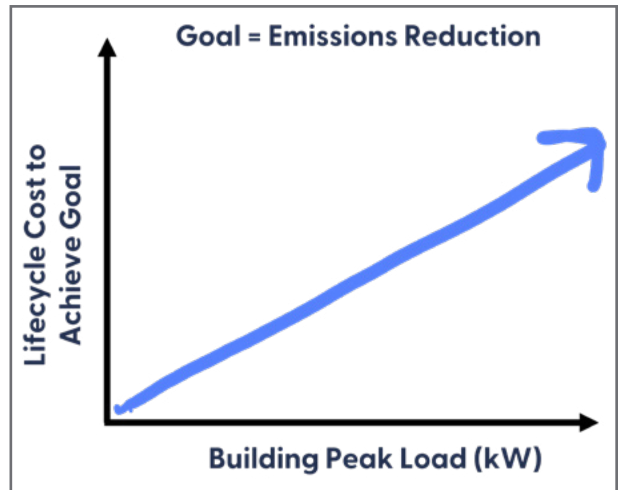


Fig. 39. Pattern of Building Peak Load vs. Lifecycle Cost to Meet Decarbonization Goals.

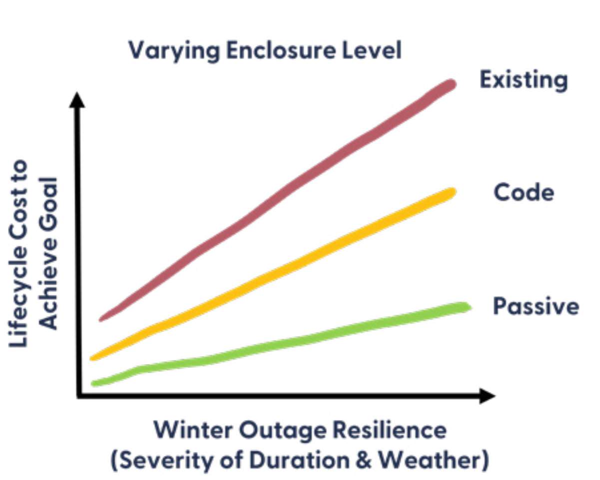


Fig. 40. Pattern of Winter Outage Resilience Severity versus Lifecycle Cost of Infrastructure to Sustain a Critical Load, Varying Enclosure Levels.

The peak load of the building heavily influenced the lifecycle cost and infrastructure requirements to meet the combined goal of both emissions reduction and decarbonization, and not quite in a linear fashion, closer to exponential. This means that reductions in peak load could scale directly with reductions in cost to achieve the same goal. In the combined objective cases, where decarbonization and resilience were both a goal, typically, the resilience goal was the dominant factor, and the solar and storage required to sustain a critical load during the winter outage also provided significant emissions reductions relative to business-as-usual.

The lifecycle cost, solar and storage requirements to meet modest emissions goals, such as 50% relative to a "business-as-usual" case, scaled fairly linearly with the building loads - both annual and peak.

For modest outages, during less extreme weather conditions, there was a noticeable but modest increase in the amount of solar and storage generation required to sustain a critical load during that outage. However, as the severity, both duration and weather condition, the critical load varied more between the buildings with varying enclosure levels and therefore the infrastructure requirements to sustain that outage varied even more. In some cases, the lifecycle costs to sustain the same critical load condition, for the same outage period, were up to 10x higher with an existing enclosure versus passive enclosure. These patterns are seen in Figure 40.

As shown in Figure 41, the enclosure level had a notable impact on the solar and storage infrastructure required to meet carbon emissions goals. As the emissions reduction goal approached 100%, the lifecycle costs increased significantly, creating a much larger gap in cost between decarbonizing the building (and neighborhood) with the existing enclosure versus the passive enclosure.

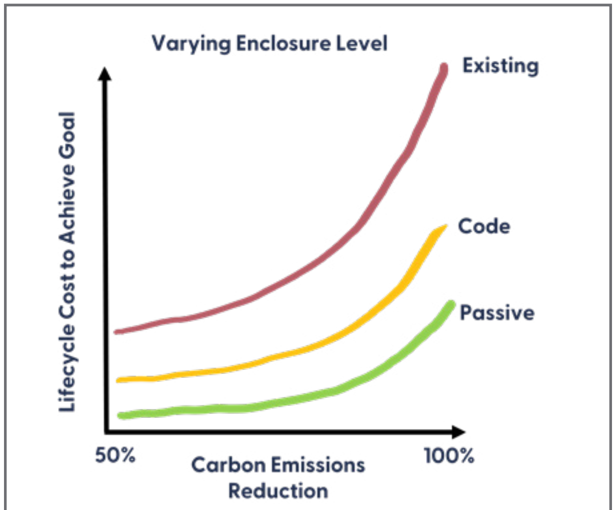


Fig. 41. Pattern of Increasing Decarbonization Toward 100% Emissions Reduction versus Lifecycle Cost of Infrastructure Required to Meet Goal, Varying Enclosure Levels.

8. CONCLUSIONS

8.1 What's the Same?

Any building can become part of a microgrid. Remember, microgrids are a collection of familiar components that are thoughtfully connected to create an optimal system.

- One of those building blocks is the building load, the shape of which is heavily influenced by the design. The building load may also be enabled with "smart" or controllable loads, enhancing the functionality of the microgrid.
- Another common building block is energy generation, which can be in the form of familiar rooftop solar PV.
- The last critical element is energy storage, which can come in familiar packaged solutions.

8.2 What's Different?

Microgrids, or even just the incorporation of some of their key elements, present new opportunities in building design. Design professionals work directly with owners to determine project goals and requirements. With the microgrid design kit, new goals such as sustained resilience during an outage, long-term energy affordability through on-site energy generation self consumption, and significant emissions reductions become a possibility. The role of the design professional includes presenting these goals to the owner, and **creating a paradigm shift on what is and isn't a possibility.**

Most commonly, the building may have on-site renewable energy generation and building-level energy storage. That renewable production may be wired through an inverter to feed building loads, or directly wired to DC loads. The building electrical service level and wiring/distribution network communication/network devices, and wiring may be different. And, the building should be set up appropriately to disconnect or "island" in the event of a macrogrid outage, which can be arranged a variety of ways–see Appendix I for more information.

For microgrids that are prioritizing resilience and reliability during main grid outages, buildings may need to be wired in a way that separates critical circuits from non-critical circuits. Alternatively, rather than physical wiring, if the devices that were used for critical load support were enabled with "smart" communication, then a signal may be able to keep those devices operational (at "critical" levels)

8.3 What's the First Thing to Do?

As demonstrated in the *Milwaukee Case Study*, the single most impactful action an architect can take is designing enclosure that creates a low-load building. If nothing else, this supports the decarbonization efforts more than any other individual effort. The effects of the low-load ripple throughout the entire system, making disruptors less disruptive, and the job easier for load aligners.

If considering a design beyond simply a low-load building, the next thing to do is consider the goals of the project and plan to integrate other distributed energy resources (DERs) such as on-site photovoltaics, energy storage, and load control/communication systems. You can use the step-by-step guide to walk through the decision tree, decide which variables matter for your project, etc.

8.4 How Much Does it Cost?

As mentioned above, the scale and extent of your microgrid components is shaped by the priorities and goals of the project. See the *Milwaukee Case Study* for further financial figures on integrating renewable energy generation and storage on-site to meet project goals.

8.5 Key Team Members & Players

As outlined in Table 1, there will be team members that are not typically involved in building design. These may be the local utility, energy provider, speciality equipment suppliers, contractors/installers for microgrid system components, etc. Table 1 outlines a suggestion of when each of these players should be involved in the design and execution of a microgrid project.

8.6 Final Thoughts

It is apparent that grid decarbonization is happening. The rate at which it will happen depends on a variety of different factors in varying markets with many players.

The decarbonization of buildings presents new challenges (and opportunities) for the relationship between buildings and the electrical grid.

Challenges are occurring due to the intermittency of renewable resources on top of aging infrastructure and increased grid load due to electrification of space heating, water heating, and vehicles.

Microgrids are often considered as a tool to enhance resilience and are more recently surfacing as an opportunity to both decrease greenhouse gas emissions and provide resilience simultaneously.

It's important for professionals who execute the design, construction, and operation of buildings to maintain awareness of the greater impact, and when possible, to design low-load buildings, with inherently flexible loads that can align with renewable resource availability to reach greater goals for carbon neutrality, security, health, and resilience.

Milwaukee Investigative Case Study

Exploring the Interrelationship between Building Enclosure Design, Decarbonization, & Resilience at a Building and Neighborhood Scale

This element of the Architect's Guide presents results from a pilot study exploring the interactions of numerous microgrid design variables with several project intents at both a building and neighborhood level setting. There is a clear trend toward electrification of existing buildings, and this study set out to examine the impact of electrifying existing buildings as-is, versus taking steps to improve the enclosure first. It is important to understand the relative impact of either approach.

This case study builds upon the concepts outlined in the Architect's Guide, simulating all-electric buildings of varying typology and enclosure levels in order to understand the impact on estimated annual energy use, carbon dioxide emissions, peak loads and critical loads. These building-level results were used to then assess project goals that extended beyond the building enclosure design to the incorporation of on-site renewable energy and energy storage systems. Such goals might include decarbonization in the form of on-site emissions reduction, or resilience in the form of sustaining a critical load at the building or neighborhood level during a macrogrid outage.

The report outlines the simulation setup, modeling process diagrams, and detailed inputs for the simulations. You will find a comprehensive list of simulations completed at the building-scale and neighborhood scale (with and without the energy generation and storage elements), twenty-eight "case-level" results, which group similar simulation objectives to study the impact of the enclosure or other variables on the infrastructure required to meet the defined objective.

This report was made possible through the 2021 AIA Upjohn Research Initiative grant.

C1. INTRODUCTION

C1.1 Narrative

This element of the *Architect's Guide* presents results from a case study exploring the interactions of numerous microgrid design variables with several project intents at both a building and neighborhood level setting.

The purpose of the study was to explore patterns of performance that result from combinations of building energy enclosure performance, on-site renewable energy components, storage components, and grid interactions to meet project goals. This research looks only at small-scale residential buildings assembled into neighborhood blocks typical of Milwaukee, Wisconsin. The climate examined is also that of Milwaukee (ASHRAE Climate Zone 5A). Conventional historic climate data sources were used (versus future climate projections).

In all study cases, the microgrid is connected to the main grid, except in instances where the project goal is explicitly to fully operate without the main grid.

The research boundaries established for this study are described in Section 2.

C1.2 Objectives and Goals

The main objective of this study was to take a holistic view of energy systems, analyzing the interdependencies between energy supply, demand, and storage to meet certain resilience, emission reduction (or clean energy) goals. This was undertaken through the framework of a microgrid, which at a minimum includes the above noted components and operates to achieve a system-wide goal. While the analysis simulations are done at a microgrid level, the results can be seen as a proxy for the macrogrid level, which is experiencing significant change as buildings and vehicles electrify and renewable energy generation systems are replacing fossil-fueled generation as touched upon in the *Architect's Guide*.

A key goal of the project is to understand how variations in specific building load impact the total infrastructure required to appropriately operate that building, in the context of operation from renewable energy supply and storage. The study hones in on three distinct building enclosure performance levels. It examines how the enclosure levels shape the building load profile, and how that affects achievement of project goals. The study also looked at energy storage and distributed energy generation to meet those goals.

C1.3 Study Plan

In order to assess a reasonable range of building loads, the study started by selecting three residential building typologies and three levels of building enclosure performance to model. These ranged from older existing building enclosures to an "above-code" high performance enclosure.

This created a matrix of 9 unique combinations to study at the building level. These results were used to examine the impact of building enclosure on both annual and peak loads in the buildings. These individual building loads were then aggregated to create neighborhood loads.

The building loads and neighborhood loads were then used in further analysis and assumed to be the "microgrid load", i.e. the load that must be met by energy generation and storage. These varying microgrid loads were then paired with decarbonization and resilience objectives, and the results provided the infrastructure and cost requirements needed to meet those objectives.

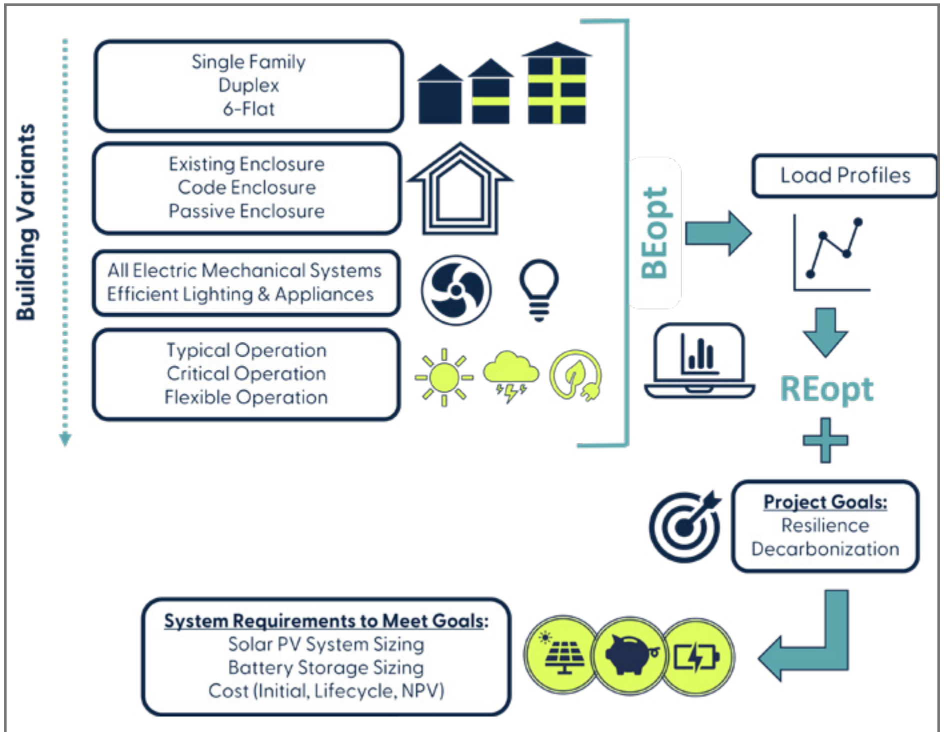


Fig. 1. Milwaukee Microgrid Case Study Flow Chart [Courtesy of Phius]

C2. STUDY SETUP

C2.1 Milwaukee / Neighborhood Context

The study focused on a typical, existing one-block neighborhood in Milwaukee, Wisconsin. Figure 2 shows the layout of such a neighborhood–with a reminder that this particular set of buildings was arbitrarily selected as representative of the existing housing stock in a Midwestern urban environment. Three building typologies emerge in this neighborhood– single-family residences, duplex residences, and six-unit dwellings (called 6-flats herein). There is no substantive commercial building intrusion in this selected block. All buildings in the neighborhood are assumed to have been built prior to the 1970s. More information on building characteristics is presented in Section 3.1.

This actual neighborhood was schematically simplified as shown in Figure 3. The building icon inserts seen in Figure 3 were developed for use with the simulation tools.

C2.2 Analysis and Assessment Tools

A variety of resources were required to set up inputs for the study, and a variety of tools were explored and utilized to carry out these simulations. Different tools were required for different steps and stages, where some outputs from a tool early on became an input in a tool used later in the process. The full list of tools explored and utilized can be found in Appendix F. The bulk of this study was carried out in WUFI® Passive, BEopt, and REopt software. The next section describes their use case throughout the process.

C2.3 Modeling Process

Section 1.3 above broadly outlines the case study analysis process. As described in greater detail below, these cases involved three residential building typologies considered under three distinct enclosure energy efficiency levels. In total, this created nine building combinations (typology + efficiency level) that were simulated in WUFI Passive first for simple analysis, followed by an hourly modeling tool (BEopt) to generate annual load profiles.

These load profiles were generated with the intent of studying their characteristics (total consumption, peaks, etc) as well as for use in the REopt modeling software tool in the next stage. The types of profiles generated were for typical operation, critical operation (the minimum load the building needed to sustain during a grid outage) and flexible operation (that can ramp down when there are emissions spikes) with different operation modes: typical, critical (during an outage), and flexible.

The study addressed many permutations, summarized and classified in Figures 5-9. Figure 4 provides a key to the iconic symbols used in these diagrams.

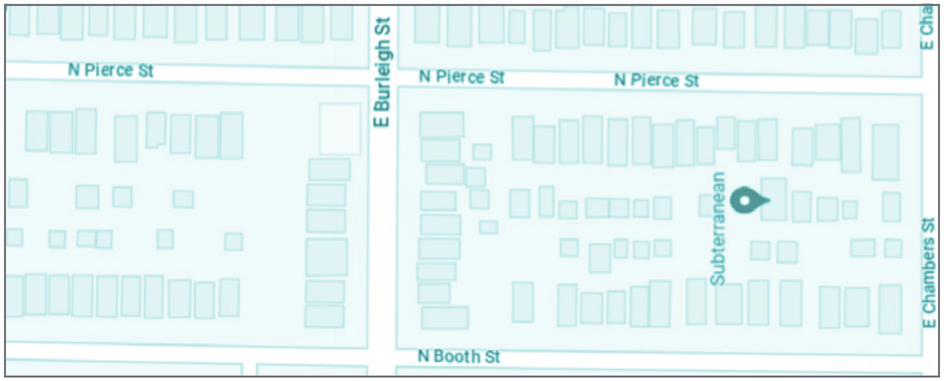


Fig. 2. Representative Milwaukee Neighborhood Selected for Microgrid Analysis. (Source: Google Maps)

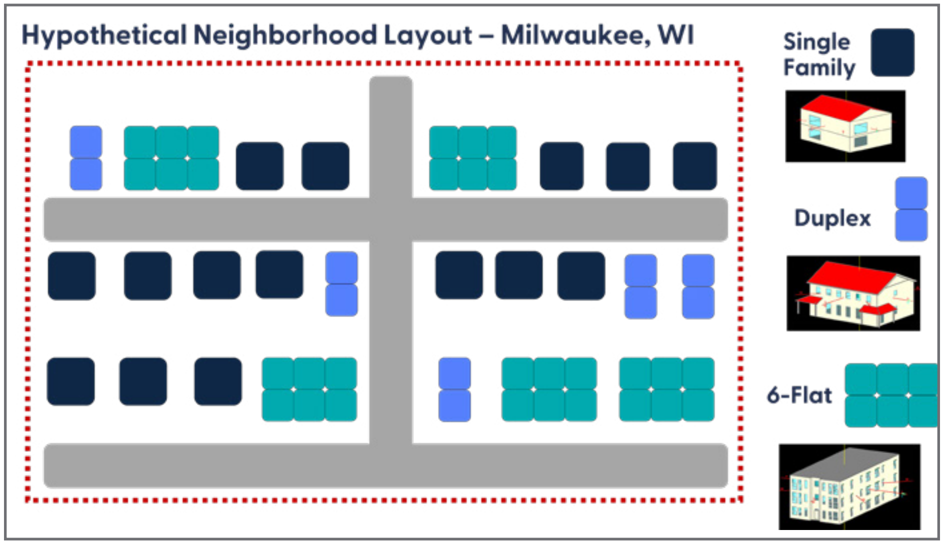


Fig. 3. Simplified Neighborhood Layout with Emphasis on Building Types.

Neighborhood Makeup	Units per Building	Number of Buildings	Total Dwelling Units
Single Family	1	15	15
Duplex	2	5	10
6-Flat	6	5	30
Neighborhood	-	**25**	**55**

Table 1. Summary Matrix of Neighborhood Building Types.

C2.3.1 Modeling Typical Loads

As shown in Figure 5b, the flow chart for generating typical load profiles:

(a) Three building sizes were considered

(b) Three enclosure efficiency levels* were used: Existing, code (IECC 2021), and passive (Phius CORE 2021 compliant).

The enclosure efficiency levels are outlined in detail under Section 3.1, Determining Building Loads. Note the additional tool required (g) to determine the enclosure levels for the passive case.

These three enclosure options are not intended to be a continuous spectrum of options–which was beyond the scope of this project. Instead, the three options represent a worst-case ("energy hog") condition, a best case (ultra-low energy), and a more-or-less middle case (current code compliant).

(c) The mechanical system approach, which was identical high-performance all electric equipment for all cases.

(d) The typical (again identical) assumptions for appliances, lighting and plug loads amongst the cases.

A "business as usual" case was also studied as a baseline but is not shown here as it was only used as a relative comparison and will be shown later in the results. This "typical" scenario assumes current electricity prices, current emission factors, and historical weather data (TMY3) as the driver for climate-influenced building loads.

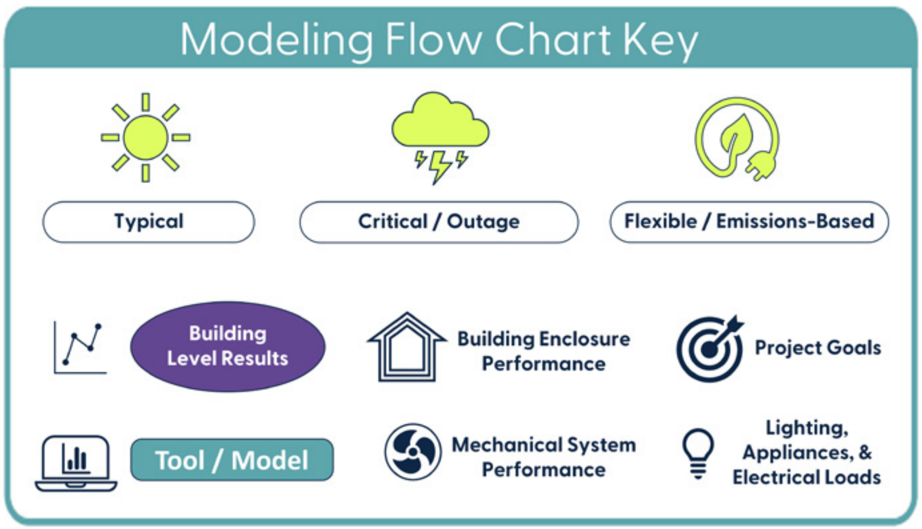
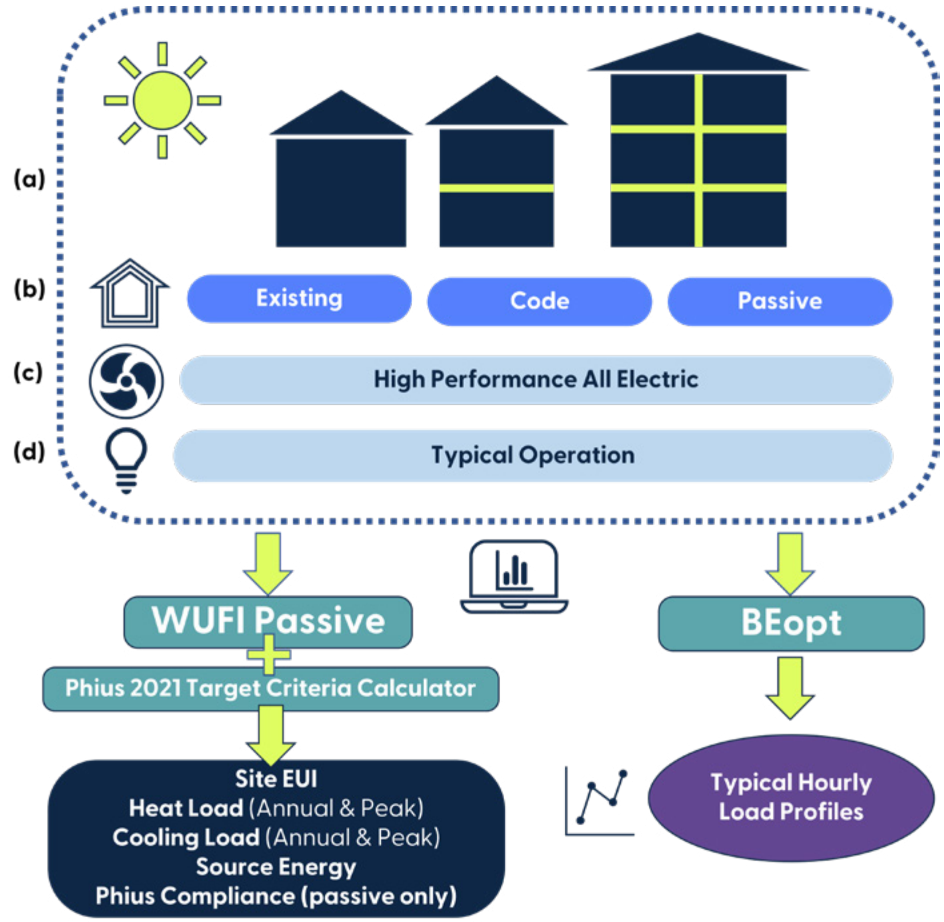


Fig. 4: Iconic Symbols Used in Modeling Flow Charts. (Courtesy of Phius)

Fig. 5. The Modeling Process for Simple Building Analysis, Phius CORE 2021 Compliance, & the Case of Typical Building Loads & Building Characteristics (Courtesy of Phius)



Technical Note: The "Annual" heating and cooling loads output by WUFI represent the amount that must be provided by the equipment over the course of the year to maintain a desired setpoint. The efficiency of that equipment determines how much heating energy it actually consumes. "Peak" load represents the maximum heating or cooling capacity required for system sizing purposes. "Source energy" (also known as primary energy) is the annual energy consumption of the building, converted from site energy to source energy using DOE recognized adjustment factors.

C2.3.2 Modeling Critical Loads

The process shown in Figure 6 was used to establish *critical* hourly load profiles for each of the building typologies and enclosure performance levels. It is based upon an outage of the macrogrid and islanding of the microgrid. It is not economically feasible to run a building full out (with typical-day load profiles) during an emergency event, thus "critical loads" (those that are deemed to be important to continue in operation during an outage event) must be addressed.

Similarly to the typical loads, the 9-building configurations shown in (a) and (b) were studied, but variations included:

(c) The use of heating and cooling systems was constrained to only what was required to sustain the defined critical building environmental conditions (defined by a wider interior temperature setpoint range and minimal ventilation)

(d) The equipment used in the space was limited to:

- The refrigerator
- 90% decreased lighting load
- Plug loads decreased to the equivalent of a few cell phone chargers

Details for the critical load conditions are outlined in Appendix B.

Fig. 6. The Modeling Process for the Case of Critical Building Loads to use in Resilience Analysis, [Courtesy of Phius]

C2.3.3 Modeling Flexible Loads

Figure 7 outlines the process used to define ‘flexible” hourly load profiles for each of the building types and enclosure performance levels. The building’s mechanical systems were modeled as “responsive” and could shed load based on suggestive signals simulated through increased electricity prices. The large appliances, lighting, and miscellaneous building loads were operated as normal.

This building loads determination process differed from the creation of typical use (the sunny icon) and critical (the stormy icon) loads in that it was carried out in Excel. The flexible load profile started as the typical load profile, and was then manipulated based upon a ‘signal’ indicating increasing grid stress that would create a response to decrease the building load.

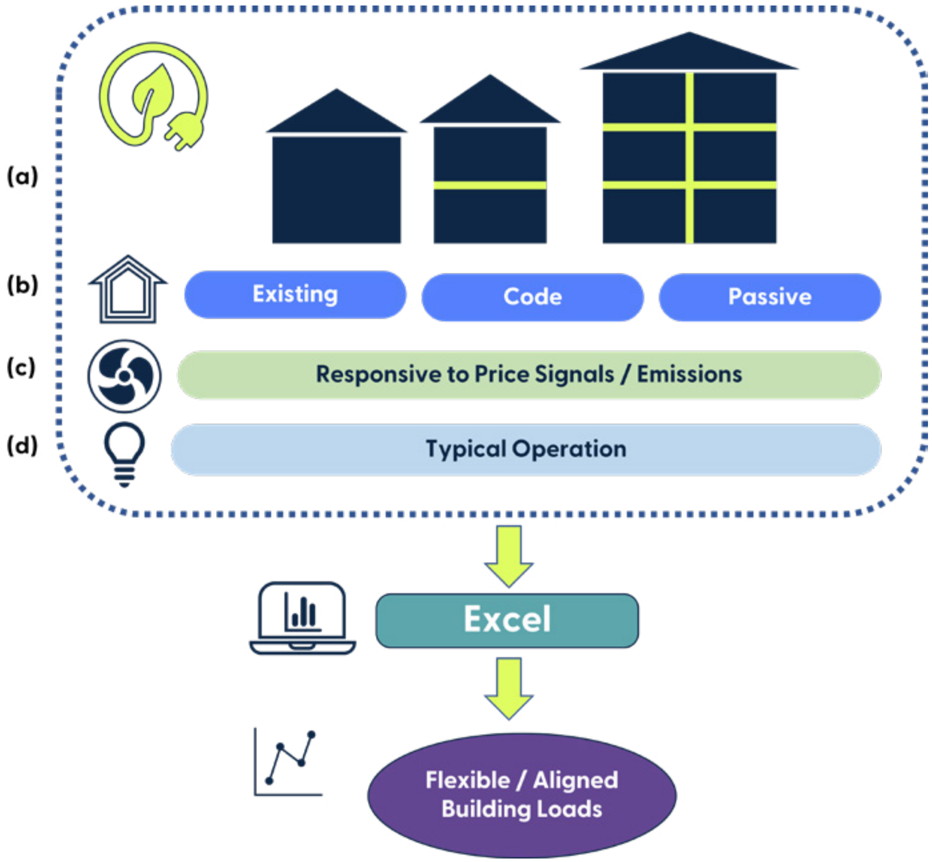


Fig. 7. The Modeling Process for the Case of Flexible Loads in the Flexible (Price/ Emissions-Based) Building Loads. [Courtesy of Phius]

The grid signal was fabricated by hourly carbon emission profiles with a price placed on the cost of carbon. During the strongest 10% of the signals (876 hours per year), the space conditioning loads were shed completely even if the signal was received during a time when heating or cooling was needed. During the next highest 15% of signals (1,314 hours) the load was adjusted (shed) to match the ‘critical’ space conditioning load (which maintained a relaxed interior setpoint during a prolonged outage period) if heating or cooling was required. The short-term shedding of space conditioning loads is assumed to have minimal impact on maintaining a comfortable setpoint in the home therefore minimal impact on occupant comfort. More detail on the creation of flexible/adjusted loads can be found in Appendix D.

C2.3.4 Modeling Building Loads with Project Goals

Figure 8 illustrates how the individual building characteristics (top row, as created by the processes shown in Figures 5,6 & 7), output into hourly loads (left to right: typical, flexible, and critical) were utilized in combination with project goals and REopt software to generate local infrastructure requirements and project costs to meet those goals. The later sections describe the project goals and other variables used in the REopt software analysis.

After the individual building analysis, the individual building loads were aggregated into the neighborhood configuration to represent a theoretical microgrid, designed to meet neighborhood-level goals. This was done for both typical loads and critical loads to obtain typical and critical load profiles for the neighborhood microgrid.

Similar to the individual building simulation objectives studied in REopt, the neighborhood scale loads were studied for similar objectives, as shown in Figure 9b.

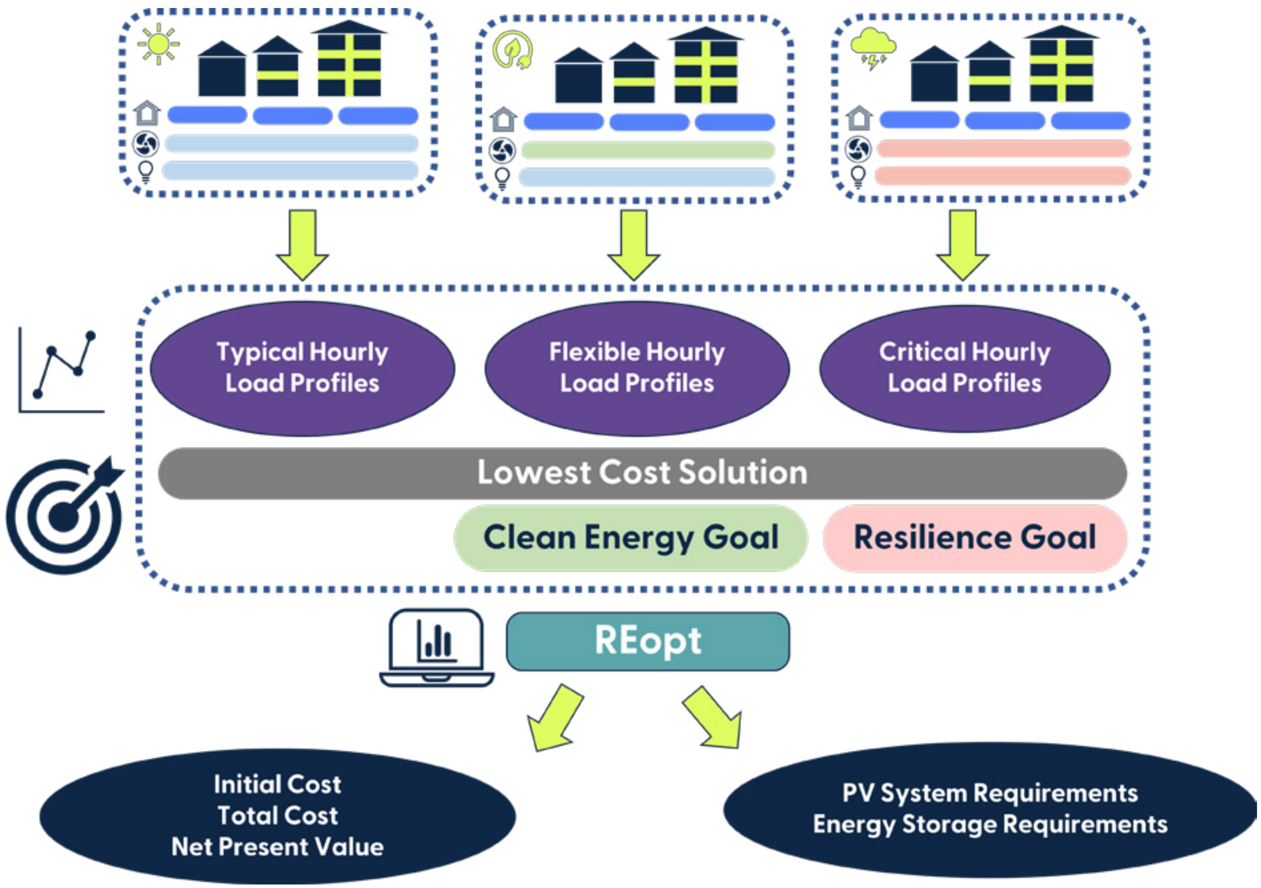


Fig. 8. Holistic Analysis Process Flow Diagram–Individual Building Scale. [Courtesy of Phius]

C2.4 Assessment Metrics

C2.4.1 Building & Neighborhood - Load Only Metrics

Table 2 is a list of performance metrics assessed at the building and neighborhood level for each type of load analyzed. The purpose of this level of simulation is to compare the differences in performance, both in annual energy consumption and peak power consumption. Typical performance-based approaches for codes or other programs utilize annual performance metrics and target reductions in annual energy use but rarely focus on differences in peak loads.

A. Annual energy consumption (kWh/yr; kWh/ft^2 yr; or kWh/person yr): This is simply a measure of the estimated (in this case, simulated) energy use of the building over the course of the year, normalized to account for building floor area or building occupancy. (Btu is commonly used in the US for thermal energy, but electrical energy is commonly expressed in kWh.)

EUI (energy use intensity, kBtu/ft^2 yr): Annual energy consumption is often expressed as an EUI value, represented in kBtu (1000 Btu) per square foot of building floor area.

B. Annual CO_2 emissions (lb CO_2/yr): This value was calculated based on an hourly load profile of the building multiplied by the carbon-intensity of the grid electricity at each hour (carbon emissions profile in pounds of CO_2 per kWh, see Appendix C for details on profile). The purposes of calculating this value were to see if annual energy savings directly scaled with annual emissions reduction.

C. Hourly load profile: This represents the hourly energy consumption of the building (in kW per hour). The highest hour is the peak load, while the sum of all hours is the annual energy consumption. Comparing hourly load profiles, daily and annually, provides insights and useful patterns–as described in the *Architect's Guide*.

D. Peak load (kW): The peak load in a building is the instance in which the building requires the highest amount of power to operate, or the moment of highest energy use. This value is rarely reported as a performance metric in codes or other programs, but has proven to hold significance and directly correlates to efforts needed to meet project goals related to resilience and utilization of clean electricity.

On top of the building characteristics listed above, we also estimated the size of the photovoltaic array that would be needed to provide a 'net zero' building, i.e. where the annual energy consumption of the building (kWh) is offset by the same renewable energy generation output of the PV system. This is intended to be informational and was also used to explore against other decarbonization goals in the next section.

PV required for "net zero" (kW): For a given climate and orientation, 1 kW (peak) of PV panels can be assumed to produce a certain amount of energy (kWh) annually. This metric was calculated based on the annual energy use (in kWh/yr) of each building, after determining the solar panel capacity required to produce energy (kWh) equal to the annual energy use. (PV (photovoltaics) was selected as the distributed renewable solar resource considered for this study. Other possible options–such as microwind or fuel cells were not considered as likely to be adopted at this time.)

Assessment Metric		Typical Load	Flexible Load	Critical Load
A	Annual Energy Consumption	X	X	
B	Annual Carbon Dioxide Emissions	X	X	
C	Hourly Load Profile	X	X	X
D	Peak Load	X	X	X

TABLE 2. Building and Neighborhood Level Assessment Measures

Fig. 9a. Load Aggregation diagram for typical and critical neighborhood loads [Courtesy of Phius]

C2.4.2 Building & Neighborhood - Project Goal Metrics

At the building level and neighborhood level, microgrid loads and project goals (simulation objectives) were used as inputs. The results of each analysis displayed the requirements (generation, storage, cost, etc) to meet that objective.

Cost Metric Results:

- Net Present Value ($): The present value of the savings (or costs if negative) realized by the project. This is calculated as the difference between the "Business As Usual" case lifecycle cost and the "Resilience Case" life cycle cost or the "Financial Case" life cycle energy cost.
- Lifecycle Cost ($): The lifecycle cost is the present value of all costs, after taxes and incentives, associated with the project option.
- Initial Cost ($): This is the initial cost of the infrastructure, calculated using the default cost of the energy generation and storage assets.

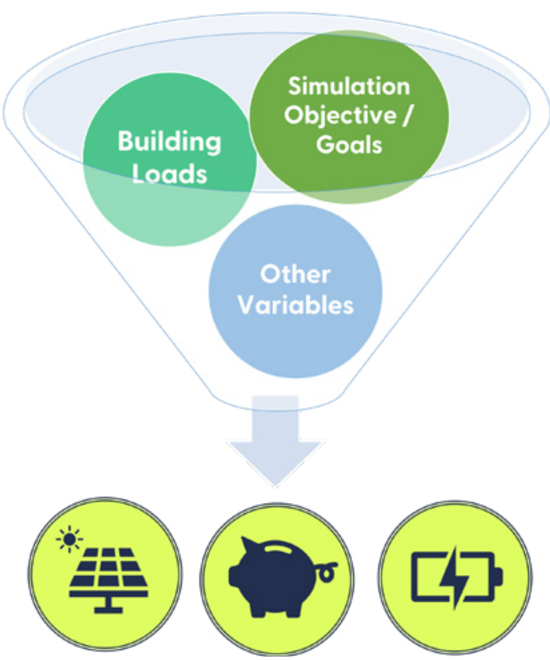


Fig. 10. Simplistic Representation of Input Parameters and Output Results in REopt Software, [Courtesy of Phius]

Energy Generation & Storage Infrastructure Results:

- Optimal Sizing of PV (Photovoltaic) System (kW): This result represents the recommended capacity, or size, of the solar PV system needed to meet the simulation objective.
- Optimal Sizing of Battery Capacity (kWh): This result represents the recommended "volume" of electrical energy storage needed (how much electricity the battery can store) to meet the simulation objective.
- Optimal Sizing of Battery Power (kW): This result represents the power rating of the battery (the rate at which it can charge and discharge) recommended to meet the simulation objective. The power components of the system (inverter, etc.) scale with this requirement.

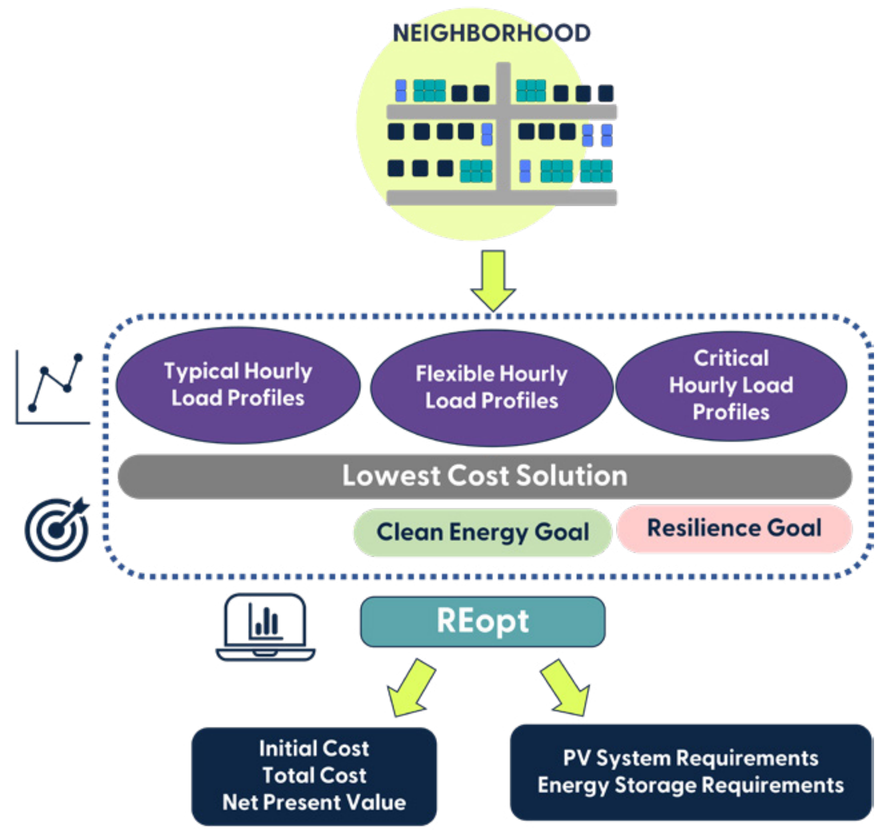


Fig 9b. Holistic Analysis Process Flow Diagram–Neighborhood Scale, Typical, Flexible, Critical Loads for Simulation in REpot [Courtesy of Phius]

C3. INPUTS

This section outlines the simulation inputs for the study, both fixed and variable. Building level inputs were packaged for building-level modeling, to obtain building loads. The results of those simulations became fixed load profiles for simulations later in the study. Other variables were also treated as "fixed" for the purposes of setting baselines and completing sensitivity analyses. All of the detailed inputs can be found in Appendix A.

