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STORING ELECTRONS

An Analysis of the Role of Long-Duration Energy Storage in a Decarbonized, Economical, Equitable, Resilient Electricity System

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Preface

We are in the midst of a complex transition from a fossil-fuel-centered energy system to a decarbonized one. Such a transition involves moving away from primary energy sources that can be mined and stored and thus can be switched on and off as needed to mainly solar and wind resources, whose supply is instead controlled by the rhythms of Mother Nature. Predictable to a large extent – yes. But controllable? No.

Achieving a balance between the technical demands of the electricity sector, which necessitate constant supply-demand equilibrium, and the rhythms of Nature, which dictate the availability of solar and wind energy, is a significant challenge. Energy storage will play a major role in addressing this challenge. However, there are several other important considerations. The energy a transition will require careful planning and investments to deal with long droughts of solar and wind supply – especially when considering more frequent and longer-duration grid outages expected due to intensifying climate change. How can we ensure that communities already overburdened with high energy costs and pollution are protected, have more affordable electricity, and a healthier environment?

Energy storage of various kinds and durations will be needed to transition to a decarbonized system in which solar and wind are the main sources of supply. Storage of a few hours using lithium-ion (Li-ion) batteries has already become common – and economical enough in many places that solar energy-plus-Li-ion batteries can replace polluting natural gas peaking generation plants. But storage for days and even weeks will be needed that is beyond the capability of this combination. It will need to be optimized with other elements like distributed solar generation and demand response, on a far larger scale than is practiced in today's electricity system. Assets in the distribution part of the electricity system, including those owned by consumers and other non-utility third parties, will be essential to an equitable affordably and decarbonized electricity system with solar and wind as the mainstays of supply.

Will storage and other elements of the energy transition be squeezed into a business-as-usual, centralized model without adequate consideration of the need for a more resilient, distributed supply that allows essential services in communities to keep functioning during long electricity outages? How will low-to-moderate income and frontline communities benefit from increased resilience? Will the distributed energy facilities that are needed also be zero emissions installations? Will the design and operation of energy storage be coordinated with other resources – notably demand response – in a way that economically benefits and empowers low- and moderate-income (LMI) households – especially the renters among them?

These are vast and difficult questions; this report aims to address them in a limited and specific way as they intersect with long-duration energy storage. By performing quantitative resilience and economic analyses we indicate a direction that will be compatible with the energy, environmental, and economic justice concerns of communities.

Chapter 1 of this report provides a summary of findings and recommendations. Chapter 2 is an overview of the need for energy storage. Chapter 3 provides a short survey of long-duration energy storage technologies. Chapter 4 is an exploration of utility-scale long-duration storage using heuristic calculations. We also illustrate the need for coordinating energy transition elements in order to promote energy affordability and advance energy democracy. This is done by examining the dispatch order of storage and aggregated demand response. Chapter 5 explores one aspect of resilience in a zero-emissions grid – disturbed solar and storage microgrids. Example calculations are performed to estimate the cost of such microgrids used for community resilience in three major cities - Baltimore, Chicago, and New Orleans. Chapter 6 provides a brief survey of the environmental justice and safety issues associated with long-duration storage technologies, including those associated with the mining of materials, production of equipment, and operation of such battery systems.

As with the companion report, *Hydrogen: What Good Is It?*, this report was prepared for Just Solutions. We deeply appreciate the confidence that Just Solutions and its Executive Director, Aiko Schaefer, have placed in the Institute for Energy and Environmental Research (IEER) in asking it to produce this report on such a critical subject. We are also very thankful to the Breakthrough Energy Foundation for funding this work via Just Solutions and to Ani Kame'enui, the Program Officer at Breakthrough Energy. We have benefited from many useful comments and suggestions from members of the Just Solutions Research Collaborative that have materially improved the scope and content of the report. The Research Collaborative was appointed by Just Solutions to develop an environmental justice framework for energy transition technologies and to review the reports being prepared by IEER for Just Solutions as part of the Breakthrough Foundation grant. This report has benefited greatly from a thorough review by Dr. Elena Krieger and from a review of microgrid calculations by Dr. Parick Murphy. However, we alone, as the authors, are responsible for any errors that remain and, more generally, for the analysis, conclusions, and recommendations in this report.

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1. Executive Summary

Storage of electricity has not been a significant issue in the electricity grid of the past. The electrical system imperative that supply and demand must be exactly balanced at all times – with only small and short transients when loads are switched on and off – has historically been met by "spinning reserves" like a car that is idling and ready to go. These reserves have mostly been met by gas turbines and, to some extent, by hydropower operating at partial power with spare capacity designated to respond to changes in demand and to grid contingencies, such as a generator going offline in an unscheduled way.

The emissions-free grid that is emerging will, by all accounts, have a major role for wind and solar electricity where the supply is variable and predictable to some extent but is ultimately controlled by Mother Nature rather than a grid operator. Periods of low supply relative to demand must, therefore, be compensated by other means; periods of surplus supply will also need to be managed. Such variability mandates that the storage of electricity will be an essential part of the mix of methods needed to ensure a reliable supply. In fact, we need an electricity system that is reliable and more resilient than the current one as weather extremes become more severe and as the frequency and duration of outages increases. Specifically, maintaining continuity in electricity supply to essential loads during prolonged outages is becoming an increasingly important imperative. In this report, we investigate the role of long-duration energy storage in a grid supplied predominantly by solar and wind energy in creating an electricity system that is not only emissions-free, but also more resilient.

We use the terms "storage of electricity" or "storage of energy" to mean that the input and output energy forms are both electricity; the actual storage could be electro-chemical (as in a battery), thermal (as in heat or cold stored in an insulated cell underground), mechanical (as in hydropower reservoirs or compressed air storage caverns), or chemical (for example, hydrogen). Other forms of output – notably thermal output for building or industrial heating requirements – are also important. We allude to their potential roles in optimizing a decarbonized energy system but do not consider them in detail. We explore the complementarity of demand response (flexibility in the time at which a load is served) and electricity storage, since such flexibility is important to the economic and energy democracy aspects of the energy transition. However, the focus of the analysis in this report is on the role of "long-duration energy storage," characterized by the storage of electricity for 10 hours or more, and primarily on electrochemical and thermal battery storage.

The term "duration" means the time for which a storage system can supply energy at the rated output. For example, a system rated at 10 hours and 5 kilowatts rated capacity would be able to supply a total of 50 kilowatt-hours (kWh) of electric energy. All outputs are in alternating current (AC) capacity, though for technologies such as batteries the output is direct current (DC). An inverter converts the DC to AC.

Historically the dominant form of storage on the grid is pumped hydro but new grid level storage deployment is primarily Lithium-ion ("li-ion") batteries. Today Li-ion batteries dominate the behind the meter market for stationary storage, and have become the dominant battery energy storage technology over the last decade in several economic sectors due major cost reductions and the rapid increase in batteries coupled to solar energy the increase in electric vehicle sales. For instance, Li-ion batteries plus solar are being increasingly built in combination to store energy during the sunniest part of the day and supply power during the high-demand evening hours. Specifically, the development of solar-plus-Li-ion storage is already economical enough in many situations to replace natural gas-fired peaking generation that creates a disproportionate pollution impact on frontline communities; the replacement of which also creates environmental and health benefits.[1]

Although Li-ion will most certainly remain an important and even critical element of the transition to a clean and equitable electricity system, the renewable energy-plus- Li-ion storage system cannot meet all the requirements for a reliable and resilient electricity supply in which wind and solar are the dominant primary sources of supply. Longer-duration storage technologies (up to a few days of storage) as well as very long-duration storage technologies (weeks or months of storage) are also necessary. Li-ion batteries are likely to be too expensive to fill this need, even apart from competing demands for lithium in other sectors like transportation. Moreover, other long-duration storage technologies hold the potential to use more environmentally-friendly materials than Li-ion batteries, thus reducing the overall adverse impacts of a renewables-based electric grid.

Two aspects of long-duration energy storage are explored in detail in this report:

- **Utility-scale long-duration energy storage requirements** in a system that has only solar and wind supply (Chapter 4);[2]
- **Community resilience and long-duration battery systems**' economic and reliability performance for supplying essential loads during prolonged outages (Chapter 5).

For the utility-scale storage exploration, we show with hour-by-hour modeling data that the storage duration and roundtrip efficiency (electricity output from the storage system divided by the electricity input into the storage system) are important, interacting properties of long-duration storage systems. We also demonstrate that long-duration storage combined with procured demand response that is aggregated to be equivalent to a significant utility-scale supply resource can play a significant role in providing households and businesses with tools to make their energy bills more affordable while meeting their energy requirements. We also modeled the economics of ensuring continuous electricity supply through multi-day outages to essential loads like provision of food, fuel, emergency response, emergency shelters, and healthcare to communities.

[1] Krieger, Casey, and Shonkoff 2016

[2] This is also serves as a partial heuristic demonstration that an electricity system with only solar and wind as primary energy sources can reliably serve all loads when combined with storage, demand response, and technologies to serve the remaining loads (such as seasonal thermal storage and fuel cell generation using hydrogen.

Principal findings

1. **Long-duration energy storage systems are likely to be essential** for a reliable, resilient, and affordable energy supply in a decarbonized electricity system with solar and wind as the mainstays of generation.
2. **Different types of storage systems are needed** with durations ranging from a few hours to a few days to several weeks or months.
3. **Long-duration storage must be appropriately combined with other resources**, including distributed resources, to reduce costs and provide opportunities to customers not available in the present centralized system – including distributed generation, distributed storage, and demand response. Optimization of various resources, as well as their dispatch order, will be needed to make the best use of the surpluses of solar and wind energy that will occur seasonally (spring and autumn) and also within any particular day or week.
4. **Community microgrids with long-duration energy storage and solar can greatly increase resilience** and ensure continuity of electricity supply to essential loads during prolonged outages.
5. **Significant technical, regulatory, and legal issues need to be addressed for communities to benefit fully** from long-duration storage, notably to increase community resilience, especially frontline communities and those disproportionately impacted by climate change and environmental injustice.

1.1 Detailed findings

1. **Several new long-duration storage batteries are close to commercialization**: Several long-duration battery storage systems that promise considerably lower cost for storage times of 10 hours or more (up to 100 hours) are expected to be commercially available this decade . Two of the most promising are iron-air ("Fe-Air") batteries, which are designed for 100-hour storage and thermal energy storage with photovoltaic electricity output (TPV) store energy in the form of high-temperature heat and can supply both heat and photovoltaic-generated electricity. While not yet commercialized, they are among the long-duration energy storage technologies projected to have considerably lower costs per unit of energy storage than the present Li-ion batteries (which are generally used for storage times of four hours or less and in electric vehicles) due to their lower-cost material inputs. However, it should be noted that the costs of both Li-ion and redox flow batteries are expected to decrease over the next decade.
2. **Different types of long-duration storage will be needed**: Storage technologies from 10 to 100 hours will be important for both utility-scale storage and the design of zero-emission community microgrids for supplying essential loads during prolonged outages. In addition, multi-day to seasonal storage will be important to meet loads during prolonged periods of low supply, especially as building heating and on-road transportation are largely or fully electrified. These include green hydrogen made from solar and wind electricity that would otherwise be curtailed, seasonal thermal storage, and compressed air storage. (Chapter 4 includes illustrative modeling of hydrogen that might be used for the purpose to illustrate the issue).
3. **Optimization of long-duration storage with aggregated demand response is important for ensuring affordability and promoting energy democracy**: Demand response compensates

customers for shifting their loads from times when resources are scarce to when they are more plentiful. They can be aggregated and offered to grid operators on the same basis as generation and battery storage resources. Demand response can allow some customers, especially those who do not have the capacity or situation to install their own solar or battery resources, to benefit from the energy transition. Aggregated demand response, if dispatched in preference to storage, could also reduce storage requirements and costs.[3]

4. **Apartment building electricity system resilience can be achieved at a modest cost:** Continuity of supply for essential loads like medical devices, refrigeration, and some lighting in medium-sized apartment buildings can be achieved at modest (though not small) cost at present costs of solar and storage, including using Li-ion batteries. Costs will decline as solar-plus-storage systems become more economical due to declines in the cost of Li-ion batteries and emerging energy storage technologies. However, there remains a need for energy storage systems that are as compact or more compact than Li-ion but cheaper; such systems are important for providing more affordable resilience in multi-family apartment buildings.
5. **Solar and long-duration storage can provide community resilience[4] more consistently and at a lower cost than emergency diesel generation**: The standard use of emergency diesel generators to provide energy resilience during long-duration grid outages has only a relatively moderate survival probability[5] and thus may not be operational when needed during an emergency. The use of long-duration energy storage equal to or greater than 24 hours, if coupled with a large solar PV plant, can provide reliable energy resilience for communities during a long-duration grid outage, although such an advantage is diminished in the winter. Generally, solar-plus-storage resilience can be as good or better than traditional diesel-based generation without the pollution and greenhouse gas emissions. The economic performance of solar-plus long-duration energy storage relative to diesel will improve further as solar and battery costs decline.
6. **Emerging long-duration technologies may have better economic performance for community microgrids:** Economic performance is evaluated in this study based on the net present value of system costs and electricity supply benefits. We modeled two emerging technologies – iron-air (Fe-Air) batteries thermal energy storage with PVat costs expected in 2030, and compared them to the projected cost of Li-ion and vanadium-flow batteries in the same year. Fe-Air is closer to deployment for electricity output than TPV. These technologies are still under development. Their costs and when they will be commercially available are uncertain. Fe-air appears to have lower environmental impact due to the use of more abundant materials. The same is also the case of the thermal storage aspect of TPV. The PV aspect involves the use of some toxic materials as is the case for other PV systems as well.
7. **Rates and rate structures are critical parameters in determining microgrid economic performance**: We modeled community microgrids for the continuous supply of critical loads

[3] While not analyzed in this report, demand response and battery storage are but two aspects of a wider demand management and load-shaping effort that is needed as part of the energy transition. For instance, intensified efficiency investments (particularly those directed at reducing summer and winter peaks), coordination of residential level distributed solar and storage resources, and community solar (other than for microgrids) are all part of the broader energy transition but are not covered in this report.
[4] Unless otherwise specified, the terms “electricity system resilience”, “community resilience” and other similar reference to resilience in this report refer to mainly continuous supply of electricity for critical loads in communities.
[5] See Section 5.3.1 for the definition of “survival probability”.

through four-day (96-hour) outages for communities in Baltimore (Maryland), Chicago (Illinois), and New Orleans (Louisiana). Electricity rates and rate structures play a crucial role in determining the economic feasibility of a particular resilience solution. It is, therefore, essential to assess whether such solutions can be adopted without raising energy costs and, in some instances, even result in a reduction of electricity expenses. Energy costs, demand charges, and time-of-use rates all impact the projected costs. For example, time-of-use rates allow for the more economical operation of microgrids. Where tariff structures are unfavorable for resilience economics, they may need to be changed; however incentives may be a preferred way since they could allow community microgrids to be affordable without raising rates, which is especially important for LMI households.

8. **Hospital diesel generators operating within PV and storage microgrids could offer lower costs and higher levels of community resilience**: Hospitals are generally required by regulation (at the state level) to have emergency diesel generators to supply essential hospital loads during outages. The generators operate only during outages (and for testing) and hence not as a microgrid. If a solar-plus-storage community microgrid operated with the hospital's existing diesel generators during outages and as a zero-emissions community solar plus storage with the grid in normal times, a lower cost system that increases hospital capacity to handle patients during outages could be achieved. However, it is important to remember that diesel generators emit pollutants when they operate during emergencies and during required routine testing. But such emissions would occur in any case whether or not there is a community microgrid. A hybrid could be considered in order to increase the capacity of the hospital to handle patients during outages without increasing emissions. This could be done in parallel with efforts to reduce or eliminate hospital reliance on diesel generators whenever possible with the same level of performance during outages.
9. **Policies and regulations that allow key LMI communities to take advantage of community solar with storage to increase community resilience do not currently exist**: There are significant challenges to addressing community resilience by building community microgrids to supply critical loads during outages, and they may vary significantly from location to location. Detailed studies are needed to understand and delineate the infrastructure involved and the technical, business, and regulatory issues associated with increasing resilience across a variety of loads. Direct communication with the impacted community, details on the load characteristics of different facilities, and iteration with the local utility and state regulators are essential. Many states have recognized these challenges, enacted legislation, initiated regulatory proceedings and public consultation about microgrids, including their role in resilience.[6]
10. **It is essential to address safety, environmental justice, and lifecycle environmental impact concerns related to long-duration storage technologies:** Like all new innovations, long-duration energy storage technologies have their own particular safety, reuse, and production concerns. Among the technologies examined, Li-ion batteries generally present the most significant concerns in terms of materials and safety, though the degree of those concerns varies by the specific Li-ion technology. Generally the lower energy density Li-ion phosphate chemistry has a lower level of safety concerns than some higher density chemistries. Other long-duration battery technologies such as Fe-Air, zinc-air, zinc hybrid, Iron-flow, and TPV appear to be safer

[6] Jones et al. 2022

and are less dependent on scarce materials than Li-ion. However, this is subject to a critical caveat that these are not yet mature and most have not yet been commercially deployed at scale to have operational experience comparable to Li-ion batteries. Non-battery technologies like compressed air storage are also safer but they have siting limitations. They are not analyzed in detail in this report.

1.2 Recommendations

1. **Increasing electricity system resilience through microgrids for communities, especially frontline communities and those impacted severely by climate extremes, should be among the highest priorities during the energy transition.**

Distributed renewable energy and long-duration energy storage (up to days) can ensure that essential loads in a community are met without disruption and with high probability and, unlike diesel or natural gas infrastructure, without producing greenhouse gases or other air pollutants. Generally, the loads in a community would consist of multiple facilities, meters, and even loads that may be connected to different feeders; therefore, unlike behind-the-meter microgrids that are "islandable" (can be disconnected from the grid during an outage to operate on behind-the-meter resources alone), community microgrids are generally more complex. In creating such infrastructure, community input should be sought and incorporated for:

- determining what loads are essential to them;
- siting where community renewable energy and storage facilities should be built in their communities; and
- selecting which storage technology to use in order to minimize environmental risks and ensure the highest safety standards.

2. **The federal government should expand community resilience design and demonstration project funding to include the use of long-duration energy storage systems in frontline communities**.
    a. Given the immense potential of community microgrids and the host of difficult issues that need to be resolved to realize them, the federal government should expand its funding of detailed resilience design exercises, as is currently performed at a limited capacity in programs like the DOE's Energy Transitions Initiative Partnership Program (ETIPP)[7] or Renewables Advancing Community Energy Resilience Program[8]. Such expansions should address how to build and operate community microgrids in frontline and LMI communities that include community solar-plus-storage, with consideration for long-duration energy storage technologies, to enable specified resilience capabilities. These efforts should also look at how one can modify state regulations on community solar-plus-storage as well as potential community microgrid tariffs to allow the system to be affordable while increasing resilience. One such detailed design exercise should be done in each climate zone. The efforts should involve the impacted communities, the utilities that own the wires, the state, and a strong microgrid design team. Addressing regulatory issues would be an essential part of each exercise. The designs should include

[7] Energy Transitions Initiative 2023
[8] DOE RACER 2022

consideration of emerging long-duration storage technologies such as Fe-Air, zinc-air, Fe-flow, and TPV. Current uncertainties on state regulations for different types of community microgrids are a major issue; microgrids with multiple meters may even be prohibited in some situations. Addressing technical and regulatory issues of utility ownership of wires and essential loads that are connected to different feeders should be integral to project design. The endpoint of the exercise should be to select a design for implementation as a demonstration project. The set of projects should be diverse enough to be scalable. Selected designs should be implemented as demonstration projects. Creating universal design principles and approaches to regulatory issues and ownership models (including community ownership models) should be one outcome of these exercises to simplify the large hurdles to scalability.

b. We also recommend detailed design exercises for hybrid solar plus long-duration energy storage interoperating with hospital emergency generators to increase community resilience similarly followed by demonstration projects.

3. **Rates, rate structures, incentives, dispatch order of demand response and storage, and the cost of resilience are intertwined issues**. Low rates and/or lack of demand charges may make increasing resilience costly. The automatic answer should not be raising rates as that could impact affordability. Incentives, such as grants to reduce the cost of community microgrids, could be an important part of the answer, especially for frontline and LMI communities. Optimization is not a two-parameter problem. It needs to be done with multiple constraints in the larger context of the electricity transition, including dispatch order of resources, their prices, incentives, affordability, and minimizing greenhouse gas emissions.

4. **Design and dispatch of demand response and utility-scale long-duration energy storage and other resources should be optimized together, preferably with other distributed resources**. Heuristic hour-by-hour modeling of solar plus utility-scale storage indicates that dispatching aggregated demand response in preference to storage can increase electricity affordability and provide opportunities for energy democracy. Most current modeling is not conducive to such optimization. There is an urgent need to develop models that integrate zero-emissions distributed resources that enhance community resilience, increase energy affordability, allow for a more diverse range of energy resources, such as seasonal thermal storage, and systematically quantify reductions in environmental injustices. Such models should be developed and be made open-source.

5. **Financial support mechanisms and incentives should be devoted to enabling LMI and frontline communities to participate in demand response.** There are several participatory barriers to demand response that limit the opportunities available to communities, such as reliable access to broadband and internet-enabled appliances, among other resources. Financial support for broadband, outreach to enable LMI families to avail themselves of the support, and incentives for landlords (especially the owners of affordable housing) are all necessary and should be part of any equity-centered energy transition policy. In fact, supporting high-demand response participation can accomplish larger goals, such as reducing the amount of assistance needed to make energy bills affordable as well as ensuring the best use of available renewable energy resources.

6. **Address the technical, regulatory, and economic challenges of increasing community resilience with high priority**. Essential community facilities, including food and fuel supply, emergency response, hospitals, and emergency shelters, are generally not on single feeders. The regulatory, legal, and technical issues confronting investment in resilience and continuity of supply in a manner that would be economical are substantial and difficult. They need to be understood more deeply; suitable frameworks for addressing them through regulation, legislation, and policy should be urgently developed.

7. **Promote environmental justice in designing utility-scale long-duration energy storage.** Peaking plants are located disproportionately in communities of color and other disadvantaged communities. Priority should be given to the early retirement of such plants. In the short term, solar-plus-storage can suffice in many or most situations. A broader suite of technologies, including green hydrogen made from electricity that would otherwise be curtailed, seasonal thermal storage, demand management, efficiency measures, and conversion of natural gas storage caverns to compressed air energy storage should be examined as the fraction of solar and wind in the electricity system increases. This can enable systematic and, over time, complete retirement of natural gas and diesel peaking plants that are currently the source of much environmental injustice.

8. **Ensure robust safety and environmental choices in long-duration storage.** Long-duration energy storage technologies that use common materials are close to broad commercialization. Several of them are also safer than Li-ion batteries. Such technologies should be preferred where technically feasible, notably in community settings.

