Energy Resilience:

Critical Load Support in Commercial and Residential Applications

Efficiency Vermont R&D Project: Resilience Investigations

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Executive Summary

Efficiency Vermont's energy resilience research portfolio consists of three independent investigations into materials and methods for increasing energy resilience in commercial and residential settings. The projects cover:

1. A DC microgrid community,
2. Phase change materials (PCMs), and
3. A residential energy thermal resilience analysis.

Each study is a multiyear effort beginning in 2021 and continuing through 2022, building on the efficiency resilience return on investment research from 2020. Each study focuses on a technology and its energy resilience impacts as well as coincident improvement in system energy efficiency. This progress report offers study updates for design and construction industry professionals and regulators interested in advancing resilience through energy efficiency projects.

DC MICROGRID COMMUNITY

In 2021, the team substantially completed the design phase for a direct current (DC) electrical distribution and microgrid system in an income-qualified development. As this will be a community-based system, the project owner needed to make decisions about what would constitute energy resilience for the community and determine acceptable means of sharing energy among the homes.

The design team encountered product availability and infrastructure challenges because existing residential systems are not typically designed to operate in a DC environment. Most household devices are developed to be used in the alternating current (AC) grid.

Upon construction completion in 2023, system designers expect the project to provide energy to critical loads during a power outage while offering grid support services during normal operation. It will also deliver more solar energy to end uses than a comparable AC system because it will have fewer inverters in the system.

PHASE CHANGE MATERIALS

PCMs improve heating system efficiency by releasing stored heat into a space so the system can lengthen cycle times and reduce total operating hours. As a heat storage medium, it can support space temperature during a power outage, making it a viable component of an energy resilience system. The team designed PCM installations at two sites in 2021 to demonstrate passive and active PCM integration. The study will evaluate each site's heating systems performance to determine whether they operate more efficiently with the PCMs integrated and assess the impact of the PCMs on space temperature maintenance. PCM manufacturers claim an average of 25% heating system efficiency improvement, and the team expects to find similar performance improvements in these systems.

RESIDENTIAL ENERGY THERMAL RESILIENCE ANALYSIS

Vermont's housing stock is old relative to that of other states, and many existing homes' energy performance is not as robust as a new home's performance would be. The residential energy resilience study uses OpenStudio modeling with field calibration samples to correlate airtightness and temperature decay, allowing building owners to estimate how long occupants can comfortably ride through a power outage. The study will further investigate homes with radiant slabs to determine the impact on interior temperature resilience when occupants preheat the slab in anticipation of a power outage or demand response event by raising the space temperature setpoint ahead of the expected event. In 2021, the team developed the energy model and began collecting field data via smart thermostats and temperature loggers. The results of this research may be used to optimize thermal shell improvements in existing and new home construction for indoor temperature resilience and to estimate the thermal storage potential of select homes in Vermont.

MEETING CARBON REDUCTION AND ENERGY EFFICIENCY GOALS

Collectively, these studies provide insights into viable, cost-effective opportunities for energy resilience and carbon reduction. Results from this work will arm Vermonters with local experience and reliable data for making science-based choices about where to invest limited resources to achieve energy security and meet greenhouse gas reduction goals. As Vermont implements recommendations from the Vermont Climate Council and prepares Vermonters for the worst effects of climate change, these investigations will complement efforts to help minimize and mitigate the social and economic impacts on citizens of this vibrant state.

Introduction

Energy resilience is a set of assets and a plan to meet the minimum energy needs to protect life and property during an outage. More frequent extreme weather events and increasing energy costs are driving consumers to explore ways to take control over their energy assurance.

As the electrical grid evolves to expand macro- and include micro-power generation, stakeholders may use site-specific energy storage and distribution resilience strategies to manage grid operations and reduce peak load demand.

In 2020, Efficiency Vermont developed formulas and variables for determining the best return on investment in energy resilience assets.[1] This 2021 portfolio of studies applies the 2020 research to three independent investigations into materials and methods of increasing energy resilience in commercial and residential settings spanning simple, inexpensive options to large capital projects. The projects include:

1. A DC microgrid community,
2. Phase change materials, and
3. A residential energy thermal resilience analysis.

Each study is a multiyear effort beginning in 2021 and continuing through 2022 and offers Vermont-based experiences in designing and implementing energy resilience technologies applicable to the design and construction industry at large. Each of the studies is unrelated to the others, however, once their energy impacts are better understood, there may be opportunity to further explore their integration.