C3.1 Determining Building Demand/Loads

C3.1.1 Fixed Inputs

The following characteristics were consistently used across all case study modeling efforts:

Location/Climate: the energy performance of all buildings was modeled using Milwaukee, Wisconsin (Mitchell International Airport) TMY3 climate data.

Building Geometry, Configuration, and Size: three residential building configurations were considered as part of the prototypical Milwaukee neighborhood:

(1) **Single-Family:** The U.S. DOE prototype single-family building[59] was used to define the building characteristics.

(2) **Duplex (stacked):** A simple, Phius-defined prototype was used for the stacked duplex. This building geometry has been used by Phius for other research and standard-setting purposes.

(3) **6-Flat (three stories, 2 wide):** The building geometry, unit configuration, and occupant density for this building type were based upon a Phius-certified project that was designed and constructed in Chicago, Illinois.

Heating, Cooling, and Domestic Hot Water Systems: the systems serving each building in the study were high-performance, all-electric systems. An air-source heat pump was used for space conditioning and a heat pump water heater for water heating. See Section C3.1.2 for discussion of ventilation.

EV Charging may become a building load when the charging infrastructure is integrated in a building. The impact of both EV charging, as well as EVs for use of bi-directional power flow (to and from a building) was not in the scope of this case study. More on this in Section C8.2, Future Work.

Appliances and Miscellaneous Electrical Loads: the large appliances (refrigerator, dishwasher, clothes washer, etc.) and lighting were consistent for all simulations. Appliances were assumed to be Energy Star rated and the lighting was assumed to be high-efficacy.

C3.1.2 Variable Inputs

The following building characteristics were varied as appropriate to the modeling case and objectives.

Building Enclosure Performance: A primary focus of this study was to explore the impact of varying building enclosures on renewable energy system requirements to operate said buildings. Rather than studying the impact of individual enclosure measures (wall insulation, airtightness, etc.), the study used three distinct enclosure packages: (1) that of the deduced existing building stock in Milwaukee, (2) a code-compliant (IECC 2021) envelope, and (3) a high performance, passive building (Phius CORE 2021-compliant) envelope.

- **ResStock (Existing) Enclosure:** The building enclosure for the existing Milwaukee housing stock was defined using NREL's ResStock data for Milwaukee, Wisconsin. The time period chosen was from pre-1940s through 1970s. The NREL database was queried and average values were extracted to create an existing envelope enclosure package. This enclosure condition represents what would likely happen if load disruptors kicked in with no previous efforts to upgrade the building stock.

- **IECC 2021 Enclosure:** The code-compliant enclosure case was defined using the prescriptive requirements for envelope thermal performance as presented in the 2021 IECC (International Energy Efficiency Code).

- **Phius CORE 2021 Enclosure:** The highest performing enclosure case, reflective of a passive building, was based on expectations for Phius certification. Two tools were used to determine these requirements: the Phius 2021 Space Conditioning Criteria Calculator and the WUFI® Passive Energy Modeling Software.

The enclosure thermal performance airtightness values used in the simulations are outlined in Table 3.

Mechanical Ventilation Systems: Ventilation systems were the one mechanical system that varied across the study. This was done to coordinate with the building enclosure performance. When the building enclosure becomes more air-tight, the requirements for mechanical ventilation to maintain indoor air quality become more critical. For the existing building enclosure scenario, no dedicated mechanical ventilation was assumed. For the code-compliant case, an exhaust-only system was modeled. For the Phius enclosure case, a balanced ventilation system with energy recovery was employed.

A full table of detailed building inputs can be found in Appendix A and Appendix B.

Note the existing building and code-compliant building use an 'exhaust only' strategy for ventilation. In these cases, indoor air quality is assumed to be maintained by the use of bathroom and kitchen exhaust fans and the generally uncontrolled leakage of outdoor air through the building enclosure–this approach has negative impacts on building energy use, thermal comfort, and enclosure durability.

Existing Building			
	Single Family	Duplex	6-Flat
Wall R-Value*	7.4	7.4	7.4
Floor R-Value*	0.6	0.6	0.6
Roof R-Value*	21.5	21.5	21.5
Window U-Factor**	0.63	0.63	0.63
Airtightness***	13	13.8	13.2
Mech. Ventilation Strategy	Exhaust-Only	Exhaust-Only	Exhaust-Only
IECC 2021 Compliant			
	Single Family	Duplex	6-Flat
Wall R-Value*	21.9	21.9	21.9
Floor R-Value*	10	10	10
Roof R-Value*	60.1	60.1	60.1
Window U-Factor**	0.3	0.3	0.3
Airtightness***	4.5	4.25	3.9
Mech. Ventilation Strategy	Exhaust-Only	Exhaust-Only	Exhaust-Only
Phius CORE 2021			
	Single Family	Duplex	6-Flat
Wall R-Value*	44	42	37
Floor R-Value*	20	20	20
Roof R-Value*	71	50	60
Window U-Factor**	0.17	0.18	0.17
Airtightness***	0.9	0.91	0.87
Mech. Ventilation Strategy****	Balanced	Balanced	Balanced
Units: *[hr.ft2°F/Btu] , ** [Btu/hr.ft2°F], ***[ACH50]			

Table 3. Building Enclosure Characteristics Used in Modeling Cases.

C3.2 Project Goals (Simulation Objectives)

Simulations to achieve project goals and objectives (such as resilience) were carried out using REopt software. Building loads and project outcomes were the main variables in the REopt studies.

C3.2.1 Fixed Inputs

Least Cost: REopt software is natively designed as a financial optimization tool. Therefore, all simulations are set to find the "least cost solution" to achieve a defined goal given the input variables. The best financial outcome is always shown as a project recommendation.

C3.2.2 Variable Inputs

Client Goals: In addition to financial optimization, two other project modes (intended outcomes) can be selected in REopt; (1) Resilience, and (2) Clean Energy, or a combination (3) Resilience & Clean Energy.

C3.2.2.1 Financial Goal Variables

Analysis Period: this is the length of the project in years, and influences the number of years in the simulation, lifecycle cost, and net present value. The default value in REopt– which was used unless noted otherwise–is 25 years. For a sensitivity analysis, a 50 year period was studied.

Variable Electricity Rate structures and Energy Cost Escalation rates were studied, which are outlined in the next section under energy supply variables.

C3.2.2.2 Resilience Goal Variables

The term resilience can be defined in many ways, but for REopt (and this study) resilience is the ability of a building to maintain a critical load during a macrogrid power outage. For simulation purposes, parameters (see directly below) that determine adequate resilience must be clearly defined and benchmarked.

Multiple single-variable iterations of these parameters were modeled to assess the relative impact of each.

Outage Duration: The outage duration is the period of time (minutes, hours, days) during which the main grid is not available as a source of energy supply for the building or neighborhood. This corresponds to the extent of microgrid islanding. Most of the simulations were set to a 72-hour outage, though 36-hour (half the baseline) and 144-hour (double the baseline) were also studied in a sensitivity analysis.

Outage Start Date and Time: These variables determine when during the year (which day) and when during that day (which hour) the modeled main grid power outage begins. For the purposes of this study, the outage was simulated starting at the calculated peak condition in the building, at the end of January. A midsummer start time for outage simulation was also studied in a sensitivity analysis.

Critical Building Load to be Maintained: The building load that is defined as "critical" may vary greatly based upon the opinion of the occupant or designer. For the purposes of this study, two different critical load scenarios were studied:

Simulated Critical Load Conditions: A "critical" load pattern was simulated with predefined parameters: a temperature setpoint range, ventilation strategy, lighting load, refrigerator load, and minimal plug loads. Details can be found in Appendix B.

% of Total Building Load as Critical Load: This approach assumed the critical load would be a fixed percentage of the total load. To determine the sensitivity of this variable, we studied setting the critical load as 10%, 25%, and 50% of total typical load.

C3.2.2.3 Clean Energy Goal Variables

Clean Energy Target: This value defines the lens or filter the analysis uses to assess "clean energy" goals, which can be viewed as (1) renewable electricity utilization, or (2) emissions reduction.

Annual Renewable Electricity Target: this input defines the desired amount of the site's annual electricity consumption that is served by renewable electricity generation. In this study, energy exported to the grid does not count toward meeting the goal. Minimum and maximum percentages can be set for this value. For the purposes of this study, we looked at setting a minimum of 50%, 90%, 99%, and 100% renewable energy scenarios.

Lifecycle Emissions Reduction: this input defines a desired emissions reduction as compared to business-as-usual (BAU). If the BAU scenario includes emissions reductions from "greening-of-the-grid", this is not counted toward this goal (since this effect is included in both the BAU and the optimized analyses). This study does not count energy exported to the grid toward meeting the emissions goal. Minimum and maximum percentages can be set for this value. For this study, we set minimums of 50%, 75%, 90%, and 100% emissions reductions.

Carbon Emissions Profiles: If an emissions reduction target is set, a grid-electricity emissions profile must be used. Emissions profiles convey the hourly emissions associated with power generation on the main grid. By default, REopt uses the US EPA AVERT emissions[14] by region, but there is also the option to use custom emissions profiles. For the purposes of a sensitivity analysis in this study, we also evaluated meeting various emissions reductions goals when assuming future projected regional (RFCW) Long-Range Marginal Emission Rates[15] (LRMER, CO_2e) for 2024, 2035, and 2050. More details can be found in Appendix C.

C3.3 Energy Generation/Supply

C3.3.1 Fixed Inputs

Types of Generation: In this study, the options for electricity generation were set as the main grid and PV (photovoltaic) panels. Wind power is an option in REopt, but was not examined for this investigation.

Many other default inputs remained fixed for the purposes of this study. Details on all fixed assumptions can be found in Appendix C.

PV System Capital Cost ($/kW-DC): This is the fully burdened cost of an installed PV system in dollars-per-kilowatt (capacity). The term fully burdened means that it includes the cost of the equipment and labor for installation.

C3.3.2 Variable Inputs

Electricity Rate ($/kWh), Main Grid: This represents the cost of each unit of electricity purchased from the macrogrid/utility. The rate structure can make a large impact on the financial viability of distributed energy resources and thus a microgrid design. For most of the simulations, a fixed price of electricity was used ($0.137/kWh), as this is the typical rate structure for residential customers. A "time of use" rate was also explored in an input sensitivity analysis, where the rate during peak hours was ($0.28/kWh), and off-peak was ($0.06/kWh).

Energy Cost Escalation Rate, Nominal (%): This input represents the expected increase in the rate described above. A default of 1.9% was used for many of the cases, based on data from the Energy Information Administration's (EIA) Annual Energy Outlook. A value of 3.8% (double the default) was explored in a sensitivity analysis.

C3.4 Energy Storage

C3.4.1 Fixed Inputs

Types of Energy Storage: Battery storage of electricity was the only form of energy storage directly assessed in this study. Indirectly, thermal (heat) energy storage within the building enclosure and within residential hot water tanks was used for the "flexible" building load cases defined above.

Battery Cost: The cost of the battery system is estimated by a combination of both capacity [kWh] and power [kW]. Results are exported separately for the two, although battery storage components may not exist in the exact ratios recommended.

> **Energy Capacity Cost ($/kWh):** This represents the cost of the "volume" of electrical energy storage components, or the capacity of the battery system (how much electricity the battery can store).
>
> **Power Capacity Cost ($/kW):** This is related to the power rating of the battery, i.e. the rate at which it can charge and discharge. The power components of the system (inverter, etc.) are captured in this cost.

Many other default REopt inputs remained fixed for the purposes of this study. Details on all fixed assumptions can be found in Appendix C.

C3.4.2 Variable Inputs

Allow Grid to Charge Battery [Yes/No]: This software toggle determines whether or not energy supply from the main grid can charge the battery at the building or neighborhood level. By default, this is set to "true" (yes). For this study, we looked at the relative impact of trying to meet a neighborhood emissions reduction goal with and without allowing the grid to charge the battery.

C4. ASSESSMENT / SIMULATION LIST

C4.1 Building Loads

Table 4 lists the building-level simulations that were run. The list includes combinations of building size, enclosure performance level, and operation mode for a total of 27 unique building loads. All simulations featured high-performance, all-electric heating, cooling, and hot water systems and efficient appliances and lighting. Detailed simulation inputs can be found in Appendix A.

The 'Typical' and 'Critical / Outage' operation modes were simulated directly in BEopt, while the 'Flexible' load was derived from a combination of the 'Typical' load simulated in BEopt, and adjusted to shed load during "high price" times. Price was curated using an hourly marginal carbon emissions ($/kg CO_2). Detailed simulation inputs can be found in Appendix D.

Diversity of loads and its impact on microgrid performance is an intriguing design variable that was not fully explored in this study. This issue will need to await further research. REopt accepts a single load profile (demand profile), which forces the aggregation of individual building loads to a neighborhood load for simulation purposes. This does not explicitly address diversity, but instead assumes that multi-building load interactions are arithmetically additive (i.e., there is no diversity). Commercially available microgrid-specific software (such as HOMER PRO[58]) accepts a maximum of two-load inputs–which does not resolve the question of how 55 distinct households (in the case of the Milwaukee neighborhood) might interact to form a collective load profile. On-site renewable resources will also experience diversity in the same neighborhood setting.

Sim #	Scale	Enclosure Level	Operation Mode
1	Single Family	Existing Enclosure	Typical
2			Critical / Outage
3			Flexible
4		Code Enclosure	Typical
5			Critical / Outage
6			Flexible
7		Passive Enclosure	Typical
8			Critical / Outage
9			Flexible
10	Duplex	Existing Enclosure	Typical
11			Critical / Outage
12			Flexible
13		Code Enclosure	Typical
14			Critical / Outage
15			Flexible
16		Passive Enclosure	Typical
17			Critical / Outage
18			Flexible
19	6-Flat	Existing Enclosure	Typical
20			Critical / Outage
21			Flexible
22		Code Enclosure	Typical
23			Critical / Outage
24			Flexible
25		Passive Enclosure	Typical
26			Critical / Outage
27			Flexible

Table 4. Matrix of Building-Level Simulations.

C4.2 Building Loads + Project Goals

Tables 5 through 8 list building-level REopt simulation runs undertaken to explore various project outcomes (design goals). Some simulations were run to test the sensitivity of outcomes to various input parameters, while others were run to analyze how the varying building enclosure levels impacted the PV generation, energy storage, and lifecycle cost required to meet defined project goals.

C4.2.1 Minimizing Cost

The run list below, runs #1-18, comprised simulations where the high-level goal was limited to financial optimization, or minimizing total costs. For the most part, these simulations were completed to set a baseline relative to the following cases. These cases also shed light on the financial feasibility of on-site energy generation and storage for "business as usual" project goals.

Run #	Project Goal(s)	Building			Simulation Objective
		Type	Enclosure	Operation Mode	
1	Minimize Cost	SF	Existing	Typical	None, All Defaults
2			Code		
3			Phius		
4		DUP	Existing		
5			Code		
6			Phius		
7		6-FLAT	Existing		
8			Code		
9			Phius		
10		SF	Existing		Double Analysis Period (50 years)
11			Code		
12			Phius		
13			Existing		Double Electricity Price Escalation Rate (3.8%)
14			Code		
15			Phius		
16			Existing		Time of Use Electricity Rates (4:1 Peak Pricing)
17			Code		
18			Phius		

Table 5. Building-Level Simulation Runs to Explore Minimum-Cost Solutions.

Run #	Project Goal(s)	Building			Simulation Objective
		Type	Enclosure	Operation Mode	
19	Clean Energy	SF	Existing	Typical	50% Emissions Reduction Goal
20			Code		
21			Phius		
22		DUP	Existing		
23			Code		
24			Phius		
25		6-FLAT	Existing		
26			Code		
27			Phius		
28		SF	Existing	Flexible	50% Emissions Reduction Goal
29			Code		
30			Phius		
31			Existing	Typical	50% Emissions Reduction Goal, Emissions Year 2024, Regional
32			Code		
33			Phius		
34			Existing		50% Emissions Reduction Goal, Emissions Year 2035, Regional
35			Code		
36			Phius		
37			Existing		50% Emissions Reduction Goal, Emissions Year 2050, Regional
38			Code		
39			Phius		
40			Existing		50% Emissions Reduction Goal, Emissions Year 2050 State-Level
41			Code		
42			Phius		
43			Existing		75% Emissions Reduction Goal
44					90% Emissions Reduction Goal
45					100% Emissions Reduction Goal
46			Phius	Flexible	75% Emissions Reduction Goal
47					90% Emissions Reduction Goal
48					100% Emissions Reduction Goal
49			Existing	Typical	100% Emissions Reduction Goal Emissions Year 2050, Regional
50			Code		
51			Phius		
52			Existing		Clean Electricity to Net Zero
53			Code		
54			Phius		
55			Existing		100% Clean Electricity
56			Code		
57			Phius		

C4.2.2 Clean Energy / Decarbonization

The table below outlines the simulations carried out with a goal of clean energy utilization or emissions reduction. The primary purpose of these simulations was to determine the impact of the building enclosure performance on meeting these goals. They were also used to:

- Study the differences between "clean electricity" and "emissions reduction" goals,
- Understand the differences between achieving various incremental increase in emissions reduction (e.g. 50% vs. 75%, 90%, 99%, 100%),
- Understand the impact of emission rate selection/ assumptions on meeting decarbonization goals, and
- Recognize how infrastructure required to meet decarbonization goals varied from typical "net zero" project goals.

Table 6. Building-level Simulation Runs to Explore Clean Energy (Decarbonization).

Run #	Project Goal(s)	Building			Simulation Objective
		Type	Enclosure	Operation Mode	
58	Outage Resilience	SF	Existing	Typical + Critical	72 Hour Winter Outage - Simulated Critical Load
59			Code		
60			Phius		
61		DUP	Existing		
62			Code		
63			Phius		
64		6-FLAT	Existing		
65			Code		
66			Phius		
67		DUP	Code		72 Hour Winter Outage - 10% Total Load = Critical
68					72 Hour Winter Outage - 25% Total Load = Critical
69					73 Hour Winter Outage - 50% Total Load = Critical
70		6-FLAT	Phius		36 Hour Winter Outage - Simulated Critical Load
71					144 Hour Winter Outage - Simulated Critical Load
72					72 Hour Summer Outage - Simulated Critical Load

Table 7. Building-level Simulation Runs to Explore Resilience, through Sustaining a Defined Critical Load during Power Outages.

Run #	Project Goal(s)	Building			Simulation Objective
		Type	Enclosure	Operation Mode	
73	Clean Energy & Outage Resilience	SF	Existing	Typical + Critical	72 Hour Winter Outage & 50% Emissions Reduction
74			Code		
75			Phius		
76		DUP	Existing		
77			Code		
78			Phius		
79		6-FLAT	Existing		
80			Code		
81			Phius		

Table 8. Building-level Simulation Runs to Explore Decarbonization and Resilience.

C4.2.3 Resilience

The table below outlines the simulations that studied resilience at the building level. The goal of the "resilience" scenarios are to maintain a predefined critical load during an outage. These were carried out to understand both the impact of the impact of the building enclosure as well as the impact on the "outage condition" to the infrastructure requirements to sustain the defined critical load.

- The "72 hour winter outage - simulated critical load" was run for all building sizes.
- The duplex was used to explore variations in critical loads (as percentages of total load).
- The 6-flat was selected to study other outage scenarios in a sensitivity analysis.
- These typologies were selected to add variety to the study, as the single family typology was used for many of the decarbonization analyses.

C4.2.4 Decarbonization and Resilience

The last set of building level simulations combined both resilience and decarbonization goals, exploring the objective of both sustained critical loads during a 3-day winter outage as well as 50% emissions reduction to the baseline. Ultimately, many projects have overlapping goals and understanding the driving variables is important.

C4.3 Neighborhood Loads (Buildings Only)

The information above this section dealt with simulations of individual buildings to meet specified project outcomes (such as decarbonization). In essence, those simulations treated a building as a stand-alone microgrid – with variations of loads, macrogrid connection, renewable energy resources, storage, and the ability to island when necessary. While not physically or financially impossible, microgrids are more likely to consist of multiple buildings. More buildings means more opportunity for load diversity. Diversity typically is a plus in system design–and enters into the typical design process for plumbing systems, HVAC air distribution, electrical panel sizing, and elevator systems.

How many more buildings–beyond one–is a reasonable microgrid design question. For this study, the answer was established by geography, the geography of an existing neighborhood in Milwaukee, Wisconsin. This is not necessarily the optimum residential scale microgrid; but it is a rational scale.

The neighborhood in this study consisted of 15 single-family homes, 5 duplexes, and 5 6-flat buildings. To create a "neighborhood electrical load" (the load within the boundary of the microgrid), the individual building loads were aggregated. As a reminder, these individual building loads varied by enclosure performance level and operation mode.

Table 9 lists the neighborhood-level load profiles used in the REopt simulations.

The "shifted" operation mode was devised to aggregate the individual building loads into a neighborhood while shifting the timing of the building loads just slightly to introduce diversity. In the shifted cases, the 25 buildings were split into groups of 5 and their loads moved apart from one another in 1-hour increments (-2,-1,0,+1,+2 from the original load pattern).

The 'Typical' and 'Critical / Outage' operation modes were simulated directly in BEopt and aggregated to create the neighborhood load.

#	Scale	Enclosure Level	Operation Mode
28	Neighborhood	Existing Enclosure	Typical
29			Critical / Outage
30			Flexible
31			Shifted +2/-2
32		Code Enclosure	Typical
33			Critical / Outage
34			Flexible
35			Shifted +2/-2
36		Passive Enclosure	Typical
37			Critical / Outage
38			Flexible
39			Shifted +2/-2

Table 9. Neighborhood (Microgrid) Simulations List.

The 'Flexible' load is an aggregation of the individual building flexible loads and was derived from the 'Typical' load simulated in BEopt, but adjusted to shed load during "high price" times. Price was curated using an aggregate of wholesale electricity price ($/kWh) and hourly marginal carbon emissions ($/kg CO_2).

C4.4 Neighborhood Building Loads + Project Goals

Tables 10 through 13 list REopt neighborhood-level simulation runs. As with building-level modeling, some simulations were run to provide a sensitivity analysis for various input parameters, while others were run to analyze how the varying building enclosure levels impacted the PV generation, energy storage, and lifecycle cost required to meet defined project goals.

Many of the same variables were studied at the neighborhood level as were the building level, with similar motivation for studying results. The only new parameter introduced at the neighborhood level was the "shifted" operation mode, which simply refers to how the neighborhood loads were aggregated (and is not applicable at the individual building scale).

C4.4.1 Minimize Cost

As above, these first neighborhood level analyses were to set a baseline for simulations to follow and understand the "business as usual" economics related to adding on-site renewable energy generation and storage at a neighborhood-scale.

C4.4.2 Clean Energy / Decarbonization

As with at the building level, the simulation list below outlines the varying emissions reduction and clean energy goals that were studied. At the neighborhood level, a single toggle was also studied related to if the macrogrid could charge the on-site energy storage, or if it could only be charged with on-site energy generation.

Run #	Project Goal(s)	Microgrid Loads			Simulation Objective
		Scale	Enclosure Level	Operation Mode	
82	Minimize Cost	NEIGHB	Existing	Typical	All Defaults
83			Code		
84			Phius		
85			Existing	Shifted	
86			Code		
87			Phius		
88			Code	Typical	Double Analysis Period (50 years)
89					Double Electricity Price Escalation Rate (3.8%)
90					Time of Use Electricity Rates (4:1 Peak Pricing)

Table 10. Neighborhood-Scale Simulations to Minimize System Cost.

Run #	Project Goal(s)	Microgrid Loads			Simulation Objective
		Scale	Enclosure Level	Operation Mode	
91	Clean Energy		Existing	Typical	50% Emissions Reduction
92			Code		
93			Phius		
94			Existing	Shifted	
95			Code		
96			Phius		
97			Existing	Typical	50% Emissions Reduction, DO NOT Allow Grid to Charge Battery
98			Code		
99			Phius		
100			Existing		75% Emissions Reduction
101			Code		
102			Phius		
103			Existing		90% Emissions Reduction
104			Code		
105			Phius		
106			Existing		99% Emissions Reduction
107			Code		
108			Phius		
109			Existing		100% Emissions Reduction
110			Code		
111			Phius		

Table 11. Neighborhood-Scale Simulations to Minimize Emissions toward Decarbonization.

Run #	Project Goal(s)	Microgrid Loads			Simulation Objective
		Scale	Enclosure Level	Operation Mode	
112	Clean Energy	NEIGHB	Existing	Flexible	75% Emissions Reduction
113			Code		
114			Phius		
115			Existing		90% Emissions Reduction
116			Code		
117			Phius		
118			Existing		99% Emissions Reduction
119			Code		
120			Phius		
121			Existing		100% Emissions Reduction
122			Code		
123			Phius		
124			Existing	Typical	Clean Electricity to Net Zero
125			Code		
126			Phius		
127			Existing		50% Clean Electricity
128			Code		
129			Phius		
130			Existing		90% Clean Electricity
131			Code		
132			Phius		
133			Existing		99% Clean Electricity
134			Code		
135			Phius		
136			Existing		100% Clean Electricity
137			Code		
138			Phius		

Table 11, continued. Neighborhood-Scale Simulations to Minimize Emissions toward Decarbonization.

C4.4.3 Resilience

The table below outlines the resilience situations studied, again to understand the infrastructure required to maintain a defined critical load during a defined outage period. The resilience studies at the neighborhood level studied a simulated critical load (defined using an hourly modeling simulation tool as defined in Section C2.3), as well as using a fixed critical load percentage based on results that came from the building-level resilience simulations.

C4.4.4 Clean Energy and Resilience

The last simulations studied the overlap in meeting both resilience and decarbonization goals. This combination was studied to understand the driving factors and incremental differences between meeting the goals separate versus combined.

Run #	Project Goal(s)	Microgrid Loads			Simulation Objective
		Scale	Enclosure Level	Operation Mode	
139	Outage Resilience	NEIGHB	Existing	Typical + Critical	72 Hour Winter Outage
140	Outage Resilience	NEIGHB	Code	Typical + Critical	72 Hour Winter Outage
141	Outage Resilience	NEIGHB	Phius	Typical + Critical	72 Hour Winter Outage
142	Outage Resilience	NEIGHB	Existing	Typical + Critical	72 Hour Winter Outage - 25% Total Load = Critical
143	Outage Resilience	NEIGHB	Code	Typical + Critical	72 Hour Winter Outage - 25% Total Load = Critical
144	Outage Resilience	NEIGHB	Phius	Typical + Critical	72 Hour Winter Outage - 25% Total Load = Critical
145	Outage Resilience	NEIGHB	Existing	Shifted + Critical	72 Hour Winter Outage - 25% Total Load = Critical
146	Outage Resilience	NEIGHB	Code	Shifted + Critical	72 Hour Winter Outage - 25% Total Load = Critical
147	Outage Resilience	NEIGHB	Phius	Shifted + Critical	72 Hour Winter Outage - 25% Total Load = Critical

Table 12. Neighborhood-Scale Simulations to Provide Electrical Resilience by Sustaining a Critical Load through the Microgrid during an Outage.

Run #	Project Goal(s)	Microgrid Loads			Simulation Objective
		Scale	Enclosure Level	Operation Mode	
148	Clean Energy & Outage Resilience	NEIGHB	Existing	Typical + Critical	72 Hour Winter Outage, 50% Emissions Reduction
149	Clean Energy & Outage Resilience	NEIGHB	Code	Typical + Critical	72 Hour Winter Outage, 50% Emissions Reduction
150	Clean Energy & Outage Resilience	NEIGHB	Phius	Typical + Critical	72 Hour Winter Outage, 50% Emissions Reduction

Table 13. Neighborhood-Scale Simulations to Utilize Clean Energy While Providing Microgrid Resilience.

C5. RESULTS - BUILDING LEVEL

C5.1 Building Loads

C5.1.1 Typical Operation

The buildings studied varied in enclosure performance but used identical all-electric mechanical systems for heating, cooling, and hot water, identical large appliance models, and consistent assumptions for lighting and plug loads.

In discussing the results, we will refer to these building enclosures as follows:

· Existing Building Stock Enclosure = **existing**

· IECC 2021 Compliant Enclosure Building = **code**

· Phius CORE 2021 Compliant Enclosure Building = **passive**

On average:

- An **existing** building used **1.8x** more annual energy and had a peak load **2.5x** higher than a **code** building**.**
- An **existing** building used **2.6x** more annual energy and had a peak load **5.5x** higher than a **passive** building.
- A **code** building used **1.5x** more annual energy than a passive building and had a peak load **2.2x** higher than the **passive** building.

In all instances, the electrified cases had a lower estimated annual carbon dioxide emissions. This is due to a combination of both a swap in equipment efficiency (from inefficient natural gas equipment to more efficient use of energy through heat pumps) as well as the efforts to decarbonize the electricity supply.

Single Family	Typical Load				Flexible Load		
	Gas	All Electric			All Electric		
	Existing*	Existing	Code	Passive	Existing	Code	Passive
Annual Energy Consumption (kWh/yr)	70,124	28,392	14,110	8,726	23,102	12,370	8,197
Site EUI (kBTU/ft^{2}yr)	112.4	45.5	22.6	14.0	37.0	19.8	13.1
Peak Electric Load (kW)**	3.1	31.3	13.0	5.3	31.3	13.0	5.1
Peak Critical Electric Load (kW)***	N/A	24.4	9.9	7.2	N/A	N/A	N/A

Duplex	Typical Load				Flexible Load		
	Gas	All Electric			All Electric		
	Existing*	Existing	Code	Passive	Existing	Code	Passive
Annual Energy Consumption (kWh/yr)	117,463	49,564	23,321	14,151	41,481	20,278	13,368
Site EUI (kBTU/ft^{2}yr)	143.8	60.7	28.5	17.3	50.8	24.8	16.4
Peak Electric Load (kW)**	4.4	52.7	23.2	9.2	52.7	23.2	9.2
Peak Critical Electric Load (kW)***	N/A	37.5	13.5	6.0	N/A	N/A	N/A

6-Flat	Typical Load				Flexible Load		
	Gas	All Electric			All Electric		
	Existing*	Existing	Code	Passive	Existing	Code	Passive
Annual Energy Consumption (kWh/yr)	256,090	109,723	53,748	40,121	93,268	48,003	38,140
Site EUI (kBTU/ft^{2}yr)	95.2	40.8	20.0	14.9	34.7	17.8	14.2
Peak Electric Load (kW)**	14.0	109.5	39.6	22.6	109.5	39.6	22.6
Peak Critical Electric Load (kW)***	N/A	80.0	24.3	16.9	N/A	N/A	N/A

Table 14a: Building Level Results, Energy Consumption & Peak Loads for Typical Building Loads & Flexible Building Loads.

Table Notes:

**For the baseline case, the existing enclosure with natural gas fired equipment for space heating, water heating, and cooking.*

***The Peak Electric Load (kW) only includes the peak driven by electrical energy use. For the baseline, gas-equipment case, this does not include the power required for space heating or water heating. This serves as a proxy for the scale of electrical service currently provided to the building.*

****The Peak Critical electric load (kW) is the peak of the electrical energy usage required for the defined critical (outage) load profile.*

	Typical Load			
	Gas	All Electric		
	Annual Carbon Dioxide Emissions (kg CO_2/yr)			
	Existing	Existing	Code	Passive
Single Family	31,896	21,610	10,724	6,603
Duplex	53,156	37,578	17,656	10,686
6-Flat	117,656	83,131	40,638	30,273

	Flexible Load			
	Gas	All Electric		
	Annual Carbon Dioxide Emissions (kg CO_2/yr)			
	Existing	Existing	Code	Passive
Single Family	N/A	16,441	9,007	6,083
Duplex	N/A	29,682	14,696	9,925
6-Flat	N/A	67,053	35,054	28,346

*Table 14b: Building Level Results, Estimated Annual CO2 Emissions for Typical & Flexible Building Loads, including Baseline Gas Cases *Note: 0.127 kg CO2/kBtu assumed for the use of natural gas on-site*

<u>On average:</u>

- An **existing** building with natural gas equipment creates **40-50% more carbon emissions annually** than the same building with the **existing** enclosure and high performance all-electric space heating and water heating equipment.
- An **existing** building with natural gas equipment creates **200% more carbon emissions annually** than the same building with the **code** enclosure + high performance all-electric space heating and water heating equipment.
- An **existing** building with natural gas equipment creates **500% more carbon emissions annually** than the same building with the **passive** enclosure + high performance all-electric space heating and water heating equipment.
- A **existing** all electric building produces **200%+ more carbon emissions annually** than the same building with the **code** enclosure
- A **existing** all electric building produces **300%+ more carbon emissions annually** than the same building with the **passive** enclosure
- A **code** all electric building produces **40-60% more carbon emissions annually** than the same building with the **passive** enclosure

All in all, given the role of architects in the design of the enclosure, architects can play a large part in slashing emissions at the forefront through the design of high performance enclosures beyond code minimums.

The flexible loads (those that incorporated shedding heating/cooling load based on high grid emissions), show great potential in reducing emissions even further, with:

- **25-30% annual emissions reductions** from typical loads for the **existing enclosure;**
- **15-20% annual emissions reduction** from typical loads for the **code enclosure**, and;
- **5-10% annual emissions reduction** from typical loads for the **passive enclosure**

As the total load decreases, the amount of load to shed also decreases and therefore results in lower overall impact.

Results of the typical building operation simulations for these three enclosure levels are illustrated in Figure 11 (single-family), Figure 12 (duplex), and Figure 13 (6-flat).

A key takeaway from Figure 11 is that improving building enclosure acts as a de-stressor for an electrical grid–at both the macro and micro grid scale. Transitioning from existing building stock to 2021 code-compliance reduces annual electrical consumption (EUI) by roughly half, but reduces peak load by roughly two-thirds. This type of building transition will allow existing utilities some room to breathe.

Transitioning existing building stock to passive building enclosures would reduce annual consumption by two-thirds, and reduce peak load to one sixth of the baseline. This type of building transition would unlock further opportunities for scaling up renewable energy resources.

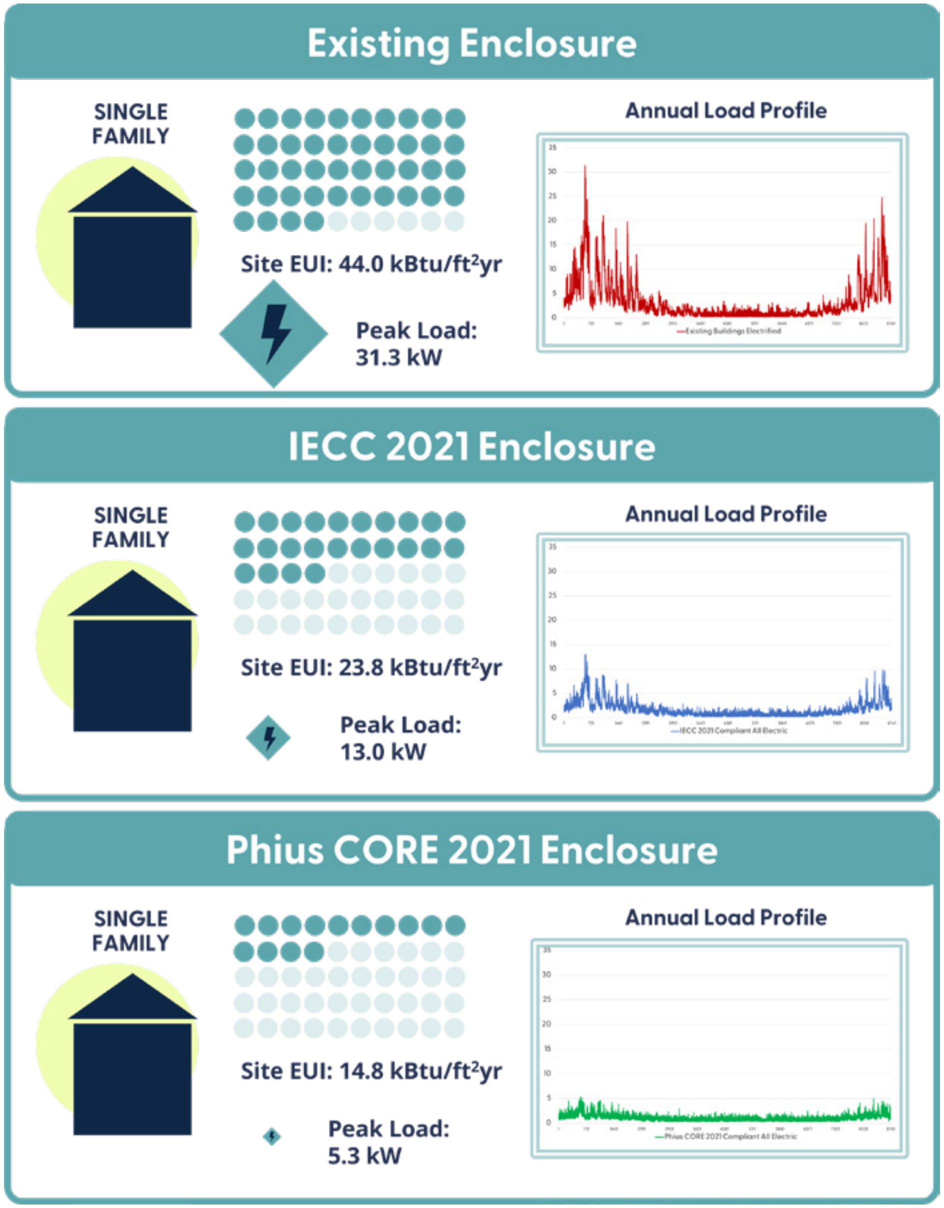


Fig. 11. Summary Results (EUI, Peak Electrical Load, and Electrical Load Profile) for Three Single-Family Buildings, Varying Enclosure Levels. [Courtesy of Phius]

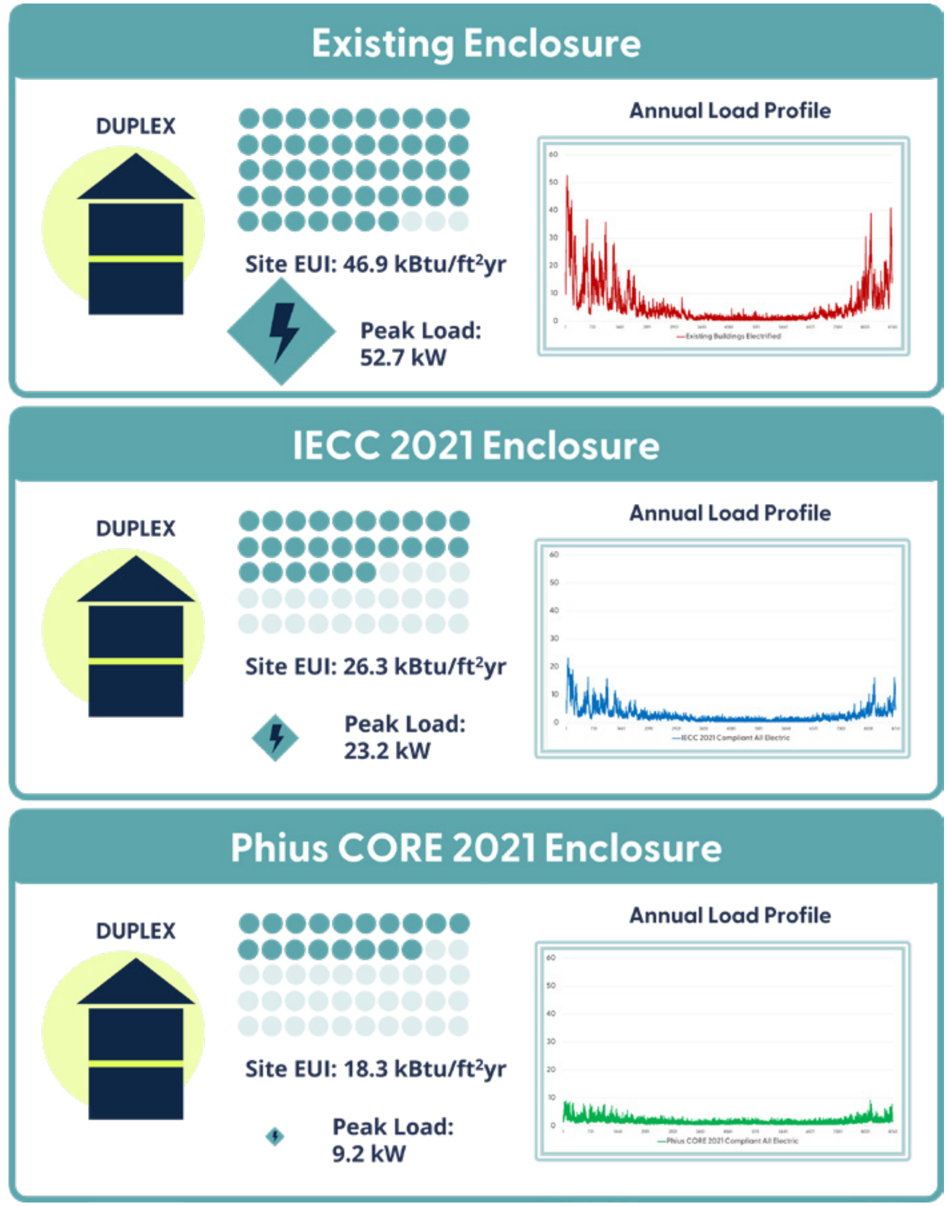


Fig. 12. Summary Results (EUI, Peak Electrical Load, and Electrical Load Profile) for Three Duplex Buildings, Varying Enclosure Levels. [Courtesy of Phius]

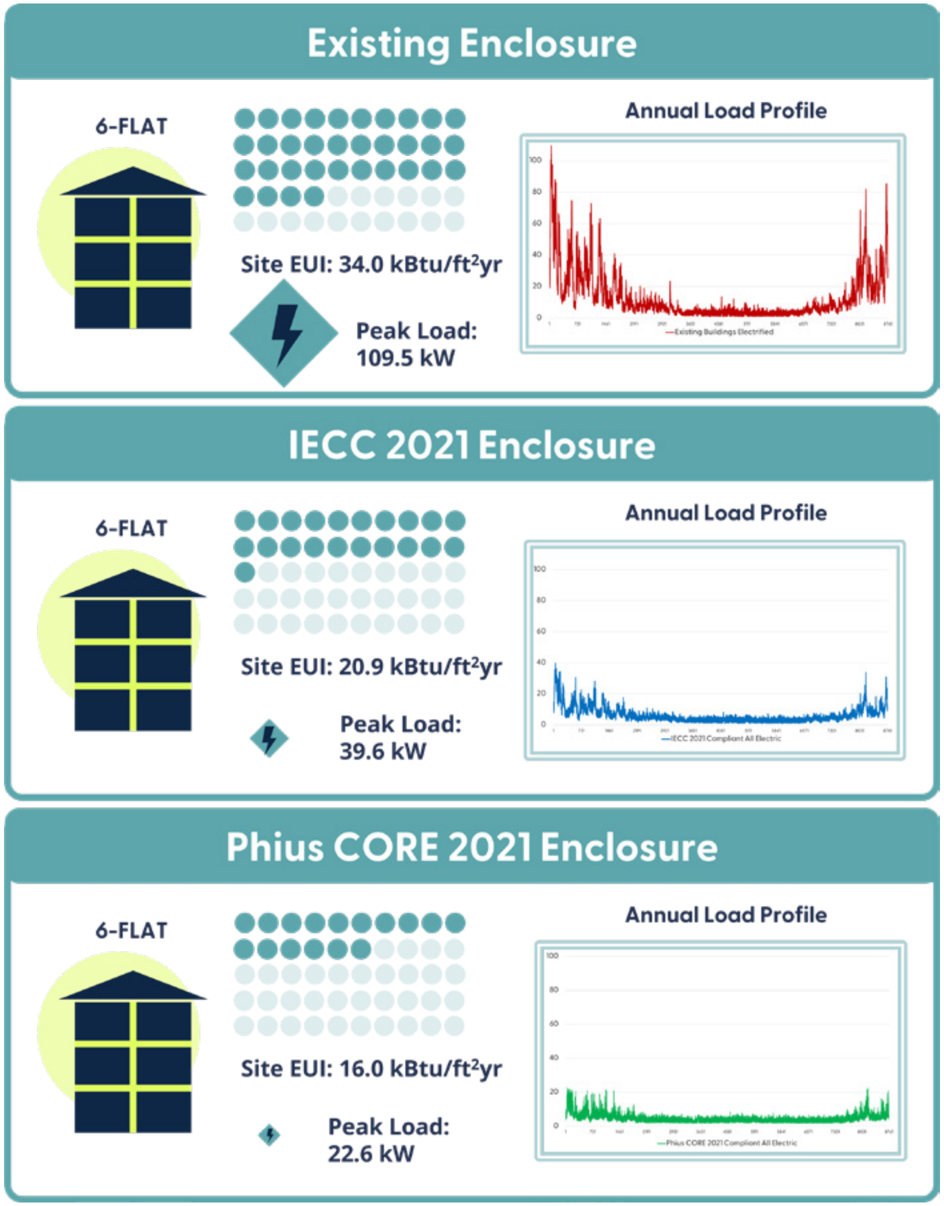


Fig. 13. Summary Results (EUI, Peak Electrical Load, and Electrical Load Profile) for Three 6-Flat Buildings, Varying Enclosure Levels. [Courtesy of Phius]

C5.1.2 Critical Operation

A "critical" load was modeled in BEopt to represent the building load that could ideally be sustained when there was a main grid outage. In this case, that load consisted of maintaining an interior air temperature between 55F-85F, keeping the refrigerator running, powering 10% of the lighting, maintaining 25% of the typical mechanical ventilation (when applicable), and enough electricity for a few cell phone chargers.