9. **Create global environmental justice metrics and standards.** Storage technologies often require rare materials. Mining and processing them can create devastating impacts, including on Indigenous lands in the Global North and in the Global South. Creating uniform and rigorous standards for work, mining, and environmental impacts – such as on local water resources – and global supply chain reporting and transparency are essential. For instance, the Initiative for Responsible Mining Assurance has published a standard for Responsible Mining that includes occupational health, community health, water quality, legal compliance, and a broad array of other considerations.[9]

   10. Support safe and environmentally sound recycling and integration of recycling into design: Mining materials and then discarding them as waste is unjust and polluting. A circular economy requires the recovery and reuse of materials. However, the lack of integration of materials recovery and reuse into the design of hardware, including batteries, often makes recycling more difficult; it becomes a polluting afterthought that often adds to environmental injustice inflicted on overburdened communities in the Global North and on communities in the Global South. Investments in safe, environmentally sound materials and in progress towards a circular materials economy are essential to equity and sustainability. Standards similar to those for mining need to be applied to the recovery and recycling of materials so that communities,

[9] IRMA 2018

workers, and the environment are respected. Integration of recovery and reuse of materials into design should be a major goal.

2. The need for storage in a renewable electricity system

Historically, storage of electricity has not been a priority for the energy system. The main reason is that it is far easier to store the fuels from which electricity has been made — coal, petroleum, uranium, natural gas, and water. There are immense coal piles at coal-fired power plants. Natural gas is stored in vast underground reservoirs. Petroleum, which is used only in a minor way for electricity generation in the United States, is stored in tanks and in underground reservoirs. Nuclear fuel, consisting of uranium enriched in the fissile isotope uranium-235 (the one that sustains the chain reaction), is so energy-dense that power reactors are refueled only every 12 to 24 months, depending on the level of uranium enrichment and plant maintenance schedules. Prior to 2010, 23 GW of pumped storage hydropower in the United States was built to provide peaking capacity and energy time-shifting for other large, less flexible generating capacity.

The need for a decarbonized energy system to avert the worst impacts of climate change and the advent of low-cost solar and wind energy have created a need for storage and changed the opportunities for it. Unlike coal or natural gas, solar and wind energy cannot be directly stored as their supply varies according to broadly predictable rhythms of nature. Thus, unlike the valve on a gas turbine, the level of supply cannot be changed according to the demand of the moment. The sun does not shine at night — that is the definition of "night"; there is a far lower solar supply in the winter than in the summer. The intensity of solar energy reaching panels can suddenly diminish when a cloud covers the sun and can increase just as suddenly when it uncovers it again. Wind variation is also driven by natural forces.

These facts are critical in an electricity system because supply and demand must be closely balanced *at all times*. If there is an excess of supply, the voltage will shoot up and cause the grid to fail. When there is a deficit, the voltage falls resulting in a "brownout" and, below a certain level, a blackout. Today's system handles rapid changes in electrical load by maintenance of "spinning reserves": generators that are spinning that can readily increase or decrease supply.

The need to keep the electrons flowing through the grid in close balance even though solar and wind energy are only available according to the rhythms of nature is the central technical challenge posed by the transition to a renewable electricity system. This challenge will become more complex as road transportation and fossil fuel heating of buildings are electrified. Yet, such electrification will also provide major economic and ecological opportunities. Storage of electricity is an essential component of the answer – though not the only one.

Two examples of how solar and wind supply vary on very different winter days in Maryland illustrate the potential role of storage in an energy system where heating and road transportation sectors are electrified. The analysis shown below is derived from an intensive study of the Maryland energy system in which the primary electricity supply was about 98% from solar and wind (in about equal amounts over the course of one year); the rest was from existing hydropower.[10] In this report, we omitted the

[10] Unless otherwise mentioned, such examples in this report are drawn from the hour-by-hour load and supply modeling done for IEER's Renewable Maryland Project. The methodological details and results of the analysis are described in the that project's final report Prosperous, Renewable Maryland. The analysis assumed that the state's nuclear capacity would be retired when the licenses of the two reactors in the state expire in the mid-2030s (Makhijani 2016).

hydropower supply and modeled only solar and wind as primary energy sources in order to illustrate the role of various kinds of storage and the complementarity of storage and demand response.

We first discuss solar and wind supply to show the necessity for storage. Figure 2-1 shows renewable energy supply (the "generation curve") and the load on a sunny January winter day, using data from Maryland, assuming that all heating and road transportation have been electrified.

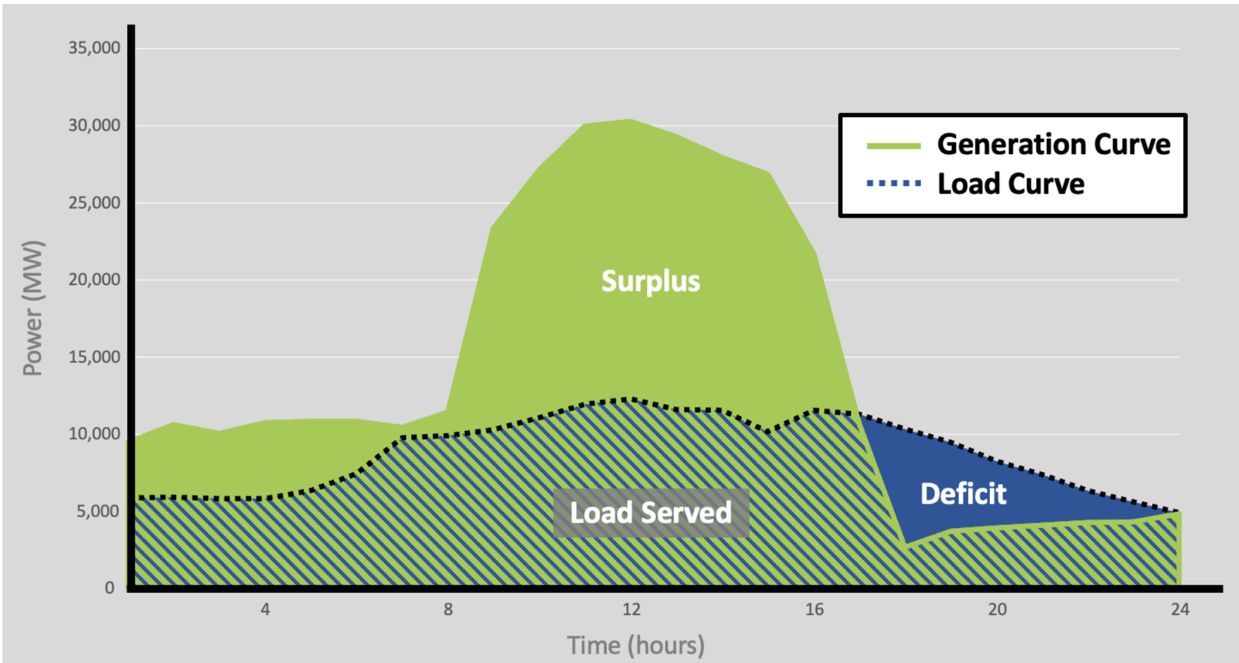

Figure 2-1: Hourly load with heating and road transport electrified and renewable energy supply (solar + wind only) in megawatts on a sunny winter day in Maryland

Figure 2-1 shows that renewable supply alone without storage meets the entire load for most of the hours in the day. A balanced mix of wind and solar ensures some supply throughout the day and night. However, even though the cumulative generation during the 24-hour period in question is vastly in excess of the cumulative load, there is a deficit of supply in the evening hours when the sun has set and, on this day, wind energy supply is insufficient from 5 pm until about midnight. In contrast, during the nighttime hours from midnight through to sunrise (about 7:30 am), wind energy alone would be sufficient to meet the demand. This illustrates the importance of balancing solar and wind so as to increase the number of hours of load served without storage and reduce the amount of storage needed.

For this January day, short-term storage would easily solve the problem of serving the load during the evening deficit hours until midnight. The modeling in the reference report (Makhijani 2016) assumed that the batteries could discharge at full capacity for four hours – a typical utility-scale storage configuration. The batteries would be charged during the surplus supply hours up to the maximum storage capacity. Because there was so much surplus on this day, there would still be a good deal of supply that could be stored in other ways (long-duration battery storage, thermal storage, pumped hydro storage, etc.), or used for hydrogen production.

Of course, not all winter days are as sunny or windy as the example shows. Figure 2-2 shows a 48-hour period in mid-December with a serious deficit of cumulative supply compared to cumulative load. A combination of resources – long-duration storage to complement short-duration storage, demand response, and emissions-free peaking generation — would typically be needed in such situations to ensure reliable supply, especially if the days immediately preceding also had cumulative deficits.

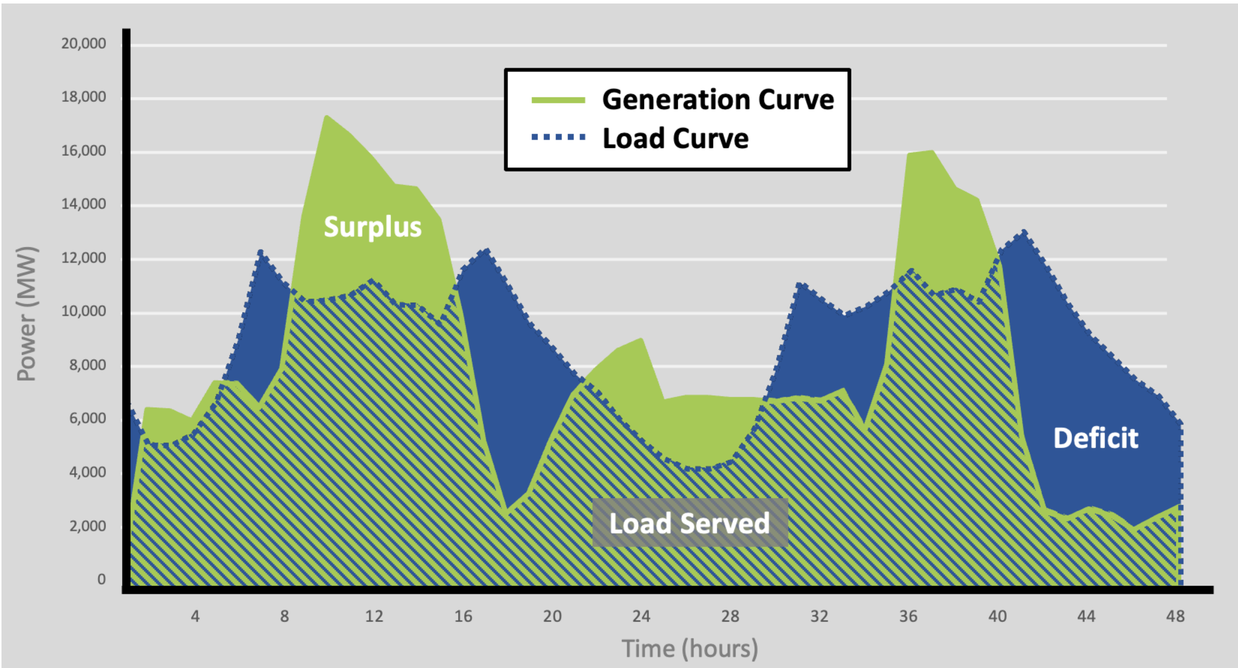

Figure 2-2: Mid-December 48-hour Maryland load in megawatts with heating and load transport electrified and renewable electricity supply (heating and road transport electrified).

Figure 2-2 shows a period in which the primary energy supply was short of the requirement. In the next chapter, we examine various types of long-duration energy storage. In Chapter 4, we will use the data for December, which has the most load not directly served by solar and wind supply, to illustrate the role of battery storage of various durations. We will also examine how demand response and storage can complement each other and the need for very long-duration storage (beyond a week) for a system that is supplied essentially completely by solar and wind electricity.

3. Types of long-duration energy storage

Long-duration energy storage can have energy inputs of different kinds: electrical, chemical, thermal, and mechanical. Outputs may also be any of these types of energy. This report is focused mainly on the types of long-duration energy storage that fall within the scope of the Department of Energy's program for the technology. This has two essential features:

- The storage device must be capable of delivering energy at the rated capacity for 10 hours or more. There are three categories for storage periods: 10 to 36 hours; multiday: 36 hours to 160 hours; and seasonal (more than 160 hours – almost one week, which is 168 hours).[11]
- The output of energy must be in the form of electricity; however, the storage of energy can be in any energy form. The input energy would generally be electrical.

In addition, we also briefly discuss complementary technologies, such as seasonal thermal storage and demand response, that could enable a more resilient or economical electricity system.

The following long-duration technologies could meet the DOE's criteria:

1. **Long-duration batteries** such as:
    - *Flow batteries*: these operate on the same principle as batteries with the major difference that the chemicals are stored in tanks outside the battery compartment where the electricity is generated or electrochemically stored; examples of this type are the vanadium redox battery, zinc-bromine flow battery, the organic flow battery, or the iron flow battery. For specificity, we used the data for vanadium flow batteries for the calculations in this report;
    - *Metal-air batteries* – examples include the iron-air battery and the zinc-air battery. For specificity, we used the data for iron-air batteries for the calculations in this report;
    - *Thermal photovoltaic batteries:* Heat storage (with electricity input) in insulated graphite blocks at very high temperatures. Electric resistance heating (also called Joule heating) provides the heating source and thus can be done with renewable energy. The infra-red radiation from these blocks is then captured by photovoltaic cells to generate electricity. The PV cells are gallium-indium-arsenide.[12] The high temperature thermal storage can also be used to supply high-temperature heat for industrial processes alone or in combination with electricity.
    - *"Second-life" battery storage* – e.g., Li-ion batteries after use in EVs.
2. **Thermal storage:**
    - *Thermal storage*: Energy stored as heat to be recovered for space heating. Coldness can also be stored and recovered for air-conditioning. If well-insulated, energy can be stored seasonally – coldness in the spring for recovery in the summer and heat in the autumn for recovery in the winter.
    - *Cryogenic storage*: Energy is used to cool nitrogen to -320^{o}F and condense it into liquid form. This liquid nitrogen will easily and vigorously evaporate at or above room temperature, of which such liberated energy can be used to turn a turbine-generator.

[11] DOE LDES Program
[12] Tervo et al. 2022

3. **Pumped hydro**: Water is pumped up to an upper reservoir; it generates electricity as it runs through a turbine down to a lower reservoir.
4. **Compressed air energy storage**: Surplus energy is used to store air at high pressures (70 to 100 atmospheres); the pressurized air is later extracted and reheated to run a turbine-generator set to generate electricity. Caverns, now used to store natural gas under pressure, can be converted to compressed air energy storage for large-scale, long-duration storage. Above-ground storage techniques are also being developed.
5. **Hydrogen**: Hydrogen can be stored after it is made by electrolyzing water (splitting H_2O into hydrogen and oxygen) using electricity which is then used when needed for a variety of purposes, such as offsetting peaking electricity generation. Both gas turbines and fuel cells have been proposed; fuel cells are generally more efficient, produce no air pollution, and can, in principle, allow for water recovery. We examine hydrogen for peaking power production using fuel cells as an illustration of long-duration energy storage beyond the few days that can be supplied by some long-duration batteries (like Fe-air or zinc-air).[13]

We cover technologies that appear to have significant applicability in the long-duration energy storage context. Certain technologies are not considered. Specifically, gravitational storage, other than pumped hydropower storage, is not included due to its short-term storage and very low energy-density – only 0.28 kWh stored for a mass of one metric ton raised to a height of 100 meters. Chemical storage in hydrocarbon forms is also not considered in this report.

Some long-duration energy storage technologies are primarily suited to large-scale storage – pumped hydro and compressed air energy storage in underground caverns are prominent examples. Other technologies are more flexible – long-duration battery storage is a prominent example. They can store energy at various scales from the community level (tens of megawatt-hours) to utility-scale (hundreds to thousands of megawatt-hours). The downside is that they are not well-suited for seasonal large-scale storage, which requires very cheap storage and low energy losses during storage.

The long-duration storage technologies considered in this report have either been used commercially or are close to commercialization. The aim is not to be exhaustive, since there are many technologies under development, but to illustrate four principal uses of long-duration storage considered in this report:

- **Utility-scale battery storage** to complement an electricity system that has mainly solar and wind supply.
- **Storage of hydrogen** produced from renewable electricity that would otherwise be curtailed for various uses – illustrated in this report by use in light-duty fuel cells for peaking generation.
- **Community-scale battery storage** for increasing the resilience of the electricity system, including the supply of essential loads without interruption during multi-day grid outages.
- **Building-scale battery storage** for the same purpose as community scale storage but with a smaller range of essential loads.

[13] We do not examine burning hydrogen in turbines for peaking they are less efficient and would perpetuate environmental pollution disproportionately on environmental justice communities. See Makhijani and HErsback 2024 (forthcoming).

We will also describe some seasonal thermal storage technologies that have electricity as the energy input but heat or cold as outputs (notably for building heating and cooling) that could serve as complements to the above cases, which have electricity output only.

It is critical to remember that long-duration energy storage is just that – storage. The greenhouse gas emissions and other environmental impacts associated with it depend, first of all, on the energy source used to charge the storage system. This report focuses on charging the storage system with solar or wind energy with the aim of dealing with their natural variability.[14]

Storage has an energy cost which involves three kinds of losses:

- Losses incurred in the process of *charging* the storage system – the energy stored is always less than the energy input into the storage system – sometimes marginally less and sometimes significantly so;
- Losses *during* storage – loss of heat, leakage of battery charge, leakage of hydrogen,[15] evaporation of water stored in reservoirs, loss of pressure and temperature during compressed air storage;
- Losses in *converting* the stored energy back to electricity, or electricity plus heat in some cases.

The ratio of output energy to input energy is called "roundtrip efficiency," which is a central figure of merit of storage systems. Some battery storage systems have roundtrip efficiencies as high as 90%[16] — which is excellent since almost all the electricity input into the battery is recovered as electricity. Other storage systems can have roundtrip efficiencies as low as 30% or 40%.

Roundtrip efficiency is only one metric, but there are many other important ones such as cost per unit electricity output from storage (which takes roundtrip efficiency implicitly into account), whether the charging rate of the storage system can be faster than the discharging rate; how long the storage system can supply energy at the rated capacity (the "duration"); the depth of discharge of any given storage system (e.g. some batteries are not meant to be discharged 100%); and the lifetime of the system, both in terms of shelf life (e.g. how long before it degrades, even if unused) and cycle life (e.g. how it might degrade over many charge-discharge cycles). There are other useful metrics as well, related to features such as safety or performance in different temperature environments.

Table 3-1 shows the long-duration storage technologies with their main features. Table 3-2 shows battery technologies in more detail, among other reasons due to their importance for increasing community electricity supply resilience, which is considered in detail in this report. The listed common duration is current and expected commercial sizes. These durations are not limited by technology but rather by market demand.

[14] Energy storage systems are also used for other reasons such as arbitrage – charging when energy is cheap, like coal-fired electricity at night, and discharging when it is expensive, such as during evening peaking hours. Such uses are not considered in this report.

[15] Hydrogen can even be lost in underground storage when eaten by microbes.

[16] All roundtrip efficiency values in this chapter are rounded to the nearest 10%. In Chapters IV and V, where illustrative calculations have been done, values closer to those expected (two significant figures) have been used.

Table 3-1: Selected long-duration energy storage systems (input and output energy in the form of electricity) and some of their characteristics.

Technology	Duration and scale	Capital cost range, $/kW	Roundtrip efficiency	Pluses and minuses	Comments
Batteries – various chemistries and durations (See Table 3-2)	Hours to days; kW to tens of MW	See Table 3-2	40% to 90% (rounded)	**Pluses**: elec. input and output; high energy density for some chemistries; **Minuses**: High cost; some safety concerns; some concerns regarding sustainable materials	Li-ion, the most efficient, has safety issues (fires) and material-related mining and processing EJ issues.
Compressed air energy storage (caverns)	Entire range: hours to seasonal; tens of MW to ~ 1000 MW	Low to ~$300/kWh (rounded). Cost declines with scale and duration	~40% to 55% ; technology with ~70% efficiency being developed	**Pluses**: utility-scale; low cost; long experience; can use existing natural gas storage caverns. At 70%, the efficiency of adiabatic CAES comparable to flow batteries. **Minuses**: Limited siting; low round trip efficiency; needs a heating fuel like natural gas or hydrogen except adiabatic compressed air storage which stores rejected heat.	2 commercial plants operating for decades (Alabama in the United States and Germany); natural gas is used for reheating air. Would likely have to be replaced by hydrogen unless wase heat is stored and reused (adiabatic systems). Potential for conversion of natural gas storage caverns. May add jobs in some cases since gas storage locations will have electricity generation facilities added to them.
Pumped storage (hydropower)	Entire range: hours to seasonal; hundreds of MW or more	Variable; location dependent	~90% but lower with evaporation losses	**Pluses**: already available on a large scale in many locations at utility-scale; **Minuses**: sites limited by geography; water evaporation losses; land use for reservoirs.	Large-scale seasonal utility-scale storage is a significant advantage for meeting long-duration storage requirements where upper and lower reservoirs exist.
Electrolytic Hydrogen	Entire range: hours to seasonal	Dependent on cost of electricity and scale of production	30% to 60%	**Pluses**: Flexible for a variety of end uses; zero GHG emissions if used in fuel cells. **Minuses**: H_2 leaks have warming impact; high water use unless recovered from fuel cell; if burned produces NO_2 pollution; low roundtrip efficiency.	Zero emissions if hydrogen produced with dedicated wind or solar energy and power is generated in fuel cells. Hydrogen is a fuel and an energy carrier that can be stored. There are significant environmental justice impacts in production of the needed materials.
Thermal storage in solid media	Hours to days	See comment column	~50%	**Pluses: W**idely available storage media **Minuses:** Requires a thermal electricity generation cycle. Relatively low efficiency	Power related capital cost ~$1000/kW plus $1/kWh to ~$30/kWh for storage medium

Sources: Overall: Vishwanathan et al. 2022 and DOE 2023. For compressed air energy storage: Rabi, Radulovic and Buick 2023. For hydrogen: Makhijani and Hersbach, forthcoming January 2024.