Microgrids, phase change materials, and home batteries are beginning to enter the market and garner attention for their potential energy savings, energy assurance, and financial benefits. As new technologies, they offer limited field data for owners to determine whether the investment will lead to long-term cash-positive benefits. These studies are designed to provide information that support Vermonters in determining whether employing these systems will support their energy goals and give them confidence in the investments they make.

[1] Ross, Allison, "Energy Resilience Return on Investment," Efficiency Vermont R&D Program Report, 2020.

Direct Current Microgrid

In the late 19th century, Thomas Edison and Nikola Tesla engaged in a battle to see their direct current (DC) and alternating current (AC) electrical systems, respectively, become the dominant electricity delivery system. Edison's direct current started strong in the New York City area, but Tesla's alternating current voltage could be increased or decreased, enabling it to travel long distances. For these reasons, today's electrical infrastructure uses AC.

Anything that operates on a battery uses DC. For example, cell phone and laptop chargers have a converter in order to be powered by a wall outlet with AC power. Electric vehicle batteries supply DC and must convert AC power at the charging source to charge the battery. Today, due to their battery integration, the majority of small electronics require DC, which means the AC delivered to homes and businesses must be converted to DC for use in the device.

Renewable energy sources such as wind and solar produce electricity in DC and are typically converted to AC using an inverter for distribution or on-site power use.

Every time power is converted from AC to DC or vice versa, some energy is lost. Limiting the number of conversions can increase the amount of renewable energy delivered to the end use. DC microgrids can significantly reduce the number of power conversion units and their size, which benefits the overall system's reliability and costs. This has implications for society's efforts to reduce greenhouse gas emissions by allowing more renewable energy production to be used rather than lost in the system. One project is planning to lower greenhouse gas emissions using a resilient microgrid while also offering affordable, comfortable homes to residents.

Randolph Area Community Development Corporation (RACDC), an affordable housing and community development nonprofit organization, is developing a brownfield into a community of income-qualified homes for sale and rent. This development, Salisbury Square, will consist of nine homes and eight apartments, all of which will be served by a DC community microgrid.[2] The microgrid will provide optimal efficiency, help lower the cost of energy for residents, and meet RACDC's energy resilience requirements, which include two days of islanded capability.[3] The microgrid will have photovoltaics and batteries, which will serve homes that have as many systems as possible operating on DC. To also accommodate plug loads that are currently available only for AC, builders will wire the homes for both DC and AC.

In 2021, progress moved from schematic design to iterative bidding and negotiation. The design team expects construction to start in the fall of 2022. As noted above, although DC electricity has existed since the beginning of widespread electricity use, today's infrastructure and systems are still made to run on AC. This makes choosing a DC system out of the ordinary, presenting challenges the design team had to overcome. The resulting learnings add up to a valuable set of

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[2] A microgrid is a self-sufficient energy system that serves a discrete geographic footprint, typically with the ability to connect to the traditional grid when not operating autonomously.

[3] Islanding is the ability of a microgrid system to automatically disconnect from the electrical grid and provide power to designated loads.

tools that can make future DC developments easier to design and develop both viably and cost-efficiently.

DEFINING RESILIENCE

A microgrid design depends on the owner's requirements, including details about how the owner would like to use the microgrid. Julie Iffland, executive director of RACDC, determined the microgrid should provide support for critical loads during a grid outage of two days. The town of Randolph's experience during Hurricane Irene in 2011 set the benchmark for a significant event causing a prolonged outage.

Critical loads are defined as assets that support life or property within the community. Those loads at Salisbury Square will include refrigeration, selected lighting, HVAC adequate to maintain safe temperatures, and a vehicle charger to allow residents to travel if necessary. The RACDC community building will serve as a shelter for the broader town to provide warming and basic power outlet access for charging cell phones and powering medical devices.