Table 15 shows the "Critical Load Factor", or the percentage that the critical load is of the total, typical load. In the REopt tool, there is the option to use a critical hourly load profile (8,760 data points) or a single critical load factor for the year. This was studied to determine the range of hourly critical load factors from the simulated results, to see if a simple static % for critical load factor could be used in place instead of the detailed hourly analysis.

- Average critical load percentage represents the annual average critical load over total load.
- Minimum critical load percentage represents the hour in which the critical load required to support critical operating conditions was the lowest percentage of total load. In all cases, this occurred during summer months when the total load was lowest, see Figure 14.
- Maximum critical load percentage represents the hour in which the critical load required to support critical operating conditions was the highest percentage of the total typical load. In all cases, this occurred during the coldest hour of the year when the energy use requirements were dominated by heating loads, see Figure 13.

Type	Enclosure Level	Critical Load - % of Total Load		
		Average	Minimum	Maximum
Single Family	Existing Building	22%	2%	78%
	IECC 2021 Compliant	21%	2%	82%
	Phius CORE 2021	20%	3%	87%
Duplex	Existing Building	24%	3%	74%
	IECC 2021 Compliant	21%	1%	78%
	Phius CORE 2021	20%	2%	83%
6-Flat	Existing Building	23%	5%	75%
	IECC 2021 Compliant	19%	5%	82%
	Phius CORE 2021	20%	6%	81%

Table 15. Critical Load Factor Results for Nine Individual Building Scenarios, based on Annual Critical Operation Simulations.

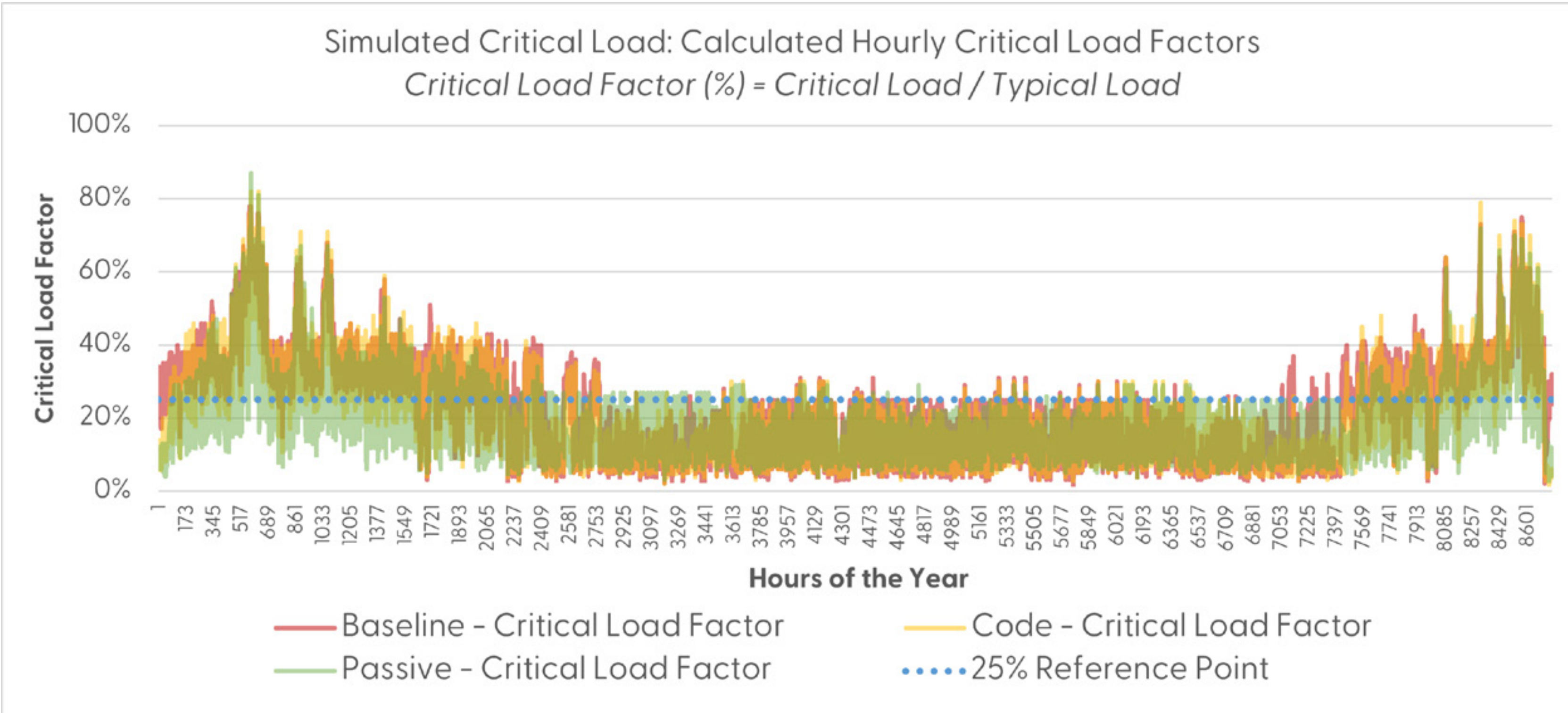


Fig. 14. Annual Variation in Calculated Critical Load Factor for 3 Varying Enclosure Cases, Single-Family Residences.

Figure 14 shows the calculated critical load factor versus time of year for the three enclosure options and a single-family residence in Milwaukee, Wisconsin. The critical load factors are calculated from the simulated critical loads. The blue horizontal line in the graph represents a critical load factor of 25%, which was a default recommendation in the analysis software. Note that although the average critical load factor is close to 25% (see Table 14 above), seasonally there is a lot of variation. Simulations for summer outages in Milwaukee could assume a lower critical load factor, while winter may be closer to 50-80% of critical load, depending on the stress condition selected for the outage.

C5.1.3 Flexible Operation

The flexible operation schedules were used to determine if shedding load during a relatively few times of high carbon emissions on the grid would assist in meeting carbon reduction goals for the building in a meaningful way. For example, if 1% of the time the load was responsive to emission signals, could a building reduce more than 1% of the emissions during typical operation, or save more than 1% of the cost for a more holistic carbon reduction goal?

Note that, ideally, such a load shifting/shedding/alignment and responsiveness would happen within a more sophisticated control environment that was able to see the typical load, the dynamic grid signal, the amount of load flexibility available to tap into (both to shed and shift), as well as the renewable resource availability on-site during times of high signals.

<u>NOTE</u>: This concept was limited in scope for this study, but load flexibility and load alignment with renewable resource availability is intended for further research and is believed to have significant impact on meeting both decarbonization and resilience goals.

C5.2 Building Performance + Project Goals

Individual REopt simulations were packaged into "cases" with common goals for the purposes of results analysis. Table 16 lists the cases evaluated.

The table is followed by results for each of the cases .

There are two main case considerations:

1. **Envelope impact and;**
2. **Input sensitivity.**

<u>Envelope Impact:</u> In these cases, a common goal was evaluated with each of the various enclosure levels to analyze the impact of the building load (as influenced by the enclosure) on requirements to meet project goals.

<u>Input Sensitivity:</u> In these cases, a common goal was evaluated with variables that were not related to the building load. These analyses provided a sensitivity analysis for determining the impact of other factors (such as electricity price increases, etc.). These impacts can be compared to the impact of adjusting building load.

Case	Type	Goal	Target	Enclosure Level			Size	Other Variable
1	Envelope Impact	Clean Energy	50% Emissions Reduction	Existing	Code	Passive	DUP	
2	Envelope Impact	Clean Energy	50% Emissions Reduction	Existing	Code	Passive	SF	Emissions Profile - Today, 2024, 2035, 2050
3	Envelope Impact	Clean Energy	50% Emissions Reduction	Existing	Code	Passive	SF	Emissions Profile - Current, 2050 Regional
4	Envelope Impact	Clean Energy	50% Emissions Reduction	Existing	Code	Passive	SF	Typical Loads vs. Flexible Loads
5	Envelope Impact	Clean Energy	75%, 90%, 100% Emissions Reduction	Existing	Code	Passive	SF	Typical Loads vs. Flexible Loads
6	Envelope Impact	Clean Energy	Net Zero	Existing	Code	Passive	SF	Financial Optimization for Storage
7	Envelope Impact	Clean Energy	100% Reneawble Electricity	Existing	Code	Passive	SF	
8	Envelope Impact	Clean Energy	100% Renewable Electricty vs. Net Zero	Existing	Code	Passive	SF	
9	Envelope Impact	Resilience	72-Hour Winter Outage - Simulated Critical Load	Existing	Code	Passive	6 FLAT	
10	Input Sensitivity	Minimize Cost		Existing	Code	Passive	SF	Electricity Cost & Analysis Period
11	Input Sensitivity	Resilience	72-Hour Winter Outage	Existing	Code	Passive	DUP	Type of Load - Simulated vs. Varying % Critical Load
12	Input Sensitivity	Resilience	Resilience During Outage	Existing	Code	Passive	6 FLAT	Outage Duration and Season
13	Input Sensitivity	Clean Energy	50%, 75%, 90%, 100% Emissions Reduction	Existing	Code	Passive	SF	
14	Input Sensitivity	Clean Energy	50% Emissions Reduction	Existing	Code	Passive	SF	Emissions Profile - Today, 2024, 2035, 2050 Regional
15	Input Sensitivity	Clean Energy	50% Emissions Reduction	Existing	Code	Passive	SF	Emissions Profile - 2050 Regional vs. 2050 State-Level
16	Input Sensitivity	Clean Energy & Resilience	50% Emissions Reduction & 72 Hour Winter Outage	Existing	Code	Passive	DUP	Individual vs. Combined Goals

Table 16. Summary of REopt Analysis Cases.

Note: All results shown below have been normalized to show the result per dwelling unit.

That is, the results for the full 6-flat building has been divided by 6 for the purposes of comparing results from varying building sizes. When reviewing results, orient yourself by taking note of the scale of the y-axis from one graph to the next.

Case 1

Case Type

Energy Goals

Enclosure Level

Scale of Simulation

PURPOSE: This case assesses the impact of building enclosure performance on meeting a 50% emissions reduction goal for the building.

RESULT: Improving the enclosure from the existing enclosure level to the Phius level reduced the on-site energy generation, battery capacity, and battery power required to halve emissions by a factor of 6-7. The variation in results per building enclosure level roughly scaled with the differences in peak loads between the buildings (see Section 5.1.1), and was slightly higher than that ratio when comparing existing to Phius and code to Phius.

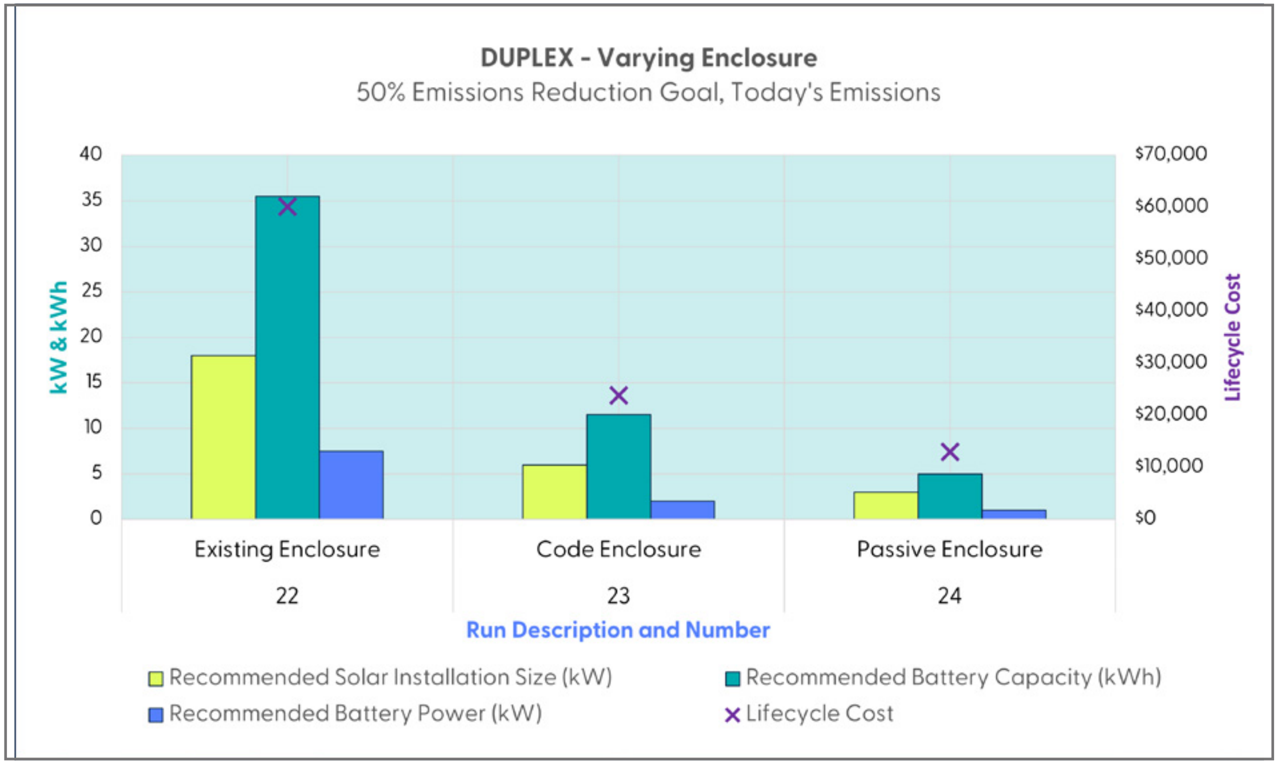


Fig. 15. Impact of Enclosure Level on PV and Battery Requirements for Emissions Reduction Objective.

Run Number	22	23	24
Net Present Value	-$15,861	-$2,435	$448
Lifecycle Cost	$60,148	$23,882	$13,019
Initial Cost	$33,374	$10,954	$4,846
Solar PV (kW)	18	6	3
Battery Capacity (kWh)	36	12	5
Battery Power (kW)	8	2	1

Case 2

Case Type | Energy Goals | Enclosure Level | Scale of Simulation

PURPOSE: This case was used to assess the impact of varying emissions factors on the simulation results when setting emissions reduction goals, as well as the impact of the enclosure on that sensitivity analysis.

RESULT: With the default, current emissions factors (EPA AVERT Midwest Region) built into the REopt software, the goal of hitting a 50% emissions reduction relative to the baseline required about half of the on-site energy generation and battery storage infrastructure of any of the future emissions scenarios. While the varying emissions factors resulted in different results, the discrepancy in results when analyzing the various emissions factors was more pronounced for the buildings with the existing enclosure. This shows that when the enclosure is improved to Phius levels, a potential change of emissions factors makes less of an impact. More on emissions sensitivity is studied in Case 14.

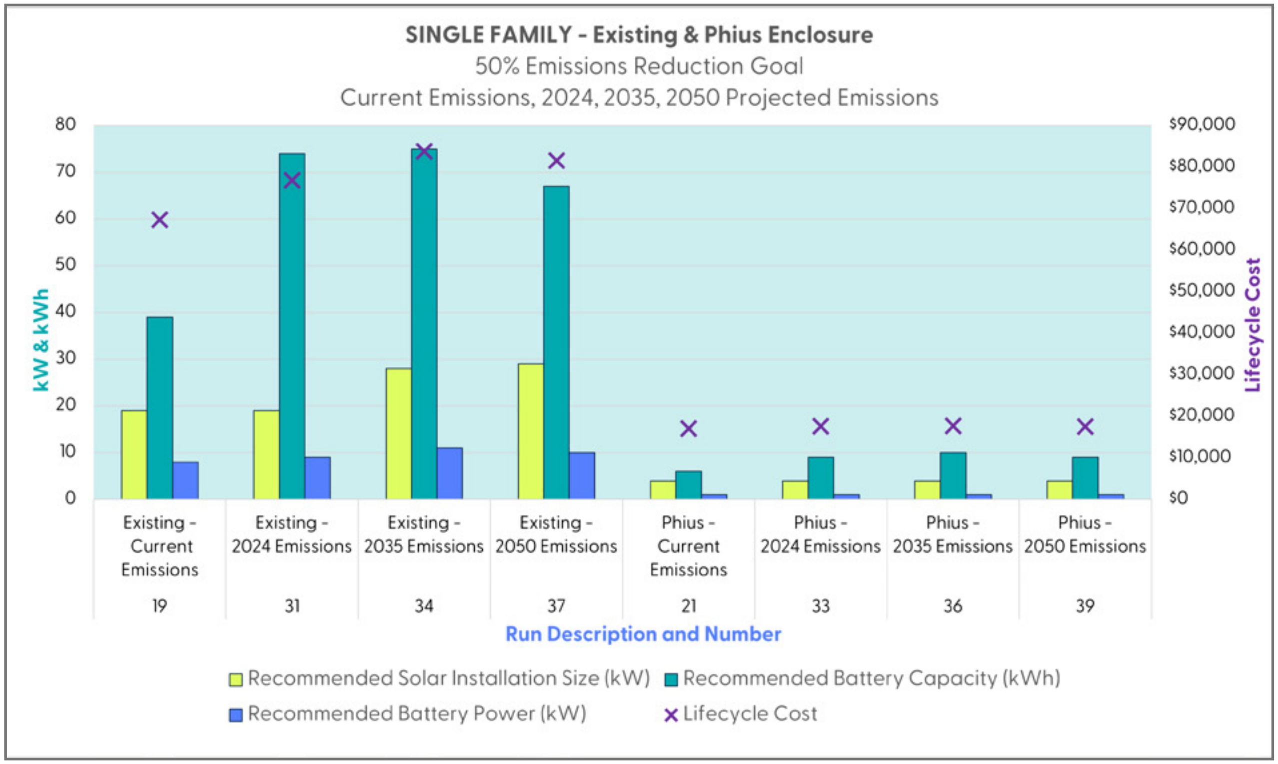


Fig. 16. Impact of Emissions Factor on PV and Battery Requirements for Emissions Reduction Objective.

Run Number	19	31	34	37	21	33	36	39
Net Present Value	-$15,624	-$25,103	-$32,080	-$29,874	$471	-$94	-$199	-$75
Lifecycle Cost	$67,345	$76,824	$83,801	$81,595	$17,018	$17,583	$17,688	$17,564
Initial Cost	$35,796	$47,114	$57,856	$55,467	$6,060	$7,601	$8,115	$7,968
Solar PV (kW)	19	19	28	29	4	4	4	4
Battery Capacity (kWh)	39	74	75	67	6	9	10	9
Battery Power (kW)	8	9	11	10	1	1	1	1

Case 3

Case Type | Energy Goals | Enclosure Level | Scale of Simulation

PURPOSE: This case was used to show the relative difference between the three enclosure levels relative to decarbonization goals (emissions reductions) considering today's emission factors versus future emissions—to see the relative impact of both the enclosure and emissions factors on the building infrastructure required to meet a 50% emissions reduction goal.

RESULT: Using today's emissions, a 50% emissions reduction goal for the existing building enclosure requires roughly 5x more on-site generation and 7x more battery storage than with the passive building enclosure. When using the 2050 emissions factors, which vary more than current factors both seasonally and hourly, the differences between the existing enclosure building and passive building requirements were even more pronounced—requiring 7x more solar and about 9x more battery storage. As there is more variation in hourly emission factors, the impact of enclosure-based efficiency becomes even more significant toward accomplishing emissions reductions.

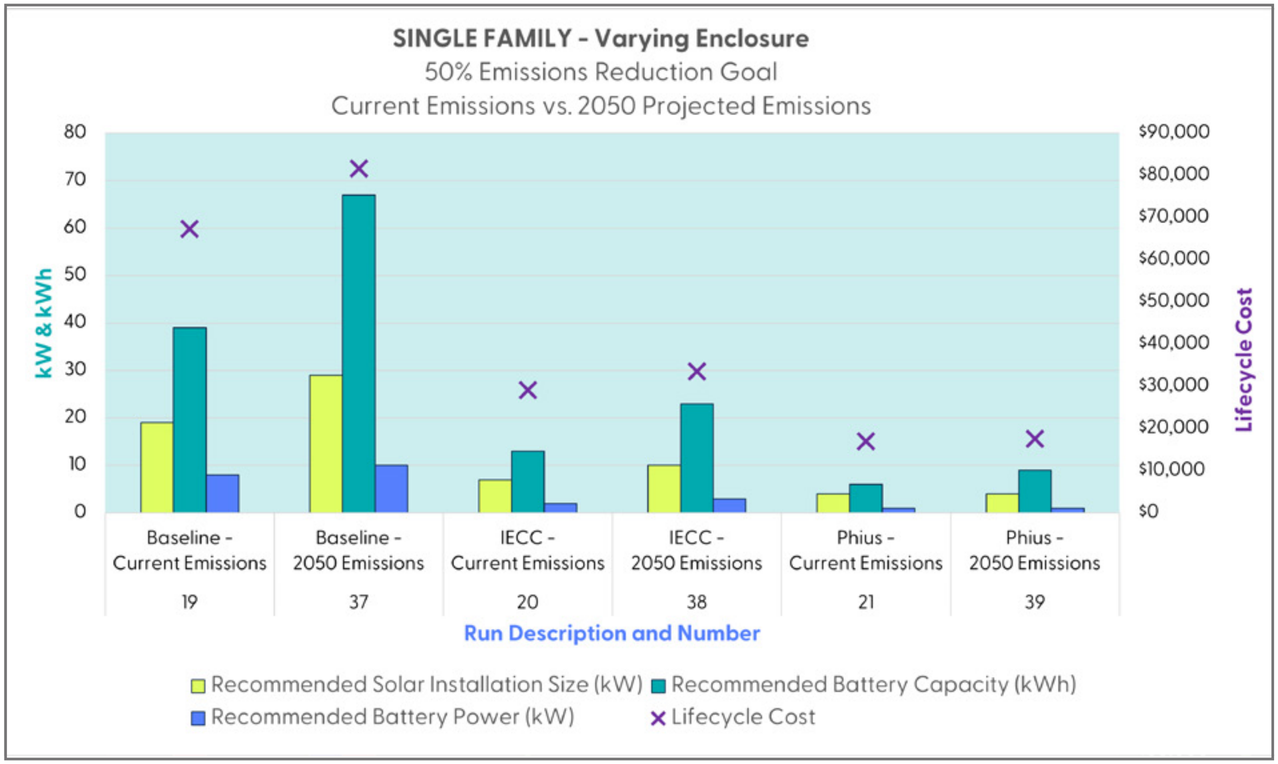


Fig. 17. Impact of Emissions Factor on PV and Storage Requirements for Emissions Reduction Objective—Single Family Building.

Run Number	19	37	20	38	21	39
Net Present Value	-$15,624	-$29,874	-$2,279	-$6,708	$471	-$75
Lifecycle Cost	$67,345	$81,595	$29,141	$33,570	$17,018	$17,564
Initial Cost	$35,796	$55,467	$12,581	$19,578	$6,060	$7,968
Solar PV (kW)	19	29	7	10	4	4
Battery Capacity (kWh)	39	67	13	23	6	9
Battery Power (kW)	8	10	2	3	1	1

Case 4

Case Type | Energy Goals | Enclosure Level | Scale of Simulation

PURPOSE: The purpose of this case was to understand the potential impact of space conditioning load flexibility (load shedding, see Section 2.3.1) on meeting emissions goals, as well as the relative impact compared to varying enclosure performance.

RESULT: The flexible load made the most impact on the building with the existing enclosure, which is in line with expectations given that that building had the highest space conditioning loads to begin with. However, while the flexible load did decrease infrastructure requirements across the board, the impact of the enclosure is much more significant than the impact of the load shedding.

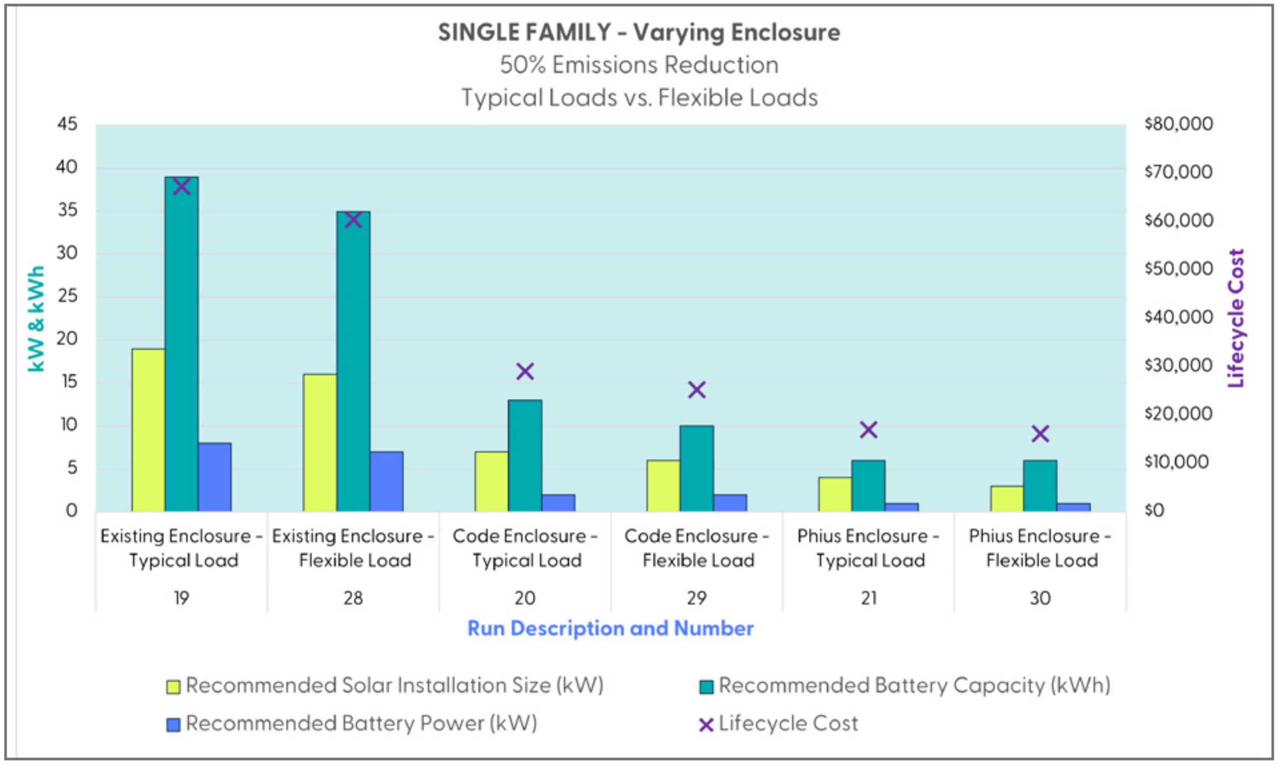


Fig. 18. Impact of Flexible Loads on PV and Battery Requirements for Emissions Reduction Objective–Single Family Building.

Run Number	19	28	20	29	21	30
Net Present Value	-$15,624	-$10,822	-$2,279	-$1,274	$471	$530
Lifecycle Cost	$67,345	$53,336	$29,141	$25,106	$17,018	$16,039
Initial Cost	$35,796	$27,489	$12,581	$10,349	$6,060	$5,570
Solar PV (kW)	19	15	7	6	4	3
Battery Capacity (kWh)	39	31	13	11	6	5
Battery Power (kW)	8	6	2	2	1	1

Case 5

Case Type

Energy Goals

Enclosure Level

Scale of Simulation

PURPOSE: Building upon Case 4, this analysis was run to determine the combined impact of improved building enclosure and load flexibility to achieve varying decarbonization goals. The case explores the bounding range of conditions established for this study, comparing the "business as usual" case (with rigid loads and existing enclosure), to the highly improved case (with flexible loads and a passive enclosure). Requirements to achieve 75%, 90%, and 100% emissions reductions goals (clean energy) were analyzed.

RESULT: For all the emissions reduction goals, the building with the existing enclosure with typical loads requires about 8-10x more PV and 10-12x more battery storage than the passive enclosure. Of course at a 100% emissions reduction level, this equates to the greatest variance in actual infrastructure requirements. In other words, this means that in a given scenario, if the goal is to reduce emissions significantly, first improving the enclosure and then enabling load flexibility should be explored as a least-cost path before turning to renewables and storage.

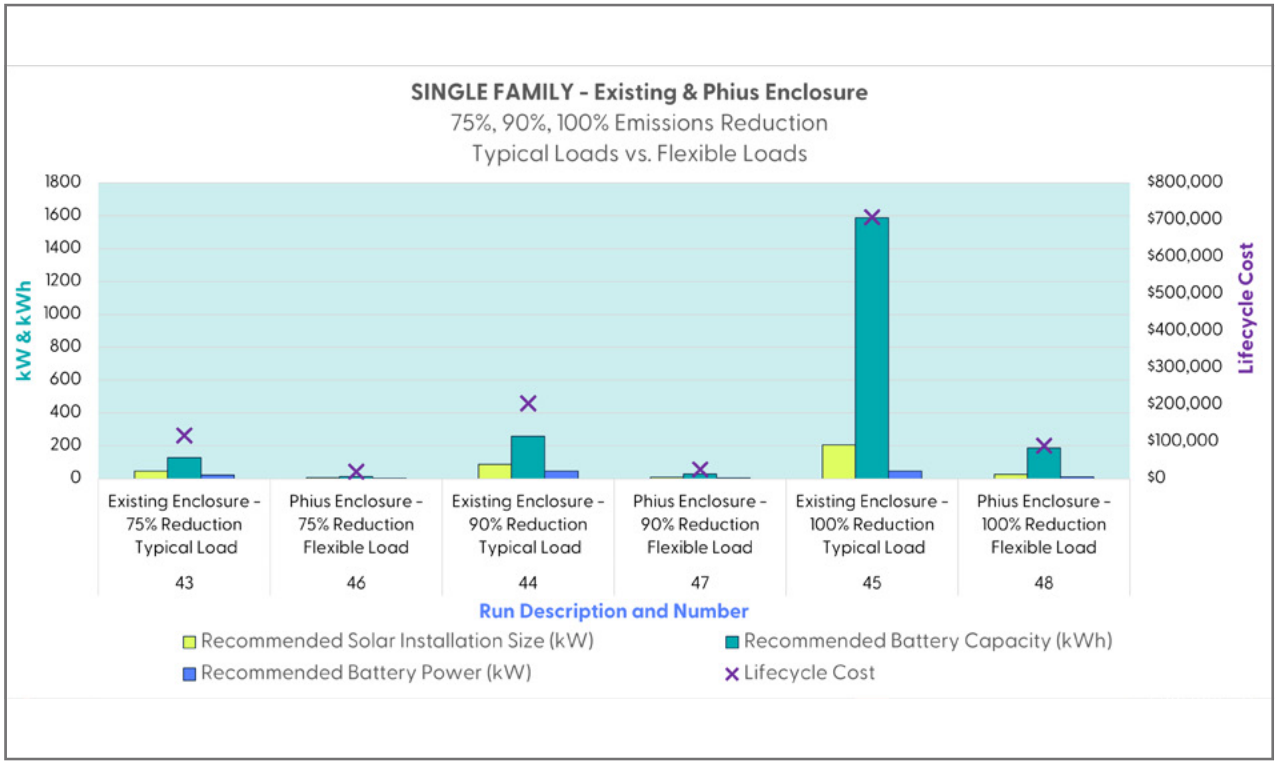


Fig. 19. Impact of Flexible Load Implementation on Distributed Energy Requirements–Single Family, Two Enclosures.

Run Number	43	46	44	47	45	48
Net Present Value	-$65,347	-$1,784	-$151,846	-$9,586	-$655,481	-$86,331
Lifecycle Cost	$117,068	$18,353	$203,567	$26,155	$707,202	$102,900
Initial Cost	$97,367	$11,163	$192,543	$21,573	$704,901	$100,599
Solar PV (kW)	45	6	87	10	207	36
Battery Capacity (kWh)	128	14	258	29	1,587	202
Battery Power (kW)	22	2	46	5	46	7

Case 6

Case Type

Energy Goals

Enclosure Level

Scale of Simulation

PURPOSE: This case was investigated to illustrate the difference in the amount of solar generation required for "net zero" performance for each of the different buildings. The simulation was set to include the minimum amount of PV necessary for "net zero" while the REopt optimizer added energy storage that was financially optimal when combined with the building enclosure and solar generation prescribed.

RESULT: The solar installation size for "net zero", shown below, scales linearly and directly correlates to the annual energy use of each building. The amount of optimized energy storage to accompany the solar installation remained the same for each simulation, despite the significant difference in PV installation size, which may conclude that energy storage is expensive, and, without variation in hourly electricity prices, only a small amount of energy storage is financially feasible when paired with on-site PV.

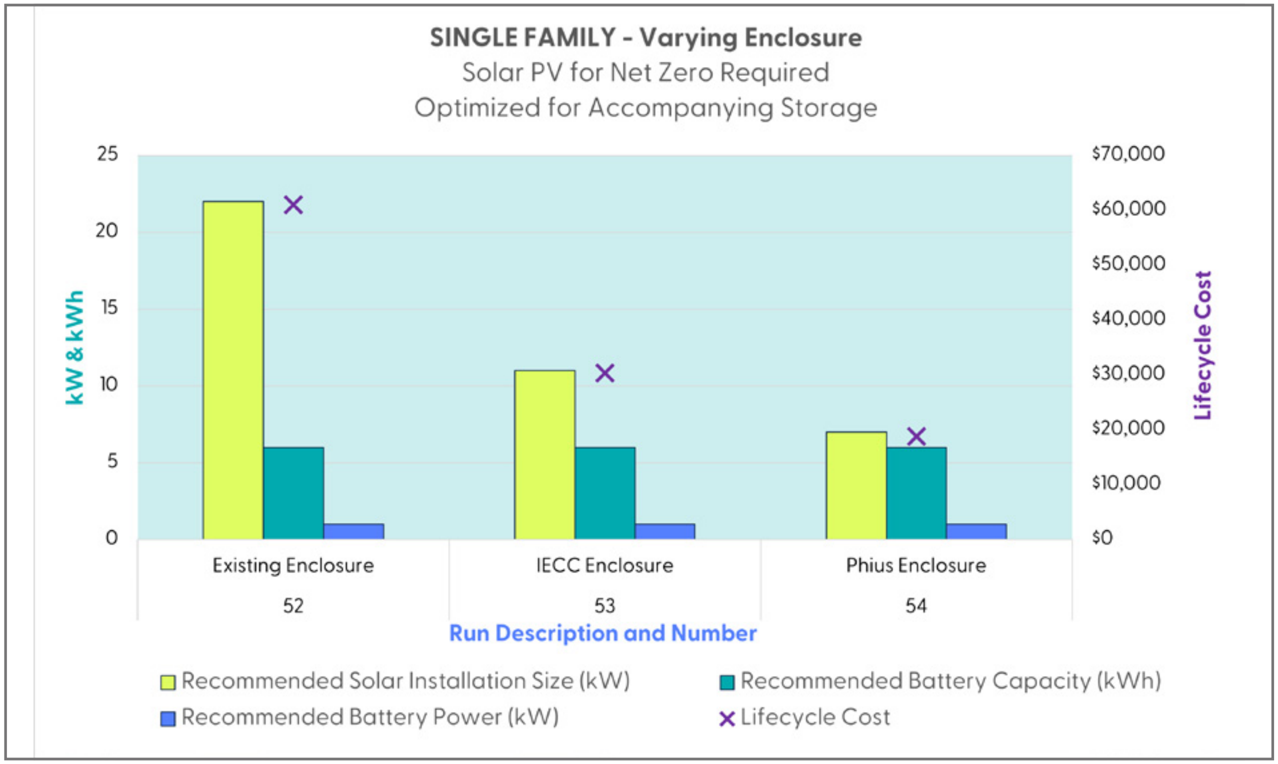


Fig. 20. Required PV Size for Net-Zero Outcome Under Three Enclosure Options–Single Family.

Run Number	52	53	54
Net Present Value	-$9,284	-$3,473	-$1,287
Lifecycle Cost	$61,005	$30,335	$18,776
Initial Cost	$24,565	$13,355	$9,201
Solar PV (kW)	22	11	7
Battery Capacity (kWh)	6	6	6
Battery Power (kW)	1	1	1

Case 7

Case Type | Energy Goals | Enclosure Level | Scale of Simulation

PURPOSE: This case was run to determine the generation and storage required for each of the varying buildings to run on 100% renewable (clean) electricity. This concept is different from "net zero" because it requires that 100% of the hours in the year are met with renewable electricity, rather than using a "net" calculation over the course of the year. While studied here at a building level, this serves as a proxy for what it would take to convert our existing energy supply stock to 100% renewables (except that the generation resource here was limited to solar and a 100% renewable scenario would include other renewable resources such as wind power, hydropower, etc).

RESULT: The most pronounced result is that battery storage is a much bigger player in running on renewable electricity than the capacity of the generation asset itself. This is due to the need to adjust the timing of clean energy availability to align with the consumption of the energy by the building. The ratio of both energy generation and storage required when migrating from the existing enclosure to the passive enclosure roughly scales with the difference in peak loads between the two building cases (5-6x higher). Note the lifecycle cost for the existing enclosure is close to $600,000.