Table 3-2 Battery storage system characteristics (See Note)

Battery technology	Common Duration, capacity	Capital Cost	Roundtrip efficiency	Pluses and minuses	Comments
Lithium-ion	Hours, possibly days kW to MW	$1,600/kW (four hours storage)	90%	**Pluses**: high roundtrip efficiency; already commercially available; **Minuses**: high cost; some fire risk; varies with chemistry; EJ impacts from mining scarce materials vary; Li-ion phosphate chemistry has lower fire risk and lower material EJ impact	Lithium-ion use as a mainstay for electricity grid support may compete with other uses of lithium – notably in transportation decarbonization. Sources: Wang et al.; NREL ATB 2022
Vanadium redox flow (V-flow)	Hours to days	$1700/kW and $600/kWh	70%	**Pluses:** Materials can be recovered relatively simply for re-use; ability to decouple energy and power capacity. Long cycle life **Minuses**: toxic metals in liquid form	Relatively less complex storage of materials. Spills can be recovered with appropriate enclosure design. Multiple commercial vendors Sources: Weber et al. 2018; He et al. 2020
Zinc bromine redox (Zn-Br flow)	Up to 12 hours	~$600/kWh according to a recent contract	~70%	**Pluses**: zinc is an abundant material and lower cost than some alternative flow battery materials like vanadium. Long cycle life **Minuses**: Significant safety issues in case of bromine gas evolution in accident situations	Sources: Khor et al. 2018; He et al. 2020; Anaergia 2021; Redflow website.
Iron flow	Up to 12 hours	Uncertain today	~70%	**Pluses**: Abundant materials; long cycle life **Minuses**:	Sources: He et al. 2020 and ESS website
Organic flow	Up to 12 hours	Uncertain today	~70%	**Pluses:** Similar to other flow batteries	Multiple chemistries all still in the testing phase
Iron-air	100 hours	longer term $2000/kW for 100 hour	~40%	**Pluses**: Low projected cost; 100-hour storage; plentiful materials; most manufacturing ecological metrics better than Zn-Br flow or V-flow **Minuses:** low roundtrip efficiency; fresh water ecotoxicity higher than Zn-Br flow or V-flow (He et al. 2020 Figure 3)	Battery manufacturing plant at scale is being built in West Virginia

Zinc-air	4 to 100 hours	Comparable to Li-ion	50% to 65%	Similar to iron-air	
Sodium-sulfur	7 hours appears typical		75-80%	**Pluses:** Commercial with significant operating experience for utility-scale storage **Minuses:** Sodium presents safety issues especially in community context.	There are similar chemistries and approaches that are not listed in this table. Source: Tamakoshi 2021
Thermal Energy Storage with TPV	24 to 100 hours	$600/kW plus $10/kWh projection for 2030	~40% from storage to output	**Pluses**: Projected to be among the lowest cost storage systems; high temperature industrial heat and electricity output; charging rate can be higher than discharge rate. **Minuses**: Low roundtrip efficiency; electricity output not commercialized yet	Electricity pilot plants are planned for 2024. As with other PV systems toxic chemicals are used in PV manufacturing. The PV material itself is gallium arsenide in at least one approach Source: LaPotin et al 2022; Antora website; Fourth Power website

Note: This list is not meant to be exhaustive but illustrative of the technology types.
Sources: General reference for cost and battery characteristics: experience of one of this report's authors and Vishwanathan et al. 2022; General reference for safety Jeevarajan et al. 2022. For flow battery materials and ecological impact: He et al. 2020. Websites: CMBlu organic flow website: https://www.cmblu.com/en/technology/; Zn-Br Redflow website: https://redflow.com/why-reflow; For iron flow ESS website: https://essinc.com/; Zinc-air: https://www.zinc8energy.com/ ; Antora website (for TPV): https://antoraenergy.com/ ; Fourth Power link (for TPV): https://www.linkedin.com/company/fourth-power-inc/about/

4. Utility-scale applications

Storage is needed for addressing wind and solar energy variability at many scales. In this chapter, we consider utility-scale storage, using the example of Maryland, for which both detailed hour-by-hour load[17] and renewable energy data were compiled in Makhijani 2016. A major advantage of this dataset is that the load included electrification of heating and road transportation so that conditions represent loads and supply that would be typical of a decarbonized grid in the 2040s with a very large fraction of solar and wind energy. Weather data are for 2011. Continued investments in efficiency for existing loads and building envelopes were included in the modeling.

The data are atypical in one respect: they are for a single state – Maryland. In reality, Maryland is part of a much larger grid, the PJM grid, that extends from the mid-Atlantic to Chicago. Thus, the examples illustrating the role of utility-scale storage in this chapter somewhat exaggerate the role of storage since the transmission of power across an East-West region would ameliorate the extent and duration of the gaps between variable solar and wind supply and the load. The examples are meant to be a heuristic, quantitative exploration of dealing with the variability of solar and wind supply using different durations and types of storage. We use weather data for December 2011, when the gaps between supply and demand were most extreme due to the assumption that heating in residential and commercial buildings was completely electrified.

We consider the following utility-scale storage examples in this chapter:

- Short-duration compared to long-duration battery storage;
- How battery storage can be coupled to demand response, and the opportunities that could arise for energy democracy and affordability;
- The role of green hydrogen produced using solar and wind electricity that would otherwise be curtailed and seasonal hydrogen storage in complementing battery storage and demand response to create a reliable electricity supply; we assumed fuel cells would be used for this peaking generation;[18]
- Other types of storage that could complement utility-scale battery storage and demand response should hydrogen not be suitable or as a complement to peaking generation from hydrogen. These are not quantitatively modeled.

We illustrate the above assuming that wind and solar would be the only sources of electricity. As we show in the next chapter, if utility-scale storage is complemented by distributed storage, a more reliable and resilient electricity supply that is also decarbonized can be created. This report does not examine the merits – or lack thereof – of using or not using other decarbonized electricity sources. We use the wind-plus-solar only framework to show the potential role of long-duration storage using an analysis

[17] Loads include transmission and distribution losses. Efficiency improvements in electricity use in existing were taken into account. See Makhijani 2016 for details.

[18] In the short-term it is more efficient and more effective from a climate point of view to use solar/wind plus battery systems to replace natural gas peaking generation. The role of fuel cells here is proposed as an option for peaking generation for a time when hydrogen can be made from solar and wind that would otherwise be curtailed.

that had already shown that solar, wind, and a small amount of existing hydropower can result in a reliable and economical electricity supply.[19]

There is a critical caveat in interpreting the calculations in this chapter. They are heuristic calculations to illustrate potential roles of long-duration energy storage technologies with different characteristics. *They are not meant to be realistic representations of a future grid architecture*. Specifically, sections 4.1 and 4.2 consider just one element – utility-scale storage that has electricity as the output – of the grid of the future that will have many elements, including demand response, distributed storage, community microgrids designed to increase resilience (Chapter 5), seasonal thermal storage, vehicle-to-grid electricity supply, and efficiency initiatives that are tailored to reduce winter and summer peaks. An illustration of how the role of storage can change dramatically is provided in Section 4.3 where the amount of storage needed changes significantly depending on the dispatch order of aggregated demand response and storage. The calculations show that it matters whether loads available to be shifted from supply deficit times to surplus times are served before utility-scale batteries are re-charged or whether battery charging is given priority.

4.1 Short- and long-duration battery storage

We examine the performance of three different durations of utility-scale battery storage during two specific periods in December. The first is a 24-hour period when renewable supply is plentiful overall but insufficient to meet the load in every hour without storage; the other is a 48-hour period when overall supply is short. Storage consists of four-hour Li-ion batteries equivalent to five-and-half hours of average annual load amounting to 50,000 MWh of energy storage and 12,500 MW of capacity. The roundtrip efficiency assumed was 87%.[20] Long-duration storage technologies like flow batteries are currently more expensive. The Department of Energy's "Long Duration Storage Shot" program aims to reduce the cost of long duration energy storage (10 or more hours) to 10% of the cost of Li-ion in 2020 by the year 2030.

For comparison with a 4-hour Li-ion battery, we modeled a 100,000 MWh, 10,000 MW flow battery system with 70% roundtrip efficiency, assuming it would be approximately equal in total capital cost in the coming years, given the DOE's 2030 target. (The calculations are for loads well beyond 2030, since all heating and load transportation is assumed to be electrified.) This is a heuristic calculation illustrating the role of 10-hour storage versus four-hour storage for roughly the same capital cost. As Li-ion battery costs drop, they may be preferred due to higher roundtrip efficiency. The calculation is agnostic as to technology; flow batteries are used in the calculation in order to be specific as to efficiency and cost.

Figure 4-1 shows load and renewable energy supply data for the 3 December, a sunny day with good wind resources after midnight but not for most of the period after sundown.

[19] Makhijani 2016 is based on hour-by-hour modeling of future electricity loads in which heating and road transportation are electrified. Maryland has two nuclear power reactors at Calvert Cliffs on the Chesapeake Bay, about 1700 MW total capacity, and a 572 MW hydropower plant at the Conowingo dam. The former were not modeled in the decarbonized electricity system for 2050 because their current licenses expire in the mid-2030s; the latter was included in the supply mix. Neither is included in the calculations in this chapter, which is designed to illustrate the role of long-duration energy storage in the most difficult circumstances.

[20] For simplicity of modeling, we assume the full range of charge is available. In practice, a minimum state of charge greater than zero would be maintained with the value depending on the type of battery and estimated life under the circumstances expected for its operation.

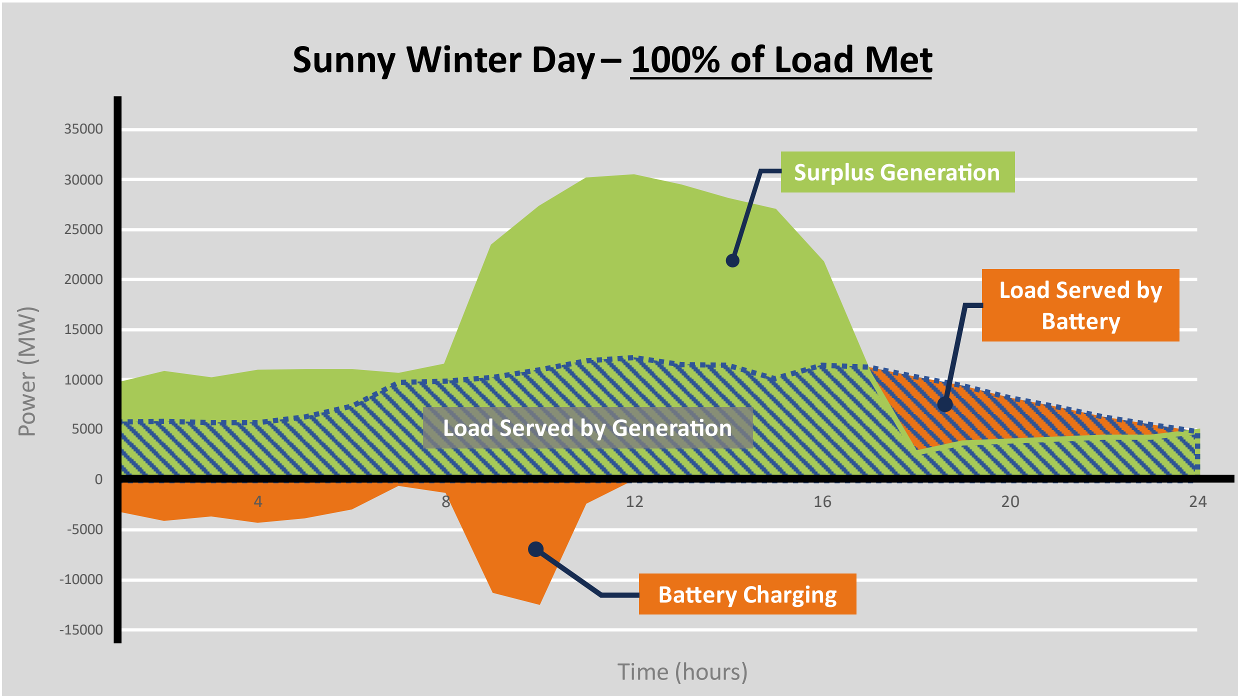

Figure 4-1: Load, renewable supply, and battery charging and discharging on a sunny winter day, Maryland data. Initial state of charge of the battery for the day was about 96%. Battery stops charging after reaching 100% of rated energy capacity.

In this specific case, there would be no problem in meeting the entire load for each hour, since the battery charge is sufficient in all the hours when renewable energy supply does not directly serve the entire load (from 5 pm to 11 pm). The solid line showing the value "0" for all hours indicates all consumers could meet all of their requirements on this day without demand response or any supplementary generation. The initial charge on the battery at the start of the day at midnight was high – the battery was assumed to be charged in the previous period to about 96%, so that battery charging occurred only for a couple of hours after midnight; the large surpluses of renewable energy in the afternoon would have to be curtailed or stored in some long-duration technology to enable its use on days when cumulative renewable supply falls short of cumulative load.

Figure 4-2 shows two consecutive mid-December days when most hours have a renewable energy supply deficit with a 4-hour lithium-ion battery. Because the prior days did not have as plentiful a renewable energy supply as the days prior to 3 December, the initial state of charge of the battery was only about 36%. As a result, the battery was quickly depleted; 11 December was reasonably sunny, so some recharging was possible in the daytime. But starting at about 10 pm on 11 December and then almost the entire day of 12 December had serious deficits of supply (solid blue line) even when the battery was included. Overall, in the two-day period, about one-third of the total load was not served, with most of the deficit being on 12 December.

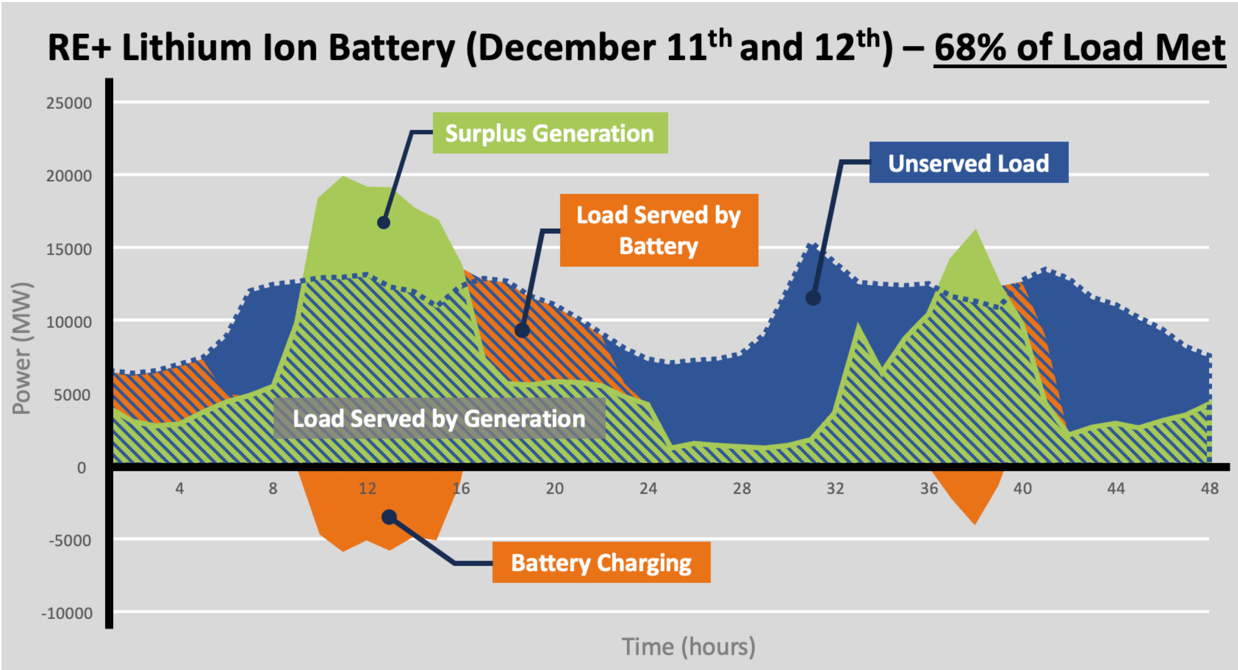

Figure 4-2: Load, renewable energy supply, lithium-ion battery charging, and generation from the battery, 11 and 12 December. Initial charge on the battery about 36%.

Figure 4-3 shows the same load and supply for the same days with a 10-hour battery, which stores more total energy storage but has approximately 20% less capacity (equivalent to "power" or "maximum discharge rate") for about the same battery capital cost. It starts these two days with almost four times the stored energy of the four-hour lithium-ion battery – the same prior-day conditions of renewable energy and load apply. As a result, the ten-hour battery performs better than the four-hour battery though the roundtrip efficiency is lower for the flow battery (70% compared to 87% for Li-ion). Overall, the four-hour battery meets 68% of the cumulative two-day load compared to 76% for the 10-hour battery. Even so, the performance on the second day leaves large deficits once the battery is depleted at 4 am on the second day. As a result, even though the 10-hour battery performs better, another resource of even *longer* duration storage (such as hydrogen – see Section 4.2) would be necessary to make the electricity supply reliable through prolonged periods of low renewable energy supply – assuming that the load is served by generation and storage technologies only.

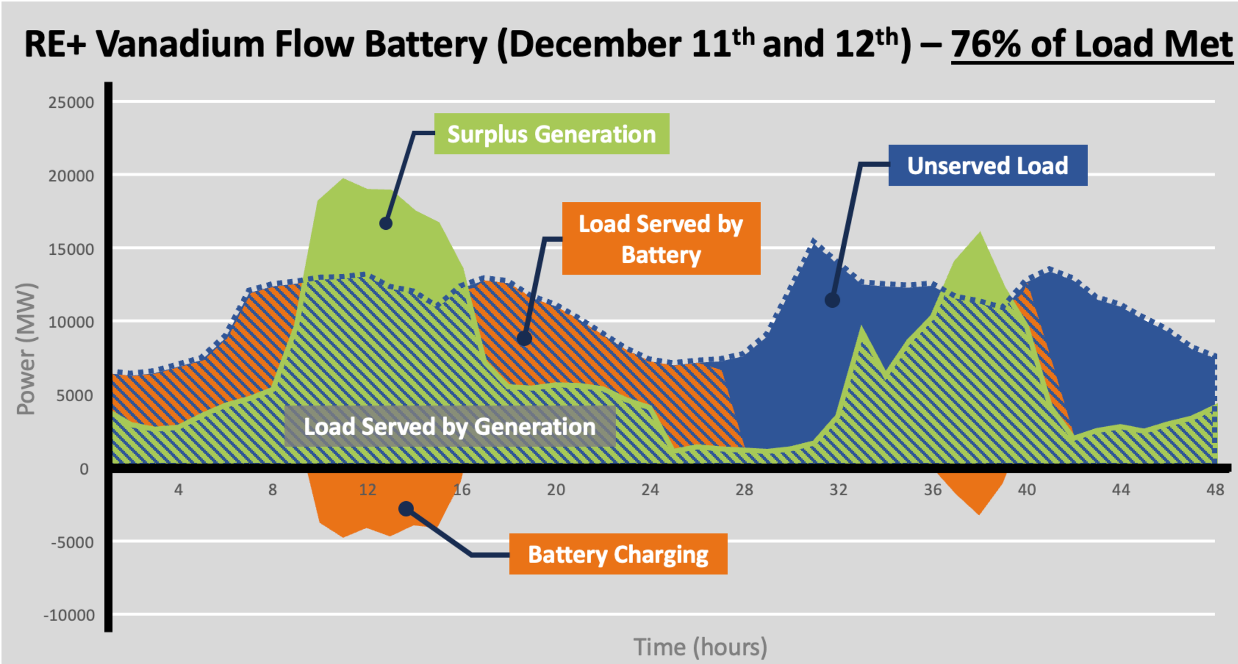

Figure 4-3: Load, renewable energy supply, 10-hour flow battery charging, and generation from the battery, 11 and 12 December. Initial charge on the battery about 67%.

We also performed the same calculations for the Fe-Air battery, which has a higher energy (i.e. MWh) storage limit for the same capital cost; however, the capacity – the power delivered in any hour is far smaller than either the lithium-ion or the vanadium flow battery. Further, the low roundtrip efficiency (assumed to be 38%) means that there is generally not enough surplus renewable energy in a month like December to fully charge the battery. As a result, less of the cumulative load is served compared to either the Li-ion or the flow battery examples.

The above heuristic calculations were done to illustrate how much load can be served in a period of low renewable energy supply relative to load with different storage system parameters - capacity, storage duration, and roundtrip efficiency for about the same capital cost. The technologies chosen for the calculations were to illustrate the effect of different parameters under the capital cost constraint. If the cost of a particular technology declines steeply, a lower roundtrip efficiency might be acceptable. In fact, that is a conclusion indicated already since a larger fraction of the cumulative load was served with a 10-hour 70% efficiency battery with a somewhat lower capacity than a four-hour 87% efficient battery.

Interestingly, though different storage durations and efficiencies are instrumental in significantly changing the fraction of the cumulative load served in a 24- or 48-hour period, none of the examples of long duration storage examined reduce the peak load by much. Reducing peak load is always an important economic objective; it is more so in the context of variable renewable energy and electrification of heating, which tends to drive the peak into winter nights and early mornings when no solar energy is available.

Finally, it should be noted that cost optimization is a complex task that involves additional considerations, including

- The amount of remaining renewable energy supply for a given level of cumulative load served – since this has some value, for instance for seasonal thermal storage or for producing hydrogen.[21]
- The consideration of utility-scale storage in the context of aggregated demand response (see section 4.3 below), distributed storage, and distributed renewable energy resources installed to increase system resilience (Chapter 5 below).

We illustrate these two issues by considering the role of seasonal storage (Section 4.2) and then of the interaction of storage and demand response (Section 4.3).

4.2 Seasonal storage and peaking generation

Attempting to solve the problem of demand deficit in the periods when there is a persistent gap between load and renewable energy supply with battery storage alone would be prohibitively expensive. Figures 4-2 and 4-3 indicate that even with a 10-hour battery, the supply falls short for most of 12 December. This pattern recurs on other days as well.

For purposes of illustration, we consider hydrogen as an example of long-duration energy storage (up to several weeks) to meet the loads not served by renewables plus battery storage using the same dataset. This is a simplified calculation; the hydrogen can be considered to represent a mix of very long-duration storage technologies such as seasonal thermal storage, compressed air storage, and hydrogen.

We extend the heuristic example by considering how much seasonal (multi-day or even multi-month) storage is needed to fill the gaps left by battery storage. We consider the entire year modeled in Makhijani 2016 with a four-hour, 12,500 MW Li-ion battery (87% roundtrip efficiency). In this section, we consider utility-scale supply of green hydrogen to simplify the illustration. In the next section, we will show how demand response can play a major role in reducing both battery storage and longer-duration seasonal storage, both of which nonetheless remain essential.

We use the following parameters for this heuristic exercise:

- Hydrogen production electricity requirements: 50 MWh/metric ton (including compression for storage);
- Efficiency of fuel cells converting hydrogen to electricity: 60%;
- The above two parameters give a roundtrip efficiency (ratio of electricity output to electricity input) of about 40%.

For the weather modeled (2011, Maryland), with heating and road transportation electrified, seasonal long-duration storage (from a few days within the month to inter-month storage) is necessary. Most of the requirement is for multi-day storage within the same month; however, in some months, notably the month with the most severe load serving deficits in the year modeled (December), some storage from prior months is needed. We calculate the long-duration storage requirement as the amount of hydrogen that would be needed to meet the load deficits in all hours of any particular month, after a four-hour battery has served most of the deficit loads. In this example, we take all supply into account, including

[21] See Makhijani and Hersbach, forthcoming January 2024.

the small amount of hydropower and on-site industrial production of green hydrogen for combined heat and power requirements; these two sources add up to less than five percent of supply.