OWNERSHIP STRUCTURE

Asset ownership structure decisions impact details in the planning, development, and economics of the microgrid system. The microgrid can have a single owner responsible for operation and maintenance, or it can be divided among multiple owners with an agreement outlining responsibilities and benefit sharing. Vermont law does not allow RACDC to charge residents for electricity use unless it is a campground, which would present challenges for ensuring all residents are responsible for paying for their own electricity use. In the Salisbury Square community structure, the utility, Green Mountain Power (GMP), will own the meters, wires, batteries, and other storage components. RACDC and the property owners will own the equipment associated with delivering electricity within the home.

GMP will be responsible for microgrid equipment operation and maintenance and will have access to the storage system to manage grid load, including having the ability to island the community to remove load from the grid.

Some aspects of the ownership structure are still unresolved. Because this is a novel development, no existing rate structure fits this case, so it is unclear whether the community could participate in a flexible load management structure or electric vehicle rate structure. GMP and RACDC are determining the full division of ownership, delineating which assets or equipment fall within RACDC's responsibility.

SHARED ENERGY

Storage distribution within a microgrid can depend on many factors, such as space, climate, local regulations, and cost. When a microgrid can be islanded to serve critical loads during an outage, it raises the question of how to equitably share stored energy among residents.

Salisbury Square evaluated methods to define storage access, including whether to define it in a community charter or bylaws so residents would know how much energy they could access.

Design team discussions centered on storage siting, maintenance access, and capital costs. Having distributed batteries in each home would address the issue of storage sharing, because each home could access the energy stored in its own battery. However, the batteries would take up space in the small basements, and maintenance would be more invasive because GMP would need to get into homes to perform service. Larger, centrally sited batteries would have lower capital costs than distributed batteries sited within each home. Centrally located batteries would also be easier to access and easier to maintain because they would be in common areas with fewer individual batteries.

The design team found that a centralized system would be better able to connect to the hybrid AC/DC distribution system within the microgrid and chose to move forward with a centralized approach. The overall costs of the centralized design and the need for the utility owning the storage to access the batteries were the factors that outweighed the advantages of the distributed system. The development will site the batteries in three pods located at different points in the community.

AC VERSUS DC DISTRIBUTION

The design team settled on a hybrid AC/DC distribution system for the microgrid. The AC/DC backbone provides assurance to residents who want to know that their AC-based plug-in devices will work in their home, and it offers assurance that any future equipment can be installed using the traditional AC or innovative DC. The team considered including both AC and DC wiring at appliance connections to allow residents to install AC appliances in the future if they chose, but for reasons of simplicity and cost, the design will only include a DC connection where DC appliances are installed during construction.

DC ELECTRICAL PANEL

The design team found that procuring an electrical panel for a residential DC system would be challenging. DC panels exist for industrial applications, but these are significantly oversized for residences. Similarly, DC panels used in recreation applications such as RVs and boats are undersized for residences. The team reached out to panel manufacturers and other professionals to identify a manufacturer willing to provide a residential sized panel.

The electrical engineer will pair the DC panel with a digital electrical system[4] designed in partnership with Voltserver, a digital electricity technology developer. Digital electricity allows an end use to safely draw line power without the use of a panel. An installation must include a plan to effectively lay more wiring than would be typical in a system with an electrical panel

[4] Digital electrical systems push DC power out in "packets" via transmitters and receivers, similar to how data are transmitted in networks. This allows high-voltage pulses to travel over low-power cable such as ethernet.

since each load has its own wire that runs back to the electricity source. Identifying loads that will be wired to the panel versus using the digital system is still in progress.

APPLIANCES AND MECHANICALS

To maximize the efficiency of the solar energy and the microgrid, the design team wants to ensure that as many of the systems and as much of the equipment in the community as possible can operate on DC. The team had discussions with HVAC and appliance manufacturers to learn what products were in development, what was ready for field deployment, and which manufacturers could commit to providing equipment. Zehnder will provide a ComfoAir 200 energy recovery ventilator compatible with DC. LG will provide the batteries for the three energy storage pods that will make up the battery energy storage system. Both LG and General Electric could provide appliances and some HVAC equipment. General Electric makes RV-sized DC appliances that the company could repurpose for residential applications. LG has DC-capable washers and ventless dryers, dishwashers, oven ranges, and ducted cold climate heat pumps. Rheem and LG are both considering their ability to provide DC water heaters.