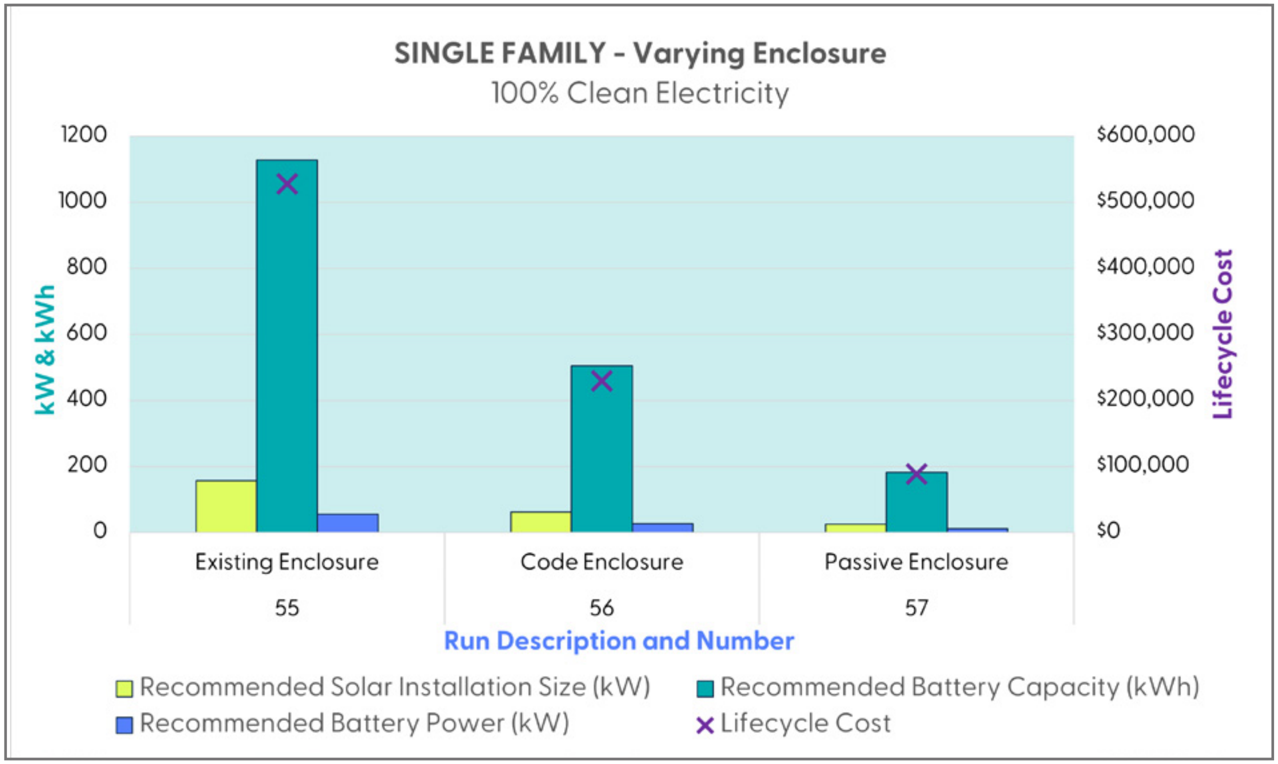


Fig. 21. Impact of Enclosure Stringency on Renewable Source and Storage Capacity–Single Family, 100% Renewable Electricity.

Run Number	55	56	57
Net Present Value	-$476,182	-$202,508	-$70,811
Lifecycle Cost	$527,903	$229,370	$88,300
Initial Cost	$524,729	$226,682	$85,868
Solar PV (kW)	157	62	25
Battery Capacity (kWh)	1,128	504	182
Battery Power (kW)	56	26	11

Case 8

Case Type | Energy Goals | Enclosure Level | Scale of Simulation

PURPOSE: This case shows the difference between a "net zero" project goal (where clean electricity generation over the course of the year is equal to the annual energy consumption of the building) and a 100% renewable (clean) electricity project goal (where clean electricity supply, or stored clean electricity, is required for 24/7/365 operation of the building).

RESULT: This case shows the stark impact of taking the timing of energy generation and use (and the mismatch between these) into account. The 100% renewable electricity cases require a significant amount of energy storage to align the clean energy generation with the building load, as well as significantly more solar generation (renewable, clean) to meet the building load in real time. The life cycle cost is 9x higher between the two goals for the existing enclosure, 8x for the code enclosure, and 5x for the passive enclosure – so once again, as the building load is decreased and flattened, the gap between meeting the two goals decreases (though there is still a significant difference here).

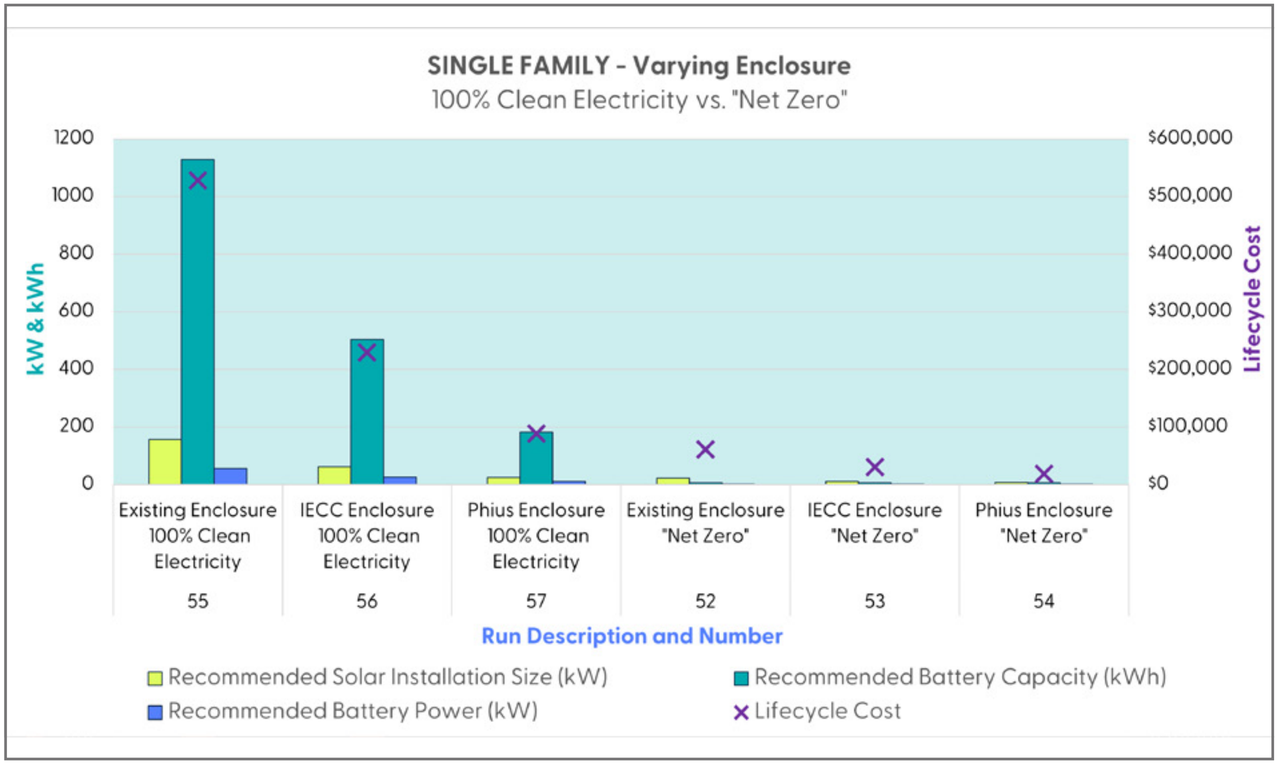


Fig. 22. Impact of Enclosure Stringency on Meeting Differing Single Family Energy Objectives (100% Renewable Electricity versus Net-Zero).

Run Number	55	56	57	52	53	54
Net Present Value	-$476,182	-$202,508	-$70,811	-$9,284	-$3,473	-$1,287
Lifecycle Cost	$527,903	$229,370	$88,300	$61,005	$30,335	$18,776
Initial Cost	$524,729	$226,682	$85,868	$24,565	$13,355	$9,201
Solar PV (kW)	157	62	25	22	11	7
Battery Capacity (kWh)	1,128	504	182	6	6	6
Battery Power (kW)	56	26	11	1	1	1

Case 9

Case Type

Energy Goals

Enclosure Level

Scale of Simulation

PURPOSE: This case analyzes the impact of the building enclosure on the required solar and battery storage required to sustain a modeled critical load (see Appendix B for details) during a 72-hour power outage.

RESULT: As illustrated below, the building with the existing enclosure required 7x more peak solar power than the passive building and 4x more than the code compliant building, which is greater than the difference between the peak loads of the buildings (5.5x and 2.5x, respectively). This means that for that same amount of solar infrastructure, 7 passive buildings could be operated (versus only one existing building).The critical load for the building with the existing enclosure was much higher during the outage period. This is because the modeled critical load required maintaining an interior temperature of 55F in the winter–so the enclosure with worse thermal performance required an increased HVAC load to maintain that setpoint. This resulted in an exponential increase in infrastructure required to sustain defined critical conditions.

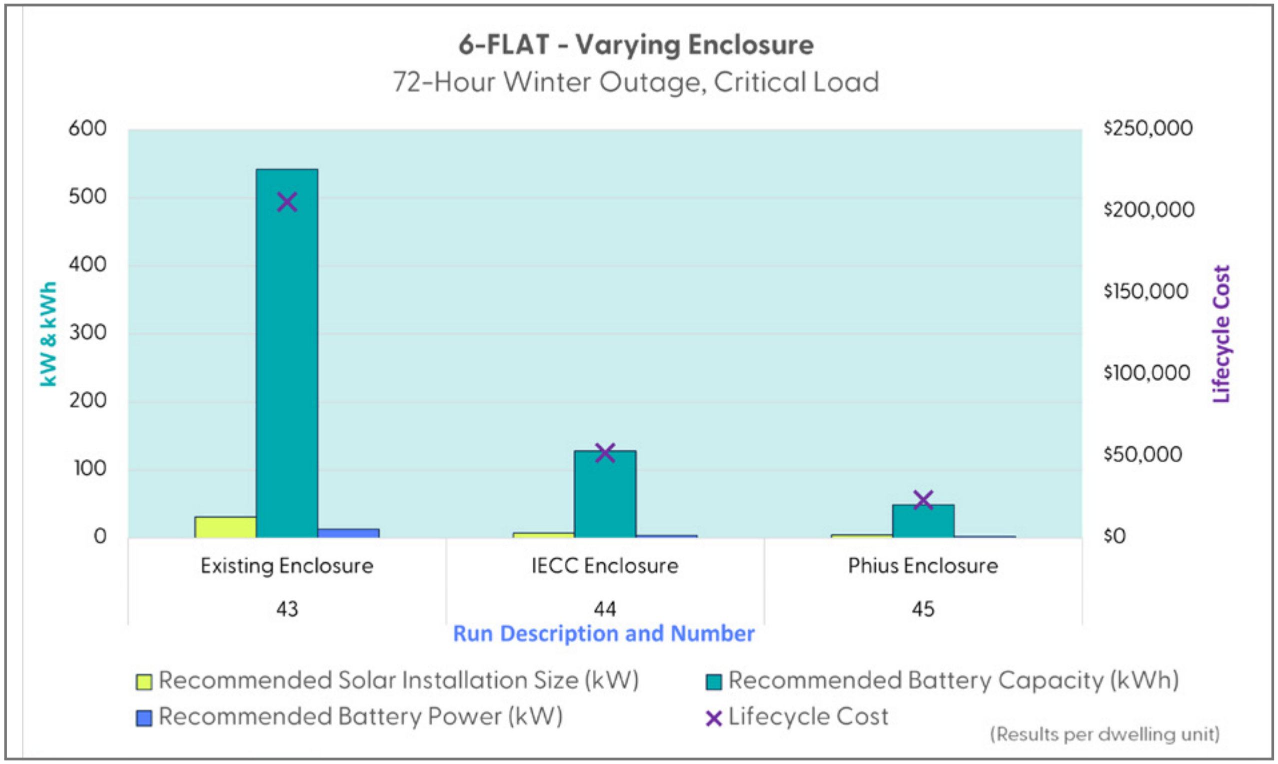


Fig. 23. Solar & Storage Infrastructure Required to Maintain Critical Load for Three Enclosure Levels–6-Flat.

Run Number	43	44	45
Net Present Value	-$65,347	-$151,846	-$655,481
Lifecycle Cost	$117,068	$203,567	$707,202
Initial Cost	$97,367	$192,543	$704,901
Solar PV (kW)	45	87	207
Battery Capacity (kWh)	128	258	1,587
Battery Power (kW)	22	46	46

Case 10

Case Type | Energy Goals | Enclosure Level | Scale of Simulation

PURPOSE: This analysis was conducted to determine the sensitivity of inputs related to the financial optimization in the software that are not related to the building enclosure. It also helps determine if there are factors that have a more significant impact on results than the building enclosure. Each factor was examined individually, though of course they could have compounding effects.

RESULT: In all cases, incorporating a small amount of solar PV made sense. If the price of electricity increases more year-over-year (electricity escalation rate), it makes financial sense to increase the amount of PV generation to offset that. With time of use rates for electricity use, which charge more for electricity during peak hours than off-peak hours, some energy storage makes financial sense. Note that this case actually has the lowest lifecycle cost, despite that the most infrastructure was recommended in the financial optimization. With a longer analysis period for the optimization, energy storage made financial sense, but didn't have as much of an impact as changing the electricity rate structure from flat to time of use.

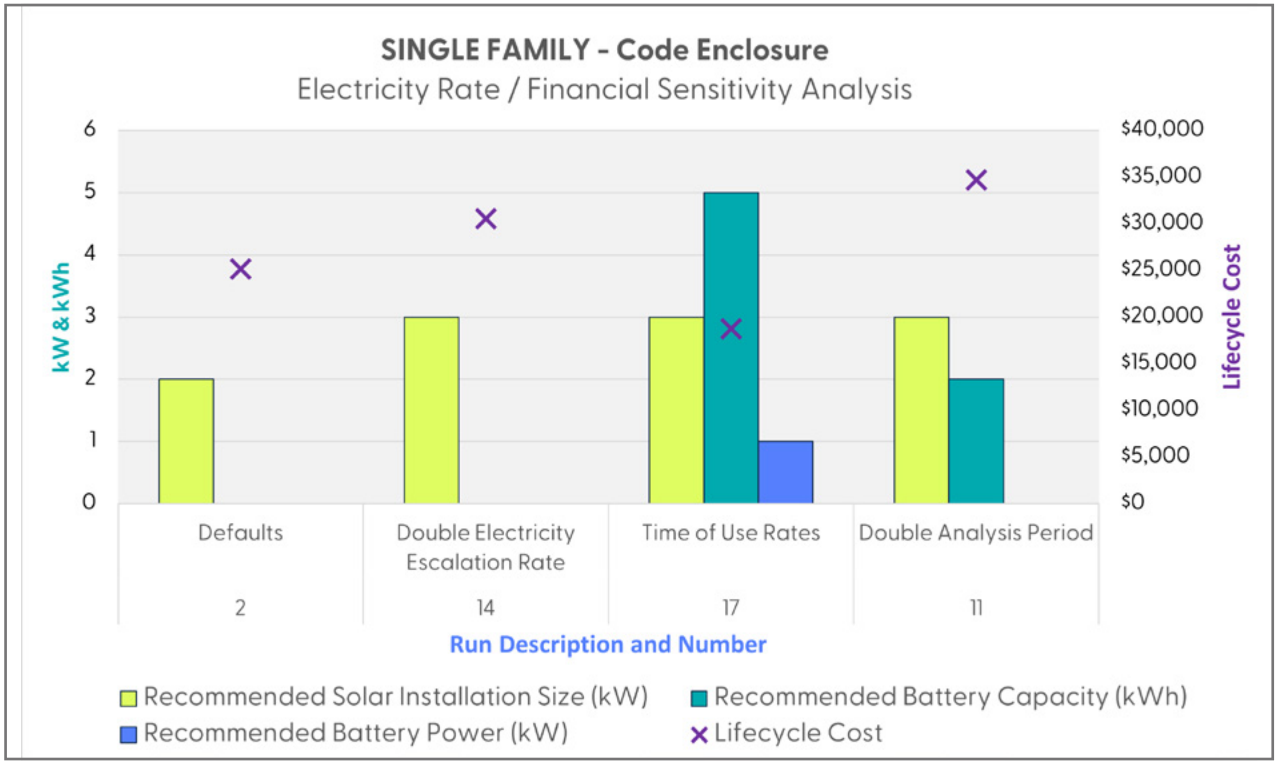


Fig. 24. Sensitivity of Solar & Storage Infrastructure Requirements to Electricity Pricing–Single Family, Code Enclosure.

Run Number	2	14	11	17
Net Present Value	$1,698	$2,754	$3,053	$3,915
Lifecycle Cost	$25,164	$30,538	$34,718	$18,748
Initial Cost	$2,446	$3,058	$4,384	$5,132
Solar PV (kW)	2	3	3	3
Battery Capacity (kWh)	0	0	2	5
Battery Power (kW)	0	0	0	1

Case 11

Case Type | Energy Goals | Enclosure Level | Scale of Simulation

PURPOSE: This case was run to analyze the difference between modeling an outage with a “simulated critical load” to sustain versus using a fixed % of the total load as a “critical load factor” in the outage (which is a much less time intensive method for creating a critical load).

RESULT: With a code enclosure, the requirements for the simulated critical load were similar to those when using a 25% critical load factor. When simulating with a critical load factor, each additional percentage increase was linearly proportional to the previous, meaning that a 50% critical load factor required just about double the 25% critical load factor. It is assumed that the outage period and duration will make an impact on which critical load percentage the simulated load aligns with, given that the percentage of total load modeled in the critical load varies throughout the year. See Section 5.1.2: Critical Operation.

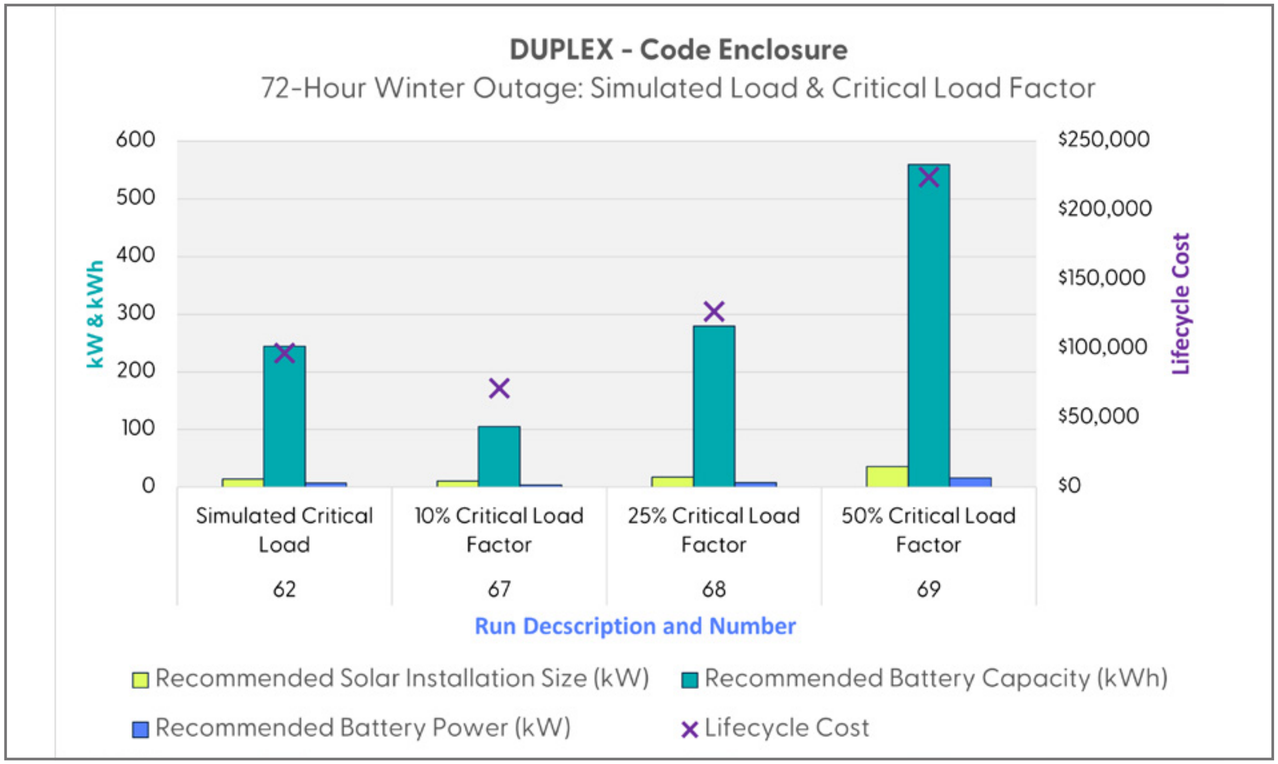


Fig. 25. Sensitivity of On-Site Solar & Storage Resources to Critical Load Selection–Duplex with Code Enclosure.

Run Number	62	67	68	69
Net Present Value	-$76,448	-$29,869	-$85,217	-$182,386
Lifecycle Cost	$96,850	$71,554	$126,902	$224,072
Initial Cost	$90,849	$44,702	$105,066	$210,066
Solar PV (kW)	15	11	18	36
Battery Capacity (kWh)	245	106	280	560
Battery Power (kW)	7	4	8	16

Case 12

Case Type | Energy Goals | Enclosure Level | Scale of Simulation

PURPOSE: This case was used to determine the sensitivity of the outage duration and season to the requirements for resilience and a sustained energy supply.

RESULT: As shown below, a 144-hour winter outage required roughly the same amount of solar generation and storage capacity as a 72-hour winter outage (i.e., an outage with half the duration). This suggests that if substantially severe conditions are used to assess the 72-hour outage, the resulting local infrastructure may be able to sustain longer outages. The 36-hour outage required half of the battery storage capacity, which may be indicative of a modeling period with more solar resource availability and less need for storage than the case with a longer outage. A 72-hour outage occurring in the summer required 2.5x less local PV capacity, 32x less battery storage capacity, and 10x less battery power output than a 72-hour outage occurring in the winter in this climate for the same building (a 6-flat with passive enclosure). This illustrates the seasonal mismatch between building load requirements and energy supply availability, as well as the variation in winter peak loads versus summer peak loads for an all electric building in Milwaukee.

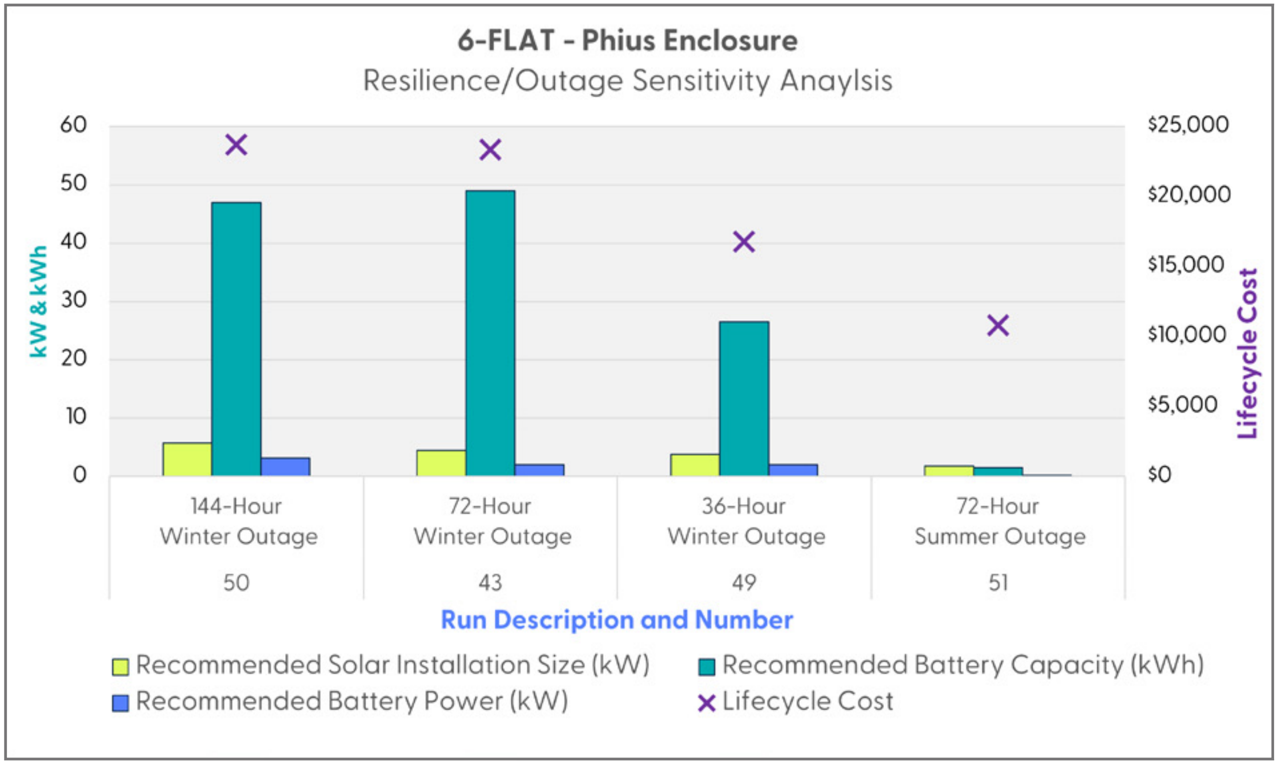


Fig. 26. Sensitivity of Local PV & Storage Infrastructure to Severity of Macrogrid Outage.

Run Number	50	43	49	51
Net Present Value	-$284,835	-$65,347	-$655,481	-$95,961
Lifecycle Cost	$311,697	$117,068	$707,202	$113,450
Initial Cost	$309,397	$97,367	$704,901	$111,149
Solar PV (kW)	99	45	207	38
Battery Capacity (kWh)	668	128	1,587	232
Battery Power (kW)	19	22	46	7

Case 13

Case Type

Energy Goals

Enclosure Level

Scale of Simulation

PURPOSE: This analysis illustrates the generation and storage requirements for varying emissions reduction goals for the same building (a single family with the existing enclosure).

RESULT: The infrastructure requirements for meeting decarbonization (clean energy; emissions reductions) goals are not linear, they are exponential. This pattern is shown below. For example, the first 25% (from a 50% to a 75% reduction) in emissions requires about 2.5x more PV capacity and 3x more battery storage capacity. While the next 25% (from a 75% to 100% reduction) requires 4.5x more PV and 12x more battery storage capacity. Meeting a 100% emissions reduction goal for this building has a lifecycle cost almost 7x higher than meeting a 90% reduction goal, and is 10x higher than a 50% reduction goal.

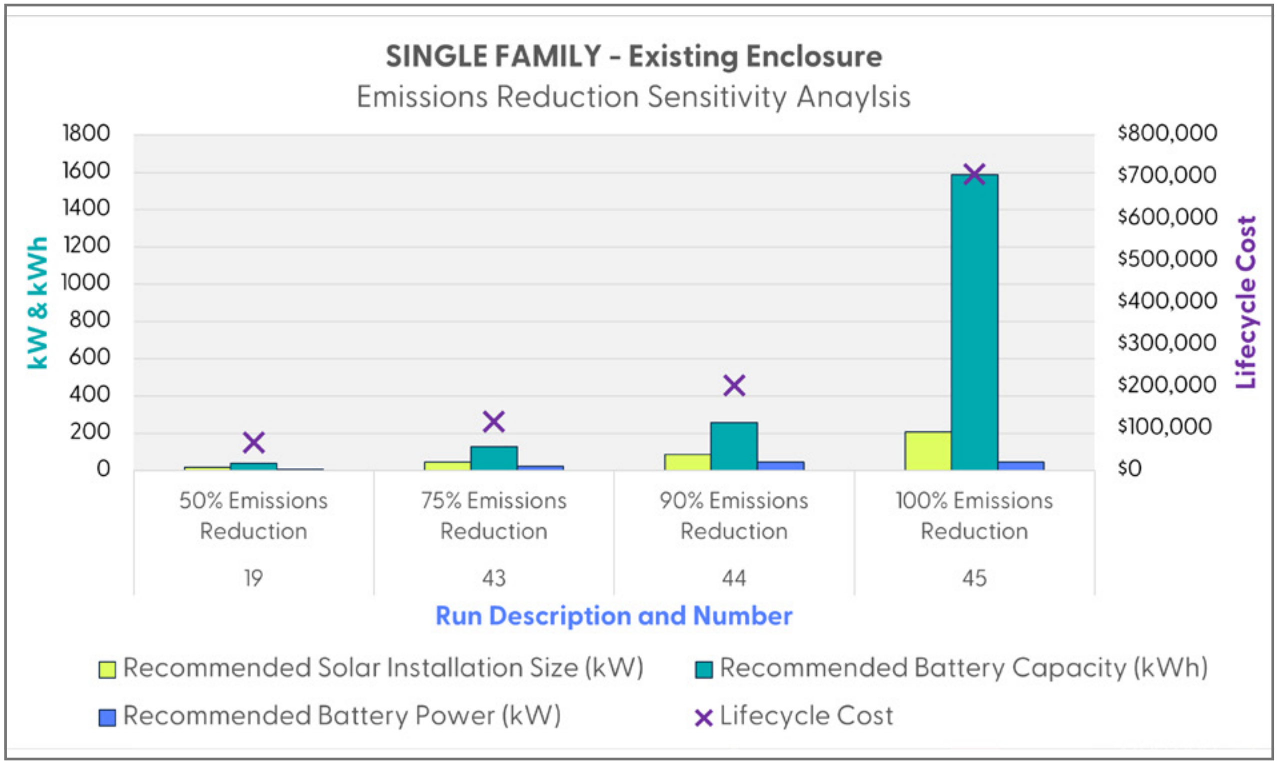


Fig. 27. Sensitivity of Local PV & Storage Infrastructure to Intensity of Clean Energy Target

Run Number	19	43	44	45
Net Present Value	-$15,624	-$65,347	-$151,846	-$655,481
Lifecycle Cost	$67,345	$117,068	$203,567	$707,202
Initial Cost	$35,796	$97,367	$192,543	$704,901
Solar PV (kW)	19	45	87	207
Battery Capacity (kWh)	39	128	258	1,587
Battery Power (kW)	8	22	46	46

Case 14

Case Type

Energy Goals

Enclosure Level

Scale of Simulation

PURPOSE: This sensitivity analysis was used to identify the impact of various future emissions projections. This case was also used to analyze whether variations in emissions profiles impact results as significantly as envelope adjustments.

RESULT: The current emission profile results varied quite a bit from the future, projected emissions values but the greatest variation was less than a factor of two difference, as shown below. There was not a significant variation between future projections for 2024, 2035, and 2050. Note that the projections all use the same 'mid-case scenario' as defined by NREL (details in Appendix B).For the same decarbonization goal (50% emissions reduction), varying the enclosure (see Case 3) had significantly more impact (a factor of 4-8x) than projected variations in emissions profiles. The 2050 emissions scenario results show slightly less energy storage required to meet the 50% reduction goal. This may be due to an overall cleaner grid in 2050, where the gap between the best and worst hours for marginal grid emissions is decreased (compared to previous years), and therefore less storage may be required for alignment with the clean hours.

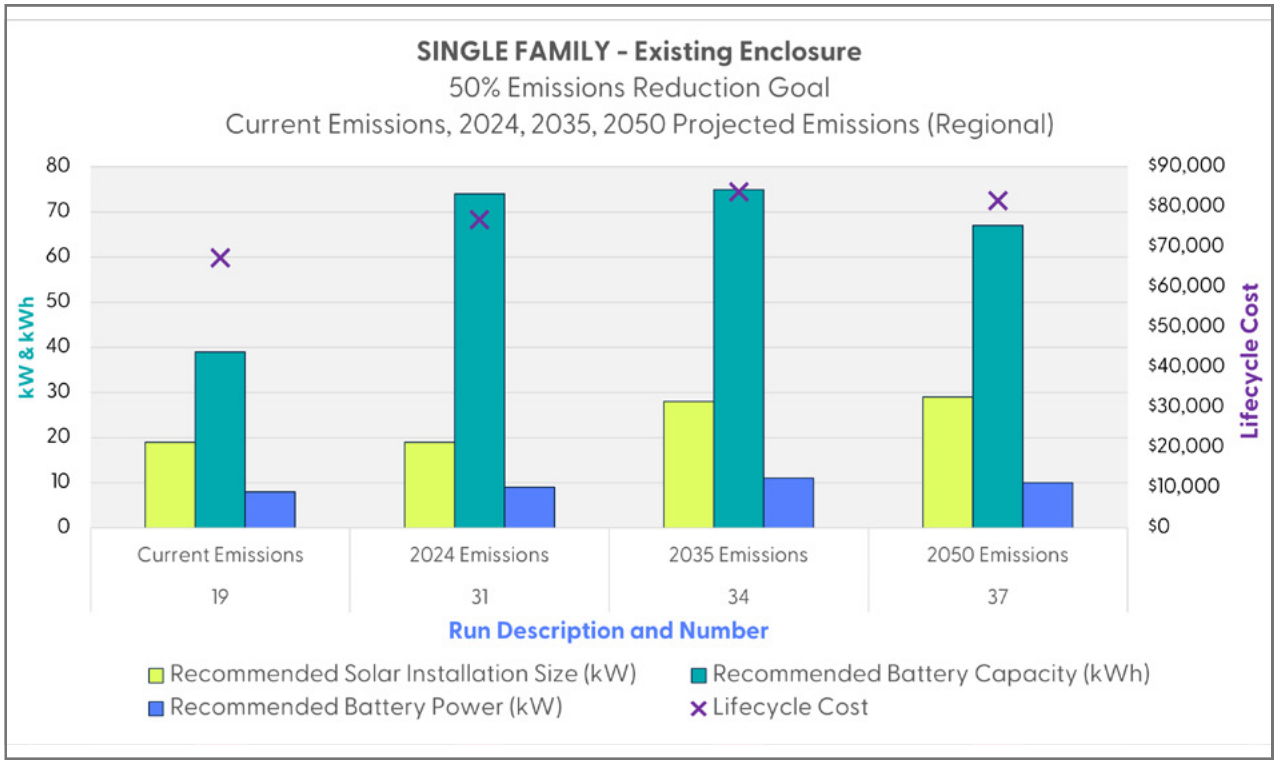


Fig. 28. Sensitivity of Local PV & Storage Requirements to Variations in Emissions Profile Assumptions–Single Family, Existing Enclosure.

Run Number	19	31	34	37
Net Present Value	-$15,624	-$25,103	-$32,080	-$29,874
Lifecycle Cost	$67,345	$76,824	$83,801	$81,595
Initial Cost	$35,796	$47,114	$57,856	$55,467
Solar PV (kW)	19	19	28	29
Battery Capacity (kWh)	39	74	75	67
Battery Power (kW)	8	9	11	10

Case 15

Case Type | Energy Goals | Enclosure Level | Scale of Simulation

PURPOSE: This case was run to determine how using regional (RFCW) versus state level (Wisconsin) emissions projections impacted the results.

RESULT: For the existing enclosure, using the regional emissions factors resulted in 50% more solar PV required than the state-level, but slightly less energy storage. The lifecycle cost for both were similar but higher for regional factors. For the code enclosure case, they were similar but again state factors required more energy storage. For the passive enclosure case, however, the difference in results between the two emissions profiles was negligible, further providing evidence that as the building load decreases and flattens as a result of enclosure decisions, other variables impact the results less.

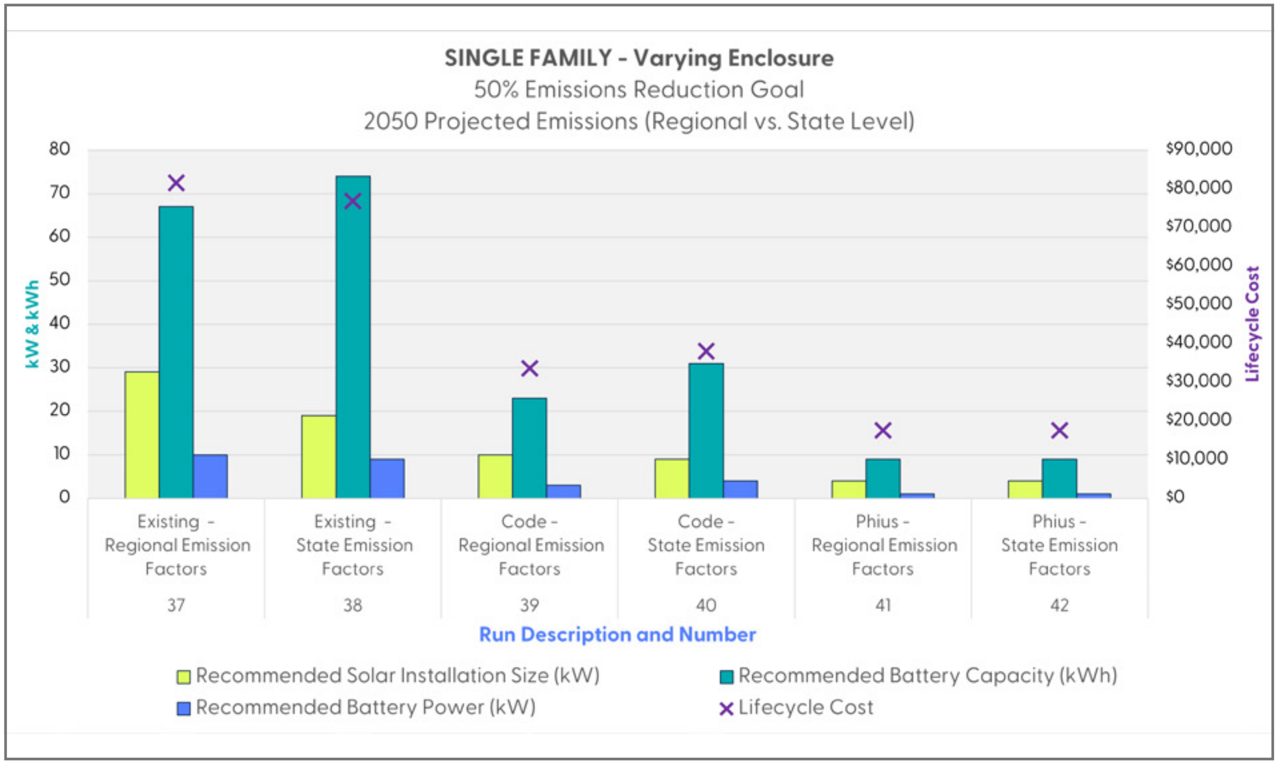


Fig. 29. Impact of the Use of State Versus Regional Emissions Factors on Meeting Emissions Reduction Goals

Run Number	37	38	39	40	41	42
Net Present Value	-$29,874	-$6,708	-$75	-$25,104	-$7,028	-$94
Lifecycle Cost	$81,595	$33,570	$17,564	$76,825	$38,065	$17,583
Initial Cost	$55,467	$19,578	$7,968	$47,090	$20,664	$7,602
Solar PV (kW)	29	10	4	19	9	4
Battery Capacity (kWh)	67	23	9	74	31	9
Battery Power (kW)	10	3	1	9	4	1

Case 16

Case Type

Energy Goals

Enclosure Level

Scale of Simulation

PURPOSE: This case considered the combined objective of resilience and decarbonization, and compared the results from this objective to results obtained by looking at each goal separately.

RESULT: When combining the goals of 72-hour winter resilience with 50% emissions reductions, resilience is the factor that determines the infrastructure requirements for the existing enclosure and code enclosure – and therefore, for older buildings with 72-hour winter resilience in mind, a project would far exceed a 50% emissions reduction goal. However, interestingly, for the Phius enclosure, the results to achieve both 72-hour resilience and 50% emissions reductions were very similar. Therefore, by improving the enclosure, with a small investment, both project goals can be met with negligible incremental cost from one another.

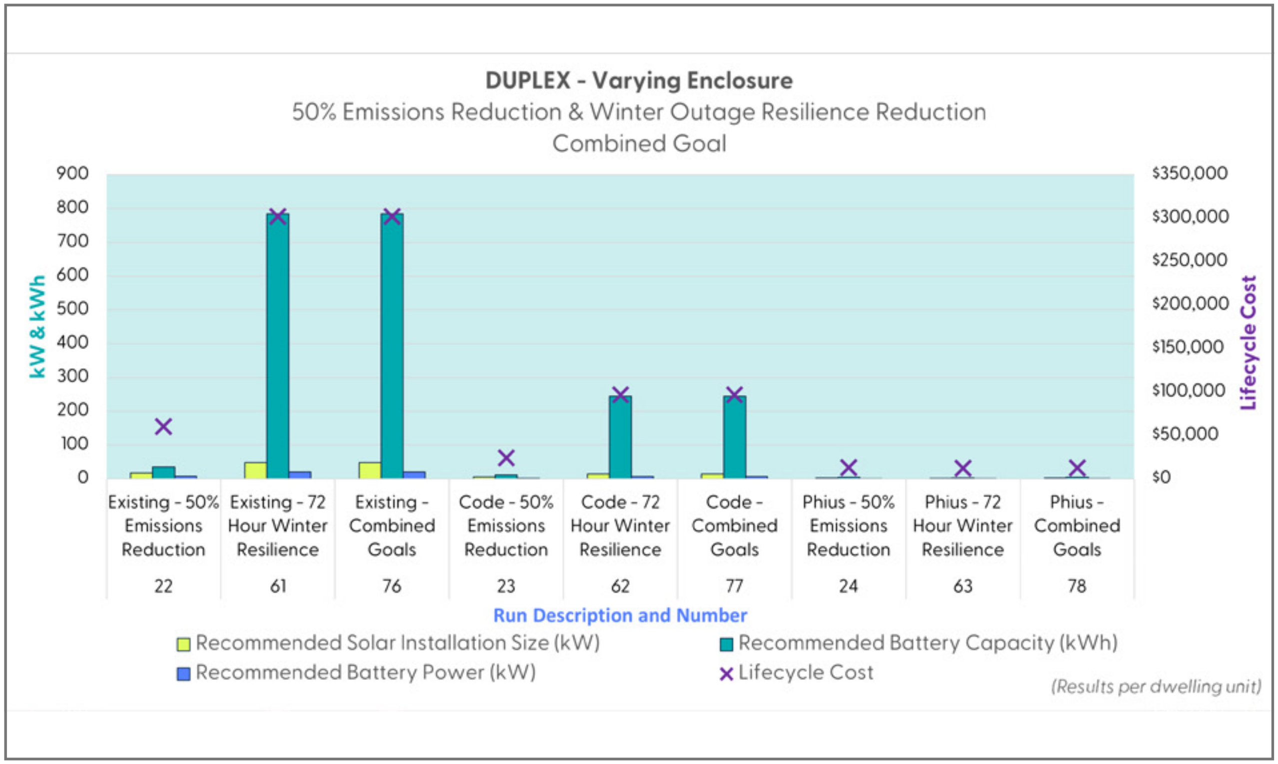


Fig. 30. Comparison of Solar and Storage Requirements for 72-Hour Resilience Versus 50% Emissions Reduction–Duplex with Varying Enclosure.