This exercise showing the amounts of hydrogen that would be needed to meet peak demand to complement battery storage. It is not meant to be a realistic exercise in the absence of methods to reduce peak loads – which is not adequately done by battery storage alone. Rather, it is an illustration for one way in which renewable energy that would otherwise be curtailed can be used to serve loads in the context of primary supply being solar and wind energy. Seasonal thermal storage at the seasonal level would be a good complementary storage technology to examine for implementation prior to examining the extent of hydrogen requirements. And as the next section shows, a reduction in generation capacity to meet unserved loads can be accomplished by implementing and dispatching aggregated demand response with higher priority than storage.

Figure 4-4 shows the cumulative deficits as a percentage of total load in that month after the solar, wind, and four-hour battery have served as much of the load as possible. In this example, these are the loads that we assume would be met by very long-duration energy storage of days to months.

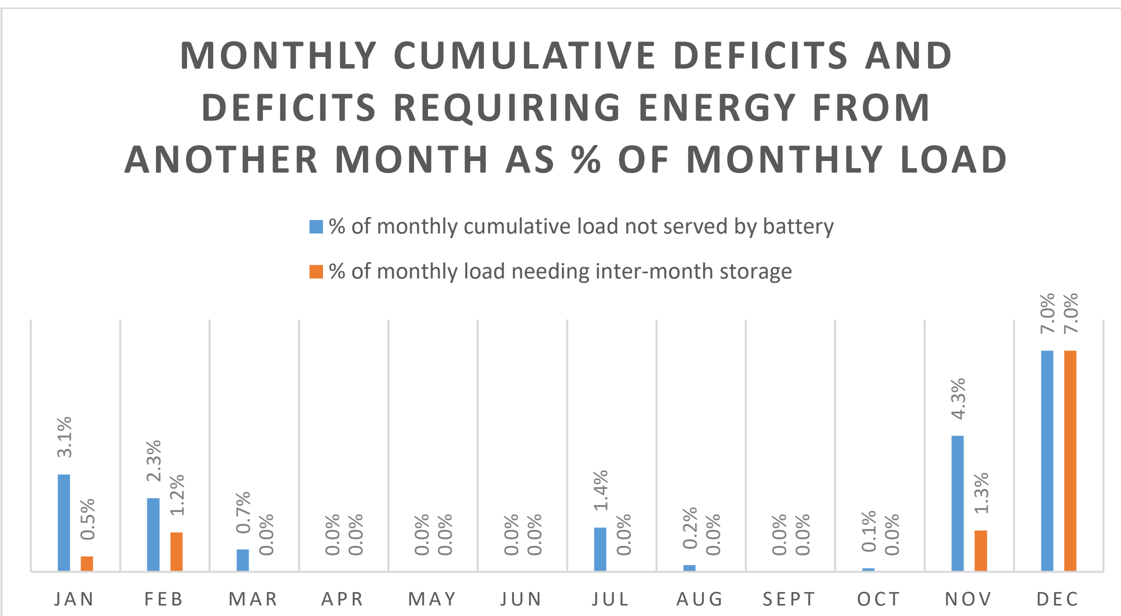

Figure 4-4: Monthly deficits to be met by very long-duration and seasonal energy storage – total (blue) and the portion needing energy stored in a prior month (orange).

Figure 4-4 also shows the fraction of the cumulative load that must be met by energy stored in a prior month. It is remarkable that almost all the deficits can be met with energy stored for a long duration but within the month. For the most part it is storage for days except for the month of December in which case requirements for long-duration storage must almost all be met with energy stored in one or more prior months.

Finally, in six months during the spring and autumn deficits are completely met by surplus renewable energy available within the month; there is no need for weeks-long storage. In addition, surplus energy during these months can provide energy supply for other months via long-duration energy storage technologies such as seasonal thermal storage and hydrogen production.

In any system with high penetration of solar and wind, there are likely to be large surpluses in most months that would have to be curtailed even if the requirements of the electricity system are fully met. In the example we have been considering, on the order of 100,000 metric tons of hydrogen would suffice for the electricity system but about 500,000 metric tons of hydrogen could actually be produced.

As noted, we have used hydrogen as a heuristic illustration of long-duration energy storage – the monthly requirements are shown in Figure 4-5. The results would be similar for some other mix of very long-duration storage – such as a mix of seasonal thermal storage, hydrogen, and compressed air storage.

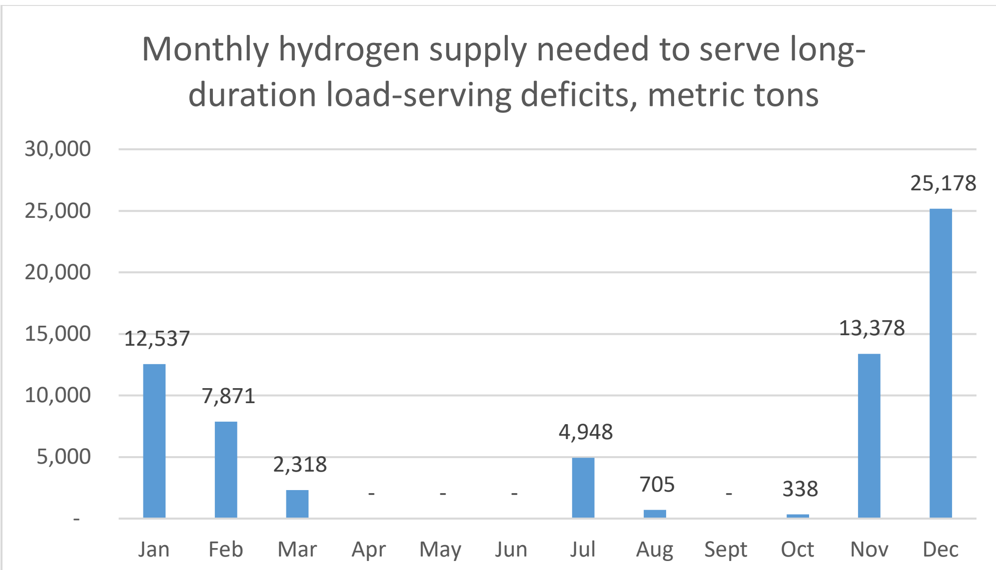

Figure 4-5: Monthly hydrogen requirements to meet loads not met by direct renewable energy supply or from four-hour battery storage. Assumes only hydrogen is used for supplying these deficits.

The hydrogen/very-long-duration storage requirement can be modestly reduced (by roughly 15%) with a 10-hour battery instead of the four-hour battery modeled in Figures 4-4 and 4-5. But most of the need for storage for several days or weeks persists. Some of the long-duration storage shown to serve loads in Figure 4-5 could also be served by batteries with 100-hour storage or possibly more, depending on how long-duration storage battery costs evolve.

There may be constraints on large-scale long-duration hydrogen storage, which is more difficult to site than natural gas or compressed air storage. The water requirements for hydrogen production are substantial.[22] However, when hydrogen is produced on site and used later in fuel cells, the water could be recovered and reused to make hydrogen, posing less of an issue if hydrogen in produced on site.

Figure 4-5 should be seen as some mix of long-duration energy storage technologies other than batteries. The mix could include long-duration batteries, such as 100-hour Fe-air or TPV batteries,

[22] Makhijani and Hersbach 2024 (forthcoming)

compressed air energy storage in caverns, hydrogen, seasonal thermal storage, and pumped hydro storage.

Among very large-scale storage options, it should be noted that compressed air can be stored in the same underground reservoirs where natural gas is now stored. This change in reservoir function can help preserve jobs in places where there is now underground gas storage – as well as increase them in at least some cases, since generation equipment would also be required to be built, operated, and maintained in addition to maintenance of the compression equipment needed for natural gas storage.

Electricity is not the only form in which final energy output is useful. Much of the stress on the system arises from heating and road transportation loads when these end uses are fully electrified. Seasonal thermal storage of cold in the spring for air-conditioning use in the summer and of heat in the autumn for heating in the winter could reduce the peak loads at times when solar and wind supply tend to be significantly lower than loads. This is especially so with short days and low solar insolation in the winter months – the times when a solar-and-wind based system (with or without other complementary supply sources) would face constraints that require major investments to overcome.

One extraordinary example of seasonal thermal storage is provided by the Drake Solar Landing Community in Alberta, where the winter is as cold, and often far colder, than in the contiguous United States. It is a 52-home community south of Calgary. The input and output energy are both thermal. In this community 90% to 100% of the heating load in the winter has been provided by solar heat that is stored in artificial insulated cells in the ground for over a decade. Natural gas is used to top up the community storage when needed. The amount of heat stored is built up over the preceding months. The source of the heat is solar thermal panels on the garage of each home. The insulated heat storage cells are for the whole community. A 22 kilowatt solar PV system has been added.[23]

The Drake's Solar Landing Community experience shows that seasonal thermal storage of energy using renewable energy is technically feasible and can fulfill almost all winter heating requirements in efficient homes in a very cold climate. The Community uses solar hot water panels (with glycol as the working fluid) to capture the heat that is stored; however, renewable energy that would otherwise be curtailed could be used instead. That would allow seasonal thermal storage to reduce winter space electricity heating loads and hence also peaking generation capacity required. Given the amount of surplus renewable energy available, top-up heating using gas would likely not be needed in most cases since almost the entire contiguous United States has winters that are far less cold than Alberta. While it would seem to be more suited to new construction than to retrofits, we note that community geothermal networks could be built as part of the process of electrification of buildings. Thermal storage with thermal output would have the added advantage of increasing the loads that are served during prolonged outages for the same amount of battery storage, such as the amounts modeled in the examples in Chapter 5. In other words, adding seasonal thermal storage for heating and cooling (especially for buildings deemed essential) can significantly increase community energy resilience.

Seasonal thermal storage and long-term energy storage in the form of hydrogen are not mutually exclusive. Seasonal thermal storage could be used to reduce peak loads and where high building density made it more suitable for heating. But thermal storage can supply only one load – and more likely a

[23] Mesquita et al. 2017

fraction of the space heating load. Hydrogen used for electricity generation can supply all the loads that electricity supplies because it is converted to electricity in fuel cells.

In sum, seasonal storage technologies are available to meet load deficits not served directly by renewable energy supply and battery systems. The roundtrip efficiency of many of these technologies is in the 40% to 50% range, which is roughly the same as two prominent battery technologies with storage durations of 24 to 100 hours (Table 3-2 above and Chapter 5).

4.3 Complimenting energy storage with demand response

So far, the analysis of the role of long-duration energy storage has been in the context of a conventional, utility-centered, large-scale view of the electricity grid. The object was to examine whether and how different types of long-duration storage could compensate for the natural variability of solar and wind energy to serve all loads with zero greenhouse gas emissions.

A transition to a decarbonized energy system that focuses on centralized resources alone will not accomplish the increase in resilience needed in a time of increasing climate extremes. It would also fail to take advantage of large opportunities for demand response that have been opened up by broadband and information technology. The brief modeling exercise in this section shows that demand response resources and the order of their dispatch by the grid operator can materially impact affordability as well as the amount of storage needed in a system where the primary supply is wind and solar energy.

Demand response is basically a system that allows the shifting of a customer's load from one time of day to another. Typically, it has been used to shift electricity use from times when the grid is under stress – usually a time at or close to peak load – to some other time. In the case of some large industrial loads, demand response can also include the shutdown of loads during emergencies. Customers who agree in advance to enroll in demand response often receive a payment in return for their participation, which could be in the form of a bill credit. In the case of large industrial customers, agreeing to remove load during emergencies can even lower their electricity rate.

A familiar demand response program is the shift of air-conditioning load from the time of peak demand on summer days. This is accomplished by voluntary enrollment of customers in advance in a demand response program in return for a credit on the customer's electricity bill. In return for the payment, the utility can cut off the customer's central air-conditioner for a short time, such as an hour, up to a specified maximum number of times a year. There is an added payment each time the air-conditioner is cut-off.

In most cases, demand response does not remove the load from the system but shifts the time when it occurs. For instance, when a central air conditioner is cut off, a house (or commercial building) gets warmer than the set temperature; when it is turned back on at a later time, the air conditioner works harder to restore that set temperature. Demand response may end up changing the total load, such as when air conditioning is cut off in the hottest part of the day and turned on when it is less hot, while in other cases, the total load may not change.[24] The main object is not to change the load but to shift it in order to provide a service to the grid – in most cases in the form of reduced peak load.

There are several technological and societal changes to the grid that have increased the necessity for and the scope of demand response, including: the rise of solar and wind generation, information technology that allows internet-enabled appliance operation, millions of sources of electricity supply in the form of rooftop solar, distributed batteries, and tens of millions of battery systems in electric vehicles that could both draw energy from or supply energy to the grid. Demand response is a prime example of what are called "non-wires" resources, where more poles, wires, and generating stations are not required to be added to provide a necessary grid service – whether it is maintaining supply or maintaining voltage and frequency within the narrow bounds necessary for reliable electricity supply. An example of a system of demand response for 14 different end uses of electricity in the state of Florida in the context of rising solar energy supply was examined by Stoll, Buechler, and Hale (2017). The study found that "demand response is able to reduce production costs, reduce the number of low-load hours for traditional generators, reduce starting of gas generators, and reduce curtailment."[25]

Demand response can be a resource equivalent to new generation when customers with large loads subscribe or when the demand response subscriptions of many small customers are aggregated (by utilities or third parties) and offered as a resource to grid operators.[26] From the point view of balancing supply and demand at all times, there is no difference between a megawatt of dispatchable generation and a megawatt of demand response which operates by removing a megawatt of demand at the specified time. This equivalence was recognized by the Federal Energy Regulatory Commission in 2020 in a formal decision: FERC Order 2222. The Order explicitly requires grid operators to "have tariff provisions that allow DER [Distributed Energy Resource] aggregations to participate directly in the organized wholesale electric markets. In addition, each RTO [Regional Transmission Organization] and ISO [Independent System Operator] must update the economic dispatch software accordingly."[27] The Commission's definition is broad and includes all resources "behind a customer meter"; it explicitly includes demand response, saying that behind-the-meter resources "may include, but are not limited to, electric storage resources, distributed generation, demand response, energy efficiency, thermal storage, and electric vehicles and their supply equipment."[28]

In this section, we explore a single issue: how the dispatch of aggregated demand response and battery storage might be arranged to improve affordability and empower consumers – including renters and those without the financial resources to invest in solar and battery storage – while reducing the environmental impact of the energy transition. Specifically, we compare two cases that have the same solar and wind supply and the same loads. We continue to use the example of Maryland loads with

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[24] In some cases, demand response may increase the total load. For instance, electric vehicles can be used to supply electricity to the grid in deficit periods in what is called the vehicle-to-grid mode. These vehicles would need to be recharged during surplus supply hours. This use of vehicles for demand response involves electricity losses, increasing the total load somewhat. It is akin to battery storage rather than to appliance run times.
[25] Stoll, Buechler, and Hale 2017
[26] In states where utilities are fully integrated and regulated, as for instance in the Southeast, regulated utilities are also the grid operators. In states where generation is de-regulated, as for instance in New England and the mid-Atlantic region, grid operators – known as regional transmission organizations (RTOs) or Independent System Operators (ISOs) are distinct entities responsible for maintaining reliable supply.
[27] FERC 2020.
[2828] FERC 2020, pdf p. (pdf p. 6) , footnote 1.

electrified heating and road transportation in December, which had the largest persistent gaps between renewable energy supply and loads. The two cases switch the dispatch order of battery storage and aggregated demand response as resources for the grid.

1. **Case 1: Batteries first**: Surplus renewable energy (RE) is used to charge batteries first; a part of the load that cannot be served directly by renewable energy supply or via batteries would be available for demand response (DR). Schematically this can be represented as
    - *Renewable energy→Batteries→Demand response.*
2. **Case 2: Demand response first**: The order of demand response and battery dispatch is reversed: the part of the load subscribed to demand response not directly served by solar and wind supply is shifted to some other hour of the same day when surplus solar and wind supply is available. The remaining surplus renewable energy is available to charge batteries. Schematically this can be represented as
    - *Renewable energy→Demand response→Batteries*

There are several metrics that can be used to compare these two cases. We used the metric that the same total cumulative monthly load should be met in both cases (just over 90%) by the combination of renewable supply, batteries, and demand response. The rest of the load would be met by very long-duration storage technologies such as hydrogen used in fuel cells, compressed air energy storage, or some mix of long-duration storage methods that can store energy from a few days to weeks (as discussed above in Section 4.2).

We used the same battery type in both cases: a 10-hour, 10,000 MW long-duration storage battery with 70% roundtrip efficiency in both cases because this was found to meet the largest cumulative monthly load in Case 1 (just above 90%).[29] In both cases, solar and wind supply directly meet about 75% of the cumulative load for December. The peak monthly load was 15,292 MW. Table 4-1 shows the results.

Table 4-1: Role of storage and aggregated demand response dispatch order in a winter month in a system with only solar and wind primary energy supply.

	Demand response amount MWh	Generation from the battery	Battery size needed MW - 10 hours 70% roundtrip	Max hourly deficit load, MW after batteries and demand response	# of hours of deficit load remaining (to be met by other methods)
Case 1: RE then battery then DR	20,856	1,088,249	10,000	13,521	144
Case 2: RE then DR then battery	745,735	290,576	4,000	9,942	181

Notes: 1. Peak load for the month without storage or demand response: 15,292 MW
2. Solar and wind supply only. Total cumulative supply for the month: 7,296,294 MWh. Cumulative monthly load: 7,179,138 MWh.

[29] The battery modeled in Makhijani 2016 was a 4-hour 12,500 MW battery (that is a maximum storage of 50,000 MWh) with 87% roundtrip efficiency. As explained above we assume that a 10-hour battery with about 100,000 MWh storage (10,000 MW capacity) with 70% roundtrip efficiency would be equivalent in cost. We use the latter for this analysis because it met a higher fraction of the cumulative monthly load than the 4-hour battery.

3. Battery parameters: 10-hour storage; 70% roundtrip efficiency
4. Demand response assumptions of hourly load amounts available for DR: 80% of electric vehicle load; 15% of heating and cooling residential load; 40% of other residential loads including water heating, clothes washing and dishwashing, but excluding lighting, cooking, and miscellaneous plug loads; 25% of commercial and industrial load. These are example values for the purposes of illustration. Participation varies significantly and depends on many factors .[30]
5. Demand response loads must be served within the same calendar day.

The results in Table 4-1 demonstrate the superiority of dispatching aggregated demand response first and utility-scale battery resources second in a number of ways:

- The requisite battery size for serving the same cumulative monthly load is reduced by 60%.
- Energy losses are lower because more load is directly met by renewable energy rather than via battery storage.
- Though the same load is available for demand response, dispatching demand response first allows for almost 40 times more load to be served via demand response than if batteries are dispatched first. *Therefore a much larger amount of the total revenue would go to consumers, lowering their overall cost of electricity, if demand response is dispatched first.*
- It provides opportunities for renters and low-income homeowners who cannot afford solar or battery investment to participate in and benefit from the energy transition in ways that they can control and benefit from economically.

This analysis does not apply to customer-owned distributed battery resources that are behind the meter because they can be managed in a demand response mode.

A washing machine participating in demand response (via an aggregator) provides a glimpse of how the system would work. A smart washing machine would have the option of being operated at the time the "Start" button is pushed or at some later time, according to programmed instructions that conform with the availability of supply on the same day for consumers who select that option to benefit from a cheaper rate.[31] A customer having a clothes washing machine in their home could sign up for that machine to be on demand response under pre-specified conditions. Enrolling in demand response would be voluntary; a set electric bill credit would be provided each year. A typical condition would be that, should supply be in deficit at a given time, the appliance operation would be deferred but guaranteed to operate within a set period, such as 24 hours. This enables matching demand response loads to available renewable energy in other hours of the day than the hour in which the "start" command is given. There would be an added payment each time the operation of the machine is deferred. The grid operator can thus meet demand by shifting loads at times of deficit to times when supply is available. *When supply is variable solar and wind electricity, demand response can be seen as harmonizing the operation of the electric grid with the rhythms of nature – though only in part*. It would be harmonized with the economic system because there would be a payment to the consumer to adapt to the rhythms of nature.

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[30] Those factors include whether the customer has access to technology such as programmable thermostats that can communicate with the grid, on pricing, and the methods of subscribing to demand response. FERC 2009.
[31] Clothes washing and dishwashing machines are interesting examples because two loads are shifted – the electricity to run the motor and the electricity to heat the water used for the washing.

i. Economic implications

The above heuristic calculations illustrate that dispatch order of supply from storage or aggregated demand response can make a significant impact on the amount of storage needed for a given amount of solar and wind energy. Demand response gives control over the timing of energy use and, to that extent, over the total cost to the customer for serving a given set of loads. It is difficult to quantify the economic impact in the abstract because the actual acceptance of aggregated demand response or battery supply by a grid operator will depend on the relative prices of the resources. If demand response is to have priority, it would have to be offered at a lower cost than electricity from utility-scale batteries; that, however, limits the incentive for customers to participate in demand response.

Dispatching demand response first reduces the battery size required by thousands of megawatts of for just one state, Maryland, that has just under 2% of the population of the United States. This indicates that the financial impact of dispatch order for the whole country in terms of investment could run into tens of billions of dollars. Demand response need not have a single price. Lower prices could be offered for loads that are relatively easy to shift such as clothes washing machines; higher prices would be offered for heating and cooling demand response.

ii. Policy implications of demand response and dispatch order

The above illustration is heuristic; it is meant to schematically illustrate the importance of integrating the various elements of the energy transition, including "non-wires" elements, notably demand response, in the right order to the benefit of efficiency, affordability and energy democracy. Promoting energy democracy and energy affordability for low-income households and disadvantaged communities (whose demand response subscriptions could be aggregated) would require universal access to broadband; renters would need smart appliances to enable them to participate in demand response.

But those minimum requirements will not guarantee significant, much less maximum, benefit from the opportunities afforded by demand response. Aggregated demand response is not yet common. Dispatch order is normally according to the price of the resources, with the cheapest being dispatched in preference, within the overall constraint of maintaining reliable supply. Dispatch would work differently in states with vertically-integrated utilities that also serve as the grid operators within each state. In most such cases, the vast majority of electricity is in the purview of investor-owned utilities whose profit is determined by the undepreciated capital investment in their account books. Shareholder interest would tend to prefer owning resources to maximize profit rather than passing revenues to customers for demand response.

In deregulated areas, resources are dispatched according to cost. The relative cost of electricity and the payments set for demand response would enter into the dispatch picture. Aggregators would have to offer demand response to grid operators at an appropriate scale and price. Enabling households and businesses, including small businesses, to benefit significantly from demand response may require the introduction of distribution system operators for the low voltage part of the electricity system as counterparts of the high-voltage large-scale dispatch of electricity now managed by independent system operators (or utilities in non-deregulated states). Demand response can enable a different partition of electricity revenues than a dispatch system based solely on overall cost. Legislation as well as regulatory changes – including refinement and elaboration of FERC Order 2222 may be needed.