CONTRACTORS

Contractor engagement and communication has presented some challenges. One general contractor submitted a bid that was 20% higher than the typical costs of local zero-energy modular construction. Due to unfamiliarity with the DC design and what is required, the contractor did not have the experience to accurately estimate what would be required on site and price it accordingly. The team found that many unneeded items were included in the bid and other items were included twice.

Pricing from modular manufacturers to wire the structures for DC is an open item.

The project will require an electrician with the skills and knowledge to work with a higher-voltage DC system and the equipment connected to it, as well as skills with digital versus traditional copper wiring. A communications system installer may be better equipped to install the digital system because it is similar to how communications wiring is installed. The team may also look to train a contractor to do the installation.

REGULATORY

The project is entering uncharted territory; no public utility commission guidance exists for interconnecting a DC system. RACDC would like residents to be responsible for their own electric bills, so there is continuing discussion about how to meter each residence within a community microgrid that has shared solar energy production and shared energy storage. GMP does not have an existing rate structure encompassing electric vehicle charging, net metering, storage that can provide grid services, and individually metered homes. RACDC, the design team, and GMP will need to find answers to their questions about equitable sharing and allowable metering and billing.

COSTS

Cost comparisons have informed design decisions. Incremental costs between AC and DC appliances are still unknown. In partnership with GMP, the team developed cost estimates for an AC community, a DC community, and the chosen hybrid community. Modeling in URBANopt[5] and REM/Rate[6] indicates that residents can expect a 10% energy cost benefit from the DC power integration as compared with the same home with AC power only.

As mentioned previously, capital costs and maintenance costs are lower for the centralized battery storage system.

The URBANopt modeling work identified that the battery size necessary to meet the island time requirement exceeded the budget. The design team is determining whether phase change materials[7] integrated into the Passive House–level building shells could permit removal of the heat pumps from the backup power requirement in order to reduce the battery system size and cost.

Further cost questions with respect to operation and maintenance remain to be answered as the ownership model becomes better defined.

NEXT STEPS

The design team will finalize the microgrid design, and RACDC will pursue funding opportunities for implementation. The housing structures themselves will move forward with construction in 2022, and the microgrid will undergo construction as the funding comes together. The owner and the designers will monitor system performance once it is online to evaluate how it is working and whether it is realizing the modeled energy savings estimates.

[5] URBANopt is a modeling tool developed by the National Renewable Energy Laboratory (NREL) for high-performance buildings and energy systems located within one geographically cohesive area. NREL staff supported the URBANopt modeling for this project. https://www.nrel.gov/buildings/urbanopt.html
[6] REM/Rate™ is a modeling software developed by NORESCO, LLC. for home energy modeling.
[7] See Phase Change Materials section of this paper.

Phase Change Materials

The most familiar material that changes phases is water. Liquid water becomes ice in a freezer or snow in winter. It evaporates from the washing on a clothesline and from dew on the grass in mid-morning. Water requires energy transfer to shift between these phases, and the process can be harnessed. For example, a steam boiler transfers heat energy from steam into a space, resulting in the steam condensing back to a liquid.

Water changes phases from ice to liquid (or vice versa) at 32 degrees Fahrenheit (F) or 0 degrees Celsius (C). The phase-change temperature of water can be altered with the addition of other materials, such as salt or alcohol. Alcohol-based antifreeze circulating in a car prevents water from changing into ice at the typical freezing temperature. Phase change materials (PCMs) use the concept of shifting between solid and liquid to capture and store energy to release later.

Recent developments are bringing new PCM products to market. NASA has been working with PCMs to advance space exploration, including as heat sinks in spacecraft to absorb excess heat, in lunar vehicles, and in space suits.[8] Research into PCM applications and configurations is ongoing, involving paints designed to protect aircraft components from heat damage or maintain cabin comfort, food storage containers,[9] refrigeration systems,[10] heating and ventilation systems, and clothing. PCMs can be purchased in the form of tiles or blankets; they can be found within a tank or 3D printed to accommodate many uses.