Run Number	22	61	76	23	62	77	24	63	78
Net Present Value	-$15,861	-$260,202	-$260,202	-$2,435	-$76,448	-$76,448	$448	$889	$438
Lifecycle Cost	$60,148	$301,888	$301,888	$23,882	$96,850	$96,850	$13,019	$12,260	$12,711
Initial Cost	$33,374	$291,306	$291,306	$10,954	$90,849	$90,849	$4,846	$3,354	$4,719
Solar PV (kW)	18	48	48	6	15	15	3	2	$3
Battery Capacity (kWh)	36	784	784	12	245	245	5	3	$5
Battery Power (kW)	8	21	21	2	7	7	1	1	$1

C6. RESULTS - NEIGHBORHOOD (MICROGRID) SCALE

C6.1 Neighborhood Performance

The purpose of assembling the three types of residences dealt with in the above cases (single-family, duplex, 6-flat) into a residential neighborhood is to explore the potential of developing block-size residential microgrids. The microgrid boundary is as described in Section C2.1. Neighborhood design variables are as explored above for individual residential building typologies. Desired microgrid outcomes mirror the outcomes addressed above for standalone buildings.

The objective of this set of computer simulations (runs) is to investigate the opportunities inherent in confronting big-picture concerns (such as decarbonization or resilience) collectively through microgrids (with aggregated loads) rather than on an individual basis.

Four varying types of neighborhood loads were explored: Typical, Critical (Outage), Flexible (responsive to spikes in grid emissions), and Shifted (a typical load aggregated differently).

C6.1.1 Typical Operation

Aggregated Load: The "typical" neighborhood microgrid scenario that was considered involved a simple aggregation of the individual building loads within the neighborhood boundaries.

Neighborhood Load = Single-Family (x 15) + Duplex (x 5) + 6-Flat (x 5)

C6.1.2 Critical Operation

The neighborhood critical loads were created by aggregating individual building critical loads, in the same way typical loads were created.

An important note about critical load operation: such operation is only possible if the local load (either a single building or a microgrid) can be islanded from the main grid. The ability to island, while maintaining some loads, implies the provision of site based power generation and/or site-based electricity storage.

C6.1.3 Flexible Operation

To create the flexible neighborhood loads, the flexible building-level loads were summed in the same way as the typical neighborhood loads. Flexible neighborhood cases were created for each enclosure level: existing, code, and passive.

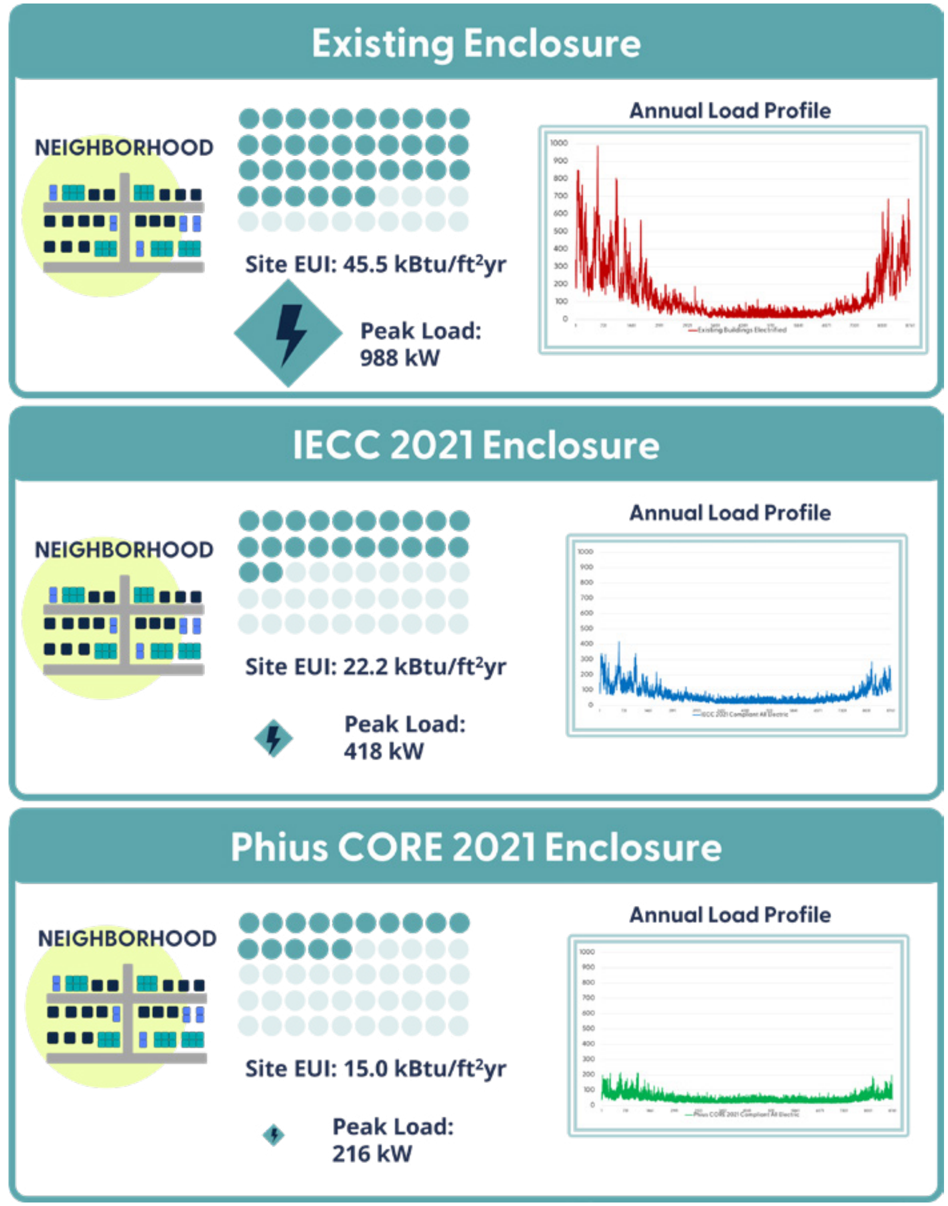


Fig. 31: Neighborhood Microgrid Loads for Varying Enclosure Types. (Courtesy of Phius)

Neighborhood	Typical Load				Flexible Load		
	Gas	All Electric			All Electric		
	Existing*	Existing	Code	Passive	Existing	Code	Passive
Annual Energy Consumption (kWh/yr)	2,919,624	1,222,316	596,998	402,250	1,020,278	526,954	380,498
Site EUI (kBTU/ft^2yr)	108.6	45.5	22.2	15.0	37.9	19.6	14.2
Peak Electric Load (kW)**	96.3	987.7	417.7	216.1	960.2	417.7	212.8
Peak Critical Electric Load (kW)***	N/A	743.3	319.3	221.7	N/A	N/A	N/A

Table 17a: Neighborhood Microgrid Load Results

Table Notes:

**For the baseline case, the existing enclosure with natural gas fired equipment for space heating, water heating, and cooking.*

***The Peak Electric Load (kW) only includes the peak driven by electrical energy use. For the baseline, gas-equipment case, this does not include the power required for space heating or water heating. This serves as a proxy for the scale of electrical service currently provided to the building.*

****The Peak Critical electric load (kW) is the peak of the electrical energy usage required for the defined critical (outage) load profile.*

Annual Carbon Dioxide Emissions (kg CO_2/yr)	Neighborhood			
	Gas	All Electric		
	Existing	Existing	Code	Passive
Typical Load	1,332,505	927,702	452,330	303,839
Flexible Load	N/A	730,293	383,854	282,594

*Table 17b: Neighborhood Microgrid Results, Estimated Annual CO2 Emissions for Typical & Flexible Loads, including Baseline Gas Cases *Note: 0.127 kg CO2/kBtu assumed for the use of natural gas on-site*

C6.1.4 Shifted Operation

Shifted Load: The shifted load case was created to incorporate the load diversity that is assumed to occur within any collection of individual users. Simply summing individual building loads–all simulated with the same timing for appliances, plug loads, etc.–will create artificial spikes of coincident power usage that should not statistically occur in reality. Table 18 describes the pattern of shifted loads assumed for this scenario. This is a limitation of the modeling software used, which has predefined profiles for appliance use, etc. We understand that future versions of software may be able to provide a more stochastic model, and would influence these results.

Figure 32 provides a visual representation of options for aggregating building loads to create a neighborhood load. The left side shows the result of taking all simulation results and adding each hour in-line. The right side shows the shifted condition, taking into account the fact that load diversity will exist between buildings.

As seen in Figure 33, the assumption of shifted (non-coincident) loads does not change the basic shape of the neighborhood electric load, but does reduce peaks (and valleys). Note the visible impact of the shifted loads, which smooths out the load profile relative to the spiky profile from coincident load aggregation.

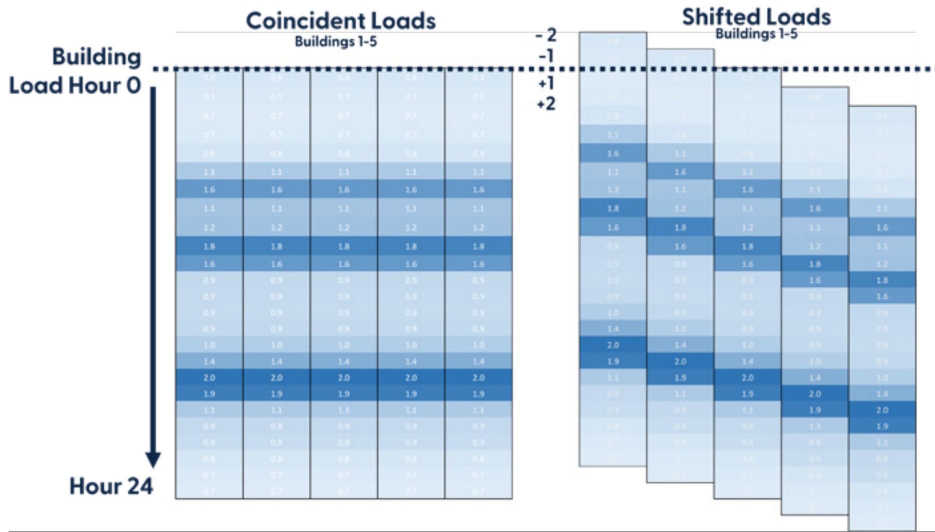


Fig. 32. Graphic Illustration of the Process of Determining Coincident Load vs. Shifted Load.

Coincident	Building Load Start Hour				
	-2	-1	0	1	2
Single Family	0	0	15	0	0
Duplex	0	0	5	0	0
6-Flat	0	0	5	0	0
Neighborhood	0	0	25	0	0

Shifted	Building Load Start Hour				
	-2	-1	0	1	2
Single Family	3	3	3	3	3
Duplex	1	1	1	1	1
6-Flat	1	1	1	1	1
Neighborhood	5	5	5	5	5

Table 18. Construction of Coincident Versus Shifted Load Profile for Neighborhood Microgrid Analysis.

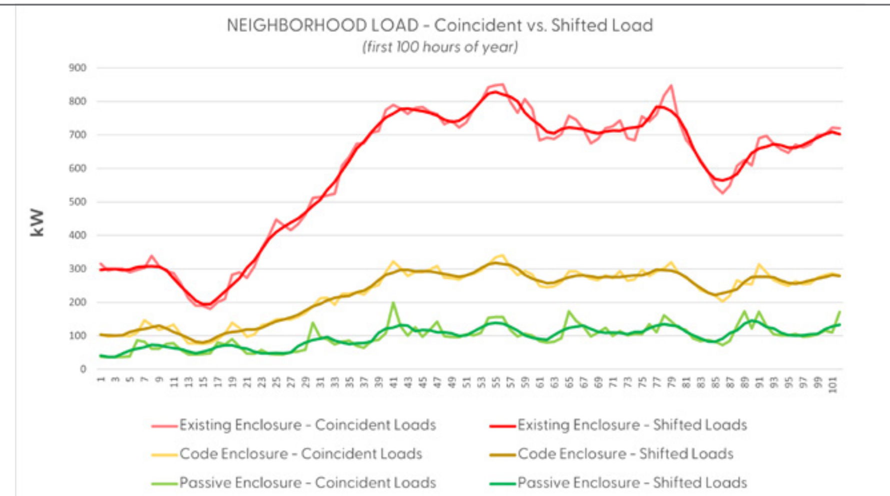


Fig. 33. Comparison of Neighborhood (Microgrid) Load for Three Enclosure Levels Using Coincident Versus Shifted Building Loads.

C6.2 Neighborhood Performance + Project Goals

The individual neighborhood-scale REopt simulations were combined into “cases” with common goals for the purposes of results analysis. Table 18 lists the cases evaluated.

There are two basic types of cases:

1. Sensitivity Analysis of Envelope Impact and;
2. Sensitivity Analysis of Non-Envelope Inputs.

Envelope Impact: In these cases, a common goal was evaluated with each of the various enclosure levels to analyze the impact of the neighborhood building load on design requirements to meet these defined project goals.

Input Sensitivity: In these cases, a common goal was evaluated with variables that were not related to the building load. These analyses provided a sensitivity analysis for determining the impact of factors such as electricity price increases, etc. on system requirements. These results also can be compared to the impact of adjusting building load.

Case	Type	Goal	Target	Enclosure Level			Scale	Other Variable
17	Envelope Impact	Minimize Cost		Existing	Code	Passive	NEIGHB	Typical vs. Shifted Load Aggregation
18	Envelope Impact	Clean Energy	75%, 90%, 99%, 100% Emissions Reduction	Existing		Passive	NEIGHB	% Emissions Reduction
19	Envelope Impact	Clean Energy	Net Zero	Existing	Code	Passive	NEIGHB	Financial Optimization for Storage
20	Envelope Impact	Clean Energy	100% Renewable Electricity	Existing	Code	Passive	NEIGHB	
21	Envelope Impact	Clean Energy	Net Zero vs. 100% Renewable Electricity	Existing	Code	Passive	NEIGHB	
22	Envelope Impact	Clean Energy	Renewable Electricity vs. Emissions Reduction	Existing	Code	Passive	NEIGHB	50%, 90%, 99%, 100% Reductions
23	Envelope Impact	Resilience	72-Hour Winter Outage - Simulated Critical Load	Existing	Code	Passive	NEIGHB	
24	Envelope Impact	Resilience	72-Hour Winter Outage - 25% Critical Load Factor	Existing	Code	Passive	NEIGHB	
25	Input Sensitivity	Minimize Cost			Code		NEIGHB	Electricity Cost & Analysis Period
26	Input Sensitivity	Clean Energy	50% Emissions Reduction		Code	Passive	NEIGHB	Allow Grid to Charge Battery? [Yes/No]
27	Input Sensitivity	Clean Energy	75%, 90%, 99%, 100% Emissions Reduction		Code		NEIGHB	Typical Loads vs. Flexible Loads
28	Envelope Impact	Clean Energy & Resilience	50% Emissions Reduction & 72 Hour Winter Outage	Existing	Code	Passive	NEIGHB	Individual vs. Combined

Table 19. Characteristics of Neighborhood Analysis Cases.

Note: All results shown below have been normalized to show the result per dwelling unit.
Total neighborhood result was divided by 55 total dwelling units. This was carried out for the purposes of comparison with building/dwelling unit results in Section C5, as well as for ease of comparing smaller numbers.

Case 17

Case Type **Energy Goals** **Enclosure Level** **Scale of Simulation**

PURPOSE: This case was set up using default settings in a simple cost optimization mode to first determine the "cost optimal" solar and storage infrastructure for the neighborhood cases and also to determine the impact of using a coincident aggregated electrical load profile for the neighborhood versus a load aggregation with a +2/-2 hour shift.

RESULT: A small amount of PV was economically feasible per unit (almost none), regardless of the enclosure level. The impact of the shifted loads was negligible on results. This outcome was assumed to be because the simulation tool to model the building loads still assumes the same patterns for occupant use of equipment, lighting, etc. So while the loads were shifted, they were still identical building-to-building (for buildings of the same type with the same enclosure level).Aggregating the loads and shifting by a few days or even weeks may provide the load diversity that would impact results, but that approach was not taken because it may not accurately represent weekday vs. weekend loads, the impact of weather, etc.

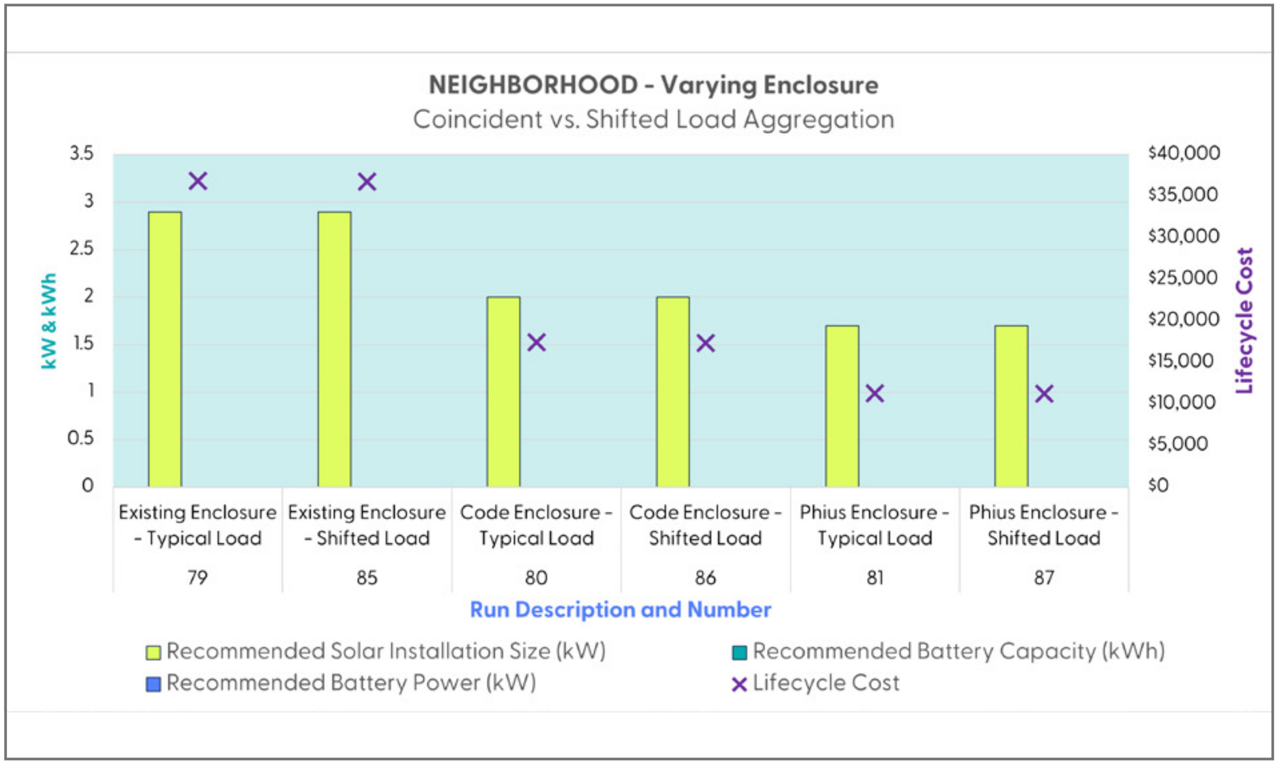


Fig. 34. Impact of Load Profile Assumptions on Local Solar Infrastructure Requirements.

Run Number	**79**	**85**	**80**	**86**	**81**	**87**
Net Present Value	-$175,596	$1,943	-$36,820	$1,577	-$11,608	$1,529
Lifecycle Cost	$206,042	$36,783	$52,174	$17,357	$23,364	$11,242
Initial Cost	$198,367	$3,023	$47,391	$2,068	$20,129	$1,734
Solar PV (kW)	31	3	8	2	5	2
Battery Capacity (kWh)	542	0	128	0	49	0
Battery Power (kW)	13	0	4	0	2	0

Case 18

Case Type

Energy Goals

Enclosure Level

Scale of Simulation

PURPOSE: Decarbonization is the key goal for this study so the case looks at local renewable resource requirements for the neighborhood to reach 75%, 90%, 99%, and 100% emissions reductions from the "business as usual" case, for both the existing enclosure building load and passive enclosure building load.

RESULT: As shown below, achieving 100% emissions reduction is significantly more challenging (and costly) than even a 99% reduction, due to outlier load hours that may be very difficult to meet with renewable energy or storage. This case suggests that after a certain reduction in emissions, further system investments do not go as far. Essentially, this demonstrates the law of diminishing returns. A goal that pairs a 75-90% emissions reduction (using renewable generation and storage) with building enclosure improvements may be the least costly solution to decarbonization. As seen repeatedly in the analysis cases, building enclosure improvements decrease lifecycle cost and infrastructure requirements. For the same life cycle cost, one all-electric existing-enclosure neighborhood could be decarbonized or six Phius-enclosure neighborhoods could be decarbonized.

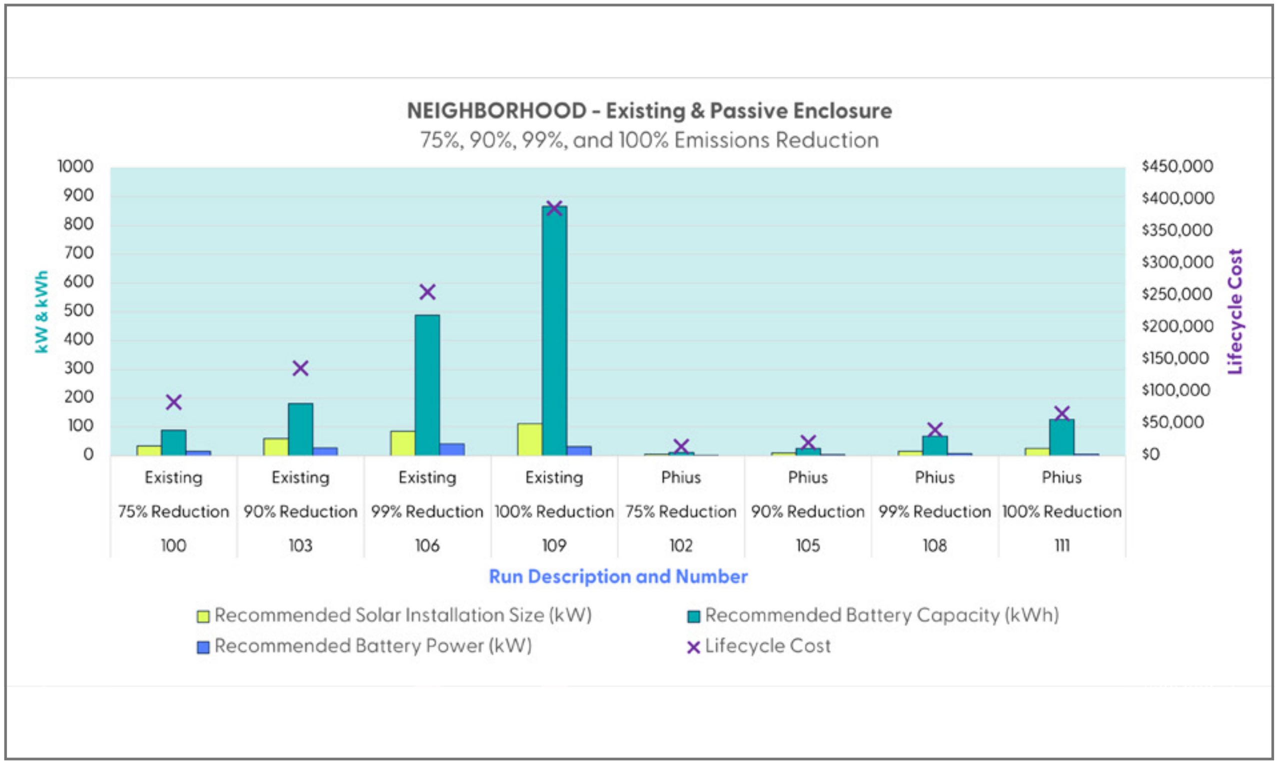


Fig. 35. Sensitivity of Building Enclosure to Meet Emissions Reduction Goals

Run Number	100	103	106	109	102	105	108	111
Net Present Value	-$44,779	-$98,312	-$217,257	-$348,100	-$1,355	-$7,965	-$27,793	-$53,193
Lifecycle Cost	$83,506	$137,039	$255,983	$386,826	$14,127	$20,738	$40,565	$65,966
Initial Cost	$69,755	$130,379	$254,823	$386,784	$9,724	$18,642	$40,198	$65,924
Solar PV (kW)	34	60	85	111	5	9	16	25
Battery Capacity (kWh)	89	181	488	866	12	25	68	126
Battery Power (kW)	16	27	41	32	2	4	6	5

Case 19

Case Type | **Energy Goals** | **Enclosure Level** | **Scale of Simulation**

PURPOSE: The purpose of this case was to illustrate the difference in solar generation required for "net zero" performance for neighborhood blocks of varying enclosure stringencies. The simulation was set to include a minimum amount of PV for "net zero", and the REopt optimizer added energy storage that was financially optimal when combined with the building enclosure and solar generation prescribed.

RESULT: The solar installation size for "net zero" scales linearly and directly correlates to the predicted annual energy use of each neighborhood "type", as illustrated below. The amount of energy storage that was optimized to accompany the solar installation was almost identical in each simulation, despite the significant difference in PV installation size. This suggests that energy storage may be costly, and without variation in electricity prices or other goals (such as emissions reduction or renewable electricity use), significant amounts of energy storage do not pay off even with on-site PV.

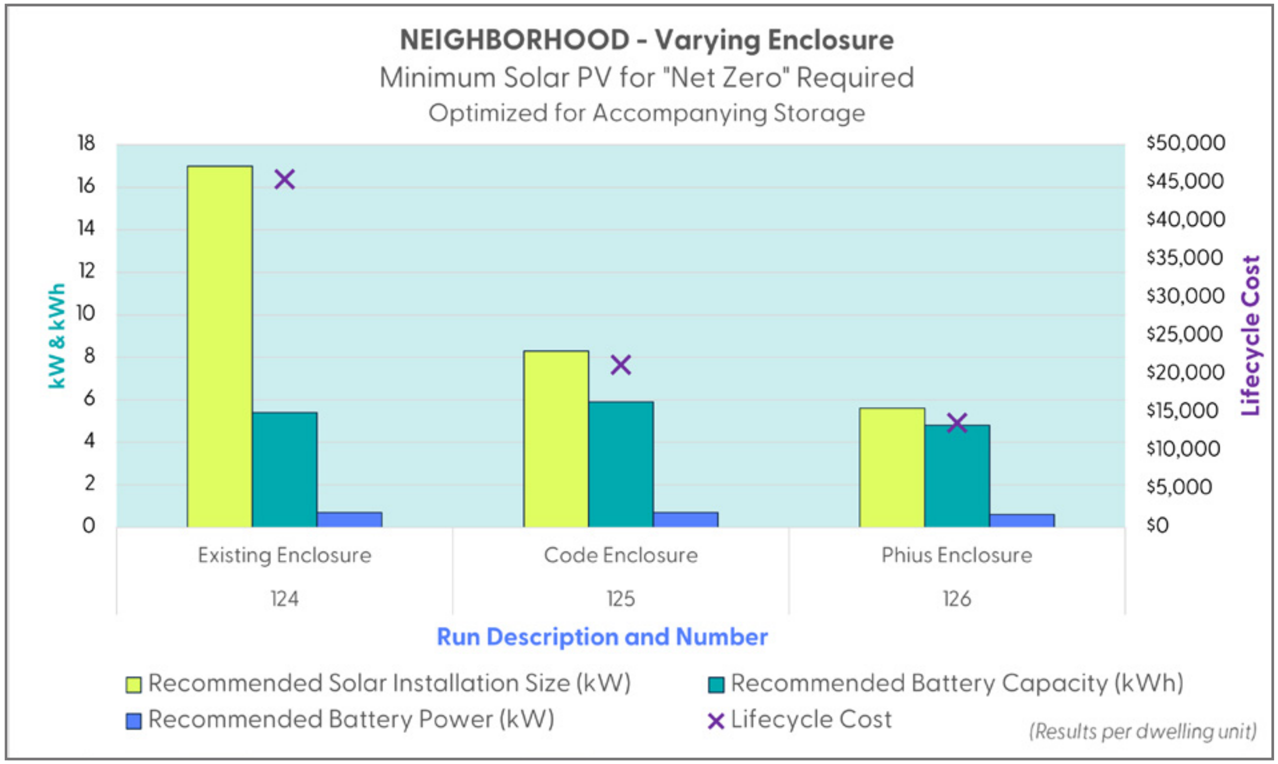


Fig. 36. Solar Requirements for Net-Zero Across Three Neighborhood Enclosure Efficiencies.

Run Number	124	125	126
Net Present Value	-$6,781	-$2,291	-$901
Lifecycle Cost	$45,507	$21,227	$13,673
Initial Cost	$19,509	$10,715	$7,538
Solar PV (kW)	17	8	6
Battery Capacity (kWh)	5	6	5
Battery Power (kW)	1	1	1

Case 20

Case Type | Energy Goals | Enclosure Level | Scale of Simulation

PURPOSE: This case was run to determine the generation and storage required for each of the varying neighborhoods to operate on 100% renewable (clean) electricity. This is different from "net zero" because it requires that 100% of the hours in the year are met with clean electricity, rather than using a "net" calculation over the course of the year. This serves as a proxy for what it would take to convert our existing energy supply stock to 100% renewables, except that the generation resource here was limited to solar (and a 100% renewable scenario would include other renewable resources such as wind power, hydropower, etc).

RESULT: The most pronounced result is that energy storage is a much bigger player in running on clean electricity than the solar generation asset itself. This is due to the need to adjust the timing of energy use to align with the availability of the energy supply. The ratio of both energy generation and storage required for the different enclosure stringencies (existing to code to passive) roughly scales with the difference in peak loads between the building-level results (see Section 5.1.1). For example, between the existing and passive neighborhoods (5-6x higher).

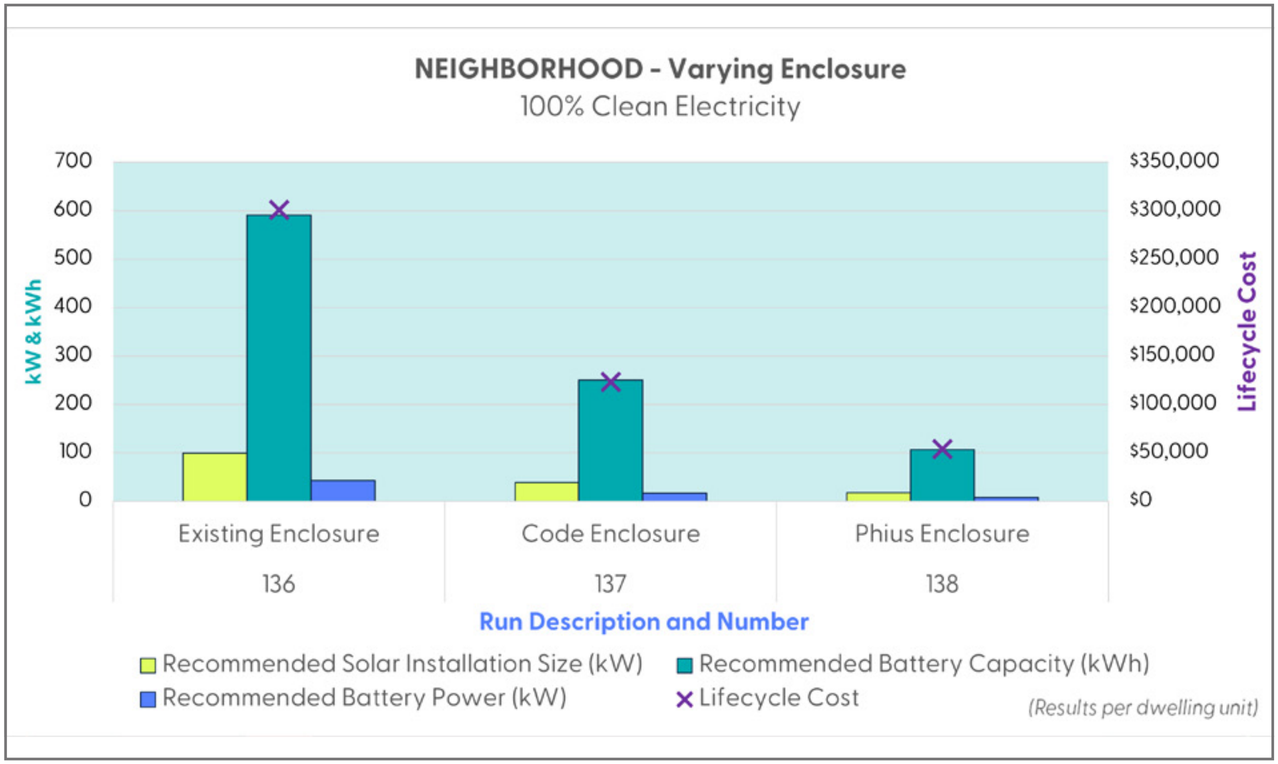


Fig. 37. Local Solar & Storage Infrastructure Required to Achieve 100% Clean Electricity Goal, Neighborhood Scale.

Run Number	136	137	138
Net Present Value	-$261,829	-$104,218	-$41,181
Lifecycle Cost	$300,555	$123,154	$53,954
Initial Cost	$300,097	$122,935	$53,841
Solar PV (kW)	99	39	18
Battery Capacity (kWh)	591	251	107
Battery Power (kW)	43	17	8

Case 21

Case Type | Energy Goals | Enclosure Level | Scale of Simulation

PURPOSE: This case shows the difference between a "net zero" project goal (where clean electricity generation over the course of the year is mathematically equal to the energy consumption of the neighborhood) and a 100% clean electricity project goal (where real-time clean electricity supply, or stored clean electricity, is required for 24/7/365 operation of the neighborhood).

RESULT: This case, illustrated below, shows the stark difference of taking the timing of energy generation and use (and the mismatch between the two) into account. The 100% renewable electricity cases require a significant amount of energy storage to align the energy generation with the neighborhood load, as well as significantly more solar generation to meet the goal. This case also reinforces two recurring themes, first that the performance of the enclosure plays a significant role in the result, and second that the high performing passive enclosure decreases the gap between the results for the two goals.

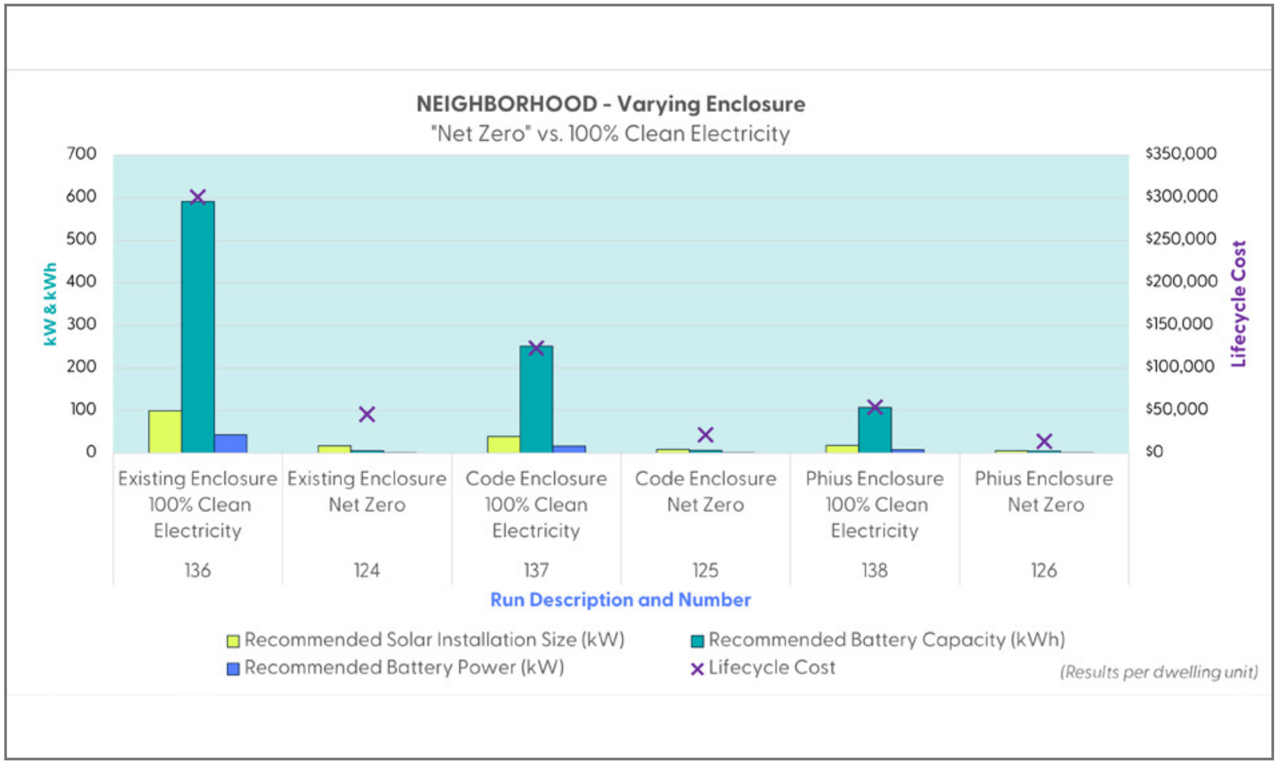


Fig. 38. Local Solar & Storage Infrastructure Requirements for Net-Zero Versus 100% Renewable Electricity Goal.

Run Number	136	124	137	125	138	126
Net Present Value	-$261,829	-$6,781	-$104,218	-$2,291	-$41,181	-$901
Lifecycle Cost	$300,555	$45,507	$123,154	$21,227	$53,954	$13,673
Initial Cost	$300,097	$19,509	$122,935	$10,715	$53,841	$7,538
Solar PV (kW)	99	17	39	8	18	6
Battery Capacity (kWh)	591	5	251	6	107	5
Battery Power (kW)	43	1	17	1	8	1

Case 22

Case Type | Energy Goals | Enclosure Level | Scale of Simulation

PURPOSE: The purpose of this case was to review how the requirements to meet the two options for “clean energy goals” varied. One goal for clean energy is to achieve a percentage of emissions reductions relative to a baseline, while the other goal is to utilize a percentage of renewable electricity. This isolated case looks at the code-built neighborhood to compare achieving these goals.

RESULT: For the most part, the infrastructure requirements and lifecycle costs were similar, with 90% and 99% renewable electricity goals coming in slightly higher than the emissions reduction counterpart. However, at the 100% reduction goal, the emissions reduction goal required significantly more energy storage (battery capacity), and therefore had a 33% higher lifecycle cost than the renewable electricity goal.

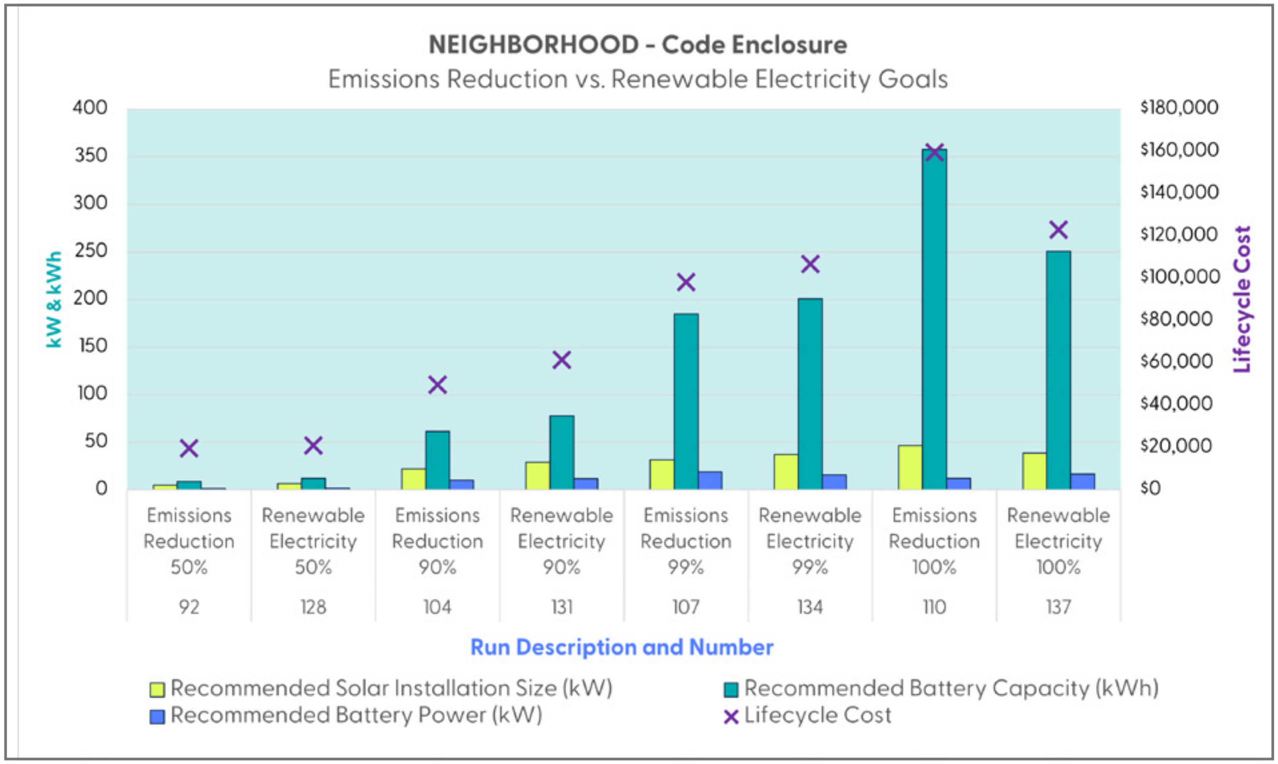


Fig. 39. Comparison of Solar & Storage Infrastructure Requirements to Meet Varying Clean Energy Goals.