Many states have recognized such issues by enacting legislation and initiating regulatory proceedings in connection with microgrids but also including demand response.[32]

There are other moving parts than those considered in this section – as is clear from the next chapter where the role of emissions-free distributed resources in increasing resilience is explored. For instance, the example above is focused only on the dispatch order between battery storage and demand response (since renewable energy supply is the same in both cases). The issue of reducing the maximum load not served was not considered; this could be done by increasing efficiency and behind-the-meter distributed solar and storage resources.

In practice increasing the cumulative load served and reducing the peak unserved load are important economic parameters when balancing batteries, demand response, as well as other distributed energy resources, including behind the meter resources. Optimization of distributed resources of various kinds as well as achievement of specified equity goals along with emission reduction targets is a complex problem. The present exploration of dispatch order of batteries and aggregated demand response illustrates the opportunities afforded by the energy transition. But much more comprehensive modeling is needed to simultaneously include multiple objectives, including decarbonization, energy equity and affordability, reducing pollution burdens on frontline communities, and increasing resilience.

It is critical to stress that demand response does require specific resources – internet-enabled appliances (also called "smart appliances") and access to broadband. Low- and moderate-income households may not have access to them. If they own their homes, they may not be in a financial position to spend extra for internet-enabled appliances. Landlords who own affordable housing have no incentive to spend more on smart appliances. While there are incentives for broadband access, many households do not take advantage of them.[33] As is generally the case with assistance programs, participation in broadband access is far from universal. It was estimated at 57% in 2021.[34] A combination of incentives, intensive outreach about broadband and demand response access (and terms), and clearly demonstrable savings on electricity bills are among the necessary conditions for demand response to contribute to an equitable and affordable energy transition.

iii. Some general storage and demand response considerations

The heuristic modeling above assumes entirely renewable energy supply, implying that battery charging will always be with zero-emissions electricity. However, today's U.S. electricity supply is far from such a situation; the majority of electricity supply is still from fossil-fuel plants. Were the charging of batteries simply to occur at the times of lowest price, carbon emissions may well rise. Thus if the goal is the lowest possible emissions on the path to a zero-emissions grid, there will have to be incentives for charging batteries at the time of low emissions or regulatory constraints or both, again illustrating the importance of locating specific measures in an overall context.

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[32] Jones et al. 2022.

[33] Broadband access is a much larger equity issue – for instance as regards education equity and tele-medicine access – points raised in National Governors Association 2022?

[34] National Governors Association 2022?

5. Community energy resilience: The role of long-duration energy storage technologies

The centrality of electricity in people's lives and the increasing frequency and intensity of extreme weather events, driven by climate change, require investments to minimize the impact of prolonged grid outages. Complete loss of electricity for days at a time has profound adverse effects on the health and well-being of individuals and communities. One important goal must be to maintain continuity of electricity supply for essential services in a community – such as a hospital, heated or cooled spaces to shelter the public that have lost their homes or access to them for some time, emergency response services, a gas station, or a supermarket. Although multi-day grid outages are rare, compared to outages of a few hours, their impacts are disproportionally larger and must be planned for.[35] They are also increasing in frequency.[36]

Current planning and investments in backup power energy systems are not equitable. Typically, communities and individual households which have the means can – and often do – install fossil fuel emergency generators, while disadvantaged communities suffer prolonged supply disruptions. In addition, outage frequency and durations are more common and have a greater impact in low- and moderate-income (LMI) communities due to long-term underinvestment in LMI community infrastructure.[37]

This chapter explores the potential both of commercially available energy storage and renewable generation technologies as well as of emerging long duration energy storage (LDES) systems to provide clean (zero carbon) energy resilience solutions for LMI communities.[38] We examine two cases: (1) providing energy resilience to a single midrise apartment building and (2) providing energy resilience to a set of facilities that house critical loads that support the whole LMI community through a community microgrid. We estimate the net costs of different long-duration storage technologies to meet the same resilience criteria.

We first focus on cases in Baltimore, Maryland in detail and then briefly examine community microgrids in New Orleans and Chicago. Baltimore City was selected for the most detailed analysis because it represents a common and widely distributed climatological zone (see Figure 5.1).

[35] Hanna and Marqusee 2022
[36] Larsen et al. 2018
[37] Do et al. 2023
[38] Denholm et al. 2021

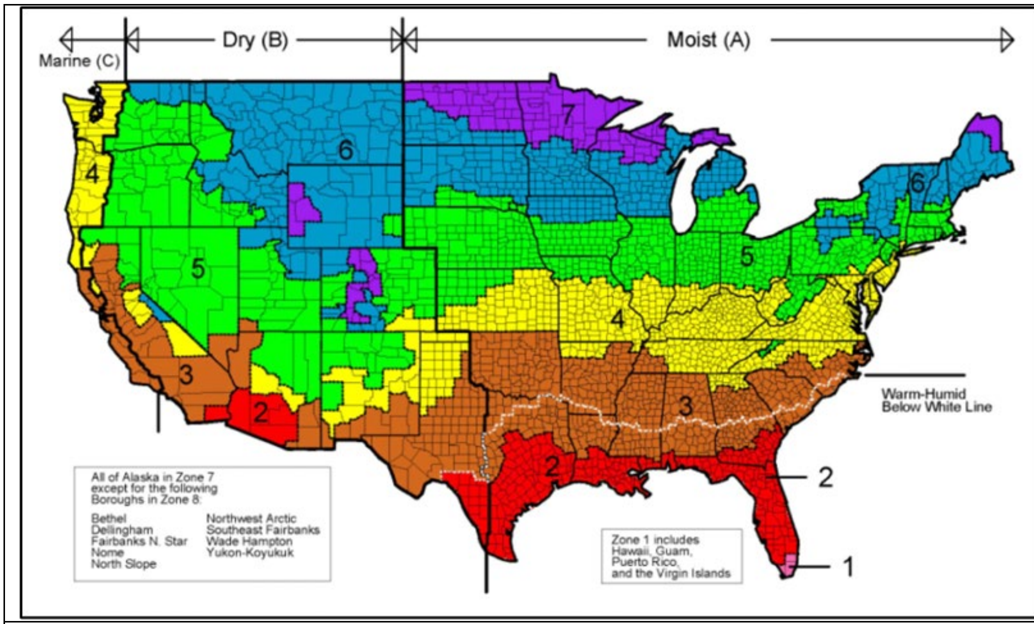

Figure 5.1 - Climate Zone Classifications for U.S. DOE Commercial Reference Building Models[39]

Unlike Chicago and New Orleans, the energy market in Baltimore city's utility territory, which is run by Baltimore Gas & Electric Company, is particularly favorable to energy storage as time-of-use rates are available to incentivize customers to consume when energy is cheapest. LDES technologies deployed in Baltimore can optimize energy use by storing electricity purchased from the grid during low-cost periods and offsetting electricity consumption during peak-demand periods when the cost is highest. These conditions are not present in cities such as Chicago or New Orleans where overall electricity prices are much lower than in Baltimore. The state of Maryland has also introduced incentive programs geared towards supporting the development of resilient community microgrids. Such competitive grants were not considered within our economic analysis as their receipt is not guaranteed.

5.1 Background

Hurricane Sandy in 2012 brought home the need for a more reliable supply of essential services. More than 20 million people lost power – many of them for days and some for weeks. Elderly people were stranded on the upper floors of apartment buildings with no functioning elevators; gas stations could not dispense gas because they needed electricity for the pumps to operate; part of the subway in New York City was flooded; even trading on Wall Street closed for two days.

Hurricane Sandy was extreme in the damage it caused, but it is part of a pattern. The count of extreme events and the total damage they cause has been increasing, as is evident from the data in Figure 5.2.

[39] Deru et al. 2011, pg. 7

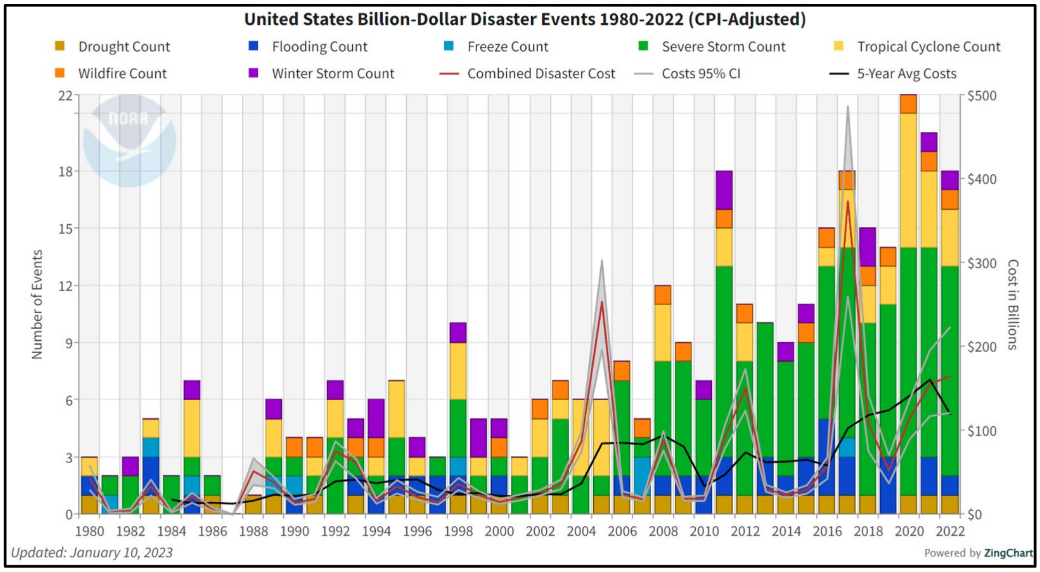

Figure 5.2: Billion-dollar-plus disasters in the United States,1980 to 2022, showing event type (colors), annual frequency (left-hand vertical axis), and annual total cost (right-hand vertical axis.) A five-year smoothed average annual cost is also shown.
Source: NOAA, 2023.

Historically, facilities and communities have relied on emergency diesel generators tied to individual buildings to provide electric power to some essential facilities during a grid outage (see Figure 5.3).

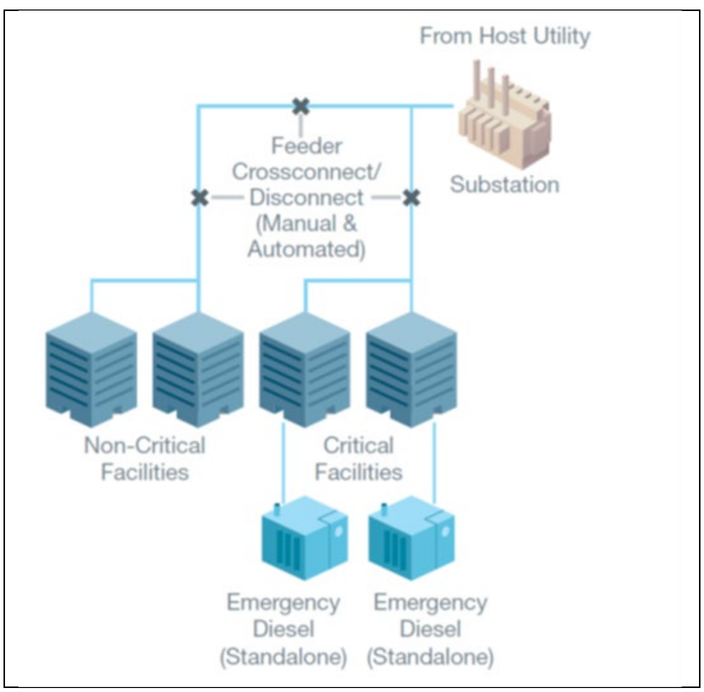

Figure 5.3 Historical Energy Resilience Approach: Standalone Generators tied to Individual Buildings[40]

Individual building-tied emergency diesel generators have proved to be a robust solution to protect individual facilities in the case of short (1 to 4 hours) grid outages. They are easy to install and for short duration outages sufficient fuel can be stored on the site with the generator. They are not designed or capable of providing reliable power for multi-day outages.[41] They are likely to fail after a few days; among other things, providing diesel fuel during a muti-day outage is a major challenge and vulnerability. Few locations can store the amount of fuel needed to meet a multi-day outage. Moreover, diesel generator release health-damaging air pollutants such as particulate matter into the surrounding community, not only during emergency events, but also during regular testing, which must occur on a weekly or monthly basis.

Today providing energy resilience to a set of critical facilities on a campus, behind-the-meter, is often done through a microgrid.[42] Networking distributed energy resources (DER) like diesel generators, energy storage, and distributed renewable energy provides a robust and reliable backup power system that can provide energy resilience over days and weeks (see Figure 5.3). In recent years the concept of a campus or a behind-the-meter microgrid has been expanded to the concept of a community microgrid where multiple customers share in the energy resilience value of the microgrid. For instance, the NGO Clean Coalition explicitly promotes large scale community microgrids that are in front of the meter and cover large numbers of customers. Increasing resilience is an explicit objective.[43]

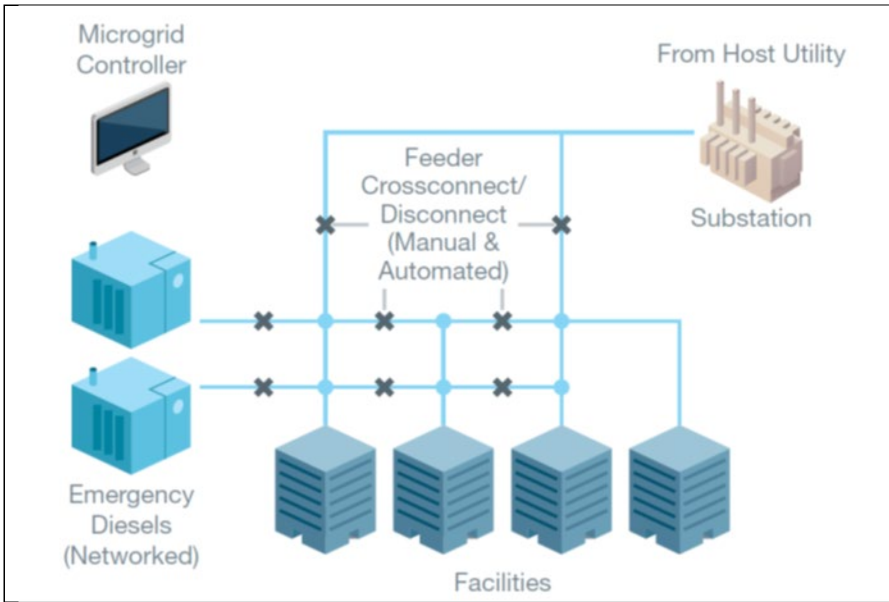

Figure 5.4 A set of diesel generators networked into a microgrid to provide energy resilience to multiple buildings.[44]

[40] Marqusee, Ericson, and Jenket 2020
[41] Marqusee and Jenket 2020 and Marqusee and Stringer 2023
[42] Van Broekhoeven et al 2013 and Marqusee, Ericson, and Jenket 2021
[43] Community microgrid webpage of the Clean Coalition at https://clean-coalition.org/community-microgrids/
[44] Marqusee, Ericson, and Jenket 2020

We will return to the differences between a behind-the-meter microgrid and a community microgrid and discuss the challenges of microgrids with customers on more than one feeder, including for LMI community microgrids.

5.2 Energy resilience metrics

The U.S. government has defined resilience as follows:

> **Resilience**: The ability to prepare for and adapt to changing conditions and recover rapidly from operational disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents.[45]

In the case of energy, this approach to resilience implies minimizing grid outages, restoring power rapidly in the event they occur, independent of the cause, and maintaining power to critical loads during outages so that communities are not deprived of electricity-dependent essential services during those times. In a fact sheet on its Energy Transitions Initiative the Department of Energy has defined “energy resilience” as follows:

> The ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from energy disruptions.[46]

Traditional grid reliability metrics do not cover disruptions expansively. They describe how frequently average customers experience outages and how long such outages persist on average.[47] However, these metrics are insufficient for assessing community energy resilience because they refer to grid outages in the normal course of events. For example, a common reliability metric, called “Loss of Load Expectation”, is that a customer’s average loss of electricity services should not exceed 0.1 day (just under two-and-a-half hours) per year. But this does not take extreme events such as storms and fires or even the preemptive public safety power shut-offs used by California utilities to reduce the risk of transmission-line-triggered fires.

States typically only regulate the local utility’s ability to meet reliability requirements during “normal conditions” or “blue sky days” and ignore what are termed, ”major event days”, when customers experience loss of power when storms down local power lines or when hurricanes or fires cause major transmission lines to fail. This is woefully inadequate even for average customers and more so for frontline communities; increasing climate extremes will aggravate the problem. As a result, it is now generally recognized that a larger concept is needed; it is expressed in the term “resilience”. Among other things, this concept includes reducing the number of outages whatever the cause, and reducing their duration. It also includes maintaining continuous electricity supply during outages to critical loads in a community. This chapter is limited to exploring this specific aspect of resilience because it illustrates the role of long-duration energy storage in achieving it.[48]

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[45] DOE 2021, paragraph 71, pdf p. 127
[46] Energy Transitions Initiative 2023
[47] IEEE 2012
[48] There are many other aspects to resilience. For instance

Incorporating equity into resilience metrics often involves departing from traditional technical approaches. These conventional methods often lead to significant gaps in understanding how diverse community members experience resilience events. In response to these gaps, many scientists have redirected their resilience research towards metrics that better capture the human and social impact of major disruptive events. Of particular note are recent applications of the Capabilities Approach Theory of Human Development[49] to creating equity-centered social burden metrics, which were first used to examine future microgrid applications in Puerto Rico after Hurricane Maria.[50] Maintaining or improving energy affordability while improving resilience is also a critical equity consideration. There are also institutional and regulatory aspects to this aspect of resilience; we discuss those briefly after describing the technical and economic aspects.

Defining essential (critical) loads must involve community input; often, they include health care (e.g. clinics, medical equipment), food (e.g. refrigeration, grocery stores), water (e.g. sump pumps, wells), fuel supply, charging for cell phones, emergency response and provision of shelter for people displaced by the impacts of extreme weather events and grid outages. The metrics for this aspect of resilience must include defining the essential services and the period of the expected outage. Another key metric is the cumulative probability with which all essential or critical loads can be served continuously for the outage design period (usually multiple days).

Evaluating the quantitative energy resilience performance of a potential backup power system requires comprehensive modeling that optimizes across (a) its resilience performance and (b) its economic performance. The key resilience metric is the cumulative probability that the backup power system can support all pre-defined critical loads (also called essential loads) for a pre-defined outage duration. To some extent, this probability depends on when the outage starts, especially in a renewable energy-plus-battery-system. We calculate this probability by averaging across all potential grid outage start times in the year. This is called the **survival probability**.

The economic performance is best measured by calculating the system's lifecycle costs or net present value (NPV).[51] That allows consideration of both upfront installation costs as well as annual operations and maintenance costs. In addition to these, issues of safety, environmental impact (particularly air emissions) and siting impacts all should be factored in, in alignment with the community's goals. There is, of course, some tension between economic performance and resilience performance. More money could, in principle, ensure better resilience performance, but that may not be very affordable. A great

[49] "The Capabilities Approach (CA) was developed and popularized by economist and philosopher Amartya Sen and philosopher Martha Nussbaum [and] offers an alternative to traditional economic perspectives of development, eschewing both utility (i.e., subjective experience) and income-based measures in favor of outcome-based understandings of well-being (i.e., what people are able to do and to be)" in Clark et. al., 2023, p. 360.

[50] Jeffers et al. 2018

[51] Net Present Value (NPV) is a financial metric that seeks to capture the total value of an investment opportunity by accounting for all future cash inflows and outflows associated with an investment, discount all those future cash flows to the present day, and then add them together. A positive NPV means that, after accounting for the time value of money, the investor will have a net positive return on investment; a negative value implies it will cost money. NPV calculations are sensitive to multiple assumptions such as equipment capital costs, sustainment costs, inflation rates, tariff structures, state regulations, tax incentives, and discount rates. In the next section and in Appendix B, we list all the assumptions used. The assumptions here are typical and used for illustrative purposes. Specific project design must correspond to the business and financial arrangements particular to the project at hand.

deal also depends on the choice of technologies and how they are combined to produce a given level of assurance of meeting critical loads during prolonged outages.

Determining the resilience needs of a community can be a challenging task requiring an in-depth understanding of both the anticipated impacts of regionally-specific extreme events and how those events may affect the health and wellbeing of the community.[52] Further complicating this matter is that communities can differ in their level of dependence on energy infrastructure to meet their basic needs. Therefore, decisions involving resilience investments must be preceded by a comprehensive process aimed at understanding a community's vulnerabilities, anticipating the scale of potential events, and then determining the critical infrastructure required to address a community's needs. This must integrally involve the communities themselves. Two key issues must be assessed during this initial phase:

- **Drivers of Consequence: Understanding community-specific interdependencies of essential services and the electric system:** This analysis should result in the identification of the critical electric loads and their priority. This assessment includes examining the interdependence between the electricity system and the other essential infrastructure that it impacts, such as communications, transportation, and water supply. The largest cost of a backup power system is determined by the peak critical power load that must be supported because that largely determines the size of the system. Carefully identifying and prioritizing critical loads is essential to create an affordable system that will serve the community effectively.
- **Outage Durations of Concern**: Resilience is inherently time-dependent, meaning that the necessity for certain goods and services is largely dependent on the duration of the event. Therefore, it is of the utmost importance to develop informed estimates of the duration of outages to ensure that there is a match between the selection of essential loads and the system size and design. A mismatch can result in poor system performance relative to expectations or in higher costs relative to the stated needs of the community.[53] Non-electricity system considerations are also involved, such as the potential for relocation in case of extremely long outages.

Answering these key questions cannot be done in the abstract. They require direct communication with the impacted community, details on the load characteristics of different facilities, and iteration with the local utility. In the two applications discussed below, we provide a set of realistic (though hypothetical) cases. They should be viewed as one of many possible realistic choices for these two applications – single apartment buildings and communities. Again, as in the analysis of lifecycle costs, the assumptions made on the community's energy resiliency requirements directly impact the design and performance of the backup power system.

5.3 Energy resilience technology

Energy technology such as diesel generators, solar PV, and energy storage can be deployed in front of the meter in support of the grid or behind the meter. In the case of microgrids, the loads have

[52] Do et al. 2023
[53] Ericson et al. 2023

historically been aggregated behind the meter so as to make it easier to create an electric island – that is, a system that usually has only a single point of connection to the grid and is easier to disconnect and operate independently of the grid during outages. This enables operation with the grid for the best economic performance (e.g. generating electricity onsite when prices are high and buying from the grid when prices are low) and automatic disconnection from the grid, called “islanding” so as to serve essential loads within that electrical island. Such a microgrid arrangement can provide direct value for consumers beyond the functions served during outages. This differs from traditional building-tied emergency generators that are normally idle; they are only operated during grid outages and when they are tested.