PHASE CHANGE MATERIAL PROPERTIES

PCMs work by taking advantage of the latent heat of the material to absorb heat from or release heat into the system. When materials change phase, they go through a stage of maintaining their temperature while absorbing or releasing energy to go through the change. Water, for example, when reaching 0 degrees C (32 degrees F), will require about 80 calories of heat to melt one gram of ice before the temperature begins to rise above 0 degrees C.

PCM manufacturers offer materials with varying chemistries to meet the temperature transitions unique to each application. They can manufacture tiles or blankets to work in spaces heated to 70 degrees F or for a setpoint of 68 degrees F, and the materials in the two products will be formulated to melt and solidify at the specified temperatures.

PCM chemistries can be either organic or inorganic materials. Inorganic PCM materials are salt hydrates. They have high latent heat values, are non-flammable, and are relatively low in cost and readily available. However, they can be corrosive, unstable, and subject to decreased storage density with cycling. Organic PCMs are more chemically stable with more favorable

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[8] Quinn, Gregory, Ed Hodgson, and Ryan Stephan. "Phase Change Material Trade Study: A Comparison between Wax and Water for Manned Spacecraft." Paper presented at the International Conference on Environmental Systems, Portland, Oregon, January 2, 2011. https://ntrs.nasa.gov/api/citations/20110010960/downloads/20110010960.pdf.
[9] "Phase-Change Coating Absorbs Heat from Rockets, Pipes, Beer." *NASA Spinoff*, 2019. https://spinoff.nasa.gov/Spinoff2019/ip_7.html.
[10] Morlino, Lauren, et al. "Phase Change Materials in Refrigeration." Efficiency Vermont, 2021. https://www.efficiencyvermont.com/Media/Default/docs/white-papers/PCM-Report.pdf.

storage capacity maintenance over cycles. They are flammable, however, and some manufacturers are evaluating methods of reducing this risk.[11]

BUILDING RESILIENCE

PCMs have the potential to provide benefits beyond saving heating energy. A core tenet of energy resilience is that energy that is not needed cannot be disrupted and does not need a backup. If PCMs can reduce the energy needed to operate HVAC equipment, homes and businesses can maintain comfortable space temperatures longer without adding heat. As explored in "Phase Change Materials in Refrigeration,"[12] PCMs could keep food safe longer and reduce frequency in cooling cycles, saving energy and preventing losses due to spoiled food. As discussed in the DC microgrid study, PCM is being modeled in homes in a neighborhood to determine whether the PCM will allow the space temperature to float long enough so that the heat pumps will not need backup power support. If it proves out, the backup power system can be downsized, resulting in lower capital costs and a smaller, easier- to- maintain system.

ESTIMATED PERFORMANCE

Two manufacturers of PCM tiles, blankets, and tanks for building heating and cooling integration claim an average of 25% HVAC efficiency savings compared with having no PCMs (Figure 1).[13,14] Insolcorp and Phase Change each manufacture a tile designed for both retrofit applications above a drop ceiling and installation behind sheetrock in walls or a ceiling. They also offer tanks of PCM that can be integrated into a heating or cooling system loop to realize similar efficiency improvements. If their claims prove to be accurate in the Vermont climate, using PCMs could be a compelling measure for achieving cost-effective energy savings. The tiles cost roughly $3 per square foot and at least 60% of the heated square footage must have tile coverage to realize the product benefit.

Methodology	# of Sites	% Coverage	Adjusted R^2	% HVAC Diff	% Whole Building Diff	Conditioned Space (sf²)	kWh Diff / sf²
HVAC isolation (multi-variable regression)	20	65%	83%	25.1%	8.5%	3,718	2.73
15-minute utility interval (Multi-variable regression)	77	62%	95%	24.3%	6.9%	4,323	1.96
Monthly Utility (DD per kWh)	457	62%	-	29.6%	10.4%	4,061	3.50
Combined	**554**	**62%**	**92%**	**28.7%**	**9.9%**	**4,085**	**3.25**

Figure 1: Manufacturer testing data for PCM tiles. Data courtesy of Phase Change.

MONITORED PERFORMANCE

This case study evaluates the energy and cost performance data of installed PCMs at two testing sites in Vermont and identifies potential resilience benefits from the applications.