Run Number	92	128	104	131	107	134	110	137
Net Present Value	-$723	-$2,056	-$30,994	-$42,709	-$79,341	-$88,052	-$140,797	-$104,218
Lifecycle Cost	$19,659	$20,992	$49,930	$61,645	$98,277	$106,988	$159,733	$123,154
Initial Cost	$8,763	$11,509	$46,782	$59,702	$97,703	$106,621	$159,691	$122,935
Solar PV (kW)	5	7	22	29	31	37	47	39
Battery Capacity (kWh)	9	12	62	78	185	201	358	251
Battery Power (kW)	2	2	10	12	19	16	12	17

Case 23

Case Type | Energy Goals | Enclosure Level | Scale of Simulation

PURPOSE: This case analyzes the impact of the building enclosure on the solar and battery storage capacity required to sustain a modeled critical neighborhood load (see Appendix B for details) during a 72-hour main grid power outage.

RESULT: The neighborhood with the existing enclosure required 6x more solar power and 11x more battery capacity than the passive enclosure neighborhood. This means that for that same amount of generation and storage infrastructure, six passive building neighborhoods could be operated versus one existing enclosure neighborhood. The existing enclosure neighborhood required 4x more solar energy generation and storage than the code compliant enclosure neighborhood. These multipliers are higher than the multiplier for the difference in peak loads between the neighborhoods (4.5x and 2.4x, respectively). The critical load for the building with the existing enclosure was much higher during the outage period than its code or passive counterparts, primarily because the modeled critical load required maintaining an interior temperature of 55F in the winter (which is directly influenced by enclosure). This resulted in an exponential increase in infrastructure required to sustain resilience.

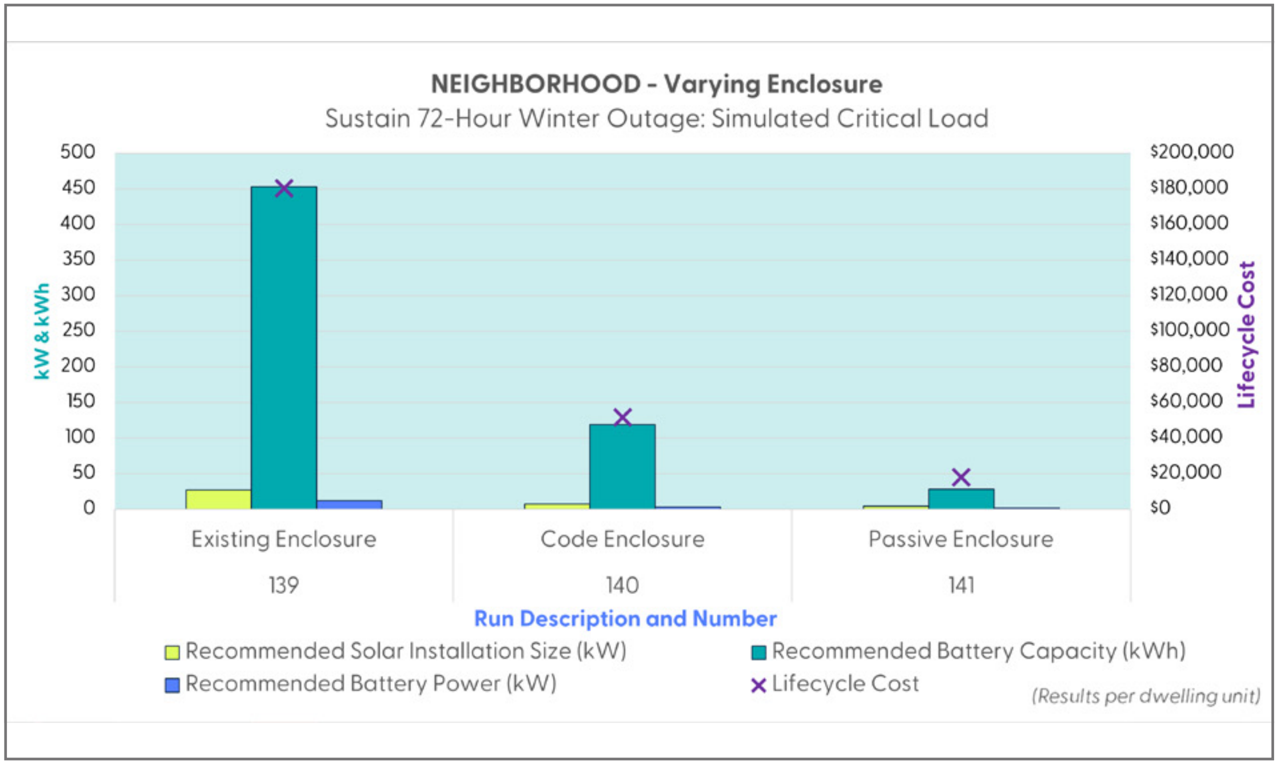


Fig. 40. Varying Local Solar & Storage Infrastructure Requirements to Meet Winter Resilience Goal

Run Number	139	140	141
Net Present Value	-$143,224	-$33,416	-$5,387
Lifecycle Cost	$180,377	$51,753	$17,914
Initial Cost	$167,551	$44,353	$14,164
Solar PV (kW)	27	7	5
Battery Capacity (kWh)	453	119	28
Battery Power (kW)	12	3	2

Case 24

PURPOSE: This case builds upon Case 23, and shows how utilizing a simulated critical load condition in an outage/resilience scenario differs from setting a fixed critical load factor (in this case, 25% of total load). A 25% critical load factor was chosen as the fixed value to assess for each enclosure level because in the individual building critical load sensitivity analysis (Case 11), the results from the 25% critical load factor matched closest to the simulated critical load results.

RESULT: As seen below, the results for using a simulated critical load during the outage versus a simple 25% critical load factor vary significantly. As the building load flattens and decreases, to code and then to passive enclosure levels, the differences in impact between the two methodologies begin to decrease. For the passive case, one would achieve almost the same result with each method, again providing the recurring theme that the low-load provides more certainty in the range of results despite the many possible simulation variables.

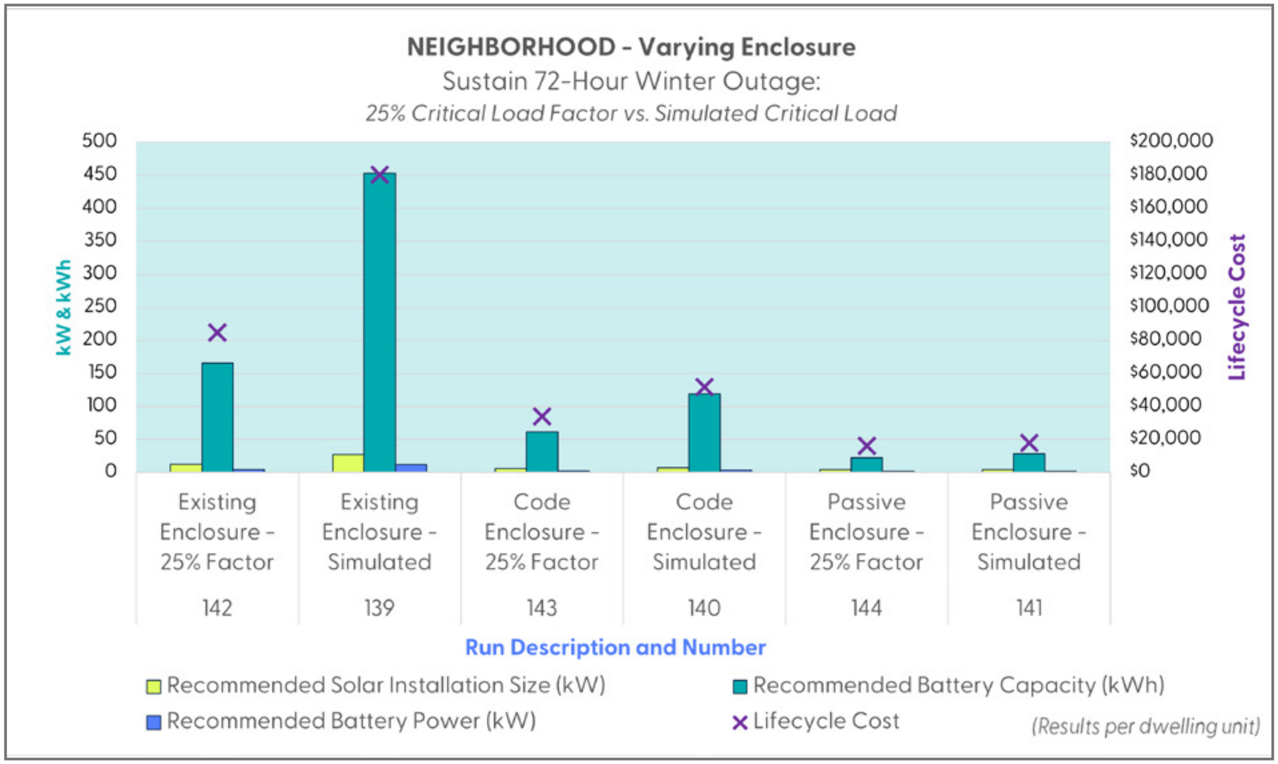


Fig. 41. Impact of Different Methods for Critical Load Assumptions on Local Solar & Storage Infrastructure Requirements to Meet Winter Resilience Goal.

Run Number	142	139	143	140	144	141
Net Present Value	-$47,659	-$143,224	-$15,625	-$33,416	-$3,623	-$5,387
Lifecycle Cost	$84,812	$180,377	$33,962	$51,753	$16,150	$17,914
Initial Cost	$63,650	$167,551	$25,058	$44,353	$12,269	$14,164
Solar PV (kW)	12	27	6	7	5	5
Battery Capacity (kWh)	166	453	61	119	22	28
Battery Power (kW)	4	12	2	3	2	2

Case Type Energy Goals Enclosure Level Scale of Simulation

Case 25

PURPOSE: This analysis was conducted without any clean energy or resilience goals to determine the sensitivity of inputs related to the financial optimization in the software that are not related to the building enclosure. It also helps determine if there are factors that have a more significant impact on results than the building enclosure. Each factor was examined individually, though they could have compounding effects.

RESULT: In all cases, incorporating a small amount of solar PV made sense. If the price of electricity increases more year-over-year (electricity escalation rate), it makes financial sense to increase the amount of PV generation to offset that. With time of use rates for electricity use, which charge more for electricity during peak hours than off-peak hours, some energy storage makes financial sense. Note that this case actually has the lowest lifecycle cost, despite that the most infrastructure was recommended in the financial optimization. With a longer analysis period for the optimization, energy storage made financial sense, but didn't have as much of an impact as changing the electricity rate structure from flat to time of use.

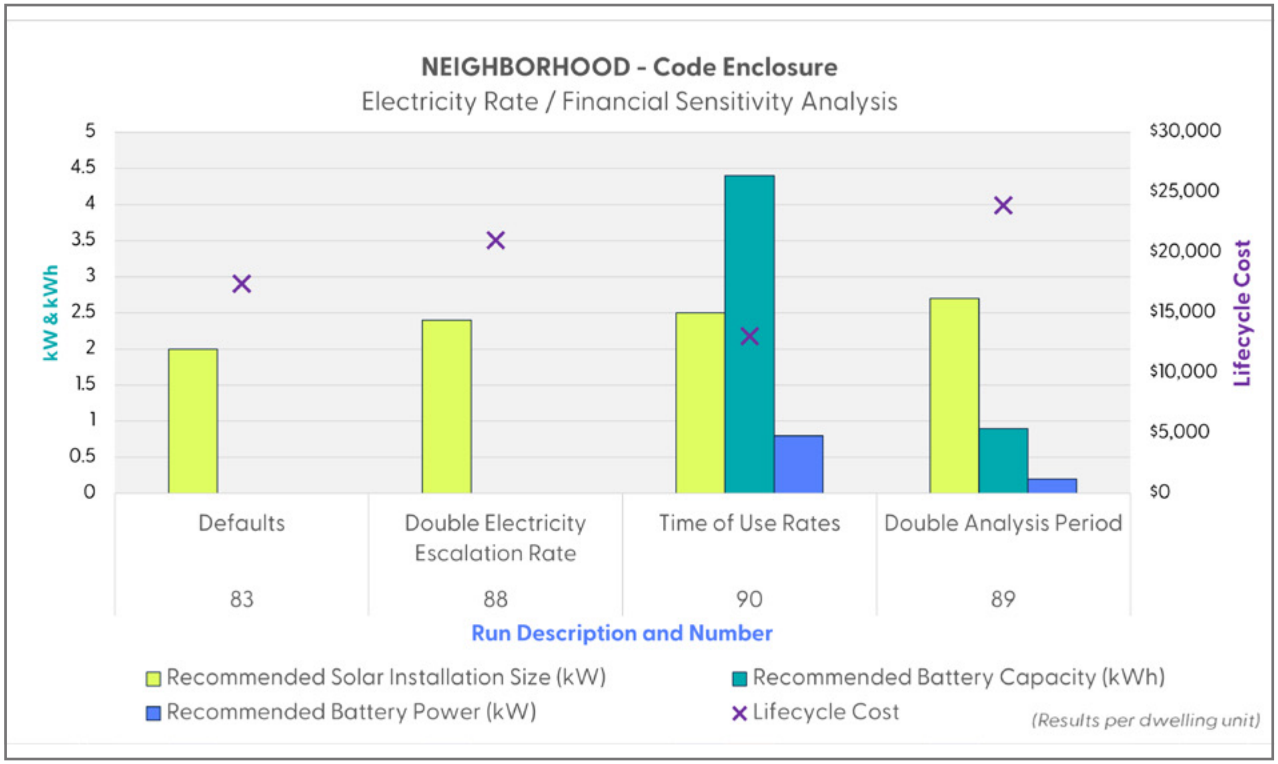


Fig. 42. Impact of Varying Electricity Rates & Analysis Period on Cost Optimal Neighborhood Solar & Storage Infrastructure.

Run Number	83	88	90	89
Net Present Value	$1,528	$2,686	$3,442	$2,429
Lifecycle Cost	$17,408	$23,940	$13,070	$21,039
Initial Cost	$2,030	$3,424	$4,317	$2,491
Solar PV (kW)	2	3	2	2
Battery Capacity (kWh)	0	1	4	0
Battery Power (kW)	0	0	1	0

Case 26

Case Type | Energy Goals | Enclosure Level | Scale of Simulation

PURPOSE: This case explored a single variable, which was whether or not the main grid (or "macrogrid") could charge the microgrid batteries while meeting a 50% emissions reduction goal. The default input in the REopt tool is to allow charging by the main grid.

RESULT: When the microgrid battery storage was not able to be charged by the main grid, about 25% more energy generation and storage was required within the microgrid to meet the same goal for the existing enclosure neighborhood, and 10% more for the Phius neighborhood—see below for these results. Once again, in cases with lower peak loads and lesser energy requirements, this variable impacted the results less.

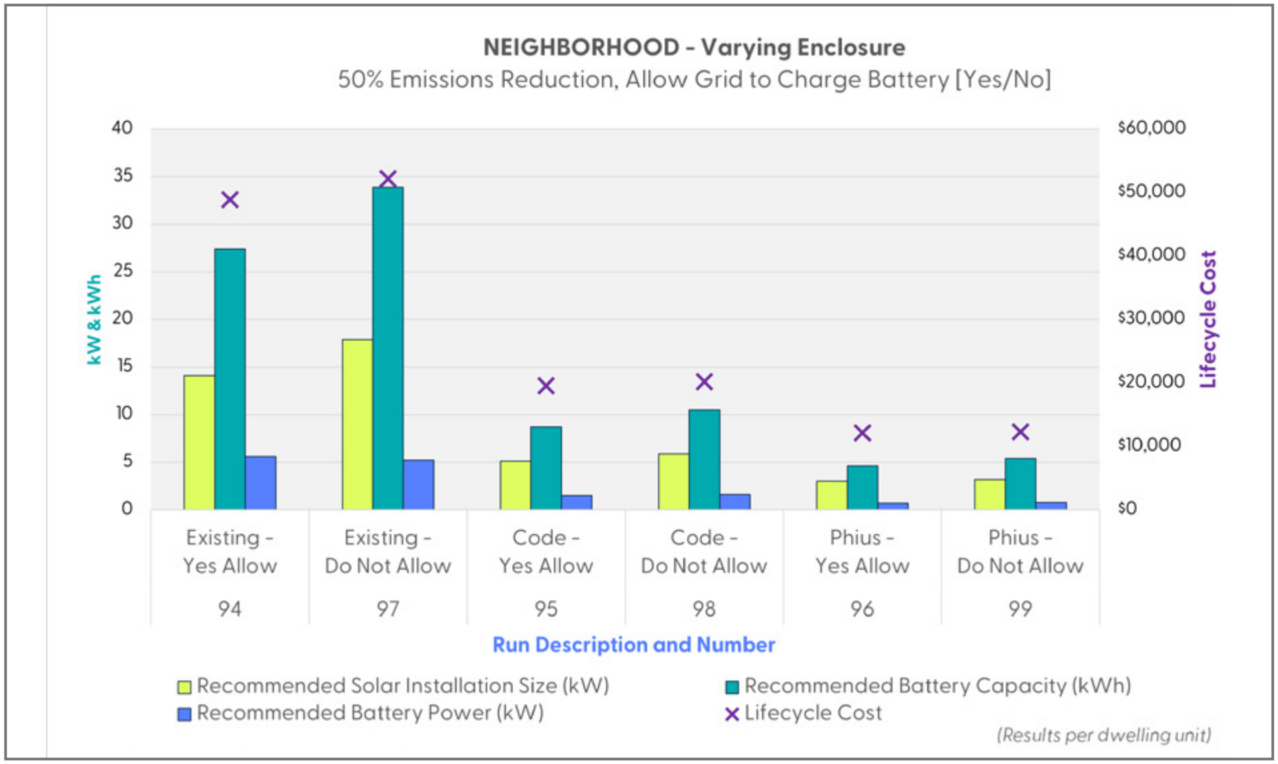


Fig. 43. Effect of Allowing/Disallowing the Macrogrid to Charge Microgrid Batteries to Meet Emissions Reduction Goals.

Run Number	94	97	95	98	96	99
Net Present Value	-$10,124	-$13,427	-$640	-$1,259	$651	$505
Lifecycle Cost	$48,850	$52,153	$19,574	$20,195	$12,120	$12,267
Initial Cost	$25,826	$31,411	$8,691	$10,077	$4,818	$5,355
Solar PV (kW)	14	18	5	6	3	3
Battery Capacity (kWh)	27	34	9	10	5	5
Battery Power (kW)	6	5	2	2	1	1

Case 27

Case Type | **Energy Goals** | **Enclosure Level** | **Scale of Simulation**

PURPOSE: This case was used to analyze incremental increases in carbon reduction goals for a code-compliant neighborhood configuration with both typical loads and flexible loads. It assesses the potential impact of load flexibility on meeting emissions reduction goals.

RESULT: In all cases, the flexible loads decreased the lifecycle cost and infrastructure requirements required to meet the same emissions reduction goals for the neighborhood. The impact of load flexibility was more prominent as the 100% emissions reduction goal was approached. This suggests that load flexibility can definitely play a role in grid decarbonization, and may play a more significant role and become a cost-effective strategy after much of the lower hanging fruit for emissions reduction is utilized. It once again displays that the path to building, neighborhood, and grid decarbonization is not linear. As the effort to decarbonize the electricity supply progresses, each incremental increase in emissions reduction will require more investment than the last.

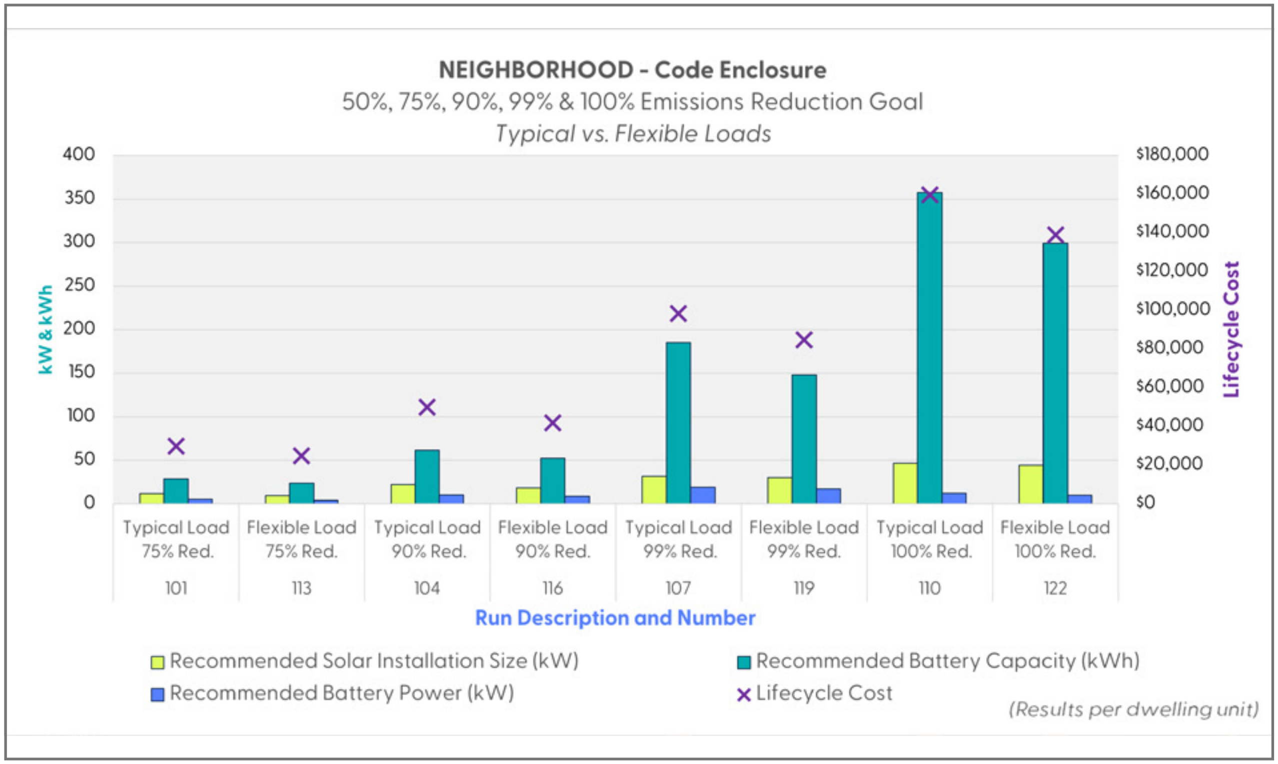


Fig. 44. Impact of Escalation of Decarbonization Expectations on Solar & Storage Resource Infrastructure Requirements.

Run Number	**101**	**113**	**104**	**116**	**107**	**119**	**110**	**122**
Net Present Value	-$10,841	-$7,973	-$30,994	-$25,113	-$79,341	-$67,957	-$140,797	-$122,157
Lifecycle Cost	$29,777	$24,692	$49,930	$41,832	$98,277	$84,676	$159,733	$138,876
Initial Cost	$23,225	$18,967	$46,782	$39,086	$97,703	$84,176	$159,691	$138,834
Solar PV (kW)	12	9	22	18	31	30	47	44
Battery Capacity (kWh)	29	23	62	52	185	148	358	299
Battery Power (kW)	5	4	10	8	19	17	12	10

Case 28

Case Type | Energy Goals | Enclosure Level | Scale of Simulation

PURPOSE: This case considered the combined objective of resilience and decarbonization, and compared the results from this objective to results obtained by looking at each goal separately.

RESULT: When combining the goals of 72-hour winter resilience with 50% emissions reductions, resilience is clearly the factor that determines the infrastructure requirements for the existing enclosure and code enclosure. However, interestingly, for the Phius enclosure, the results to achieve both 72-hour resilience and 50% emissions reductions were much closer. This suggests that by first improving the enclosure, only a small investment is required to meet both project goals, with almost negligible incremental cost from one another (+$5,000 lifecycle cost per dwelling unit to achieve winter resilience after a 50% emissions reduction is achieved).

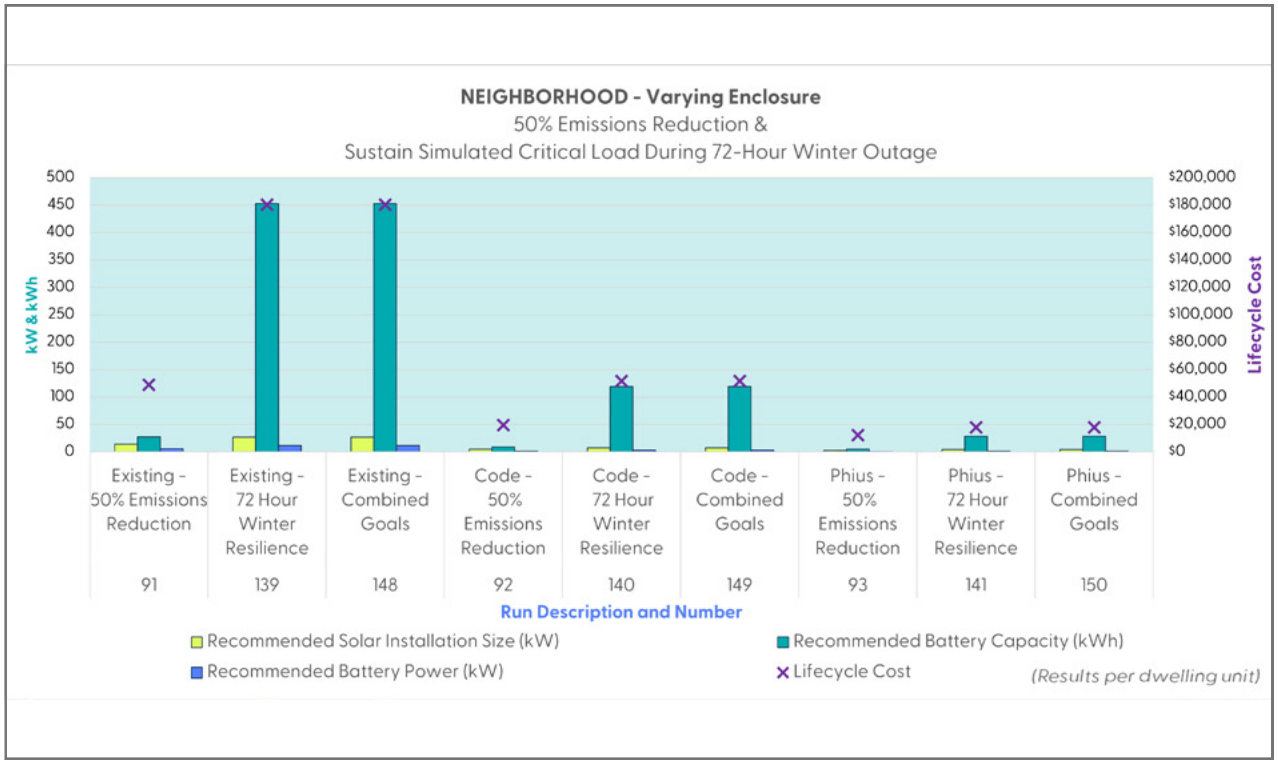


Fig. 45. Effect of Enclosure on Local Solar & Storage Infrastructure Required to Obtain Neighborhood Decarbonization and Winter Resilience.

Run Number	91	139	148	92	140	149	93	141	150
Net Present Value	-$10,339	-$143,224	-$143,224	-$723	-$33,416	-$33,416	$572	-$5,387	-$5,387
Lifecycle Cost	$49,065	$180,377	$180,377	$19,659	$51,753	$51,753	$12,200	$17,914	$17,914
Initial Cost	$25,979	$167,551	$167,551	$8,763	$44,353	$44,353	$4,901	$14,164	$14,164
Solar PV (kW)	14	27	27	5	7	7	3	5	$5
Battery Capacity (kWh)	28	453	453	9	119	119	5	28	$28
Battery Power (kW)	6	12	12	2	3	3	1	2	$2

C7. KEY FINDINGS & CONCLUSIONS

Roughly 27 building level simulations were carried out, with varying building sizes, enclosure performance, and operation modes to determine the energy performance of the buildings alone. These were aggregated into 9 neighborhood level performance metrics.

These 36 varying building loads were then used in a total of 150 REopt simulations and combined into 28 cases to study the combination of variable building loads with on-site renewable energy generation and storage to meet project goals (decarbonization and resilience). Each case involves several design variables and is structured by a desire for a specific performance outcome. This makes for many permutations–the results of which are described in Sections C5 and C6 above (Results–Building Level and Results–Neighborhood Level respectively). This section wades into these many results and extracts key observations that should be of use to design teams considering the development of neighborhood-scale microgrids.

C7.1 Summary of Building-Level Takeaways

- In all cases, electrifying the buildings reduced associated operational carbon dioxide emissions substantially. However, in all of these cases, the peak electrical load of the building also increased significantly (by a factor of 10 in the cases with the existing building enclosure).
- The improved enclosure can dampen annual energy consumption by up to a factor of more than 3, and peak load consumption by a factor of up to 6.
- Load flexibility can play a significant role in operational energy consumption and therefore emissions. Depending on the signal for load shedding/response, it may not decrease the peak load of the building.

C7.2 Summary of Microgrid Takeaways

- The lower the building load, the less the other variables impacted the results – creating less uncertainty or a smaller "range" of possible results. **In other words, the low load profile (passive enclosure) provides more certainty in the range of results despite the many possible simulation variables.**
- The path to building and microgrid decarbonization is not linear. As the electricity supply decarbonizes, each incremental increase in emissions reductions will require more investment than the last (see Case 13).
- When considering decarbonization goals, the emissions factors used in the simulation make an impact. Future emissions factors tend to have greater variation between hours (as more renewable energy is integrated into the grid-mix) and therefore typically more energy storage is required to meet decarbonization goals using future emissions factors versus today's (see Case 2).
- Load flexibility, in the form of shedding space conditioning loads based on high grid emissions factors, has significant potential to reduce on-site emissions and meet emissions reductions goals with less solar PV and storage (see Case 4).
- The cost, solar generation capacity and storage requirements to achieve resilience depend heavily on the critical load assigned as well as the outage duration and severity of the weather during the outage (see Case 12). Sustaining a survivable interior condition during a 3-day summer outage is far different than a 3-day winter outage in Milwaukee, Wisconsin (climate zone 5). During severe weather conditions, the impact of the enclosure is more profound on the critical load – i.e. the load on the HVAC system to meet a relaxed setpoint (see Case 9). Therefore, with the low-load passive enclosure, the duration and severity of the outage had less of an impact on the results.
- When aiming for 100% emissions reduction goals, there are significant diminishing returns when only utilizing renewable generation and storage to achieve that goal. (See Cases 5 & 18). A solution that pairs building enclosure improvements and load flexibility with a more modest emissions reduction using renewable generation and storage may be the least costly holistic solution to decarbonization, rather than attempting to decarbonize with generation and storage alone.
- **For the same life cycle cost, one all-electric existing-enclosure neighborhood could be 100% decarbonized, or six Phius-enclosure neighborhoods could be 100% decarbonized (see Case 18).**
- Electricity rate structures can make a large impact on the financial feasibility of on-site generations and storage projects. Time of use rates encourage the use of more on-site energy storage, which can help avoid purchasing electricity from the macrogrid during peak hours and align purchasing for building operation and energy storage charging during low-cost hours (see Cases 10 & 25)
- There is a significant difference in the solar PV (and storage) required to meet a typical "Net Zero" goal versus a 100% renewable electricity goal (see Cases 8 & 21).
- When using only solar + battery storage to decarbonize the electricity supply of the neighborhood, **the last 10% of emissions reduction will require more infrastructure and cost more than the first 90%** (see Case 27). What that first 90% requires is highly variable based on the electrified building load, which is a product of the building enclosure performance (see Case 18).

C7.3 Patterns

Below is a summary of patterns between building enclosure, decarbonization and resilience goals and lifecycle cost. Note that for all simulations listed, the lifecycle cost does not include the cost to upgrade the building enclosure. The simulations optimized for decarbonization and resilience goals used varying building load inputs to study the impact, but the cost to achieve those enclosure levels is not included in the lifecycle cost.

C7.3.1 Low Load Impact

In all cases, the improved building enclosure dampened the energy generation and storage required to meet project goals - whether they be related to emissions reductions, clean electricity, or outage resilience.

In many cases, the impact of the enclosure was exponential. And in all cases, the impact of the enclosure was greater than any other variable.

In the sensitivity analyses, the non-envelope variables had less impact on the final results with the passive enclosure simply because the results required less infrastructure (an incremental change to a small value versus a large value). Therefore, this suggests that the better performing the enclosure, the less other variables such as electricity escalation rate, analysis period, etc. will matter in estimating the total lifecycle cost of the system.

C7.3.2 Decarbonization Goals

No matter the enclosure level, it is clear that each incremental increase in decarbonization efforts will be more costly and require more infrastructure than the previous. Chasing the last percentages toward total decarbonization is incredibly difficult and costly, and likely not going to be the least-cost solution to a decarbonized grid. It is surmised that it would be more cost effective for building loads to become flexible to align with energy availability than energy supply aligning with a rigid building load.

However, there is a clear pattern that for a constant decarbonization goal (for example, 50%), reductions in peak load correlate directly with reductions in lifecycle costs as shown in Figure 47.

C7.3.3 Resilience Goals

The specified critical load, duration of outage, and timing of outage will make a substantial impact on the specified system size for resilience. However, in all cases, a low-load building dampens the effect of the other variables as shown in Figure 48.

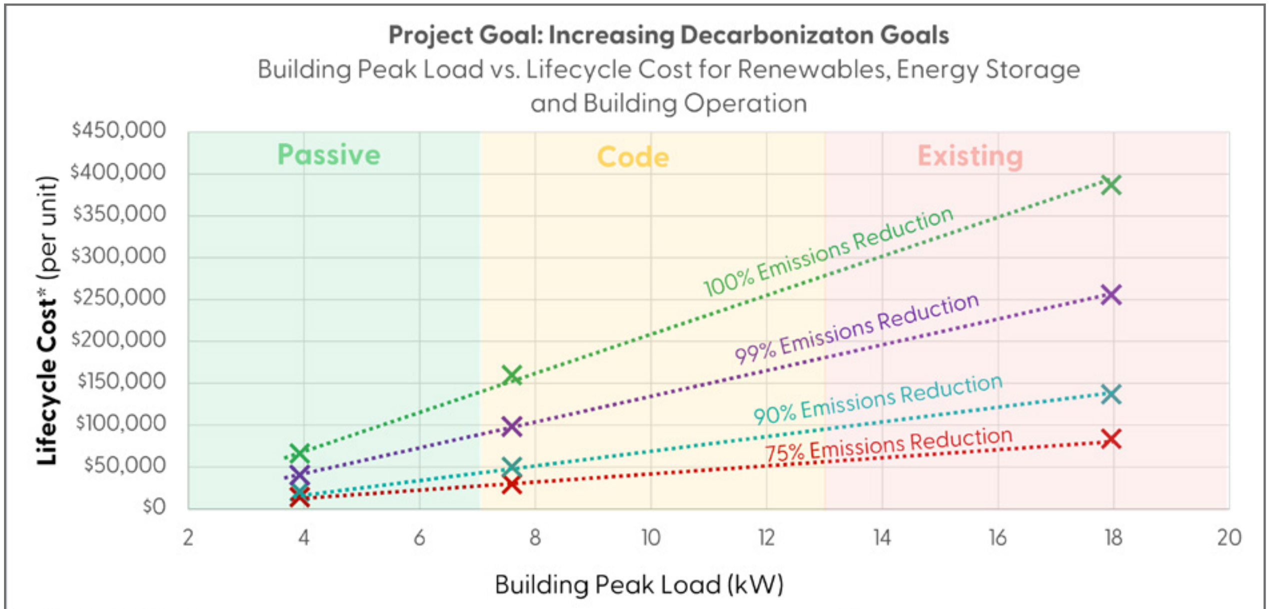


Fig. 46. Pattern of Increasing Decarbonization Toward 100% Emissions Reduction versus Lifecycle Cost of Building Operation, Solar, and Storage Infrastructure Required to Meet Goal, Varying Enclosure Levels.

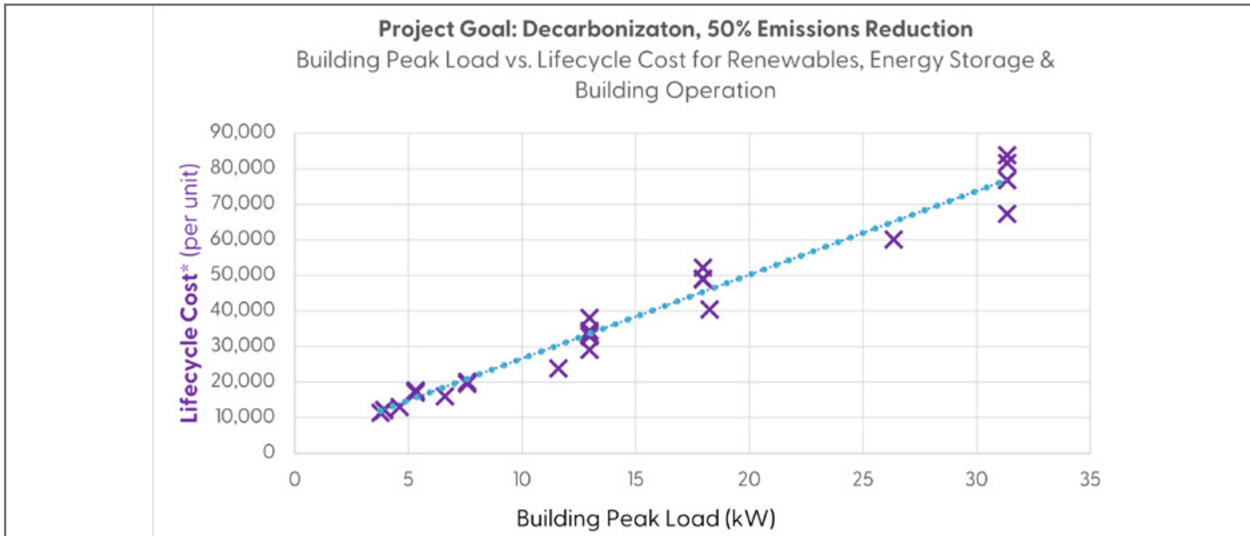


Fig. 47 Pattern of Building Peak Load vs. Lifecycle Cost of Building Operation, Solar, and Storage Infrastructure to Meet Decarbonization Goals

When looking at the combination of winter outage resilience and decarbonization goals, resilience was often the driving force requiring more infrastructure A critical load that is also flexible could potentially provide more resilience with less solar and storage infrastructure.

Electrical resilience can only be accomplished through establishment of a microgrid (of whatever scale). The ability to island from the macrogrid is essential to ongoing operations during main grid power outages.

C7.4 100% Renewable Electricity Goals

When aiming for 100% renewable electricity with a single generation resource, there will be a significant seasonal mismatch in a heating dominated climate. Meeting this goal without resource diversity and load diversity will likely not be cost effective. However, the discrepancy between winter and summer loads can be dampened by the use of passive building and a high performance enclosure – which creates more alignment between energy supply and energy demand, both daily and seasonally.

Below are outputs from the REopt software reports for a case where the goal was to cover the annual load of the neighborhood with 100% renewable electricity. Figures 49 and 50 show the winter versus summer generation and storage dispatch to meet 100% of the annual load with only PV + storage.

Winter Period–January 1-21, Existing Enclosure Only: Note the amount of time in Figure 49a that the battery is charging (orange) and how often even a full day's charge from the PV array doesn't fill the storage (denoted by the dashed state of charge line). Also note the amount of time that the storage is responsible for covering the load (blue) versus PV meeting the building load directly (red).

Curtailed generation (the yellow peak of the PV spikes) represents potential electrical generation that is not realized because there is no unused battery capacity and there is no need for the electricity on the macrogrid. The effect of several days of cloudy (low solar) weather is clearly seen in the middle of the plot.