Both in-front-of-the-meter and behind-the-meter locations can contribute significantly to energy resilience. In front of the meter resources provide support to the grid to avoid grid outages and improve grid reliability. Behind the meter resources, that can be islanded during a grid outage and provide power directly to critical loads when the grid goes down, and provide community energy resiliency. In this subsection, we review the expected costs and performance of traditional emergency diesel generators, solar PV, and energy storage technologies ranging from commercial stationary Li-ion batteries to emerging LDES technologies such as Fe-air batteries and TPV storage. We consider only electricity output in the case of TPV systems even though they are capable of both thermal and electrical output.

Generation and storage technology costs and performance depend on the power level required. Thus, we provide estimates for the scale required for a single building (tens of kilowatts) and that required for a community microgrid, which are much larger (megawatt-scale). For technologies that are commercially available we provide estimates for today’s costs and performance. For emerging LDES, as well as existing commercially available technologies, we provide estimates of expected costs in 2030 before which the two emerging technologies we model are expected to be commercially available.

Providing backup power, whether to a single building or a community microgrid, involves costs beyond the generation and storage technologies, though these two elements are the dominant cost drivers.[54] Costs associated with design, interconnection agreements, controllers, and switches are also important, as well as system maintenance and training and support for people to operate the facilities and make critical decisions during an outage scenario. These costs tend to vary greatly site to site but are very similar for a given site, independent of the generation and storage technology choices. Given that , we have ignored these factors to compare only the relative costs of the distributed energy resources (DERs) for simplicity.

The costs (negative NPV) or revenue (positive NPV) of the DERs must be added to the other costs to fully define the total system costs. An overall negative NPV means the system will not pay for itself given everyday operation on the electric grid; a positive NPV means that it will yield a surplus – or profit. Another way to look at it is that a negative NPV provides an estimate of the cost of achieving a specified level of resilience and translates into higher energy costs in the absence countervailing action. A positive NPV would translate into lower annual energy costs – a benefit in addition to improved resilience.

Individual energy generation and storage assets have finite reliability as well as fuel limitations. For example, the length of diesel generator operation is determined by the capacity of the fuel tank (if more fuel cannot be delivered during an outage as is sometimes the case). Sunlight is a determinant for solar

[54] Giraldez et al. 2018

PV generation – making the outage start time more important; the state of charge of the battery at the start of an outage and recharge rates are important for storage technologies. Three metrics define generation and storage reliability:[55,56]

- Failure to Start (FTS) probability = number of failures to start/number of attempts to start.
- Availability (A_o) = (lifetime − time offline due to repairs and maintenance)/lifetime.
- Mean Time to Failure (MTTF) = total runtime/number of failures while running.

These reliability factors have a very large impact on diesel generator performance and are one of the reasons diesel generators have limitations in providing energy resilience over multi-day grid outages. We factor these impacts into our analysis of generators and solar PV. We also fully account for diesel fuel limitations, solar PV variability, and charge constraints explicitly in the analysis presented in the later sections. Before that, we survey the technologies we use in the analysis of resilience in this chapter.

5.3.1 Emergency diesel generators

Diesel generators are a common and mature technology. Their installed and annual operations and maintenance (O&M) costs depend on their power level (kW), whether multiple units can run in parallel, the size of the diesel fuel storage, and the level of air pollution control required. Emergency diesel generators that only run for testing and during emergencies are exempt from EPA air pollution control requirements.

An individual diesel generator, even if well maintained, will fail to start almost 1% of the time, be available 99.5% of the time; and, on average, fail after 1,100 hours of operation (see Table 5.1).

Table 5.1 Diesel Generator Reliability

Reliability Metric	Values
Failure to start	0.94%
Availability	99.5%
Mean time to failure	1,100 hours

Source: Marqusee and Stringer 2023

If the generators are not well-maintained reliability is much worse. A single well-maintained emergency diesel generator has a survival probability after 96 hours of approximately 90%.[57] That is why hospitals, which depend on emergency diesel generators, are required to have a diesel generator backup to the

[55] Marqusee and Stringer 2023.

[56] Not all three are required for every technology. For the DERs we are considering, failure to start is only relevant for diesel generators.

[57] In mathematical terms, the survival probability at time *t* for a single generator is (1-FTS) x A_o x exp(-*t*/MTTF), where FTS is the probability of failure to start, A_o is the availability, exp is the exponential function, t is time, and MTTTF is the mean time to failure. The values in Table 5.1 give the survival probability after 96 hours as equal to (1-.0094)*.995*exp(-96/1100) = 0.90 or 90%.

diesel generator backup to ensure critical loads are met with a cumulative probability far higher than 90%.

Typical emergency diesel generator costs[58] are shown in Table 5.2. The installed costs include the generator, fuel tanks, balance of system, and installation costs. The O&M costs include generator maintenance, testing costs, and fuel cleaning.

Table 5.2 Diesel Generator Costs

Case	Installed Costs ($/kW)	O&M Costs ($/kW-year)
Single building	$1362	$87
Community microgrid	$856	$61

Source: Calculated using the Generac Online calculator

Both systems have 96 hours of fuel storage and assume diesel costs $3/gallon. Single building diesel generators are only tens of kWs while the community microgrid generators are in the hundreds of kW range (or larger). A single building generator with only 48 hours of fuel storage will have only slightly lower costs, $1324/kW and $73/kW-year. Increasing the duration of backup power with generators has a modest cost impact because all that is required is larger fuel storage. The community microgrid also requires multiple generators running in parallel while the single building would use only one generator.

5.3.2 Solar PV

Solar PV is a mature, widely available technology. We consider two scales of solar PV. For the single building we assume a fixed roof top system (small commercial scale) at a cost available today. For community microgrids we assume a large community (or small utility-scale) solar system at a cost available today and expected in 2030 that is ground mounted. Both scales are highly reliable. Detailed solar PV reliability modeling demonstrates that the mean time to failure for solar PV is very long and failures during an outage can be ignored.[59] In other words, if the solar PV is operating when the grid outage occurs it is highly unlikely to experience a failure during the grid outage. Although component failures are rare, it can take days to months to repair a solar PV system. Analysis shows that utility scale solar PV has an availability of greater than 99% and commercial scale PV is greater than 98%.

We assume the following costs for solar PV.[60]

Table 5.3 Solar PV Costs

Case	Installed Costs ($/kWdc)	O&M Costs ($/kW-year)
Single building 2023	$1857	$21
Community microgrid 2023	$1370	$24
Community microgrid 2030	$1030	$18

Source: NREL ATB 2022

[58] All cost estimates were converted into 2023 dollars.
[59] Marqusee and Stringer 2023
[60] The single building is based on a fixed roof mounted system between a commercial and residential size and the community is based on a fixed ground mounted small utility scale system.

5.3.3 Energy Storage

In this report, we characterize energy storage by four values: power output, energy storage capacity, roundtrip efficiency, and maturity.

- **Power output in kilowatts** (kW) is the rate at which energy can be exported; the higher the value, the larger the electrical demand that can be supplied. An important caveat for some energy storage is that power output—the rate at which power is supplied by the storage to loads—can be different from power input, or the rate at which energy can be stored into the battery.
- **EnergyStorage capacity in kilowatt-hours** (kWh) is the amount of electrical energy stored within a battery and is also represented by the amount of time (hours) at which the rated power output can be sustained without recharging.
- **Roundtrip efficiency** (RTE), expressed as a percentage (%), is the amount of exportable energy by a storage system as a fraction of the energy input into the system after all conversion inefficiencies (i.e., losses) are accounted for. There are losses both when the storage system is charged and when it discharges. We report AC electricity to AC electricity roundtrip efficiency. A separate metric, the self-discharge rate, is often used to describe loss of stored energy while the battery is idle. We have not considered the impact of self-discharge rates in this analysis.
- **Maturity of the technology** reflects our consideration of the current state of development. We use the technology readiness level to describe maturity. A commercial product will be at a technology readiness level of 9, a late-stage prototype will be an 8, and an early beta prototype will be at a 7. Lower technologies readiness levels reflect technologies still under development; they are not considered here, but many are being explored and hold potential to come to market in the coming decades.

We have modeled four types of energy storage systems. Two commercially available systems: stationary Li-ion batteries[61] and Redox flow batteries; and two emerging LDES systems that are expected to be commercially avaible by 2030.[62] [63] The two emerging LDES we consider are Iron-Air ("Fe-Air") batteries, and thermal storage coupled to a Thermal PV (TPV). In this last example, input electricity is stored as thermal energy; the heat can be used directly in industrial processes, or used to generate electricity using infrared-sensitive photovoltaics, or both. We model only the electricity output aspect of TPV here.

Our intent is not to model any specific vendor's system; the aim is to illustrate the variety of systems that are either currently available or will be in the next several years. For commercially available storage technologies where there are multiple vendors our estimates reflect typically available cost and performance. For emerging technologies there is no typical data. We have chosen to look at two widely discussed technologies that are being specifically designed for long duration storage, Fe-air and thermal storage coupled to a TPV. They are intended to serve as examples of what could be available in the future and not selected to endorse them over other emerging LDES technologies. The specific

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[61] There are many chemistries used in Li-ion batteries; we do not distinguish between them for the purposes of the illustrative analysis done here. Battery chemistry impacts safety among other factors.
[62] Sepulveda et al. 2021
[63] There are many vendors of commercially available Redox flow batteries. The most common type are vanadium flow batteries. Performance of Redox flow batteries are very similar independent of the chemistry.

technologies modeled does not mean that they are the specific type (much less vendor) that should be chosen in any specific development effort; situation specific analysis is always required.

There are a large number of manufacturers of stationary Li-ion batteries, typically sold with storage durations between 1- and 8-hours duration. For the flow battery, we modeled vanadium redox. It is the most common type of redox flow; multiple manufacturers provide vanadium redox products, typically with storage durations between 8 to 12 hours. The performance of other redox chemistries is very similar (see Tabel 3-2). As a result, the vanadium flow battery analysis also roughly applies to zinc-bromine[64] or iron-flow batteries[65] or hybrid zinc batteries.[66]

Fe-air batteries are part of a broader class of metal-air batteries. Currently, Form Energy[67] is demonstrating an LDES Fe-Air system and plans to commercialize a 100-hour duration battery. Antora Energy[68] is testing a prototype TPV system that will likely be first available in the market at a 24-hour duration and is expected to be available up to 100-hour duration. We used data available on these two systems to estimate potential cost and performance in 2030; they are expected to be commercially available before that time. Other TPV companies, like Fourth Power, are testing their own approaches as well.[69]

LDES systems tend to be quite large in terms of power levels and physical footprint, for a single building where the available space is very limited. For that reason, we have only considered Li-ion for the single apartment building case.

Table 5.4 Storage Performance

Case	AC to AC RTE (%)	Charging to Discharging Ratio[70]	Technology Readiness Level	Commercially Available
Li-ion	90%[71]	1	9	Yes
Redox Flow	69%	2	8	Yes
Fe-Air	38%	1	8	No
Thermal Storage & TPV	38%	>3	7	No

[64] Manufactured by redflow at https://redflow.com/zbm3-battery
[65] https://essinc.com/iron-flow-chemistry/
[66] https://www.eose.com/technology/
[67] https://formenergy.com/
[68] https://antoraenergy.com/
[69] Fourth Power (at https://www.linkedin.com/company/fourth-power-inc/about/
[70] In principle charging/discharging ratio can be greater than 1 for Li-ion batteries. In practice, charging is limited by inverter capacity as well; this is the reason for choosing a ratio of 1 for resilience applications. A higher cost could accommodate a larger ratio if justified by the specific design situation.
[71] The 87% roundtrip efficiency used for the utility-scale calculations in Chapter 4 was chosen to stay consistent with the calculations in Makhijani 2016 since that hour-by-hour modeling analysis was used to illustrate the calculations there.

Table 5.5 Storage Costs[72]

Case	Current Installed Costs	15-year Replacement Costs (Today)	Installed Costs (2030 deployment)	15-year Replacement Costs (2030 deployment)
Li-ion Single building	$1500/kW and $500/kWh	$220 kWh and $440/kW	-	-
Li-ion Community microgrid	$775/kW and $388/kWh	$220 kWh and $440/kW	$465kW and $230/kWh	$265/kW and $130/kWh
Redox Flow Community microgrid	$1700/kW and $600/kWh	$50/kW (Note 1)	$1000/kW and $300/kWh	$50/kW (Note 1)
Fe-Air Community microgrid	-	-	$2000/kW for 100-hour duration	$1000/kW for 100-hour duration
TPV community microgrid	-	-	$600/kW and $10/kWh	$50/kW (Note 1)

Notes: 1
1. $50/kW represents only replacement of the inverter that converts DC to AC.

The cost estimates listed above should be viewed with caution. The costs today for Li-ion and Redox flow batteries are based on empirical data though costs do differ depending on the specific vendor. The cost projection for Li-ion is based on detailed independent modeling[73] while the other 2030 cost estimates are based on industry's projected future costs. As indicated in tables 5.4 and 5.5, costs, roundtrip efficiency (RTE), and ratios of power charging to discharging are quite varied. To understand the relative value proposition, one must look in detail at the application and system level performance. For short duration storage applications, Li-ion batteries are the default technology since it is mature, fully commercial, and has a very high RTE. But as the requirement for long duration storage grows, other technologies show potential. The reliability of all the LDES technologies in Table 5.4 and 5.5 is expected to be quite high but that of emerging technologies is currently uncertain due to insufficient operating experience in the field. For modeling purposes, we assume they are 100% reliable. In the next section we review the modeling approach and then describe the results for a single building in Baltimore and community microgrids in Baltimore, Chicago, and New Orleans.

5.4 Modeling energy resilience

Evaluating the resilience performance and net present value of various resilience solutions is difficult, requiring a series of complex modeling techniques that can optimize dispatch profiles considering both resilience needs and economics. The National Renewable Energy Laboratory developed the Renewable

[72] When a cost is provided both per kW and per KWh the total costs per kW can be calculated by multiplying the cost/kWh by the required duration in hours and added to the cost per kW.
[73] NREL ATB 2022

Energy Integration and Optimization Tool, or REopt,[74] designed to perform such tasks. Utilizing REopt, we examined the resilience and economic performance of several renewable, non-renewable, and hybrid configurations to compare their costs and benefits.

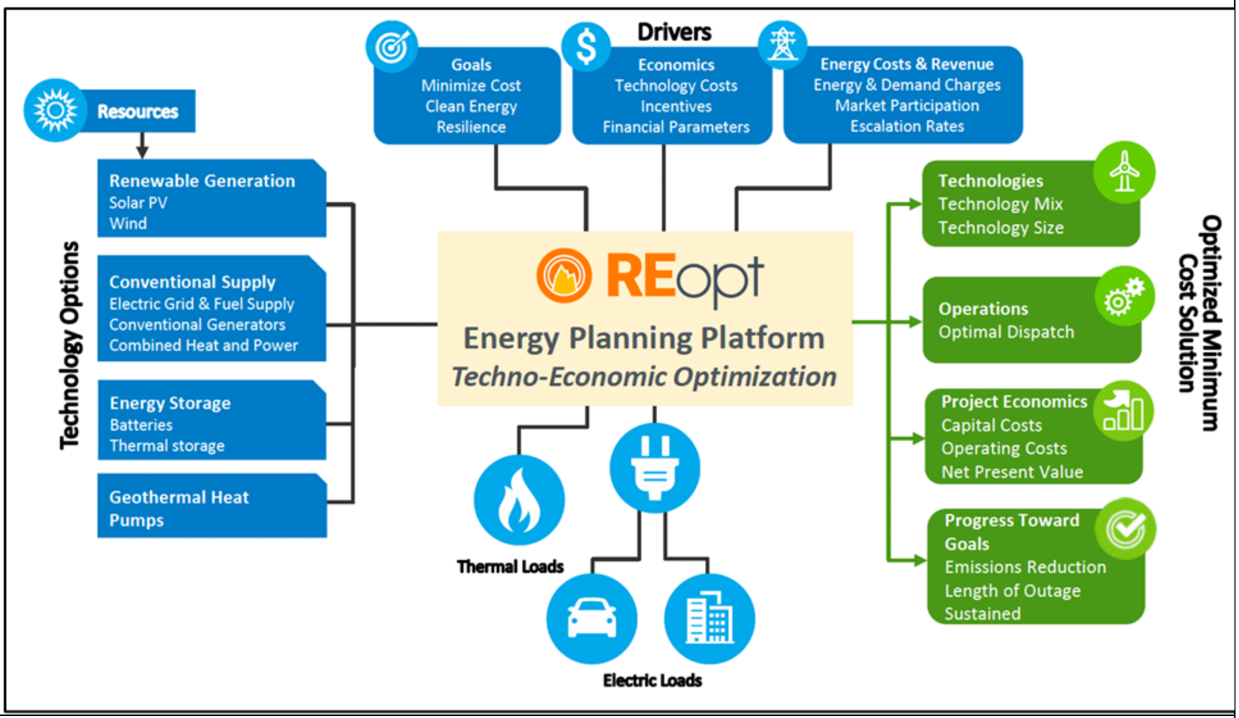

Figure 5.5 REopt Flow Diagram[75]

REopt is a public modeling tool for evaluating the viability of distributed energy resources as resilience solutions. It does so by identifying system sizes and dispatch strategies to minimize costs while providing energy to power the critical loads over a specified outage. These strategies can be defined by the modeler to be consistent with technology constraints. Recently, the tool has also incorporated equipment reliability metrics which more fairly compare the survivability of renewable versus non-renewable (i.e., diesel-based) solutions.

The public version of REopt cannot represent different charging and discharging rates of the LDES technologies we consider for a community microgrid nor optimize the system to have less than 100% survival probability during a specified outage.[76] We created a spreadsheet model to identify potential community microgrid systems to account for this rate differential in the TPV and flow battery because it

[74] https://reopt.nrel.gov/tool The REopt user manual at https://reopt.nrel.gov/tool/reopt-user-manual.pdf provides details on the tool and the inputs required. The financial assumptions used in the REopt NPV calculations are listed Appendix B of this report.
[75] NREL REopt, p. 6
[76] The public version of REopt does not have the capability to model all the complexities of LDES systems – such as different charging and discharging rates or self-discharging rates. Higher charging rates than discharging rates – a feature of the TPV and flow batteries – can be quite advantageous in certain situations. A more developed version of REopt that is not yet public can represent these complexities. The difference is described in a recent paper: Marqusee et al. 2023.

is important to obtaining more realistic results. These spreadsheet findings were fed back into REopt to evaluate system economics which is set by the grid tied performance of the system. Greater details on this process are described in the following two sections in the case of an apartment building and a community microgrid.

5.5 Single building resilience: midsize apartment building

The first example we investigate is providing energy resilience to a single residential apartment building. The question we asked is whether a green backup power solution combining rooftop solar PV with a modest size Li-ion battery could provide energy resilience for an apartment in an LMI community and how it would compare to a single emergency diesel generator tied to the building. Our intent is not to find an optimal system but rather to compare two potential solutions. A common residential apartment building in an LMI community consists of midsize apartments. Providing power directly to the apartment building does not fully address all potential energy resilience concerns but would allow most of the apartment occupants to stay in their apartment with basic support. Table 5.6 provides the details about the modeled midsize apartment building.

Table 5.6 Midsize Apartment Building in Baltimore

Characteristics	Values
Number of Floors	4
Total Square Feet	33,740 square feet
Average Electric Load	31.2 kW
Peak Electric Load	92.2 kW
Roof Area Available for PV[77]	6,250 square feet
Utility	Baltimore Gas & Electric
Tariff	Schedule G

Source: REopt modeling done for this report. Model and related documents at https://reopt.nrel.gov/

The Schedule G tariff is the most common tariff in Baltimore for small commercial and residential properties. Typical of residential and small commercial properties, it has no demand charges.[78] A significant value proposition for energy storage is its ability to reduce demand charges through peak shaving. That is not an option in the case of the Schedule G tariff; but that could, of course, be changed by policies designed to encourage apartment building microgrids or by providing direct incentives, for instance, in the case of low- and moderate-income households.

We assume that the critical load is 25% of the total load. This should be sufficient for occupants to maintain their lights, phones, and refrigeration, essential medical equipment such as oxygen supply, and possibly more. The assumption of 25% is for purposes of illustration. In an all-electric building, it would

[77] Assuming a typical 6-foot setback from roof edge.
[78] A demand charge is the rate per kilowatt of peak demand – the largest load in the period being billed -- by the customer. Demand charges are typically part of the tariffs of large customers who also pay for the energy – the kilowatt-hours of electricity used in the billing period. Demand charges are generally not part of residential rate structures.

cover most loads other than space heating and cooling and water heating. If those loads are restricted for instance by excluding plug loads such as televisions and clothes washing machines, restricting lighting to that necessary to provide safety during the outage, it may be possible to include some space conditioning and water heating within that 25%; a great deal would depend on the efficiency of building envelope, of the lighting, and of the space conditioning equipment. A site-specific analysis would be required to understand the distribution of loads across the apartment building. Air-conditioning may become more important to safety as summer heat becomes more extreme especially in buildings with vulnerable populations. The critical loads may need to be larger in such circumstances. This also raises the issue of whether apartment buildings have the room for the PV and battery storage system. In these cases, improving the efficiency of electricity use and specially space conditioning is likely to be critical and may be essential.

Figure 5.6 illustrates the total and critical hourly load for a midsize apartment in Baltimore over the course of one year – hour "0" is midnight on the first of January. Note the air-conditioning driven peak loads in the summer.