[11] "Phase Change Materials for Thermal Energy Storage." UN Environment Programme: Climate Technology Centre & Network, accessed October 25, 2021. https://www.ctc-n.org/technologies/phase-change-materials-thermal-energy-storage.
[12] Morlino, Lauren, et al. "Phase Change Materials in Refrigeration."
[13] Mick Dunn of Insolcorp, discussion with author, March 23, 2021.
[14] Jason Baker of Phase Change, discussion with author, February 17, 2021.

Site 1, Mann and Machine Auto Repair in Richmond will install Insolcorp manufactured phase change tiles above the drop ceiling. The approximately 1,000-square-foot office space will employ 600 square feet of PCM tiles. Site 2, the Woodstock Emergency Services building, will install a Phase Change manufactured PCM tank in the heating loop that serves a new addition. These two sites will evaluate, respectively, the HVAC efficiency impacts on the small propane boiler at Mann and Machine and the air-to-water heat pump efficiency impacts at the Woodstock Emergency Services building. The data will encompass a fossil fuel system and an electrically powered system to show how the different PCM applications perform in these systems.

NEXT STEPS

The projects will install the PCM tiles and tank with monitoring equipment in late 2021. Existing and post-installation indoor air temperature and weather-normalized performance data will be compared for Mann and Machine Auto Repair to determine whether the boiler operates more efficiently when paired with the PCM tiles.

The study will compare indoor air temperature and weather-normalized performance data from the Woodstock system with the PCM tank in operation with similar heat pump performance data without PCM, and with modeling, to determine energy and comfort impact.

Study results will inform potential research expansion exploring the roles PCMs may play in scalable decarbonization measures.

Residential Space Temperature

One in four homes in Vermont was built before 1939, and the state's rental housing stock is, on average, older than owner-occupied housing. Approximately 25% of housing units in the state are rental units.[15] Renters do not own the building or its systems and usually cannot alter them even if they do have the financial resources. This dynamic creates a disconnect between the party financially responsible for the building and its systems and the party experiencing daily life within the structure.

Given that a quarter of homes were built before air-sealing and insulation measures were commonplace, many homes do not meet the current Residential Building Energy Standards (RBES) for maximum air leakage of three air changes per hour (ACH). A leaky home's most immediate consequences are higher-than-necessary heating and cooling costs and uncomfortable drafts; less obvious impacts include poor indoor environmental quality and ice damming.

Additionally, leaky building shells lower home resilience during severe weather and power failures due to increased heat loss in winter and heat gain in summer. Installing new equipment to enable energy resilience requires planning and an adequate budget. Common considerations include power generation and storage, heating and cooling systems, water supply, and critical loads like refrigeration, medical devices, and communication. The building shell has direct effects on every other system in the home and provides a reasonable-cost opportunity for improving building resilience.

HEAT LOSS

A building's air-sealing level has the most significant impact on heat loss, so understanding the relationship between the air-sealing level and the space temperature float time will provide occupants with an understanding of how long they can sustain comfort during an outage. According to Green Building Advisor's Peter Yost and Martin Holladay, although insulation is important and necessary, air sealing is the single most important way to keep building comfort and energy use in check.[16] Tighter buildings hold heat longer and allow for a smaller, simpler, and cheaper heating system. When a heating system cannot operate due to a power failure, heat remains in the building longer, keeping occupants comfortable and keeping supplies, such as food and medicine, safe.

Heat loss through building shell leakage in winter for a home that meets the residential energy code can be estimated using heat loss calculations, which can provide a ballpark estimate for temperature drop duration. Efficiency Vermont projects offer anecdotal stories from tight

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[15] State of Vermont Agency of Commerce and Community Development. "Vermont Housing Needs Assessment: Housing Stock."
https://accd.vermont.gov/sites/accdnew/files/documents/Housing/Fact%20sheet%203%20Housing%20stock.pdf.
[16] Gibson, Scott, "What's More Important, Air-Sealing or Insulation?" Green Building Advisor, August 25, 2014.
https://www.greenbuildingadvisor.com/article/whats-more-important-air-sealing-or-insulation.

buildings that experienced a heating system failure but remained comfortable enough that no one noticed for a few days. The residents in these buildings could remain in place and stay comfortable for a long duration outage. Homeowners interested in weatherization projects can take temperature float time into account when planning a project to get as close to their energy resilience goals as their budget and capacity for retrofit work allow. The energy resilience benefit can complement the energy and cost savings owners will achieve when improving the building shell.