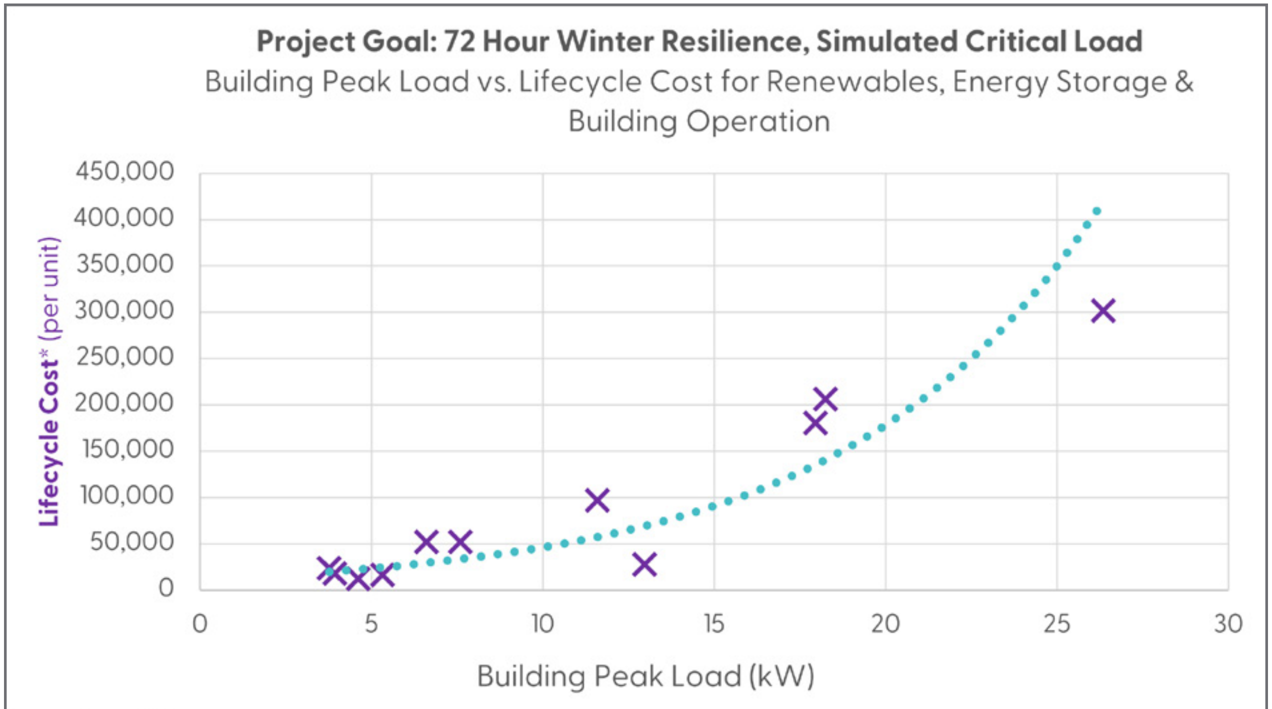


Fig. 48. Pattern of Building Peak Load vs. Lifecycle Cost of Building Operation, Solar, and Storage to meet Resilience Goals

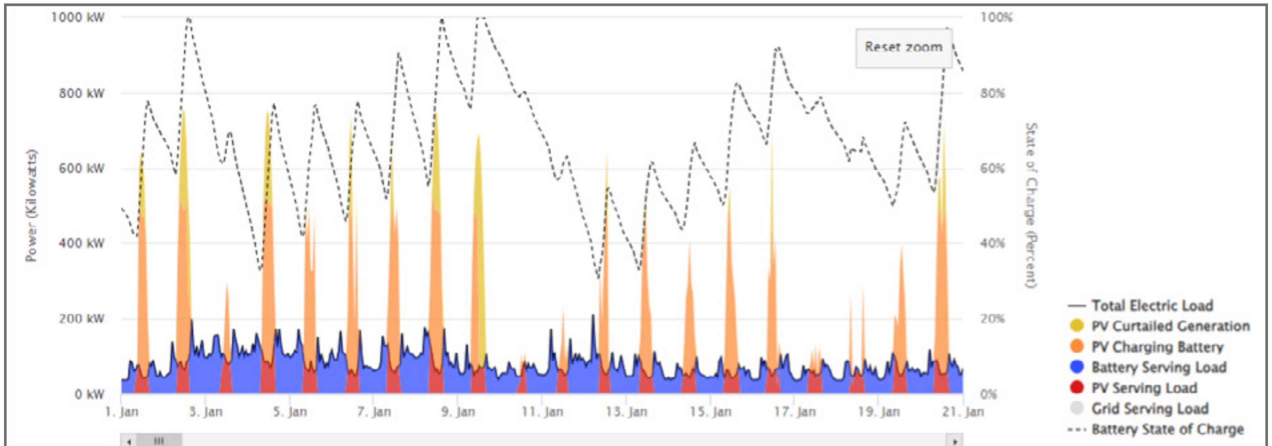


Fig. 49a. Interactions of Neighborhood with Existing Enclosure Loads and Electricity Resources for a Three-Week Winter Time Period.

Zooming into a winter week (January 1-7), Figure 49b compares the neighborhood loads and dispatch for the 100% clean electricity neighborhood with loads from buildings with existing enclosures versus the 100% clean electricity neighborhood with loads from buildings with passive enclosures. Note the callout on the left for a 1000 kW marker – the entire dispatch cycle for the passive enclosure case fits under this line, whereas the existing enclosure dispatch cycle is often 4x that. These differences in neighborhood peak loads have implications on the capacity of other components in the system, such as distribution lines.

Summer Period–July 1-21: Figure 50 shows the same system size in a summer season, note the amount of time that the battery is charging (orange) and covering the load (blue), versus direct from PV load coverage (red), it is almost not visible relative to the scale of the output of the PV system. Also note the state of charge of the battery, remaining above 90% almost the entire summer as a result of the consistent excess PV charging. And, possibly most importantly, note the amount of curtailment (yellow) that must occur because the system was sized to meet peak loads (not the summer) – in most cases this could be fed back to the macrogrid but as the grid decarbonizes with similar renewable resources, the macrogrid may also have excess production during this time due to seasonal differences in resource output for a given capacity.

Fig 49b. January 1-7, Comparison of Neighborhood with Existing Enclosure vs. Neighborhood with Passive Enclosure

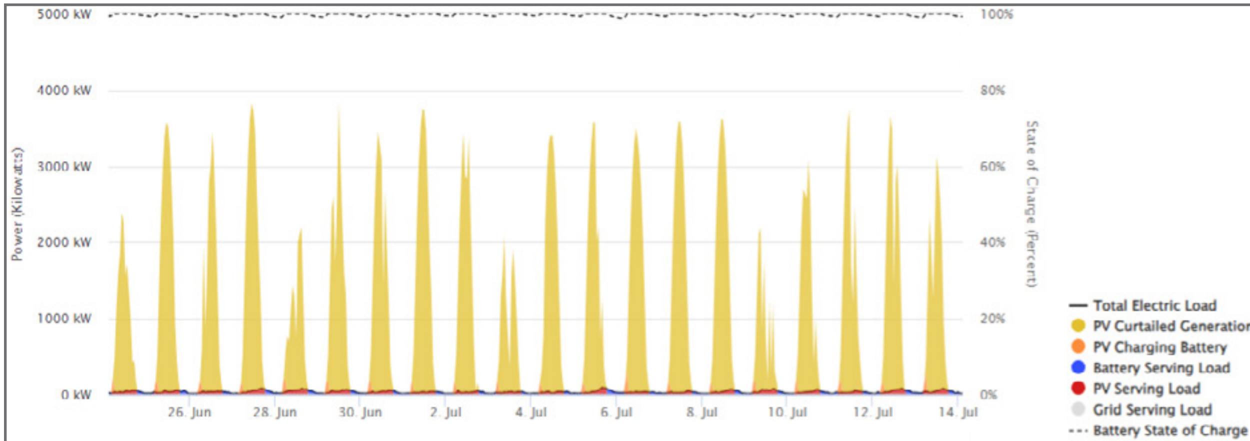


Fig. 50. Interactions of Neighborhood with Existing Enclosure Loads and Electricity Resources for a Three-Week Summer Time Period.

C8. OTHER NOTES

C8.1 Supplemental Architect's Guide

The research embodied in these case studies was conducted to support the development of the *Architect's Guide to Ultra-Low-Energy Buildings, Microgrids, and Direct Current*. This case study report is a companion document to that *Architect's Guide*. Background information on the constituent components of these cases–specifically low and ultra-low energy buildings, microgrids, and direct current–will be found in the *Guide*. The *Guide* also provides more context on the design variables and design objectives that are explored in these cases. Conversely, key findings from these case study investigations are presented as design recommendations in the *Guide*.

C8.2 Future Work

This study serves as a pilot study to the interactions between building enclosure, decarbonization, and resilience. However, it became clear early on in this investigation that the industry is lacking tools to model all of the interactions desired, which includes:

- Exchange of energy between buildings,
- The central balancing of loads within a microgrid boundary based on energy supply availability
- De-centralized coordination of DERs through signal exchanges
- Load flexibility of other elements such as water heating and large appliances
- A real-time dynamic flexible load (with REopt, a fixed load profile is input), with the incorporation of maintaining desired outcomes (i.e. not floating above or below a defined a setpoint, maintaining a critical volume of water in a water heater)
- Real time dynamic pricing for electricity including cost of marginal carbon emissions
- Capturing efficiencies from reduction of conversion losses when using direct current distribution networks (versus alternating current) for on-site solar and storage systems
- Stochastic modeling of occupant behavior for use of large appliances, plug loads, and general occupancy (though we believe this is include in the next release of BEopt)
- Cost (or avoided cost) of electrical service upgrades upon electrification, and payoff of reduced peak load. This occurs at both the individual building and neighborhood scale.

Given the amount of variables in the simulation, many other sensitives could be studied. Some of interest are:

Cost of Carbon Emissions - Studying a range of emissions, similar to a scenario where a "carbon tax" or fine to see how this impacts decarbonization goals and financial feasibility of generation and storage systems

Cost of Health Impact - The REopt tool allows the user to include the cost of health impacts in the financial analysis for decarbonization goals. This was not studied, but would be interesting to understand the implications.

Cost Benefits of Security - Self sustaining microgrids

Varying Net Metering Structures - To study variances like utility buying back excess power at real-time wholesale prices vs. a monthly net metering structure.

Financial Opportunity for Microgrid Owner/Neighborhood - In many of the scenarios, the solar and storage that may be required for sustained resilience during outages may be oversized for optimal use during daily operation. In these instances, it would be interesting to explore the financial case for the neighborhood microgrid selling excess power back to the grid, whether that is excess generation while produced, or from energy storage resources when the grid is peaking and marginal prices are high. This exchange would likely allow for cost savings on the utility/energy providers end, as well.

Direct Current - It was initially believed that a transition within residences to direct current (DC) loads would have a substantive impact on the electrical and energy performance of buildings–especially when such buildings were assembled into neighborhood microgrids. At this time, the tools (both simulation and financial) to fully explore this supposition are not readily available.

It is clear that a building or neighborhood that operates fully on DC power can improve efficiency by 10-15% compared to a situation where AC (alternating current) is converted to DC to operate DC devices (which are becoming ever more common in buildings). Likewise, converting DC produced by PV arrays and/or stored in batteries into AC for re-conversion back to DC at end use is not terribly logical.

Hybrid systems may be set up that use a DC distribution network between on-site generation/storage to DC loads, however, unless the entire system runs on DC, there is still a need for an AC distribution network which means redundancy and more infrastructure required. The only way to truly avoid AC-DC or DC-AC conversion losses is to operate a system that is either fully AC or fully DC. It is unlikely that the macrogrid will become a DC grid, thus going fully DC at this time would require development of standalone buildings or microgrids that are not normally connected to the macrogrid. The implications of such an approach might be studied in follow-on research.

Electric Vehicles (EVs) - Electric vehicle charging (and discharging) could make a significant difference in the load profiles studied. The charging could be incorporated as a "smart" building load, utilizing excess renewable energy. The battery of the EV itself could essentially serve as "mobile energy storage", whereas the storage studied was assumed to be fixed or stationary within the microgrid.

Other Climates - Milwaukee is a heating dominated climate, and therefore the peak loads occur in the winter. Other climates that are more balanced or cooling dominated may offer different solutions.

Neighborhoods with Load Diversity - As mentioned in the study, a group of residential buildings tends to have similar loads. Including buildings with patterns of occupancy that don't align with residences, like offices or schools, would impact the system requirements and likely allow for greater utilization of the renewable and storage systems.

On top of varying simulation factors, it is clear that the efficiency of the low-load building ripples throughout the entire system. *Future studies will include gaining an understanding of all of the individual components in the system that are affected by peak loads and how reducing the building load has a cascading effect. How much savings truly can be realized through a low-load design?*

To be continued.

GLOSSARY

AC: alternating current; electric distribution method in which voltage and direction of current change sinusoidally with time; today's standard for power distribution in US electric grids

Battery: an energy storage device that stores electricity

Critical Load: defined electricity loads desired to be available during a macrogrid outage

Critical Load Duration: desired length of availability of a critical load during a macrogrid outage

DC: direct current; electric distribution method in which voltage and direction of current are constant over time; many loads and some sources are direct current

Decarbonization: effort to reduce the carbon emissions associated with some human activity (such as heating, cooling, or transportation)

Demand (kW): the power draw of a system at some defined point in time (such as at 5:00 pm)

> **Peak Demand:** the maximum power draw experienced by a system during some defined time frame (such as a week, season, year); common secondary basis for electricity billing for commercial/institutional customers

Design Filter: a value proposition (such as low monthly bills, resilience, low carbon emissions, grid stability) that is used to evaluate the appropriateness and effectiveness of a proposed solution

Electrification: effort to replace consumption of natural gas with electricity–on the assumption that resulting carbon emissions will eventually be lower than from gas

Energy (kWh): the product of power and time; represented by the area under a load profile; typical basis for electricity billing for residential customers

EV (Electric Vehicle): for this Guide–a car or light truck that will be charged from a residence

Grid: for this Guide–a physical network that distributes electricity between sources and loads

> **Microgrid:** a small-scale electricity grid (relative to existing commercial grids) that includes loads, generation and/or storage elements, controls–and that can be isolated from the macrogrid
>
> **Macrogrid:** a large-scale electricity grid; city, county, state, and intrastate grids are macrogrids
>
> **Nanogrid:** typically refers to a one-building microgrid

Islanding: the temporary and intentional isolation of a smaller grid from a larger grid

Load Aligner: a device or activity that will act to better match electricity consumption with electricity availability and/or renewable resources with times of consumption

Load Disruptor: a device or activity that will substantially (> 15%) decrease or increase the energy or power use of a building upon installation or activation

Load Modifier: a device or activity that will incrementally (+/- 10-15%) decrease or increase the energy or power use of a building upon installation or activation

Point of Common Connection (PCC): the single point where a microgrid connects to a macrogrid

Power (kW): the magnitude of energy draw at a given point in time

Profile (Load or Generation): a plot of power versus time, often expressed at daily or annual time scales

PV (Photovoltaics): an energy conversion process or device that converts solar radiation directly into electricity; produces DC power

Resilience: the ability of a system to survive and come back after experiencing a severe disruption event (such as a flood, ice storm, hurricane, system hack), or the ability to maintain some level of critical load during a severe disruption event

Storage: a process or device that can accept a resource at one time for release or use at a later time

> **Thermal Storage:** a device that stores heat, such as a hot water tank, concrete mass, or even building enclosure
>
> **Electrical Storage:** a device that stores electric charge, such as a battery or capacitor

APPENDIX I: OTHER RESOURCES

I-1: Key Microgrid Resources

US Department of Energy Initiatives:

- The US Department of Energy is working toward the implementation of microgrid pilot projects in their "Connected Communities" Program: https://www.energy.gov/eere/solar/connected-communities-funding-program
- GEB Roadmap: grid-interactive technology is a key component of microgrid operation. The GEB Roadmap discusses the existing and emerging technologies related to GEB deployment:

Microgrid Knowledge: Is an organization devoted to providing news on microgrids including markets, policies, trends and technologies. They publish articles and white papers.

https://www.microgridknowledge.com/

SEPA (Smart Electric Power Alliance): Is a non-profit organization with a mission to accelerate the electric power industry's transformation to a modern energy future through education, research, standards, and collaboration. They focus on electrification, grid-integration, and regulatory and business innovation.

https://sepapower.org/

EMerge Alliance: is a member based non-profit organization formed to create and promote the adoption of new standards for DC and hybrid AC/DC power infrastructure in buildings, neighborhoods, and communities with the goal of providing greater power resiliency, surety, and equity. They provide educational resources, webinars, etc.

https://www.emergealliance.org/

NASEO (National Association of State Energy Officials): NASEO is a US non-profit association that provides support for the governor-designated energy officials from each of the 56 states and territories, NASEO facilitates learning among state energy officials and serves as a resource for and about State Energy Offices; NASEO has a number of publications related to smart electric grids and microgrids.

https://www.naseo.org/publications

I-2: Islanding: Understanding PV Disconnect Systems

The components and arrangement of a PV disconnect system can vary based on the intent of the system and in the presence of energy storage. A detailed guide can be found here:

https://www.mayfield.energy/technical-articles/nec-2017-pv-disconnect-placement/

APPENDIX A: SIMULATION INPUTS & RESULTS (WUFI PASSIVE)

Table A1 - Common WUFI Inputs (All Project Types)			
WUFI Branch	Parameter	Units	Inputs
Localization/ Climate	Location	TMY3 Location	Milwaukee Mitchell Intl AP
PH Case	Heating Setpoint	°F	68
	Cooling Setpoint	°F	77
	DHW Consumption	Gal/person/day	6.6 @ 140°F
Visualized Components	Shading	Summer Reduction Factor	0.7
		Winter Reduction Factor	0.7
Internal Loads/ Occupancy	Dishwasher	kWh/yr	269
	Laundry - washer	kWh/yr	120
	Laundry - dryer	CEF	5.79
	Fridge	kWh/yr	445
	Cooking (w/electricity	kWh/use	0.2
Ventlation/ Rooms	Utilization Pattern	hrs/day/week	24/7/365
		Fraction of design air flow	1
Systems	Water Heating	HPWH EF	2.3
		Material, dia.	Copper, 1/2"
	Heating	Annual COP	1.92
		Performance Ratio	0.52
	Cooling	SEER	18.9
		EER	17.4
		Dehum COP	1.75
	Ducts	Duct length (ft)	10
		Duct diameter (in)	6
		Insulation thickness (in)	2
		R/in (hr.ft^2 °F/Btu.in)	4

Table A-1. Common Inputs for all WUFI Passive Models

Table A2.1 - Common WUFI Passive Inputs (SINGLE FAMILY)			
WUFI Branch	Parameter	Units	Inputs
PH Case	Number of units	Total	1
	Number of floors	Total	2
	Floor slab area	ft^2	1200
	Floor slab perimeter	ft	140
Space Conditioning	iCFA	ft^2	2128
Internal Loads/ Occupancy	Occupant Quantity	# bedrooms + 1	4
	Number of bedrooms	# bedrooms	3
	Int Lighting	kWh/yr	718.4
	Ext Lighting	kWh/yr	41.3
	Garage Lighting	kWh/yr	20
	Misc Electric Loads (MEL)	kWh/yr	2045
Ventilation/ Rooms	Room Quantities	# kitchens	1
		# bathrooms	2
Systems	DHW Distribution	Pipe length per unit (total, ft)	65
	Cooling	Recirc air flow rate (cfm)	1200
		Recirc air cooling capacity	48

Table A-2.1. Common Inputs for All Single-Family WUFI Passive Models

Table A2.2 - Unique WUFI Passive Inputs (SINGLE FAMILY)					
WUFI Branch	Parameter	Units	WUFI Inputs		
			Existing	IECC 2021	Phius CORE 2021
PH Case	Airtightness	cfm/ft^2 (envelope) @ 50 Pa	0.86	0.28	0.06
	Ventilation System	Type	Exhaust only	Exhaust only	Balanced
	Perimeter insulation	Position	N.Def	N.Def	Vertical
		R (hr.ft2 °F/Btu) / Depth (ft)	-	-	20 / 2
Visualized Components	Above Grade Walls	R (effective, hr.ft^2 °F/Btu)	9.6	23.1	45.1
	Roof / Ceiling	R-Value (hr.ft^2°F/Btu)	21.2	60.7	70.2
	Opaque Door	R-Value (hr.ft^2°F/Btu)	3.5	3.5	5
	Windows/Glazed Doors	U-Factor (Btu/hr.ft^2°F)	0.63	0.3	0.17
		Whole window SHGC	0.64	0.4	0.3
	Slab	R (hr.ft^2 °F/Btu)	0.6 (uninsulated)	10 ci (4ft perimeter)	20.6
Ventilation/ Rooms	Airflows	Kitchen - Exhaust (cfm)	100	100	35
		(itchen - Exhaust (run time - min/yr)	8,000 (def.)	8,000 (def.)	(cont.)
		Bathroom - Exhaust (cfm), ea.	50	50	24
		throom - Exhaust (run time - min/yr	21,900	21,900	(cont.)
		Fresh air - Supply (cfm)	-	-	83 (cont.)
		erage air flow rate (cfm) continuo	5.7	5.7	83
	Summer Ventilation	Summer H/ERV Recovery Mode	None	None	Temperature controlled bypass
Systems	Ventilation Equipment	% Heat Recovery Efficiency	-	-	0.82
		% Humidity Recovery Efficiency	-	-	0.4
		Electric Efficiency	0.5	0.5	0.75
	Auxiliary Energy (Kitchen Exhaust)	Device Type	Other	Other	-
		Quantity	1	1	-
		Energy Demand (rated, W)	26	26	
		Period of Operation (khr/yr)	0.133	0.133	-
	Auxiliary Energy (Bath Exhaust)	Device Type	Other	Other	-
		Quantity	2	2	-
		Energy Demand (rated, W)	13	13	
		Period of Operation (khr/yr)	0.365	0.365	-

*Run time is WUFI default based on exhaust device type and number of units.
**Run time per BAHSP protocol (60min/day)

Table A-2.2. Variable Inputs for All Single-Family WUFI Passive Models

Table A3.1 - Common WUFI Passive Inputs (DUPLEX)

WUFI Branch	Parameter	Units	Inputs
PH Case	Number of units	Total	2
	Number of floors	Total	2
	Floor slab area	ft^2	1,656
	Floor slab perimeter	ft	164
Zone 1	iCFA	ft^2	2,788.2
Internal Loads/ Occupancy	Occupant Quantity	# bedrooms + 1	8
	Number of bedrooms	# bedrooms	6
	Int Lighting	kWh/yr	1,063
	Ext Lighting	kWh/yr	69
	Misc Electric Loads (MEL)	kWh/yr	3,070
Ventilation/ Rooms	Room Quantities	# kitchens	2
		# bathrooms	2
		# 1/2 baths	2
Systems	DHW Distribution	Pipe length per unit (total, ft)	65
	Cooling	Recirc air flow rate (cfm)	600
		Recirc air cooling capacity	24

Table A-3.1. Common Inputs for All Duplex WUFI Passive Models

WUFI Branch	Parameter	Units	WUFI Inputs		
			Existing	IECC 2021	Phius CORE 2021
PH Case	Airtightness	cfm/ft^2 (envelope) @ 50 Pa	0.91	0.28	0.06
	Ventilation System	Type	Exhaust only	Exhaust only	Balanced
	Perimeter insulation	Position	N.Def	N.Def	Vertical
		R (hr.ft2 °F/Btu) / Depth (ft)	-	-	10 / 2
Visualized Components	Above Grade Walls	R (effective, hr.ft^2 °F/Btu)	9.6	23.1	40.1
	Roof / Ceiling	R (hr.ft^2 °F/Btu)	21.2	60.1	50.1
	Windows/Glazed Doors	Uw (Btu/hr.ft^2 °F)	0.63	0.3	0.18
		Whole window SHGC	0.64	0.4	0.4
	Slab	R (hr.ft^2 °F/Btu)	0.42 (uninsulated)	10 ci (4ft perimeter)	20.0
Ventilation/ Rooms	Airflows	Kitchen - Exhaust (cfm), ea.	100	100	35
		Kitchen - Exhaust (run time - min/yr)*	16,000 (def.)	16,000 (def.)	(cont.)
		Bathroom - Exhaust (cfm), ea.	50	50	24
		athroom - Exhaust (run time - min/yr)	21900	21900	(cont.)
		1/2 Bath - Exhaust (cfm), ea.	50	50	12
		1/2 Bath - Exhaust (run time - min/yr)	21900	21900	(cont.)
		Fresh air - Supply (cfm) per unit	-	-	71
		verage air flow rate (cfm) continuou	11.38	11.38	144
	Summer Ventilation	Summer H/ERV Recovery Mode	None	None	Temperature controlled bypass
Systems	Ventilation Equipment	% Heat Recovery Efficiency	-	-	0.8
		% Humidity Recovery Efficiency	-	-	0.4
		Electric Efficiency	0.5	0.5	0.75
	Auxiliary Energy (Kitchen Exhaust)	Device Type	Other	Other	-
		Quantity	2	2	-
		Energy Demand (rated, W)	26	26	
		Period of Operation (khr/yr)	0.133	0.133	-
	Auxiliary Energy (Bath Exhaust)	Device Type	Other	Other	-
		Quantity	4	4	-
		Energy Demand (rated, W)	13	13	
		Period of Operation (khr/yr)	0.365	0.365	-

*Run time is WUFI default based on exhaust device type and number of units.
**Run time per BAHSP protocol (60min/day)

Table A-3.2. Variable Inputs for All Duplex WUFI Passive Models

Table A4.1 - Common WUFI Inputs (6-Flat)			
WUFI Branch	**Parameters**	**Units**	**Inputs**
PH Case	Number of units	Total	6
	Number of floors	Total	3
	Floor slab area	ft²	3,539
	Floor slab perimeter	ft	263.2
Zone 1	iCFA	ft²	9,177.0
Internal Loads/ Occupancy	Occupant Quantity	# bedrooms + 1	24
	Number of bedrooms	# bedrooms	18
	Int Lighting	kWh/yr	3,100
	Ext Lighting	kWh/yr	202
	Misc Electric Loads (M	kWh/yr	8,965
Ventilation/ Rooms	Room Quantities	# kitchens	6
		# bathrooms	6
		# laundry	6
Systems	DHW Distribution	Pipe length per unit (total, ft)	100
	Cooling	Recirc air flow rate (cfm)	1350
		Recirc air cooling capacity	54

Table A-4.1. Common Inputs for All 6-Flat WUFI Passive Models

Table A4.2- Unique WUFI Passive Inputs (6 FLAT)

WUFI Branch	Parameter	Units	WUFI Inputs		
			Existing	**IECC 2021**	**Phius CORE 2021**
PH Case	Airtightness	cfm/ft^2 (envelope) @ 50 Pa	0.983	0.28	0.06
	Ventilation System	Type	Exhaust only	Exhaust only	Balanced
	Perimeter insulation	Position	N.Def	N.Def	Vertical
		R (hr.ft2 °F/Btu) / Depth (ft)	-	-	10 / 2
Visualized Components	Above Grade Walls	R (effective, hr.ft^2 °F/Btu)	9.6	23.1	35.1
	Roof / Ceiling	R (hr.ft^2 °F/Btu)	21.5	60.1	60.1
	Opaque Door	R (hr.ft^2 °F/Btu)	3.5	3.5	5
	Windows/Glazed Do	Uw (Btu/hr.ft^2 °F)	0.63	0.3	0.17
		Whole window SHGC	0.64	0.4	0.32
	Slab	R (hr.ft^2 °F/Btu)	0.42 (uninsulated)	10 ci (4ft perimeter)	20.0
Ventilation/ Rooms	Airflows	Kitchen - Exhaust (cfm), ea.	100	100	25
		Kitchen - Exhaust (run time - min/yr)*	48000 (def.)	48000 (def.)	(cont.)
		Bathroom - Exhaust (cfm), ea.	50	50	20
		Bathroom - Exhaust (run time - min/yr)**	21900	21900	(cont.)
		Laundry (cfm) per unit	-	-	15
		Fresh air - Supply (cfm) per unit	-	-	60
		Average air flow rate (cfm) continuous	21.63	21.63	144
	Summer Ventilation	Summer H/ERV Recovery Mode	None	None	Temperature controlled bypass
Systems	Ventilation Equipment	% Heat Recovery Efficiency	-	-	0.8
		% Humidity Recovery Efficiency	-	-	0.4
		Electric Efficiency	0.5	0.5	0.75
	Auxiliary Energy (Kitchen Exhaust)	Device Type	Other	Other	-
		Quantity	6	6	-
		Energy Demand (rated, W)	26	26	
		Period of Operation (khr/yr)	0.133	0.133	-
	Auxiliary Energy (Bath Exhaust)	Device Type	Other	Other	-
		Quantity	12	12	-
		Energy Demand (rated, W)	13	13	
		Period of Operation (khr/yr)	0.365	0.365	-

*Run time is WUFI default based on exhaust device type and number of units.

**Run time per BAHSP protocol (60min/day)

Table A-4.2. Variable Inputs for All 6-Flat WUFI Passive Models

APPENDIX B: SIMULATION INPUTS & RESULTS (BEOPT)

The tables below outline the detailed inputs for BEopt software. The first table outlines the inputs shared by all of the models for the typical loads. The following outline the project-type specific inputs, both those that were common throughout each type (single-family, duplex, 6-flat) and those that varied based on enclosure performance (existing, code, passive)

Table B-1 - Common BEopt Inputs (All Project Types)			
BEopt Branch	**Parameter**	**Units**	**BEopt Inputs**
Site	Location	TMY3 Location	Milwaukee Mitchell Intl AP
Building	Orientation	n/a	South
	Neighbors	Distance (ft)	None, n/a
Thermal Mass	Floor Mass	Material	Wood
	Other (Gyp)	Thickness (in)	1/2"
Windows & Doors	Interior shading	Reduction factor (summer)	0.7
		Reduction factor (winter)	0.7
Space Conditioning	Air Source Heat Pump	Efficiency	SEER 19; HSPF 9.5
	Ceiling fan	Efficiency (W)	Standard efficiency (45)
Space Conditioning Schedules	Cooling set point	°F	77
	Heating set point	°F	68
Water Heating	Water Heater (HPWH)	EF (Energy Factor)	2.3
		Tank Volume (gal/unit)	80
	Distribution	Pipe Material	Copper
		Pipe Layout	Trunk/Branch
		Pipe location	Interior
		Recirc Type	Demand
		Pipe Insulation, R (hr.ft^2 °F/Btu)	2
Appliances & Fixtures	Refrigerator	kWh/yr	445
	Cooking Range	kWh/unit/yr	400 (Elec, 80% usage)
	Dishwasher	Rated annual consumption (kWh)	269
	Clothes Washer	Rated annual consumption (kWh)	120
		MEF	2.47
	Clothes Dryer	CEF	5.79
	Hot Water Fixtures	gal/person/day	9.9 @ 110°F

Table B-1. Common Inputs for all BEopt Models

Table B-2.1 - Common BEopt Inputs (Single Family)			
BEopt Branch	**Parameter**	**Units**	**Inputs**
Geometry	General Layout & Spaces	# Units (total)	1
		# Beds (per unit)	3
		# Baths (per unit)	2
		# Floors (total)	2
		ft^2 (per floor, gross)	1,200
		Roof type	Unfinished attic
Windows & Doors	Window Areas	ft^2 (per elevation)	90
	Door Area	ft^2 (total)	20
Water Heating	Distribution	Pipe Length (ft)	65
Lighting	Annual Elec Use	kWh/unit/yr	760
Miscellaneous	Annual Elec Use	kWh/unit/yr	2,045

Table B-2.1. Common Inputs for all Single-Family BEopt Models

Table B-2.2 - Unique BEopt Inputs (Single Family)					
BEopt Branch	Parameter	Units	BEopt Inputs		
			Existing	IECC 2021	Phius CORE 2021
Walls	Wood Stud	R-effective, cavity (hr.ft^2°F/Btu)	10.9	11.9	12
	Sheathing	R-Value (hr.ft^2°F/Btu)	n/a	10	32
Ceilings/ Roofs	Unfinished Attic	R-Value (hr.ft^2°F/Btu)	21.5	60.1	71
Foudation/ Floors	Slab	R-Value (hr.ft^2°F/Btu)	0.65 (uninsulated)	10 ci (4ft perimeter)	20
Windows & Doors	Windows / Glazed Doors	U-Factor (Btu/hr.ft2°F)	0.633	0.3	0.17
		Whole window SHGC	0.64	0.4	0.30
	Doors	R-Value (hr.ft^2°F/Btu)	3.5	3.5	5
Airflow	Air Leakage	ACH_{50}	13	4.51	1.05
	Mechanical Ventilation	Flow Rate (cfm/unit)	n/a	54	83.1
		Total Power (W/unit)	n/a	8.1	62.3
		Ventilation Type	n/a	Supply	Balanced
		Fraction of 62.2	n/a	1	0.815
		Total Recovery Effectiveness [.]	n/a	n/a	0.6
		Sensible Recovery Effectiveness [.]	n/a	n/a	0.82
Space Conditioning	Ducts	Selection	15% Leakage, R-8	15% Leakage, R-8	In finished space

Table B-2.2. Variable Inputs for all Single-Family BEopt Models

Table B-3.1- Common BEopt Inputs (DUPLEX)			
BEopt Branch	Parameter	Units	Inputs
Geometry	General Layout & Spaces	# Units (total)	2
		# Beds (per unit)	3
		# Baths (per unit)	2
		# Floors (total)	3
		ft^2 (per unit, gross)	1,656
		Roof type	Unfinished attic
Windows & Doors	Window Areas	ft^2 (South)	141
		ft^2 (North)	52
		ft^2 (West/East)	45
		ft^2 (total)	n/a
	Distribution	Pipe Length (ft)	65
Lighting	Annual Elec Use	kWh/unit/yr	566
Miscellaneous	Annual Elec Use	kWh/unit/yr	1535

Table B-3.1. Common Inputs for all Duplex BEopt Models

Table B-3.2 - Unique BEopt Inputs (DUPLEX)					
BEopt Branch	Parameter	Units	BEopt Inputs		
			Existing	IECC 2021	Phius CORE 2021
Walls	Wood Stud	R-effective, cavity (hr.ft^2°F/Btu)	10.9	11.9	12
	Sheathing	R-Value (hr.ft^2°F/Btu)	n/a	10	30
Ceilings/ Roofs	Unfinished Attic	R (hr.ft^2°F/Btu)	21.5	60.1	50
Foudation/ Floors	Slab	R (hr.ft^2°F/Btu)	0.65 (uninsulated)	10 ci (4ft perimeter)	20
Windows & Doors	Windows / Glazed Doors	U-Factor (Btu/hr.ft^2°F)	0.633	0.3	0.18
		Whole window SHGC	0.64	0.4	0.30
	Doors	R (hr.ft^2°F/Btu)	n/a	n/a	n/a
Airflow	Air Leakage	ACH_{50}	13.8	4.25	0.91
	Mechanical Ventilation	Flow Rate (cfm/unit)	n/a	46.6	71
		Total Power (W/unit)	n/a	7	53.2
		Ventilation Type	n/a	Supply	Balanced
		Fraction of 62.2	n/a	1	0.891
		Total Recovery Effectiveness [.]	n/a	n/a	0.6
		Sensible Recovery Effectiveness [.]	n/a	n/a	0.8
Space Conditioning	Ducts	Selection	15% Leakage, R-8	15% Leakage, R-8	In finished space

Table B-3.2. Variable Inputs for all Duplex BEopt Models

Table B-4.1 - Common BEopt Inputs (6-FLAT)			
BEopt Branch	**Parameter**	**Units**	**Inputs**
Geometry	General Layout & Spaces	# Units (total)	6
		# Beds (per unit)	3
		# Baths (per unit)	2
		# Floors (total)	3
		ft^2 (per unit, gross)	1,740
		Roof type	Flat roof/deck
Windows & Doors	Window Areas	ft^2 (South)	394
		ft^2 (North)	126
		ft^2 (West)	448
		ft^2 (East)	430
	Door Area	ft^2 (per unit)	28.5
Water Heating	Distibution	Pipe Length (ft)	100
Lighting	Annual Elec Use	kWh/unit/yr	550
Miscellaneous	Annual Elec Use	kWh/unit/yr	1,494

Table B-4.1. Common Inputs for all 6-Flat BEopt Models

Table B-4.2 - Unique BEopt Inputs (6-FLAT)					
BEopt Branch	Parameter	Units	BEopt Inputs		
			Existing	IECC 2021	Phius CORE 2021
Walls	Wood Stud	R-effective, cavity (hr.ft^2°F/Btu)	10.9	11.9	13
	Sheathing	R-Value (hr.ft^2°F/Btu)	n/a	10	24
Ceilings/ Roofs	Unfinished Attic	R-Value (hr.ft^2°F/Btu)	21.7	60	60
Foudation/ Floors	Slab	R-Value (hr.ft^2°F/Btu)	0.65 (uninsulated)	10 ci (4ft perimeter)	20
Windows & Doors	Windows / Glazed Doors	U-Factor (Btu/hr.ft2°F)	0.633	0.3	0.17
		Whole window SHGC	0.64	0.4	0.35
	Doors	R-Value (hr.ft^2°F/Btu)	3.5	3.5	5
Airflow	Air Leakage	ACH_{50}	13.2	3.93	0.87
	Mechanical Ventilation	Flow Rate (cfm/unit)	n/a	47.4	60.8
		Total Power (W/unit)	n/a	7.1	45.6
		Ventilation Type	n/a	Supply	Balanced
		Fraction of 62.2	n/a	1	0.74
		Total Recovery Effectiveness [.]	n/a	n/a	0.6
		Sensible Recovery Effectiveness [.]	n/a	n/a	0.8
Space Conditioning	Ducts	Selection	15% Leakage, R-8	15% Leakage, R-8	In finished space

Table B-4.2. Variable Inputs for all 6-Flat BEopt Models

Table B-5 outlines the inputs used specifically to simulate the critical load during an outage. This critical load was defined somewhat arbitrarily, and included the load required to maintain a setpoint on the interior that is within a reasonable comfort range. It also included some lighting, mechanical ventilation (for the Phius cases with mechanical ventilation equipment), keeping the refrigerator running at normal load, and enough plug load energy to charge cell phones.

The definition of critical loads is not standardized, and different projects may have different goals.

Table B-5 - Outage / Critical Load Simulation (Beopt)		
BEopt Branch	**Parameter**	**BEopt Inputs**
Ventilation	Airflow Rate	None (Existing, Code) 25% of Typical Balanced Rate (Phius)
Space Conditioning Schedules	Cooling set point	85°F
	Heating set point	55°F
Appliances, Lighting & Plug Loads	Refrigerator	445 kWh/yr
	Lighting	10% of typical usage
	Plug Loads	20 W, 6 hrs/day (phone charger)

Table B-5 Inputs for all Critical Load / Outage Simulations in BEopt

APPENDIX C: SIMULATION INPUTS & ALL RESULTS (REOPT)

C-1: REopt Simulation Inputs & Defaults

Below is a table of all inputs used in the REopt simulations carried out for this study. The table lists the default values, or some may be described as "main" values used in the simulation (for places where default values are not possible such as climate and load profile).

The full description of model inputs can be found in the REopt User Manual: https://reopt.nrel.gov/user-guides.html

Table C-1. Reopt Simulation Inputs: Defaults and Variables

Project Data		
Energy Goals	Financial, Clean Energy, Resilience	
Technologies	PV, Battery, Grid	
Site Data		
Site and Utility	**Default / Main**	**Variables**
Site Location	Milwaukee, WI	N/A
Source	*Built In*	N/A
Electricity Rate	Wisconsin Electric Power Co: Residential (Single Phase) Rg 1	Wisconsin Electric Power Co: Residential Time of Use
Source	*Built In*	*Built In*
Use custom electricity rate? [x]	No	N/A
Load Profiles	**Default / Main**	**Variables**
Load Profiles Uploaded	See Section 4.1 & 4.3 in Main Report	
Source	*BEopt Export*	
Electrical Load Adjustment (% of orig consumption)	100%	N/A
Year of Simulation	2017	N/A
Simulation Start Date	Sunday	N/A
Resilience	**Default / Main**	**Variables**
Critical Electrical Load (%, Upload, Build)	% and Upload, reparately	N/A
Simulated Critical Loads	See Section 4.1 & 4.3 in Main Report	
Source	Beopt Export	
Critical Load Factor (%)	25%	10%, 50%
Outage Information	**Default / Main**	**Variables**
Outage Duration (hours)	72	36, 144
Source	*chosen*	*Selected*
Outage Start Date	January 1	15-Jun
Source	*Autoselect using critical load profile*	*Selected*
Outage Start Time	11:00 PM	N/A
Source	*Autoselect using critical load profile*	*Selected*
Financial	**Default / Main**	**Variables**
Analysis period (years)	25	50
Source	*default*	*Selected*
Host discount rate, nominal (%)	5.64%	N/A
Source	*default*	N/A
Electricity cost escalation rate, nominal (%)	1.9%	3.8%
Source	*default*	*Selected*
Use third-party ownership model? [x]	No	N/A
Host effective tax rate (%)	26%	N/A
Source	*default*	N/A
O&M cost escalation rate (%)	2.5%	N/A

Table C-1, cont. Reopt Simulation Inputs: Defaults and Variables

Renewable Energy & Emissions	Default / Main	Variables
Entering Emission Factors (Hourly, Annual, Upload)	Hourly (Built in)	Upload
Source	*Built in*	*NREL Cambium*
Electricity Grid Emissions Factors	US EPA AVERT Great Lakes	2024, 2035, 2050
Source	*default*	*NREL Cambium*
Projected annual percent decrease in grid emissions factors (%/year)	1.17%	N/A
Source	*default*	N/A
Include climate costs in the objective? [Yes, No]	No	N/A
Include health costs in the objective? [Yes, No]	No	N/A
Count renewable electricity (RE) exported to the grid towards annual RE goals? [Yes, No]	By default, this is 'Yes'. However, the simulations in this study did not treat excess PV as exported to the grid and therefore simulated this as "No" in all cases.	
Count electricity exported to the grid towards emissions offsets? [Yes, No]		
CO_2 cost (\$/t CO_2)	\$51	N/A
Clean Energy Goals	**Default / Main**	**Variables**
Clean Energy Target	Renewable Electricity, Emissions (separately)	N/A
Minimum annual renewable electricity (%)	0	50, 75, 90, 99, 100
Maximum annual renewable electricity (%)	Unlimited	N/A
Minimum lifecycle emissions reduction (%)	0	50, 75, 90, 99, 100
Maximum lifecycle emissions reduction (%)	Unlimited	N/A
PV	**Default / Main**	**Variables**
System Capital Costs (\$/kW-DC)	\$1,592	N/A
Source	*default*	N/A
Minimum new PV size (kW-DC)	0	Net Zero Size
Maximum new PV size (kW-DC)	Unlimited	N/A
Module Type	Standard	N/A
Array Type	Fixed	N/A
Array Azumith (deg)	180	N/A
Array Tilt (deg)	10	N/A
DC to AC Size Ratio	1.2	N/A
System Losses (%)	14%	N/A
PV Incentives and Tax Treatment	All Default	N/A
Battery	**Default**	**Variables**
Energy Capacity Cost (\$/kWh)	\$388	N/A
Source	*default*	N/A
Power Capacity Cost (\$/kW)	\$775	N/A
Source	*default*	N/A
Allow Grid to charge battery [Yes, No]	Yes	No
Source	*default*	N/A
Minimum Energy Capacity (kWh)	0	N/A
Maximum Energy Capacity (kWh)	Unlimited	N/A

C-1.1: Carbon Emissions Profiles

For this study, multiple carbon emission profiles were used for simulations and sensitivity analysis.