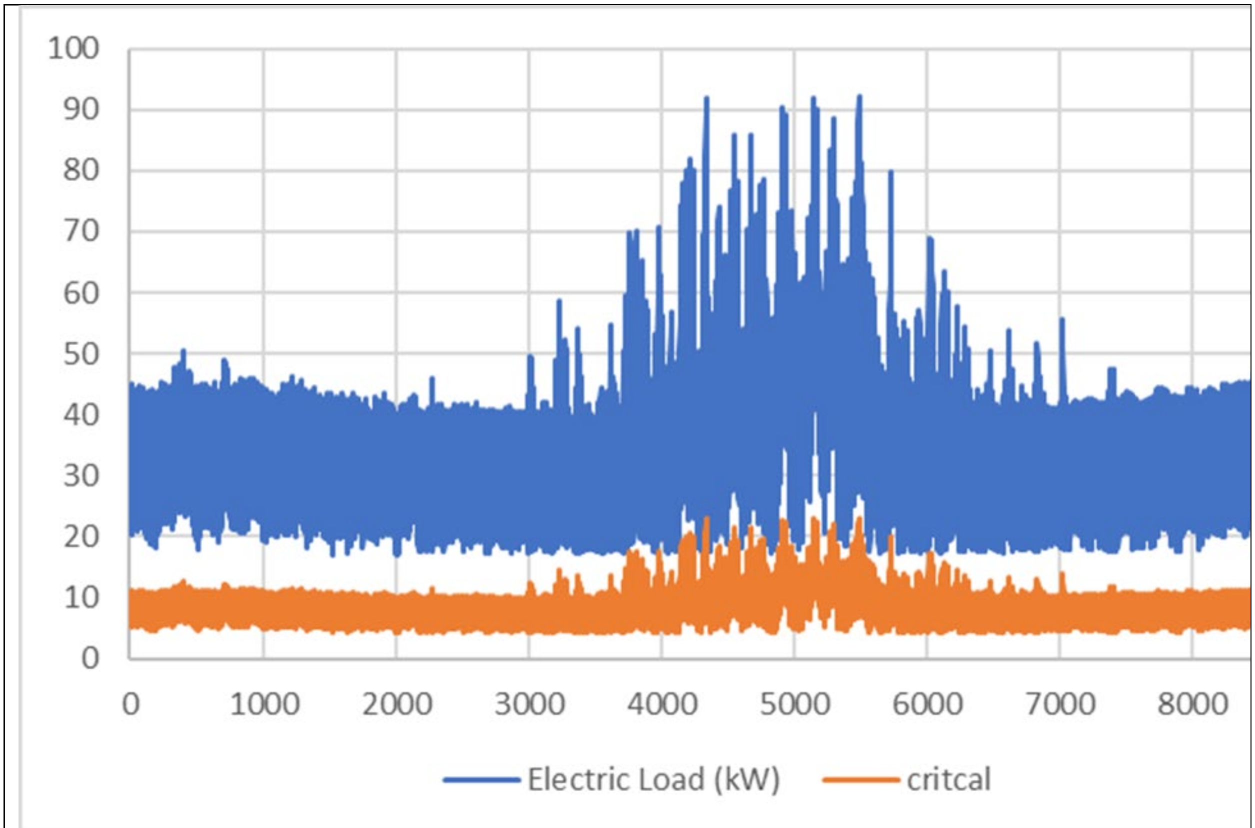

Figure 5.6 Baltimore mid-size apartment hourly electric load over one year

The peak critical load is slightly over 23 kW.

For this simple case of a single modest size building there are two options: (1) a single emergency diesel generator operated only during outages and (2) a rooftop commercial scale PV combined with a compact battery such as a Li-ion battery operated as a microgrid with solar and storage being behind the meter. We have assumed the residents would want to serve essential loads either during a 96-hour or a

48-hour grid outage. Given the peak critical load and commercial availability we assume either an emergency diesel generator of 25 kW coupled to a 96-hour or 48-hour diesel storage tank and compare this to a 25 kW Li-ion battery coupled to a 62 kW_{dc} rooftop PV (the maximum size such a building could support with current typical solar panel efficiencies). REopt is used to calculate the optimal battery energy to survive a single outage starting at the peak hourly load assuming 100% PV and battery reliability. To survive a 96-hour outage, 508 kWh is required or approximately a 20-hour battery. To survive a 48-hour outage, 395 kWh or approximately 16-hour battery is required.

Table 5.6 compares the 25-year NPV (net present value) for the two choices of outage duration requirements and the two choices of supply.

Table 5.7 Mid-Size Apartment Building (Baltimore) Energy Resilience NPV

Case	25-Year NPV (96-hour outage)	25-Year NPV (48-hour outage)
Diesel Generator	-$62k	-$52k
PV and Battery	-$140k	-$101k

Noe: Diesel cost assumed to be $3 per gallon (since fuel for emergency generators is not taxed)

In both cases the NPV is negative, meaning that over the lifecycle these systems will cost money. The diesel generator system has a lower cost. But the diesel and PV/storage-based systems have different performances. The survival probability, factoring in the expected PV availability of 98%, for the 96-hour systems compared to the diesel-based system is shown in Figure 5.7. But as modeled, the solar-plus-storage system has a higher cost.

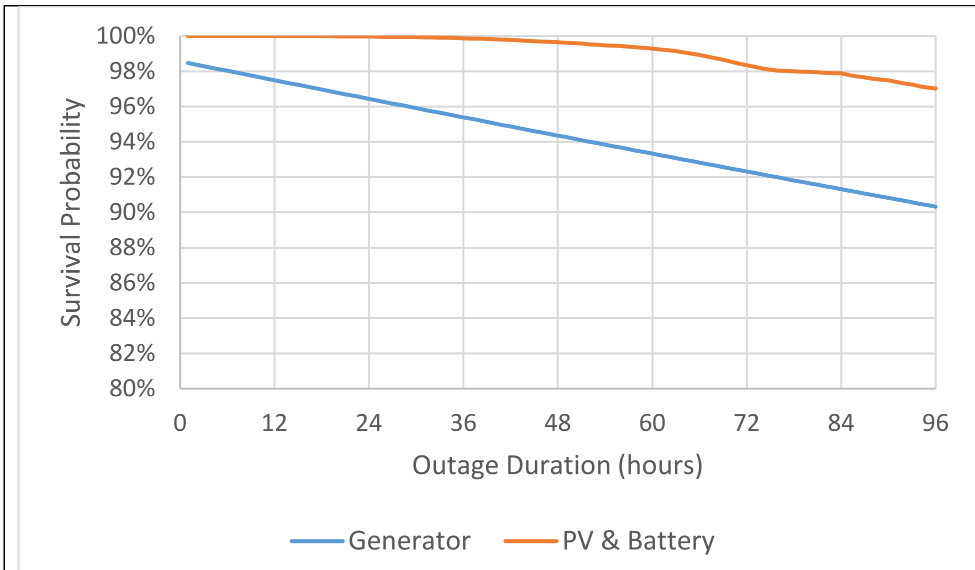

Figure 5.7. Survival Probability Comparison

The cost of achieving this resilience per apartment (assuming 30 apartments in the building) would be between $6 and $16 per month. The cost for the solar-plus-battery system could be reduced if there were a resilience-oriented microgrid tariff that allowed the residents to benefit from demand response and other ways to reduce costs during normal operating periods. The solar-plus-storage system would also reduce electricity-related CO_2 emissions by 200 to 400 metric tons over 25 years (depending on assumptions about when the grid might achieve zero emissions). At $100 per metric ton of CO_2, the undiscounted value of reducing CO_2 emissions ranges from $20,000 to $40,000. The renewable system would also eliminate health damaging air pollutant emissions.

The solar-plus-battery system has a significantly better resiliency performance. One way of looking at the cost result is that the added cost of the PV-plus-battery system pays for greater supply security during outages. Further, the costs of solar are expected to decline so that the economic performance of such a system can be expected to improve over time.

Decreasing the Li-ion battery's duration to 16 hours or 12 hours for the 96-hour and 48-hour duration requirements respectively, leads to systems that still outperform the diesel generator but reduces the cost differential to only $40k and $20K.

We also examined similar apartment buildings in Chicago and New Orleans. The results were similar and therefore are not displayed.

> ***Single building resilience conclusion #1:*** *Continuity of supply for essential loads using a zero-emissions system in a medium-sized apartment building in Baltimore can be achieved at modest (though not small) cost with the present tariff structure even at present costs of solar and storage. Costs estimated here will decline as solar-storage systems become more economical.*
>
> ***Single building resilience conclusion #2:*** *Solar-plus-storage microgrid costs can be reduced by appropriate rate design or other incentives encouraging distributed, zero-emissions resilience and by factoring in the value of reduced greenhouse gas emissions.*
>
> ***Single building resilience conclusion #3****: Because of the small electric load in a midsize apartment and limited space, emerging low-cost LDES technologies such as TPV or Fe-air cannot be used. Li-ion batteries are expensive for long durations and the absence of demand charges and/or time-of-use rates in Baltimore limits their economic value when grid tied. Zinc-air batteries could also be used but without much impact on cost. There is a significant LDES space for a technology that in the future is lower-cost, but one that occupies an area comparable to (or less than) Li-ion or zinc-air systems.*

As we will show in the next section, community-based systems, as opposed to individual building systems, can exploit emerging LDES technologies and show a positive NPV in Baltimore with zero greenhouse gas emissions. But they come with their own challenges.

5.6 Community microgrid resilience

Our second example examines a larger energy resilience effort targeting multiple critical loads in an LMI community that supports the entire community's energy resilience needs. The principal technical difference between an apartment building and community essential loads is that the latter are spread over a larger area with many buildings and systems (like gas stations and grocery stores) whose supply generally necessitates the use of utility-owned wires.

We first review what a microgrid is and how a community microgrid is different from a campus level microgrid where all the loads are on a single feeder behind the meter. Next, we describe the loads which require support during a long duration grid outage. Then a summary of the modeling process is introduced before describing the results for three different configurations: a diesel-based system, a PV/storage-based system, and a hybrid system that combines existing diesel generators with PV and storage. We conclude by highlighting the potential technical and regulatory hurdles in designing and operating such a system.

5.6.1 Microgrids and community microgrids

Traditional microgrids are situated behind the meter. Often the facilities are located on a campus, hospital complex, military base, or industrial park; they might even be a single building. DOE has proposed the following definition for these types of microgrids:[79]

> 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 and island-mode.

The loads have a relatively simple common coupling with the grid. Often, it's a single connection to the grid, but it can sometimes involve more than one connection. Islanding from the grid requires at most a few isolated switches. The power distribution system, which is behind the meter, may be medium or low voltage and is owned by the facilities or managed privately for them. This allows the facilities to optimize their loads and generation assets behind the meter to reduce costs or produce revenue while grid tied, and sustain critical loads when islanded.

Although interconnection agreements are often required for the generation assets, the role of state regulatory authorities is limited as the facilities do not fall into the legal definition of a utility; nor are their distribution systems on public land or use public rights of way. Given that the aggregate load behind the meter can be significant, traditional microgrids typically have time-of-use rates and pay significant demand charges. This allows them to take advantage of renewable energy and storage while grid tied to reduce their utility bills and generate revenues through participation in electricity markets. There is a large body of literature on the role and economic value of integrating energy storage into traditional grid-tied microgrids.[80] Storage can reduce the microgrid's cost by utilizing renewable generation, peak shaving, energy arbitrage, or other market opportunities during non-emergency periods.

Community microgrids share many features of traditional microgrids. Yet they are quite different because they involve multiple participants who own different facilities within the community microgrid. We propose a broad definition of a community microgrid as follows:

> A community microgrid is a microgrid with multiple customers actively or passively participating while receiving economic and energy resilience benefits. Community microgrid participants include energy consumers, generation and energy storage providers, and the owner of the local distribution system.

Because the connection between participants involves the local utility distribution system, the state regulatory agency plays a key role. Individual customers' loads are behind multiple meters and subject

[79] DOE 2011
[80] Alsaidan et al. 2017

to their individual utility tariffs. Given that customers can be a mix of residential, commercial, and industrial, these tariffs are often quite different. The generation and storage assets are often a mix of in front of the meter assets and behind the meter assets. For example, in the hybrid case we will describe, the diesel generators, owned by the local hospital, are behind the meter, and a community solar with storage would likely be in front of the meter. The aggregate loads, generation assets, and storage are unlikely to be a single controllable entity in a community microgrid while grid tied. Islanding the community microgrid may require multiple switches on the utility's distribution system and a clear responsible decision-maker and process for determining when to island and how much supply to allocate to each customer during a grid outage.

To date, most community microgrids have been constructed on part of the distribution system which is easy to isolate. California has several such community microgrids. This type of community microgrids is called an "End-of-Line" microgrid since it requires only a single point of coupling to the grid. There is sufficient experience with these types of community microgrids that PG&E, California's largest utility, has published a best practice manual on their design and deployment.[81] These "End-of-line" community microgrids may be a low voltage feeder to a suburban residential community or a single medium voltage feeder to a set of large facilities.

However, these end-of-the-line cases rarely fit the conditions found in an LMI community. The more complicated situation is when an LMI (or other) community that wishes to support multiple dispersed public facilities that have many grid-connection points. Such cases involve extensive utility-owned wires, but may rely on a single community solar with storage project. This type of community microgrid is referred to as a "Mid-Feeder Microgrid". It requires multiple connections to the grid; its design will be more complex due to the need to coordinate more devices when transitioning between normal and islanded operation. This also introduces additional challenges in achieving potential savings while grid tied. We will return to these issues in Section 5.7.

5.6.2 Community loads

The community microgrid we have analyzed involves In-Patient Healthcare (a hospital), Out-Patient Healthcare, Shelter, Multi-Residential apartment building, Food Sales, Pharmacy, and Order & Response Services (referred to as "Other Emergency Response" in the rest of this report).[82] Appendix C of this chapter has the details of how loads are distributed among these facilities. The probability these are all on the same feeder is small. We assume the critical load for each facility is: 50% for In-Patient Healthcare, 100% for Other Emergency Response, and 25% for all other loads for our baseline case. In the hybrid case we assume the inpatient health care facility already has 50% of its load supported by diesel generators and therefore the resilience goal for our modeling for this hybrid approach is to support 100% of the inpatient healthcare facility. The aggregate total load for these seven critical facilities is described in Table 5.7. Note that the number of facilities included in an emergency resilient microgrid will differ dependent upon a community-determined resilience needs assessment. The seven

[81] PG&E 2023

[82] Order & Response Service commonly include fire, police, and other emergency response facilities such as ambulance and those needed for evacuation; the scope of emergency response facilities included as critical loads in community microgrids should be determined by stakeholders (including government and community leaders).

facilities selected as a part of this assessment only represent an approximation of the types of services that a community may need at varying capacity levels during an emergency event.

Table 5.8 Aggregate Load Data – Baltimore community

Characteristics	Values
Number of Facilities	7
Average Electric Load	1,694 kW
Peak Electric Load	2,725 kW
Baseline Critical Peak Load	1,378 kW
Hybrid Critical Peak Load	1,870 kW
Utility	Baltimore Gas & Electric
Tariff	GL General Service large

We made two key assumptions in modeling this large, aggregated load. They are:

- **Loads Treated as One Entity Subject to a Single Tariff:** A community resilience project would likely contain a plethora of electricity customers each with their own meters, loads, and interfacing equipment, but powered by a central generating system like an emergency diesel generator during outages or a clean energy plus storage system. The decentralized nature of these individual customer loads is not accounted for in our analysis and was instead treated as an aggregate load value at an individual node. As our analysis was focused on the technical aspects of the resilience problem, we assumed that the aggregated load would be treated as a single entity under a single tariff, an assumption which was held constant across all solutions compared. This is a significant simplification because customers of different types would have different rate structures. This means that a more detailed financial assessment would be required when assessing a resilience solution for a real community, however, this does not change the efficacy of the comparative results discovered in this report. We return to this issue in our discussion of community microgrid challenges.
- **External Markets Are Not Considered:** Although there are a growing number of opportunities for distribution-connected systems to participate in wholesale energy markets, we decided to limit the financial options for dispatchable LDES systems to state programs only. Specifically, Order 2222 of the Federal Energy Regulatory Commission[83] allows aggregated distributed resources, including aggregated demand response, to be offered as the equivalent of dispatchable generation on interstate electricity markets. Consequently, the financial results of our modeling are conservative and understate the actual economic potential; this leaves the door open for future economic evaluations as new wholesale opportunities are created over the next decade.

[83] FERC 2020

The single tariff is chosen that is commonly used for large commercial customers. In Baltimore it has a time of use energy structure and a demand charge component. In our modeling, both features are critical for energy storage to achieve utility savings when grid tied.

5.6.3 Modeling process

It is difficult to fully model the complexity of LDES with publicly available tools. Rather than attempt to find an optimal solution, we only considered distributed energy resources in units of megawatts and durations in increments of 12 hours or constrained by expected commercial availability.

A simple energy balance Excel based tool[84] was developed and used to look at the resilience performance of various combinations of solar PV and storage. The tool includes the impact of non-equal charging and discharging rates which commonly occur in some newer LDES technologies which is not included in publicly available tools. Using this tool, we rapidly surveyed a variety of Li-ion and LDES based systems coupled to a small utility-scale PV. Based on this analysis the size of the solar PV and energy storage technology was selected and its lifecycle costs, which is determined by its grid tied behavior, was calculated using the REopt model.

5.6.4 Diesel based community microgrid

The diesel-based system was chosen based on standard engineering practice and its resiliency calculated based on the newly released REopt tool[85] that includes the impact of reliability of distributed energy resources (DER). To meet the baseline peak critical load requires approximately 1,500 kW of capacity or two 750 kW generators. A non-redundant generator-based system will yield resilience performance similar to what was found for a mid-rise apartment or only a 90% survival probability at the end of a 96-hour grid outage. For community level critical loads like a hospital or shelters, that level of resilience is far too limited and does not meet typical state regulatory requirements for hospitals. An "N+1"[86] redundant diesel-based system using three 750 kW generators was selected in accordance with standard emergency power requirements.

Table 5.9 Diesel-Based Baseline Community Microgrid in Baltimore

25-Year NPV	Survival Probability at 48 hours	Survival Probability at 96 hours
-$3.7M	99.2%	97.6%

The diesel-based system is designed to have sufficient fuel to last through the grid outage. It has a negative NPV or equivalently a net lifecycle cost of $3.7M over 25 years. It has a high survival probability

[84] The tool tracks generation, storage, and consumption. The user selects a state of charge at start at the start of an outage based on previous published work (Marquesee et al. 2023) . Outages starting any hour in the year are modeled using the hourly critical load profile and local solar energy profile. The tool tracks the energy and accounts for roundtrip efficiency and charging and discharging constraints. Cumulative survival probability of not supporting the hourly critical load at any time up to and including a specified time limit "t" is tracked.

[85] Available at https://reopt.nrel.gov/tool

[86] An N+1 redundant system is one in which N generators can meet the peak load and one additional generator is added to provide a higher reliability to the system

for outages less than 48 hours; the cumulative probability declines to 97.6% at 4 days and less than 90% at 10 days assuming the outage can start anytime during the year.

> ***Community resilience conclusion #1****: The standard use of emergency diesel generators to provide energy resilience during a long-duration grid outage has only a moderate survival probability due to the inherent reliability characteristics of diesel generators even when sufficient diesel fuel is available. Lack of a reliable diesel fuel supply would decrease this reliability further. The life cycle costs of diesel generators for a modest community microgrid will be in the millions of dollars.*

We view this as a baseline cost and performance of providing energy resilience for critical community loads described above and in Chapter 5 Appendix C below. We have assumed that there are no existing generators that have already been paid for. This would be an unlikely situation in that most hospitals are required as part of their state licensing process to have back up emergency diesel generators. We return to the issue in our discussion of a hybrid system.

5.6.5 PV and energy storage-based community microgrid

We explored potential combinations of solar PV, with Li-ion and Redox flow and two different LDES technologies that are expected to be commercially available before 2030. We did not search for an optimal system but rather looked at systems of equivalent sizes that meet or exceed the resiliency performance expected for an "N+1" commercially available diesel-based backup power. The solar-plus-storage can therefore be directly compared to existing diesel systems so far as serving loads during outages is concerned. A key assumption in the energy balance modeling is about the amount of electricity stored in the storage unit at the start of the grid outage (known as "the state of charge, or "SOC". In previous work we have shown that constraining energy storage to SOC equal to or greater than 60% achieves a balance between life cycle costs and energy resilience.[87] The storage technology will typically operate between a SOC of 60% to 80% while grid tied; in this operating configuration, it will typically have sufficient energy available at the start of a grid outage. This assumption is important for grid outages whose timing is unforeseeable – such as an outage due to a cyberattack. In most cases, such as weather-related outages, this constraint can be relaxed.

To meet the peak critical load, we restricted all the energy storage technologies to 2 MW[88] and the solar PV to 8 MWdc. Larger storage power levels were not required, and smaller PV sizes were unable to meet the resilience goals. We compared the resilience performance for different storage technologies as a function of storage durations (hours) assuming an SOC of 60% to 80% at the start of the outage. Table 5.8 describes the selected systems and their expected range of survival probability as a function of outage duration. Each system is coupled to an 8MWdc solar PV, has a 2MW storage power level and the roundtrip efficiency described in Table 5.4. Note that while Fe-Air and TPV are emerging technologies, their performance estimates are reasonably reliable. The primary uncertainty for these technologies relates to their cost.

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[87] Marqusee et al. 2023

[88] The peak critical load in the example modeled is approximately 1.4MW. Energy storage units are expected to be commercially available in units of 1 MW; therefore the system chosen has a 2 MW (AC)storage system.

Table 5.10 Solar and Energy Storage-Based Community Microgrids Performance

Storage Technology	Duration	Survival Probability at 48 hours	Survival Probability at 96 hours
Li-ion	24 hours	100%	95% to 98%
Redox Flow	24 hours	100%	94% to 98%
Fe-Air	100 hours (Note 1)	100%	100%
Thermal-TPV	36 hours	100%	97% to 100%

Note 1: The expectation is that Fe-Air batteries will be available only as 100-hour storage systems

.

These systems all have comparable or better resilience performance than the diesel-based system.

> ***Community resilience conclusion #2****: The use of long duration energy storage equal to or greater than 24 hours if coupled to a large solar PV can provide reliable energy resilience for communities during a long duration grid outage. The energy resilience can be as good or better than traditional diesel-based generation.*

Using REopt, the NPV for a system of DERs in a community microgrid was calculated including the costs and benefits of an 8MWdc community solar PV. REopt does not currently model unequal charge and discharge rates, so the NPV estimates for LDES that have unequal charge and discharge rates should be viewed as a conservative estimate. Net present values are calculated assuming no outages. This means that any negative net present value is the cost of insuring against outages for loads deemed essential for the defined period (96 hours in the case studied here). Positive net present values mean that the insurance is free and that there also a profit above that. Seen another way, a positive NPV means a reduction in the cost of electricity relative to prevailing rates plus an increase in resilience.

Table 5.11 Solar and Energy Storage-Based Community Microgrid DER Costs – Baltimore neighborhood

Storage Technology	Duration	Storage Power	25-year NPV (currently deployed)	25-year NPV (deployed in 2030)
Li-ion	24 hours	2MW	+$1.7M	+$9.5M
Redox Flow	24 hours	2MW	-$2.4M	+$7.7M
Fe-Air	100 hours[89]	2MW	-	+$10.9M
Thermal-TPV	36 hours	2MW	-	+$12.6M

Except for a currently deployed redox flow battery, all the NPVs are positive. That means they are revenue generating. At present, the redox flow battery has costs similar to the diesel-based system. These results are very sensitive to the storage and PV cost assumptions in Table 5.5 and Table 5.3 and

[89] The expectation is that commercial Fe-Air batteries will only be available in units of 100-hour durations

the tariff structure. These cost assumptions are based on estimates of today's costs for Li-ion and Redox flow batteries and projected costs in 2030 for all four technologies. Li-ion and Redox flow batteries costs today depend on the vendor and are sensitive to supply chain issues. In addition, extrapolating today's commercial costs for batteries sold that have durations of less than 12 hours to 24 hours may have inaccuracies. If we allow the cost estimates of Li-ion and Redox flow batteries to increase or decrease only by 10% we find the NPV value for a deployment today ranges from -$0.6M to +$2,4M using Li-ion batteries and from -$4.1M to -$0.8M for a Redox flow battery. These variations are significant but do not change the general conclusions but point to how important site-specific deployment cost estimates must consider costs associated with a specific vendor's offer. All the technologies show very high positive NPVs in 2030; that estimate depends of course on whether these technologies reach the assumed cost goals. The tariff modeled has both a time of use energy rate and a demand charge. Using energy storage to both maximize the use of solar energy and reduce the demand charges plays a significant role in the costs.