THERMAL STORAGE

Installing equipment to enable energy resilience requires planning and an adequate budget. Renters are unable to change the systems since they do not own them. Homeowners must be willing to conduct a large project that includes significant capital costs and disruption to the home.

Using existing components of the building structure, it may be possible for occupants to realize some degree of energy resilience in the event of an anticipated power outage such as when a major storm is forecast. One such component is a radiant slab heat distribution system. Homes using a radiant slab heat distribution system may be able to "precharge" the concrete temperature to allow the space temperature to float longer through an outage when the heating system is offline.

ASHRAE 90.1-2019 details heat capacity for concrete. Heat capacity is the product of mass per unit area and specific heat. In Table A3.1-2, ASHRAE indicates that six inches of concrete at a density of 20 pounds per cubic foot has a heat capacity of 2.0 Btu/ft^2 * F up to a density of 144 pounds per cubic foot at 14.4 Btu/ft^2 * F.[17] Homes that use a radiant floor to heat portions of the building are effectively using the heat capacity of the concrete to store and transfer heat to the space. The heating system heats the concrete so that it can then transfer the heat into the space.

Given the large thermal mass in the concrete and the heating source running through it, this system may offer thermal storage opportunities to enhance energy resilience. When a weather event that may cause a power outage is in the forecast, occupants can increase the temperature setpoint to raise the concrete temperature. If power is lost and the heating system is not operational, the concrete will have stored heat energy that it can release into the space as the temperature drops, prolonging comfort while the system cannot add heat.

MODELING AND FIELD EVALUATION

Researchers will model a theoretical home in OpenStudio to create a data set highlighting the relative space temperature float times correlated to changing indoor temperature, outdoor temperature, and air-sealing levels; this will show the extent to which thermal energy resilience

[17] American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. "Energy Standard for Buildings Except Low-Rise Residential Buildings." ASHRAE; 2019. (90.1-2019). https://www.ashrae.org/technical-resources/bookstore/standard-90-1.

changes in tighter versus leakier buildings. To support model calibration, a handful of existing homes will be equipped with smart thermostats. Occupants will be asked to precharge their space temperature and then simulate a power outage by setting their temperature back. The time it takes for the temperature to drop will be measured and associated with the home's air-sealing and insulation levels. Some of the study homes will have radiant slab heating. Researchers will use the data from those homes to inform a slab's capacity to serve as a thermal battery.

The study will collect data via a smart thermostat and temperature sensors in the homes. In addition to temperature measurements, the thermostat will capture how often and how long the HVAC system operates when there is a call for heat.

NEXT STEPS

Study participants will conduct the temperature adjustments during the heating season. The data on their homes' performance will calibrate the theoretical home model. Once it is calibrated, energy modelers will use it to develop an analysis of how temperature float times correlate to air sealing. This will provide a framework for occupants to understand how long their homes will remain comfortable during a power outage and provide some estimates for measures that might increase the time duration.

Conclusion

These three studies will continue into 2022, and they will provide data to support or refute some of these theories. As the data begin to offer insight into viable, cost-effective paths toward energy resilience, Vermonters will be better armed to make knowledge-based choices about where to invest limited resources to achieve a measure of energy security.

If society is to adapt and live with a changing climate, it cannot advance solutions that only the most well-off can afford. The best solutions will be affordable and accessible to communities, local governments, and individuals. As these investigations move into 2022, their data will be used to recommend ways in which they can be accessible to everyone so that all Vermonters can contribute toward a resilient Vermont and reap the benefits of resilience in their daily lives.

Emerging technologies entering the market are offering promising opportunities for society to take action now to reduce carbon emissions and adapt to a changing climate. As these projects develop, they will help provide the data necessary to move the state in the best direction to prepare for the worst impacts and ensure all Vermonters can continue to prosper for generations to come.