The built-in emissions profile in REopt is from EPA AVERT, which reflects the current grid emission levels at a regional level. This emission source was used in all simulations unless noted otherwise.

Four different emissions profiles were studied. These profiles were sourced from NREL Standard Scenarios 2022 Cambium Mid-Case scenario data which represents a future grid-mix projection based on policies in place. From this data, the CO2e (equivalent) long range marginal emission rates (LRMER) were selected, and both the GEA region level and state level data was studied. The rates that were used in the REopt simulations were:

- 2024 RFCW Regional Emissions
- 2030 RFCW Regional Emissions
- 2050 RFCW Regional Emissions
- 2050 Wisconsin State Level Emissions

The NBI (New Buildings Institute) Grid Optimal Emissions Rates were also studied relative to these other options. These rates were also derived from Cambium data, NREL Standard Scenarios 2021 Cambium Long Run Marginal Emissions Rate Forecasts, at US State level, averaged over each even year 2036-2044. More information on that program can be found here: https://newbuildings.org/resource/gridoptimal/

	EPA AVERT - Great Lakes Region	Cambium - RFCW Region 2024	Cambium - RFCW Region 2030	Cambium - RFCW Region 2050	Cambium - Wisconsin (State-Level) 2050	NBI Grid Optimal (State-Level) Average, 2036-2044
	CO2/MWh	CO2e/MWh	CO2e/MWh	CO2e/MWh	CO2e/MWh	CO2/MWh
Minimum	101	2.9	7.8	70	131.5	145
Maximum	1139	858	871.2	707.8	661.8	545
Average	751	461	396	285	303	284

Table C-2: Emissions Rates - Minimum, Maximum, Average

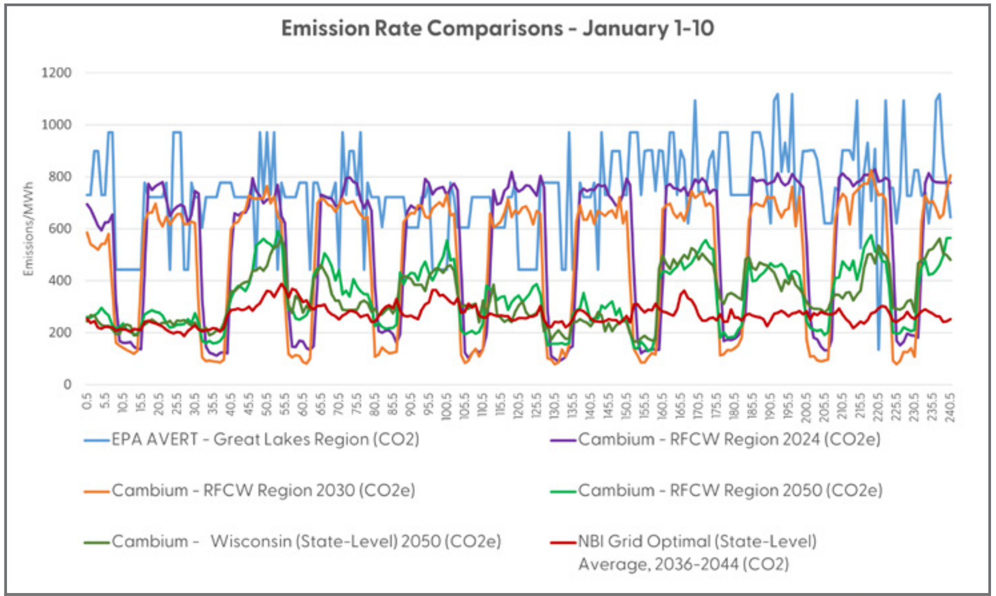


Fig. C-1. Comparison of Hourly Emissions Rates from Various Sources, January 1-10

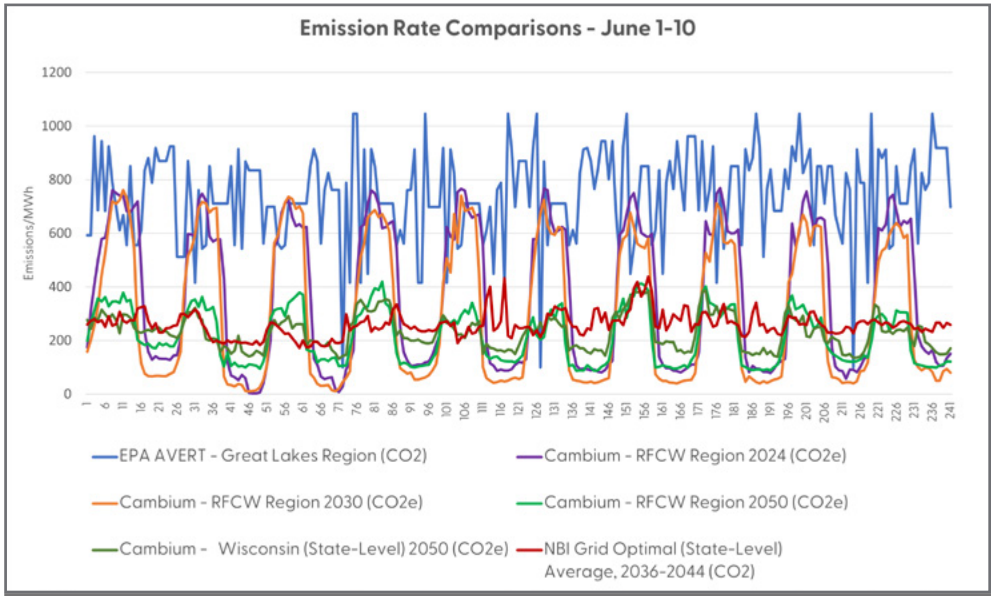


Fig. C-2. Comparison of Hourly Emissions Rates from Various Sources, June 1-10

C-2: REopt Simulation Results

Below is the full list of unit-level results for all 150 REopt simulations completed. The results are normalized per dwelling unit for means of comparison between case results–the single-family results were left as-is, the duplex level results were divided by 2, the 6-flat results divided by 6 units, and neighborhood results divided by 55 dwelling units.

Run #	Project Goal(s)	Building			Simulation Objective	Net Present Value	Lifecycle Cost	Initial Cost	PV Size (kW)	Battery Capacity (kWh)	Battery Power (kW)
		Type	Enclosure	Operation Mode							
1	Minimize Cost	SF	Existing	Typical	All Defaults	$2,168	$49,553	$3,654	4	0	0
2			Code			$1,698	$25,164	$2,446	2	0	0
3			Phius			$1,610	$15,879	$1,927	2	0	0
4		DUP	Existing			$1,688	$42,599	$2,842	3	0	0
5			Code			$1,350	$20,097	$1,889	2	0	0
6			Phius			$1,349	$12,117	$1,612	2	0	0
7		6-FLAT	Existing			$1,644	$30,571	$2,421	2	0	0
8			Code			$1,396	$14,580	$1,750	2	0	0
9			Phius			$1,390	$10,633	$1,579	2	0	0
10		SF	Existing		Double Analysis Period (50 years)	$4,070	$68,656	$7,400	5	3	0
11			Code			$3,053	$34,718	$4,384	3	2	0
12			Phius			$2,794	$21,798	$3,541	3	1	0
13			Existing		Double Electricity Price Escalation Rate (3.8%)	$3,691	$60,412	$4,753	5	0	0
14			Code			$2,754	$30,538	$3,058	3	0	0
15			Phius			$2,497	$19,179	$2,429	2	1	1
16			Existing		Time of Use Electricity Rates (4:1 Peak Pricing)	$5,105	$37,410	$7,783	5	7	1
17			Code			$3,915	$18,748	$5,132	3	5	1
18			Phius			$3,711	$11,620	$4,523	2	5	1

Table C-3.1. Building Level Results for REopt Runs 1-81

19	**Clean Energy**	SF	Existing	Typical	50% Emissions Reduction Goal	-$15,624	$67,345	$35,796	19	39	8
20			Code			-$2,279	$29,141	$12,581	7	13	2
21			Phius			$471	$17,018	$6,060	4	6	1
22		DUP	Existing			-$15,861	$60,148	$33,374	18	36	8
23			Code			-$2,435	$23,882	$10,954	6	12	2
24			Phius			$448	$13,019	$4,846	3	5	1
25		6-FLAT	Existing			-$8,198	$40,413	$21,393	12	23	4
26			Code			-$101	$16,077	$6,819	4	7	1
27			Phius			$600	$11,423	$4,430	3	4	1
28		SF	Existing	Flexible	50% Emissions Reduction Goal	-$10,822	$53,336	$27,489	15	31	6
29			Code			-$1,274	$25,106	$10,349	6	11	2
30			Phius			$530	$16,039	$5,570	3	5	1
31			Existing	Typical	50% Emissions Reduction Goal, Emissions Year 2024, Regional	-$25,103	$76,824	$47,114	19	74	9
32			Code			-$6,006	$32,868	$17,661	8	26	3
33			Phius			-$94	$17,583	$7,601	4	9	1
34			Existing		50% Emissions Reduction Goal, Emissions Year 2035, Regional	-$32,080	$83,801	$57,856	28	75	11
35			Code			-$7,605	$34,467	$20,645	10	27	4
36			Phius			-$199	$17,688	$8,115	4	10	1
37			Existing		50% Emissions Reduction Goal, Emissions Year 2050, Regional	-$29,874	$81,595	$55,467	29	67	10
38			Code			-$6,708	$33,570	$19,578	10	23	3
39			Phius			-$75	$17,564	$7,968	4	9	1
40			Existing		50% Emissions Reduction Goal, Emissions Year 2050 State-Level	-$25,104	$76,825	$47,090	19	74	9
41			Code			-$7,028	$38,065	$20,664	9	31	4
42			Phius			-$94	$17,583	$7,602	4	9	1
43			Existing		75% Emissions Reduction Goal	-$65,347	$117,068	$97,367	45	128	22
44					90% Emissions Reduction Goal	-$151,846	$203,567	$192,543	87	258	46
45					100% Emissions Reduction Goal	-$655,481	$707,202	$704,901	207	1587	46
46			Phius	Flexible	75% Emissions Reduction Goal	-$1,784	$18,353	$11,163	6	14	2
47					90% Emissions Reduction Goal	-$9,586	$26,155	$21,573	10	29	5
48					100% Emissions Reduction Goal	-$86,331	$102,900	$100,599	36	202	7

49			Existing	Typical	100% Emissions Reduction Goal Emissions Year 2050, Regional	-$655,481	$707,202	$704,901	207	1587	46
50			Code			-$284,835	$311,697	$309,397	99	668	19
51			Phius			-$95,961	$113,450	$111,149	38	232	7
52			Existing		Clean Electricity to Net Zero	-$9,284	$61,005	$24,565	22	6	1
53			Code			-$3,473	$30,335	$13,355	11	6	1
54			Phius			-$1,287	$18,776	$9,201	7	6	1
55			Existing		100% Clean Electricity	-$476,182	$527,903	$524,729	157	1128	56
56			Code			-$202,508	$229,370	$226,682	62	504	26
57			Phius			-$70,811	$88,300	$85,868	25	182	11
58	**Outage Resilience**	SF	Existing	Typical + Critical	72 Hour Winter Outage - Simulated Critical Load	-$11,436	$62,662	$27,907	12	47	4
59			Code			-$946	$27,552	$10,206	5	13	1
60			Phius			$887	$16,447	$4,575	3	5	1
61		DUP	Existing			-$260,202	$301,888	$291,306	48	784	21
62			Code			-$76,448	$96,850	$90,849	15	245	7
63			Phius			$889	$12,260	$3,354	2	3	1
64		6-FLAT	Existing			-$175,596	$206,042	$198,367	31	542	13
65			Code			-$36,820	$52,174	$47,391	8	128	4
66			Phius			-$11,608	$23,364	$20,129	5	49	2
67		DUP	Code		72 Hour Winter Outage - 10% Total Load = Critical	-$29,869	$71,554	$44,702	11	106	4
68					72 Hour Winter Outage - 25% Total Load = Critical	-$85,217	$126,902	$105,066	18	280	8
69					72 Hour Winter Outage - 50% Total Load = Critical	-$182,386	$224,072	$210,066	36	560	16
70		6-FLAT	Phius		36 Hour Winter Outage - Simulated Critical Load	-$4,888	$16,784	$12,933	4	27	2
71					144 Hour Winter Outage - Simulated Critical Load	-$12,182	$23,708	$21,576	6	47	3
72					72 Hour Summer Outage - Simulated Critical Load	$1,136	$10,809	$2,514	2	2	0

Table C-3.1, cont. Building Level Results for REopt Runs 1-81

73	**Clean Energy & Outage Resilience**	SF	Existing	Typical + Critical	72 Hour Winter Outage & 50% Emissions Reduction	-$15,889	$67,115	$35,866	20	39	8
74			Code			-$2,356	$28,962	$12,555	7	13	2
75			Phius			$206	$17,128	$6,983	4	8	1
76		DUP	Existing			-$260,202	$301,888	$291,306	48	784	21
77			Code			-$76,448	$96,850	$90,849	15	245	7
78			Phius			$438	$12,711	$4,719	3	5	1
79		6-FLAT	Existing			-$175,596	$206,042	$198,367	31	542	13
80			Code			-$36,820	$52,174	$47,391	8	128	4
81			Phius			-$11,608	$23,364	$20,129	5	49	2

Table C-3.1, cont. Building Level Results for REopt Runs 1-81

Run #	Project Goal(s)	Building			Simulation Objective	Net Present Value	Lifecycle Cost	Initial Cost	PV Size (kW)	Battery Capacity (kWh)	Battery Power (kW)
		Type	Enclosure	Operation Mode							
82	**Minimize Cost**	NEIGHB	Existing	Typical	All Defaults	$1,892	$36,834	$2,983	3	0	0
83			Code			$1,528	$17,408	$2,030	2	0	0
84			Phius			$1,477	$11,296	$1,696	2	0	0
85			Existing	Shifted		$1,943	$36,783	$3,023	3	0	0
86			Code			$1,577	$17,357	$2,068	2	0	0
87			Phius			$1,529	$11,242	$1,734	2	0	0
88			Code	Typical	Double Analysis Period (50 years)	$2,686	$23,940	$3,424	3	1	0
89					Double Electricity Price Escalation Rate (3.8%)	$2,429	$21,039	$2,491	2	0	0
90					Time of Use Electricity Rates (4:1 Peak Pricing)	$3,442	$13,070	$4,317	2	4	1

Table C-3.2. Neighborhood Level Results for REopt Runs 82-150

91	Clean Energy	NEIGHB	Existing	Typical	50% Emissions Reduction	-$10,339	$49,065	$25,979	14	28	6
92			Code			-$723	$19,659	$8,763	5	9	2
93			Phius			$572	$12,200	$4,901	3	5	1
94			Existing	Shifted		-$10,124	$48,850	$25,826	14	27	6
95			Code			-$640	$19,574	$8,691	5	9	2
96			Phius			$651	$12,120	$4,818	3	5	1
97			Existing	Typical	50% Emissions Reduction, DO NOT Allow Grid to Charge Battery	-$13,427	$52,153	$31,411	18	34	5
98			Code			-$1,259	$20,195	$10,077	6	10	2
99			Phius			$505	$12,267	$5,355	3	5	1
100			Existing		75% Emissions Reduction	-$44,779	$83,506	$69,755	34	89	16
101			Code			-$10,841	$29,777	$23,225	12	29	5
102			Phius			-$1,355	$14,127	$9,724	5	12	2
103			Existing		90% Emissions Reduction	-$98,312	$137,039	$130,379	60	181	27
104			Code			-$30,994	$49,930	$46,782	22	62	10
105			Phius			-$7,965	$20,738	$18,642	9	25	4
106			Existing		99% Emissions Reduction	-$217,257	$255,983	$254,823	85	488	41
107			Code			-$79,341	$98,277	$97,703	31	185	19
108			Phius			-$27,793	$40,565	$40,198	16	68	6
109			Existing		100% Emissions Reduction	-$348,100	$386,826	$386,784	111	866	32
110			Code			-$140,797	$159,733	$159,691	47	358	12
111			Phius			-$53,193	$65,966	$65,924	25	126	5
112			Existing	Flexible	75% Emissions Reduction	-$35,095	$67,427	$56,335	28	71	12
113			Code			-$7,973	$24,692	$18,967	9	23	4
114			Phius			-$1,011	$13,095	$8,915	5	11	2
115			Existing		90% Emissions Reduction	-$80,954	$113,286	$107,838	49	151	23
116			Code			-$25,113	$41,832	$39,086	18	52	8
117			Phius			-$6,548	$18,632	$16,635	8	22	4
118			Existing		99% Emissions Reduction	-$181,140	$213,472	$212,516	74	382	41
119			Code			-$67,957	$84,676	$84,176	30	148	17
120			Phius			-$24,214	$36,298	$35,946	15	57	7

Table C-3.2, cont. Neighborhood Level Results for REopt Runs 82-150

121			Existing		100% Emissions Reduction	-$283,330	$315,662	$315,620	99	674	27
122			Code			-$122,157	$138,876	$138,834	44	299	10
123			Phius			-$47,746	$59,830	$59,788	25	106	5
124			Existing	Typical	Clean Electricity to Net Zero	-$6,781	$45,507	$19,509	17	5	1
125			Code			-$2,291	$21,227	$10,715	8	6	1
126			Phius			-$901	$13,673	$7,538	6	5	1
127			Existing		50% Clean Electricity	-$16,866	$55,592	$36,227	21	39	6
128			Code			-$2,056	$20,992	$11,509	7	12	2
129			Phius			$306	$12,467	$6,063	3	7	1
130			Existing		90% Clean Electricity	-$128,611	$167,337	$163,374	78	217	33
131			Code			-$42,709	$61,645	$59,702	29	78	12
132			Phius			-$12,382	$25,155	$23,840	12	30	5
133			Existing		99% Clean Electricity	-$235,742	$274,469	$273,691	96	514	41
134			Code			-$88,052	$106,988	$106,621	37	201	16
135			Phius			-$32,845	$45,617	$45,397	16	82	7
136			Existing		100% Clean Electricity	-$261,829	$300,555	$300,097	99	591	43
137			Code			-$104,218	$123,154	$122,935	39	251	17
138			Phius			-$41,181	$53,954	$53,841	18	107	8
139	**Outage Resilience**	NEIGHB	Existing	Typical + Critical	72 Hour Winter Outage	-$143,224	$180,377	$167,551	27	453	12
140			Code			-$33,416	$51,753	$44,353	7	119	3
141			Phius			-$5,387	$17,914	$14,164	5	28	2
142			Existing		72 Hour Winter Outage - 25% Total Load = Critical	-$47,659	$84,812	$63,650	12	166	4
143			Code			-$15,625	$33,962	$25,058	6	61	2
144			Phius			-$3,623	$16,150	$12,269	5	22	2
145			Existing	Shifted + Critical		-$47,501	$84,655	$63,544	12	165	4
146			Code			-$15,523	$33,858	$24,966	6	61	2
147			Phius			-$3,495	$16,022	$12,168	5	22	2
148	**Clean Energy & Outage Resilience**	NEIGHB	Existing	Typical + Critical	72 Hour Winter Outage, 50% Emissions Reduction	-$143,224	$180,377	$167,551	27	453	12
149			Code			-$33,416	$51,753	$44,353	7	119	3
150			Phius			-$5,387	$17,914	$14,164	5	28	2

Table C-3.2, cont. Neighborhood Level Results for REopt Runs 82-150

APPENDIX D: SIMULATION INPUTS (FLEXIBLE LOADS)

Flexible loads were generated from the typical loads by manipulation of data in Excel.

The 876th highest emission hour was determined as the value in which above that signaled the highest 10% of annual grid emission factors. For hours with an emission factor in the top 10%, the space heating and space cooling was subtracted from the total building load.

The next 15% highest emission factor hours (between 877th 2190th) were determined to signal a reduction in space conditioning load. The "typical" heating or cooling load was subtracted from the total load, and the "critical" heating or cooling load at that time was added back in. This was to represent that the space conditioning system may shed load but not completely cut it. The HVAC system was set to maintain a range of 68-77F during typical operation, and 55-85F during critical operation.

There is also significant potential in load flexibility through load shifting with water heating and adjusting the timing of appliance energy use. For this study, this was excluded. Future tools, such as BEopt 3.0 may include more built-in capabilities for more sophisticated demand response measures.

APPENDIX E: RESSTOCK DATA

To define the existing building stock in Milwaukee, Wisconsin, NREL's ResStock database was utilized. The filters for data extraction were for buildings from 1970's to pre-1940's, and for Milwaukee Mitchell Intl Airport. The tables below summarize the data retrieved, in which averages were carried into the simulations.

Windows	U-Value	SHGC	Count	Percent	Source
Triple Low-E Non-metal Air L-Gain	0.29	0.26	8475	1%	BEopt
Double Low-E Non-metal Air M-Gain	0.38	0.44	99274	17%	BEopt
Double Clear Non-metal Air	0.49	0.56	106538	18%	BEopt
Double Clear Non-metal Air Exterior Clear Storm	0.49	0.56	26634	5%	BEopt
Double Clear Metal Air	0.76	0.67	65618	11%	BEopt
Double Clear Metal Air Exterior Clear Storm	0.76	0.67	7506	1%	BEopt
Single Clear Non-metal	0.99	0.74	181840	32%	2008 Building Energy Efficiency Standards
Single Clear Non-metal Exterior Clear Storm	0.99	0.74	21550	4%	2008 Building Energy Efficiency Standards
Single Clear Metal	1.28	0.8	51332	9%	2008 Building Energy Efficiency Standards
Single Clear Metal Exterior Clear Storm	1.28	0.8	7748	1%	2008 Building Energy Efficiency Standards
AVERAGE	**0.633**	**0.64**			

Table E-1: ResStock Existing Window Data

Windows	U-Value	SHGC	Count	Percent	Source
Triple Low-E Non-metal Air L-Gain	0.29	0.26	8475	1%	BEopt
Double Low-E Non-metal Air M-Gain	0.38	0.44	99274	17%	BEopt
Double Clear Non-metal Air	0.49	0.56	106538	18%	BEopt
Double Clear Non-metal Air Exterior Clear Storm	0.49	0.56	26634	5%	BEopt
Double Clear Metal Air	0.76	0.67	65618	11%	BEopt
Double Clear Metal Air Exterior Clear Storm	0.76	0.67	7506	1%	BEopt
Single Clear Non-metal	0.99	0.74	181840	32%	2008 Building Energy Efficiency Standards
Single Clear Non-metal Exterior Clear Storm	0.99	0.74	21550	4%	2008 Building Energy Efficiency Standards
Single Clear Metal	1.28	0.8	51332	9%	2008 Building Energy Efficiency Standards
Single Clear Metal Exterior Clear Storm	1.28	0.8	7748	1%	2008 Building Energy Efficiency Standards
AVERAGE	**0.633**	**0.64**			

Table E-1: ResStock Existing Window Data

Insulation - Roof	Effective R-value	Count	Percent
Finished Uninsulated	0.75	6295	1%
Unfinished Uninsulated	0.75	367071	64%
Finished R-7	5.25	12349	2%
Finished R-13	9.75	29540	5%
Finished R-19	14.25	36078	6%
Finished R-30	22.5	66828	12%
Finished R-38	28.5	45036	8%
Finished R-49	36.75	13317	2%
AVERAGE = R-7.7			

Insulation - Ceiling	Effective R-value	Count	Percent
None	0.75	209443	36%
R-7	5.25	11864	2%
R-13	9.75	34140	6%
R-19	14.25	53995	9%
R-30	22.5	101937	18%
R-38	28.5	48910	8%
R-49	36.75	116223	20%
AVERAGE = R-16.1			

Table E-3: ResStock Roof & Ceiling Insulation Data

Insulation - Wall	Effective R-Value	Count	Percent
Brick 12-in Uninsulated	0.75	4600	1%
Wood Stud Uninsulated	0.75	87409	15%
Brick 12-in R-7	5.25	5085	1%
Wood Stud R-7	5.25	99274	17%
Brick 12-in R-11	8.25	7264	1%
Wood Stud R-11	8.25	242857	42%
Brick 12-in R-15	11.25	3632	1%
Wood Stud R-15	11.25	85472	15%
Brick 12-in R-19	14.25	969	0%
Wood Stud R-19	14.25	39952	7%
AVERAGE = R-7.4			

Table E-2: ResStoc Wall Insulation Data

Insulation - Slab / Floor	Value	Count	Percent
None	0.6	487168	0.8450237
Uninsulated	0.6	89346	0.1549763
AVERAGE = R-0.6			

Table E-4: ResStock Slab / Floor Insulation Data

Infiltration (ACH)	Count	Percent
2 ACH50	242	0%
3 ACH50	1695	0%
4 ACH50	3148	1%
5 ACH50	7990	1%
6 ACH50	13559	2%
7 ACH50	15012	3%
10 ACH50	64891	12%
15 ACH50	161259	29%
20 ACH50	123487	22%
25 ACH50	68039	12%
30 ACH50	40920	7%
40 ACH50	38257	7%
50 ACH50	12833	2%
AVEARAGE = 13.8 ACH50		

Table E-5: ResStock Infiltration / Airtightness Data

APPENDIX F: BUILDING SIMULATION / MODELING TOOLS

A. **ResStock[47]:** This free online database was used to define the existing enclosure conditions for the individual buildings in Milwaukee, WI.

B. **2021 IECC[48]:** The 2021 IECC, specifically the prescriptive enclosure requirement tables, was used to define code-compliant enclosure performance for the code-compliant cases in the simulation.

C. **Phius 2021 Space Conditioning Criteria Calculator[49]:** This tool was used to find the project-specific performance metrics required for compliance with Phius CORE certification, and was used to set certification requirements for the passive-building compliant buildings. It requires the input of: (a) Climate, (b) Building Floor Area, (c) Building Enclosure Area, and (d) Building Occupancy.

D. **WUFI® Passive Energy Modeling Software[50]:** This tool verifies compliance with the performance targets output from the critica calculator above. As with most building energy models, it requires the full building configuration, the thermal performance of the building enclosure, efficiency of mechanical equipment, appliances, and lighting.

E. **Phius CORE Prescriptive Snapshot & Compliance Checklist[51, 52]:** Though not used specifically for this study, this tool could have been used to determine Phius-compliance with the prescriptive path for the single-family case study. If this were the case, the single-family project would not have required the use of the criteria calculator or WUFI Passive tool.

F. **NREL BEopt (Building Energy Optimization) Modeling Software[53]:** This tool runs on EnergyPlus and simulates hourly (and sub-hourly) building loads based on input building characteristics or optimization goals. The tool itself is natively an optimization software which can run parametric studies to determine least-cost solutions, but that mode was not utilized for the purposes of this study. In this study, BEopt was used simply to generate hourly load profiles (typical and critical) for the various building sizes and enclosure performance. *Note that the optimization engine in BEopt was used for a significant portion of the standard-setting process for Phius' climate specific passive building standards

G. **NREL REopt (Renewable Energy Optimization) Modeling Software[54]:** This tool was used for all simulations and goals that included renewable energy generation, energy storage, resilience, emissions reductions, clean energy goals, etc.

H. **URBANopt (Urban Renewable Building and Neighborhood Optimization) Modeling Software[55]:** At face value, this tool was described to perform the exact simulations one may be looking for in microgrid design. However, after initial exploration, it was determined that while the tool specifications seemed to fit the goals of the project, the tool and user interface were not ready for public consumption. Therefore it was not used directly in the research.

I. **NREL Cambium[56]**: This tool was specifically used to derive profiles for grid-electricity emissions in future years, used for REopt simulations and sensitivity analysis when studying requirements to meet emission reduction goals.

J. **Microsoft Excel / Google Sheets:** This tool was used to manipulate hourly load profiles from typical loads on flexible loads, using spikes in hourly emissions to shed space conditioning loads.

K. **HOMER Grid[57]**: A trial license of this tool was obtained for the purposes of exploration in the study. While the description of this tool appeared in line with research objectives, ultimately we did not find that this tool was useful in the bounds of the research but is still included here as it is believed to be useful with future research. With limited exploration, the tool appears to be utilized by large utility customers to determine various scheduling of loads and storage to avoid peak demand charges and other tariffs.

L. **HOMER Pro[58]:** Similar to HOMER Grid, a trial license was obtained for exploration. Again, the intent of the tool is in-line with the research objectives but this tool was not used. Although intended for use during the design of microgrids of the type discussed herein, the input lumps all individual building loads into one load profile (without interaction potentials)--which is what REOpt also does. It is included in this list because further exploration will be included in future research.

REFERENCES

1. *Engineering and Technology History WIKI*. "Milestones: Pearl Street Station, 1882." https://ethw.org/Milestones:Pearl_Street_Station,_1882 Photographic Services of the Consolidated Edison Company of New York, Inc.
2. *Wikipedia*. "North American Power Transmission Grid." https://en.wikipedia.org/wiki/North_American_power_transmission_grid. By Bouchecl - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=6750405
3. U.S. Energy Information Administration. "Today in Energy: Record U.S. Electricity Generation in 2018 Driven by Record Residential, Commercial Sales." March 2019. https://www.eia.gov/todayinenergy/detail.php?id=38572
4. U.S. Energy Information Administration. "Today in Energy: Per Capita Residential Electricity Sales in the US Have Fallen Since 2010." July 2017. https://www.eia.gov/todayinenergy/detail.php?id=32212
5. Bloomberg NEF. *Sustainable Energy in America: 2023 Factbook*. https://bcse.org/market-trends/
6. TWI. "What is Decarbonisation?" https://www.twi-global.com/technical-knowledge/faqs/what-is-decarbonisation
7. Elevate. 2022. "Building Decarbonization Is Essential: Here's How It Works." 10 February 2022 (accessed 18 September 2022) https://www.elevatenp.org/climate/building-decarbonization-is-essential-heres-how-it-works/
8. AIA. 2022. *Zero-Carbon*. (accessed 19 September 2022) https://www.aia.org/landing-pages/6456754-zero-carbon
9. ASHRAE. 2022. Public Policy Issue Brief: "Building Decarbonization." (accessed 19 September 2022) https://www.ashrae.org/file%20library/about/government%20affairs/public%20policy%20resources/briefs/ppib-on-building-decarbonization2022-23-final.pdf
10. ASHRAE. 2022. ASHRAE Task Force for Building Decarbonization. (accessed 19 September 2022) https://www.ashrae.org/about/ashrae-task-force-for-building-decarbonization
11. Forbes. 2021. "Top 5 U.S. Electrification Policy Wins Of 2021: Federal Investment, Electric Vehicles, Building Electrification." 20 December 2021 (accessed 18 September 2022). https://www.forbes.com/sites/energyinnovation/2021/12/20/top-5-us-electrification-policy-wins-of-2021-federal-investment-electric-vehicles-building-electrification/?sh=35a25c7a554c
12. PNNL. Nd. "Grid Resilience and Decarbonization." (accessed 18 September 2022) https://www.forbes.com/sites/energyinnovation/2021/12/20/top-5-us-electrification-policy-wins-of-2021-federal-investment-electric-vehicles-building-electrification/?sh=35a25c7a554c
13. AIA. 2022. *AIA Architect:* "Across the U.S., A Surge Toward Electrification." 1 August 2022, Patrick Sisson (accessed 18 September 2022) https://www.architectmagazine.com/aia-architect/aiafeature/across-the-u-s-a-surge-toward-electrification_o
14. Silvio Marcacci. *Forbes*. "Top 5 U.S. Electrification Policy Wins of 2021: Federal Investment, Electric Vehicles, Building Electrification." December 2021. https://www.forbes.com/sites/energyinnovation/2021/12/20/top-5-us-electrification-policy-wins-of-2021-federal-investment-electric-vehicles-building-electrification/?sh=648ad143554c
15. Various Organizations. 2016. "Industry Statement on Resilience." (accessed 19 September 2022) https://content.aia.org/sites/default/files/2016-05/Res-StatementOnResilience_2.pdf
16. AIA. 2022. *AIA Resilient Project Process Guide*. (accessed 19 September 2022) https://www.aia.org/resources/6512008-aia-resilience-project-process-guide
17. ASHRAE and CIBSE. 2019. "ASHRAE and CIBSE Position Document on Resiliency in the Built Environment." (accessed 19 September 2022) https://www.ashrae.org/file%20library/about/position%20documents/ashrae_cibse_resiliencyinthebuiltenvironment_2019.pdf
18. Glasgo, Avezedo, Hendrickson. *Applied Energy*. "How Much Electricity Can We Save by Using Direct Current Circuits in Homes?" Vol. 180, October 2016, pp. 66-75. https://www.sciencedirect.com/science/article/pii/S0306261916309771#t0020
19. Becky Sullivan and Nick de la Canal. NPR. "What We Know About the Attack on Two North Carolina Power Substations." December 2022. https://www.npr.org/2022/12/05/1140775417/north-carolina-substation-attack-what-we-know
20. PGE. Wildfire Outages and PSPS (Public Safety Power Shutoffs). (accessed 17 May 2023) https://portlandgeneral.com/outages-safety/wildfire-outages
21. Russell Gold and Katherine Blunt. *The Wall Street Journal*. "PG&E's Radical Plan to Prevent Wildfires: Shut Down the Power Grid." April 2019. https://www.wsj.com/articles/pg-es-radical-plan-to-prevent-wildfires-shut-down-the-power-grid-11556337671
22. Chuck Brooks. Forbes. "3 Alarming Threats to the U.S. Energy Grid–Cyber, Physical, and Existential Events." February 2023. https://www.forbes.com/sites/chuckbrooks/2023/02/15/3-alarming-threats-to-the-us-energy-grid--cyber-physical-and-existential-events/?sh=69156856101a

23. National Renewable Energy Laboratory, *ResStock*. https://resstock.nrel.gov/
24. We Energies (Wisconsin Electric Power Company). 2023 Electric Rates. (accessed 18 May 2023) https://www.we-energies.com/pdfs/etariffs/wisconsin/electric-rates.pdf
25. NREL (National Renewable Energy Laboratory). *Cambium*. (accessed 22 May 2023). https://www.nrel.gov/analysis/cambium.html
26. NREL (National Renewable Energy Laboratory). *Cambium: Scenario Viewer*. (accessed 22 May 2023) https://scenarioviewer.nrel.gov/
27. IEA (International Energy Agency). "Unlocking the Potential of Distributed Energy Resources." May 2022. https://www.iea.org/reports/unlocking-the-potential-of-distributed-energy-resources
28. 28. David Chandler. *MIT News*. Minimizing Electric Vehicle's Impact on the Grid." 15 March 2023. https://news.mit.edu/2023/minimizing-electric-vehicles-impact-grid-0315
29. US DOE. Energy Star. *Energy Star Impacts*. (accessed 22 May 2023). https://www.energystar.gov/about/impacts
30. US DOE. Office of Energy Efficiency and Renewable Energy: Building Energy Codes Program. DOE Building Energy Codes Program Infographics. (accessed 30 June 2023) https://www.energycodes.gov/infographics
31. Phius. *Passive Building Principles*. (accessed 26 May 2023) https://www.phius.org/passive-building/what-passive-building/passive-building-principles
32. US DOT. "Charger Types and Speeds." (accessed 26 May 2023) https://www.transportation.gov/rural/ev/toolkit/ev-basics/charging-speeds#:~:text=Level%201%20chargers%20can%20take,%2C%20workplace%2C%20and%20public%20charging
33. EERE. 2017. "Confronting the Duck Curve: How to Address Over-Generation of Solar Energy." October 2017. https://www.energy.gov/eere/articles/confronting-duck-curve-how-address-over-generation-solar-energy
34. US DOE. "A National Roadmap for Grid-Interactive Efficient Buildings." May 2021. https://gebroadmap.lbl.gov/
35. NASEO (National Association of State Energy Officials). *Grid-Interactive Efficient Buildings: State Briefing Paper*.
36. ASHRAE. 2020. *Smart Grid Application Guide: Integrating Facilities with the Electric Grid.* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA.
37. Jason Svarc. Clean Energy Reviews. "Bidirectional Chargers Explained-V2G vs V2H vs V2L." 10 April 2023. https://www.cleanenergyreviews.info/blog/bidirectional-ev-charging-v2g-v2h-v2l
38. Vagelis Vossos, Karina Garbesi, and Hongxia Shen. "Energy Savings from Direct-DC in U.S. Residential Buildings." *Energy and Buildings*. Vol. 68, Pt.A. 2014.
39. Dan Ton and Merrill Smith. 2012. "The U.S. Department of Energy's Microgrid Initiative," *The Electricity Journal*. (accessed 5 October 2022) Reprinted at: https://www.energy.gov/sites/prod/files/2016/06/f32/The%20US%20Department%20of%20Energy%27s%20Microgrid%20Initiative.pdf
40. Gartner. 2022. "Gartner Glossary: Microgrid." (accessed 5 October 2022) https://www.gartner.com/en/information-technology/glossary/microgrid
41. Juan Rey, Pedro Vergara, Javier Solano, and Gabriel Ordóñez. 2019. "Design and Optimal Sizing of Microgrids" in *Microgrids Design and Implementation*. https://doi.org/10.1007/978-3-319-98687-6_13
42. IEEE. 2011. IEEE Standard 1547-4: *IEEE Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems.*
43. AIA. 2022. "AIA Awards Research Grants to Advance Climate Action." 3 March 2022. https://www.aia.org/press-releases/6481390-aia-awards-research-grants-to-advance-clim
44. AIA. *AIA Upjohn Research Grant Initiative*. (accessed 27 May 2023) https://www.aia.org/pages/11911-aia-upjohn-research-initiative-grant
45. Elisa Wood, Microgrid Knowledge. 2018. "Farewell to "If You've Seen One Microgrid, You've Seen One Microgrid" https://www.microgridknowledge.com/editors-choice/article/11430180/farewell-to-if-youve-seen-one-microgrid-youve-seen-one-microgrid
46. Energy Networks Aotearoa, Microgrids. 30 June 2022. https://www.poweringup.org.nz/charging-electric-vehicles/fact-sheets/microgrids/`
47. National Renewable Energy Laboratory (NREL). ResStock: Highly Granular Modeling of the U.S. Housing Stock. https://resstock.nrel.gov/
48. International Code Council (ICC). 2021 International Energy Conservation Code (IECC). Chapter 4 [RE]--Residential Energy Efficiency, Section R402--Building Thermal Envelope. https://codes.iccsafe.org/content/IECC2021P1/chapter-4-re-residential-energy-efficiency
49. Phius. Phius 2021 Performance Criteria Calculator. https://www.phius.org/phius-2021-performance-criteria-calculator
50. Fraunhofer Institute for Building Physics. WUFI Passive (Wärme Und Feuchte Instationär). https://wufi.de/en/software/wufi-passive/
51. Phius. Phius Core Prescriptive Snapshot. https://www.phius.org/phius-core-prescriptive-snapshot
52. Phius. Phius Core Prescriptive 2021 Checklist. https://www.phius.org/phius-core-prescriptive-2021-checklist
53. National Renewable Energy Laboratory (NREL). BEopt: Building Energy Optimization Tool. https://www.nrel.gov/buildings/beopt.html

54. National Renewable Energy Laboratory (NREL). REopt: Renewable Energy Integration and Optimization. https://reopt.nrel.gov/
55. National Renewable Energy Laboratory (NREL). URBANopt: Advanced Analytics Platform. https://www.nrel.gov/buildings/urbanopt.html
56. National Renewable Energy Laboratory (NREL). Cambium. https://www.nrel.gov/analysis/cambium.html
57. HOMERSoftware. HOMER Grid: Distributed Generation (Hybrid Optimization of Multiple Energy Resources). https://www.homerenergy.com/products/grid/index.html
58. HOMERSoftware. HOMER Pro: Standalone Microgrids (Hybrid Optimization of Multiple Energy Resources). https://www.homerenergy.com/products/pro/index.html
59. US Department of Energy (DOE). Building Energy Codes Program–Prototype Building Models. https://www.energycodes.gov/prototype-building-models#Residential
60. US Environmental Protection Agency (EPA). AVoided Emissions and geneRation Tool (AVERT). https://www.epa.gov/avert
61. National Renewable Energy Laboratory (NREL). Long-run Marginal Emissions Rates for Electricity: Workbooks for 2021 Cambium Data. https://data.nrel.gov/submissions/183#:~:text=The%20LRMER%20is%20an%20estimate,years)%20change%20in%20electrical%20demand