Tables 5.12 and 5.13 show the same calculations done for Baltimore in 2023 for two other neighborhoods in very different climates and with different rate structures – a Chicago neighborhood and a New Orleans neighborhood.

Table 5.12 Solar and Energy Storage-Based Community Microgrid DER Costs – Chicago neighborhood

Storage Technology	Duration	Storage Power	25-year NPV
Li-ion	24 hours	2MW	-$10.4M
Redox Flow	24 hours	2MW	-$13.7M

Table 5.13 Solar and Energy Storage-Based Community Microgrid DER Costs – New Orleans neighborhood

Storage Technology	Duration	Storage Power	25-year NPV
Li-ion	24 hours	2MW	-$10.3M
Redox Flow	24 hours	2MW	-$13.7M

The financial outcomes for Chicago and New Orleans are very different from the net present values estimated for Baltimore. Neither storage technology provides a positive NPV today. The main reason is that the cost of electricity is lower in Chicago and New Orleans, with annual average bills being 60% and 50% respectively of those in Baltimore.

> ***Community resilience conclusion # 3****: The use of long duration energy storage equal to or greater than 24 hours, if coupled to a large solar PV, potentially offers a cost competitive*

advantage compared to diesel-based backup in markets where solar is cost effective and tariffs reward the use of storage through demand charges and time of use rates.

***Community resilience conclusion #4**: Community microgrid net costs are expected to decline (where now negative), and the net savings are expected to grow (where now positive) in the future.*

***Community Resilience Conclusion #5:** Rates and rate structures are critical parameters in determining whether community microgrids that increase resilience also have a positive net present value. However*, increasing low rates due to resilience economics alone would impact affordability. Incentives and grants would be a useful alternative to raising rates. In general, rates should be seen as one tool in the energy transition toolbox. It is essential to maintain affordability for low- and moderate-income households while increasing resilience, including in frontline communities and areas with higher concentrations of lower income households.

5.6.6 Hybrid community microgrid

A hybrid microgrid is one in which diesel-based generators are used in combination with solar PV and energy storage. For traditional behind-the-meter microgrids, such configurations are known to have both cost and performance advantages.[90] In the case of community resilience where a hospital is a critical load there are additional reasons to consider such a configuration. Hospitals require diesel generation backup for their critical loads and thus one expects a hospital in an LMI community would already have a set of diesel generators and the associated fuel storage. Moreover, hospitals are required to have emergency diesel generators so that it may be advantageous to take advantage of that fact until a secure and reliable arrangement for zero-emission or low-emission hospital emergency supply can be worked out and regulations changed accordingly.

We consider the case in which the hospital already has sufficient diesel generation to meet its critical load, which is assumed to be 50% of the total hospital load. To meet the redundancy requirement,[91] the hospital would already own three 400 kW diesel generators. Given that the hospital already meets its critical backup power requirement, why would it participate in a community microgrid? Meeting its critical load (50% of total load) is required but does not fully support its mission. During a prolonged grid outage, a hospital could easily be required to meet much greater patient needs than during a typical day. Having 100% of its load met would allow the hospital to be a key resilience resource during an extended grid outage. As shown in Table 5.8, we assume the hybrid community microgrid will support a larger peak critical load.

Using the same approach as described above we consider the following hybrid systems today: restrict the energy storage technologies to 1 MW and the solar PV to 6 MWdc. Larger storage power levels were not required, and smaller PV sizes were unable to meet the resilience goals.

Table 5.14 Hybrid Community Microgrid DER Costs for Baltimore

Storage Technology	Duration	Storage Power	25-year NPV

[90] Marqusee, Becker, and Ericson 2021

[91] The third 400 kW generator covers the contingency of one of the two 400 kW generators being unavailable during a long outage.

Li-ion	24 hours	1MW	+$5.5M
Redox Flow	24 hours	1MW	+$3.2M

Both hybrid systems have positive net preset values ranging from $3.2M to $5.5M using present day costs. Future costs in 2030 would yield increased savings similar to what has been shown in the non-hybrid case. These hybrid systems also all have better resilience performance than a diesel-based system.

> ***Community resilience conclusion #7****: If a community microgrid employs the hospital's existing diesel generators, a hybrid clean energy scenario offers significant cost reduction and resilience benefits across all applicable technology scenarios. Since the diesel generators operate during emergencies and for routine testing, air pollutant and CO_2 emissions would be limited to those periods – such emissions would occur in any case whether or not there is a community microgrid.*

These configurations would allow the hospital to support 100% of its load with higher probability than it can currently support only 50% of its load using its own diesel generators.

5.7 Community microgrid challenges

The community microgrids we have discussed involve continuous electricity supply during outages to In-Patient Healthcare, Out-Patient Healthcare, Other Emergency Response, Shelter, Multi-Residential, Food Sales, and Pharmacy facilities. The probability these are all on the same feeder is remote. Designing, building, operating, and gaining utility and regulatory approval for such a community microgrid involves challenges for both grid-tied and islanded operations.

In a grid-tied configuration, how does one exploit the economic opportunities in a community microgrid when the key assets are not behind the meter or even isolated on the feeders the loads are located on? Current rules for community solar with and without storage often do not allow the commercial type facilities we are modeling to take full advantage of community solar plus storage. In addition, any future opportunity will need to be written into state regulations and supported by statute. Community solar today works through virtual net metering. This is well defined and established for community solar but a similar process for storage is not yet established. Interest in community energy storage is growing, but is uncommon and lacks clear compensation signals, policy support, and deployment experience as with community solar.

> ***Community resilience conclusion #8****: Policies that allow key LMI community facilities to take advantage of community solar with storage that would make communities more resilient by ensuring continuity of electricity supply to a variety of essential community loads do not currently exist and need to be enacted in statute and regulations.*

The few states that have or plan to expand or convert community solar into community solar-plus-storage have not structured their programs to support community microgrids, where the critical loads are commercial facilities. Often a large percentage of the community solar facilities require LMI residential customers and limit the percentage that large anchor customers can consume. Value streams for community energy storage are more disparate than those associated with shared renewables. Most state programs such as those in California, Maryland, Massachusetts, New York, and Washington, are not structured to allow commercial customers to directly offset their demand charges through use of community storage.

The islanding challenge for generation and storage assets and loads distributed across multiple feeders is significant. There are only a few examples where the cost and technical challenges of quickly and safely isolating a local microgrid have been addressed.

> ***Community resilience conclusion #9****: There are significant challenges to addressing community resilience by building community microgrids to supply critical loads during outages. Detailed studies are needed to understand and delineate the infrastructure involved and the technical, business, operational, and regulatory issues associated with increasing resilience across a variety of loads. Direct communication with the impacted community, details on the load characteristics of different facilities, and iteration with the local utility and state regulators are essential.*

There is not a fundamental technical barrier, but regulatory and business practices are not well established. In addition, issues of cost and equity for customers who may or may not live along the portion of the distribution lines which would be energized during an islanded event will be important.

Many states as well as regulators are aware of the need to increase resilience via microgrids and the legal, regulatory, and related issues that need to be addressed. The National Association of Regulatory Utility Commissioners has issued a report that discusses a framework that would help states address microgrid-related issues. In relation to areas where there is competition in generation the report notes the following in regard to utility-owned wires:

> The ownership and operation of microgrids is subject to competition, and electric distribution utilities in restructured environments may be formally prohibited from owning and / or operating parts or all of a microgrid. Still, regulated utilities own the distribution network in either scenario, and any microgrid distributing electricity from one customer to another, across a public right-of-way, requires the use of utility-owned, PUC-regulated distribution infrastructure and must coordinate with the distribution utility. This issue is commonly identified as a barrier to multi-customer microgrids; regulated utilities and PUCs are responsible for the safety of the distribution network and require some level of visibility and / or control over distribution-connected resources.[92]

Electricity rates and rate structures are also critical issues. As the Chicago and New Orleans examples show low rates may not be compatible with community microgrid economics in a way that lowers costs while resilience is increased. However, this does not mean that rates should be increased. Low rates are one important aspect of energy affordability. Rates for behind-the-meter solar (with or without storage) and compensation for demand response are also critical to the economic design of the energy transition.

Rates too often are the vehicle for addressing a host of issues ranging from higher rates to finance energy assistance to low- and moderate-income households to cross-subsidy issues for financing investments in energy efficiency. Incentives that are not tied to rates – including grants for community

[92] Jones et al. 2022, Section I.

resilience projects in low- and moderate-income communities and front line communities – may well be preferable vehicles where rates are low in order to achieve resilience while maintaining affordability. These may also be coupled with incentives for subscribing to aggregated demand response and grid operation initiatives such as introduction of distribution system operators to facilitate aggregated demand response dispatch.

Chapter 5 – Appendix A: Chicago and New Orleans examples

Analysis of potential community microgrids for the same set of facilities as modeled in Baltimore was conducted for Chicago and New Orleans. The differences in these three locations are the differences in solar resources, weather (which impacts load predictions) and the utility tariffs. By far the biggest effect is the difference in tariffs.

Table A-1. Utility and Tariff

Location	Utility	Tariff
Chicago	Commonwealth Edison	BES – Med Load
New Orleans	Entergy New Orleans	SE-24

Both tariffs have demand charges similar to Baltimore, but New Orleans has a fixed energy rate and Chicago has a two-tier energy rate. The aggregated annual utility bills in Chicago and New Orleans are 60% and 50% of the costs in Baltimore.

The community solar and energy storage systems defined for the Baltimore community microgrid will provide similar energy resilience performance in Chicago and New Orleans but their NPV for a system of commercially available DERs in a community microgrid are millions of dollars a year more expensive than a diesel-based system (net present value over 25 years).This is qualitatively different than the results in Baltimore and is driven by the higher cost electricity in Baltimore relative to Chicago or New Orleans. The results would be financially more favorable if one looks at potential future lower storage costs or hybrid systems but there is still a significant difference between Baltimore and Chicago or New Orleans.

Chapter 5 – Appendix B: Modeling financial assumptions

The REopt calculation used the financial assumption in Table B-1. For both solar PV and storage the Inflation Reduction Act provides a large federal tax credit (30%) which was modeled.

Table B-2. Financial Assumptions

Economic Input	Assumption
Analysis period	25
Developer discount rate	5.6%
Developer tax rate	26%
O&M cost escalation rate	2.5%

Electricity escalation rate	1.9%
Diesel Cost	$3/gallon

Most of the financial assumptions are default values provided in the REopt tool at the time the calculations were made.

Chapter 5 – Appendix C: Baltimore community loads

Table C-3. Baltimore Facility Loads

Facility	Average Load	Peak Load
Hospital	1,135 kW	1,546 kW
Out-Patient Care	160 kW	318 kW
Shelter	102 kW	342 kW
Multi-Residential	28 kW	67 kW
Food Sales	194 kW	381 kW
Pharmacy	38 kW	109 kW
Other Emergency Response	38 kW	109 kW

6. Environmental and justice considerations

The scope of this report is primarily technical. It addresses how communities and especially LMI and otherwise disadvantaged communities may benefit from long-duration energy storage by increased resilience of electricity supply and greater control of energy costs by consumers. We outline here some environmental justice benefits and environmental justice concerns (such as mining and safety issues) associated with LDES technologies. This chapter provides only an outline of some of the environmental and justice-related implications of long-duration energy storage technologies for possible further consideration by Research Collaborative formed by Just Solutions.

6.1 Safety concerns

Safety risks associated with LDES technologies can be characterized by four main categories: risk of electric shock, arc-flash incident exposure, combustion, and toxicity of leaked substances. Both shock and arc-flash hazards are well-understood qualities of electric system infrastructure with mitigation measures identified in national electrical codes, thus these categories are not included as part of this discussion.

Combustion Risks – As mentioned previously, the fire risks of Lithium-Ion battery cells are perhaps the best-known safety issue associated with energy storage technologies. Such fires can occur after equipment failure or due to physical damage causing the battery cells to undergo thermal runaway, "a chemical process where self-heating in a battery exceeds the rate of cooling causing high internal temperatures, melting, off-gassing/venting, and in some cases, fire or explosion".[93] Such an event occurred in 2019 at a Li-ion battery facility owned and operated by the Arizona Public Service Company, and resulted in the hospitalization of eight emergency workers after a concentrated amount of flammable gas underwent combustion during firefighting operations.[94] Note that thermal runaway risks can differ between Li-ion battery chemistries and applications:[95]

> Battery safety is profoundly determined by the battery chemistry […], its operating environment, and the abuse tolerance […]. The internal failure of a LIB is caused by electrochemical system instability […]. Thus, understanding the electrochemical reactions, material properties, and side reactions occurring in LIBs is fundamental in assessing battery safety,"

We have not addressed these risks differences in the modeling in this paper since the risk tolerances between chemistries did not overshadow the risk differentials between Li-ion and other battery technologies. Unlike Lithium-Ion, batteries like Vanadium Flow, Iron-Air, and Zinc-Bromine do not pose a risk of thermal runaway. Hydrogen storage and use risks involve the potential for accidents at

[93] Rosewater & Williams, 2015, p. 461
[94] Sylvia 2020
[95] Chen et al. 2021 – and ang et al. 2021 – Report investigating the thermal runaway risk differentials between Li-ion battery chemistries.

explosions. Rigorous safety evaluation and community protection will be essential. Safety and storage issues are discussed in more detailed in a companion IEER report.[96],[97]

Toxicity of Leaked Substances – Some LDES technologies have risks associated with the potential release of hazardous substances into the surrounding community, either in the form of vented gas or leaked electrolyte fluid. For instance, during a thermal runaway event, even a relatively small *Lithium-Ion* battery can vent gasses such as hydrogen fluoride and carbon monoxide at concentrations exceeding both the Irreversible Effects Threshold and First Lethal Effects Threshold.[98] Zinc-Bromine batteries also have some characteristic safety risks associated with the venting of Bromine (B_2) gas that could be liberated from the electrolyte fluid during an excessive temperature (>50°C) event.[99] However, the primary concern with such batteries is leakage of the electrolyte fluids during transportation or installation, or container failure in which chemical reactions with the environment promote bromine gas evolution. Vanadium flow batteries contain large amounts of liquids so that is essential to ensure that any spills are contained within an enclosure and that toxic spilled material can be recovered and recycled without discharge into the environment.

While still in development, both Fe-Air and TPV batteries appear to have relatively good safety profiles. The graphite used in TPV batteries to store energy at high temperatures is resistant to fire with one of the companies developing the technology claiming that there is essentially no fire hazard. [100] This is because the configuration of the graphite would be insulated and not exposed to air. However, it should be noted that the ignition temperature of graphite is 400°C, which is far lower than the design temperatures for storage. While the battery appears to be safe, there is some uncertainty since it has not yet been tested at scale.

6.2 Mining and related issues

While energy storage systems are an essential part of reducing global reliance on fossil fuels, the environmental justice impacts of their production should not be overlooked. Energy storage systems are composed of materials that are often more exotic and more geographically scarce than fossil fuel resources. For instance, cobalt, an element used in the cathodes of many Li-ion battery designs, is mainly mined in the Democratic Republic of the Congo (Congo), which has nearly 50% of the world's total reserves and accounts for nearly 70% of mined material worldwide in 2022.[101] Similar global dependencies can be seen for vanadium, used in vanadium redox flow batteries, where China both has the largest mineral reserves (37%) and controls 70% of the world's yearly production[102].

Human-rights violations, unsafe working conditions, and environmental abuses are common in many mining operations. Examples include cobalt mines in Congo, where rampant soil and water pollution, high worker death rates, increased exposure to toxic and radioactive materials, and widespread child

[96] Makhijani and Hersbach 2023 (forthcoming)
[97] There also risks when there is a fire in the structure where the battery is located; for instance, firefighters may not realize there is a battery in the structure and may not know the risks associated with it during a building fire. Such risks are important but outside the scope of this report.
[98] Rosewater & Williams, 2015, p. 462
[99] Hill 2016
[100] Antora Energy 2023
[101] USGS, 2023, p. 61
[102] Ibid 190.

labor violations have all been recorded.[103] The especially exploitative conditions for cobalt are widely recognized and have been a major factor in global policy decisions aiming to shift away from battery chemistries containing cobalt.

Environmental justice issues are global when it comes to mining and processing – as evidenced by mining on Indigenous lands in the United States, Canada, and Australia as well as mining in China. For example, radioactive pollution in mine tailings is common in rare earth metal processing.[104] Rare earth ores are generally associated with traces of radioactive uranium and thorium.[105]

Graphite mining presents safety and environmental hazards as well – including methane gas and dust. Processing of mined rock is necessary. The main producers are China, India, and Brazil.

Nickel is used in many Li-ion designs, and its mining has been linked to vast deforestation, labor exploitation and endangerment, and marine pollution in both Indonesia and Botswana.[106] Materials used in other LDES technologies lack EJ concerns of similar magnitude, such as the mining of zinc used for Zinc-Bromine flow batteries, which has most of its environmental impact driven by its electricity use.[107]Iron-air batteries appear not to use any rare materials and therefore do not appear to present EJ concerns of magnitudes comparable to current Li-ion technology. The PV in TPV is gallium-indium-arsenide.[108] Gallium, which is used in the PV part of TPV technology, is produced largely as a byproduct of zinc and aluminum production since it is present in their ores. High demand is changing that and primary production is growing. Indium, which is also part of the PV, is extracted as a byproduct of processing ores for other materials.[109] Arsenic is also used in TPV cells. It is highly toxic in air and water. It is produced mainly in China and Morocco; smaller quantities are produced in several other countries. The United States has produced no arsenic since 1985. It imports arsenic mainly from China and Malaysia, along with far smaller amounts from a number of other countries including Belgium, Hungary, Germany, and Japan.[110]

Like all PV production, including the common silicon-based PV, the manufacture of photovoltaic materials and the high purity required generally involves toxic materials. However, it should be noted that the PV in TPV is in addition to the PV that is used to generate the electricity that is stored as thermal energy in the TPV; as a result, this technology requires more PV production for a given amount of electricity output than other solar-plus-storage combinations.

Generally, labor, environmental, and safety standards are needed and transparency across the supply chain is needed as regards their enforcement. In this, LDES technologies have environmental justice issues in common with other energy and materials mining and production. The Initiative for Responsible Mining Assurance has published wide-ranging standards that include human rights, safety, as well as environmental protection.[111] The adoption and enforcement such standards, including in the Global South and on indigenous lands, an essential part of environmental justice.

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[103] Tsurukawa et al., 2011
[104] EPA 2023
[105] UNSCEAR 2017.
[106] Naryono, 2023 and Ekosse, 2008
[107] Van Genderen et al. 2016.
[108] Tervo et al. 2022.
[109] Frenzel et al. 2017
[110] USGS 2023a
[111] IRMA 2018.

6.3 Reuse and recycling potential

LDES technologies require the extraction and processing of various materials to create battery components with limited lifecycles. It is therefore important to consider the recycling potential of the materials within each battery design to limit the overall environmental impact of the system. This is especially important with technologies like Li-ion batteries were rare metals often mined in the Global South and in Indigenous lands in the Global North; it is also important more generally for achieving sustainability.

The prevalence of Li-Ion batteries across the consumer electronics space prompted the creation of several reuse and recycling pathways, which could be expanded as Li-ion come to be used in the electricity and transportation systems. There are three primary recycling techniques today which can be used in combination with one another to recover and reuse materials for other applications: direct recycling where the cathode is reconditioned for reuse, pyrometallurgy recycling which uses heat to isolate certain valuable materials such as cobalt, and hydrometallurgical recycling which uses various acids to isolate materials. In general, direct recycling is the preferred method as it requires less energy and processing than the other methods; however, variations in battery types, cathode materials used, and overall battery condition often make this method difficult to implement at scale.[112] Recycling poses its own safety and environmental hazards that need to be addressed in siting – to avoid further harming already overburdened communities.

Redox flow batteries, which include Vanadium and Zinc-Bromine batteries, have shown particular promise when considering their recyclability compared to other battery technologies. First is the fact that some redox flow battery electrolytes have extremely long theoretical lifetimes with some literature citing 20,000 cycles equating to a 20-year operational lifespan,[113] much higher than Li-ion batteries. In addition to this longer lifespan, reprocessing and purifying the electrolyte for reuse,[114] or extracting the vanadium for reuse has relatively low environmental impact. However, there is a cost to offsite recycling which requires potentially expensive transportation services and risks of accidents during transportation. These processes have yet to be commercially scaled.[115]

The recyclability of novel technologies like Fe-Air and TPV batteries has yet to be established since they are not yet commercially deployed on a significant scale. There are, however, academic reports on non-iron metal-air batteries which appear to indicate that such systems are highly amenable to materials recovery. .[116]

As a general note, mining is by its very nature an extractive industry, no matter the specific material being mined. Near-complete recovery of materials is one necessary element of a sustainable economy. However, recovery and recycling of materials itself often involves toxic materials with a potential for significant adverse impacts on workers, communities, and the environment. Frontline communities and communities in the Global South are generally the most affected. Safeguards similar to those or mining including community, worker, and environmental protection regulations, as well as general respect for human rights, are all essential for recovery and recycling of materials. Ideally ease and safety of materials recovery should be built into the design of all goods including batteries – especially those that

[112] Baum et al. 2022
[113] Woolery 2021 and Blume et al., 2022
[114] Weber et al., 2018
[115] Woolery 2021
[116] See Gao et al., 2023 for a discussion on Zinc-air battery recycling

contain materials that have a large impact when they are first mined and processed to be made part of new goods.

6.4 Diesel-related considerations

Diesel peaking generation, while generally operated for very short periods, contributes to air pollution. It is also well-known that such facilities have been disproportionately located in environmental justice communities.[117] Replacing them with long-duration energy storage would ameliorate such problems. We should also note that today's microgrids often use emergency generators that are generally natural gas or diesel-fueled. Replacing them with solar-plus-storage would alleviate pollution concerns while still providing resilience benefits to frontline communities. The reliance of hospitals on emergency diesel generators is a more complex problem. It is required by regulations. The capacity needed is substantial and the space available – especially in existing structures – is very limited. These generators operate when they are tested and during grid outages creating sporadic but very real pollution. There is a significant technological gap in converting hospitals to zero emissions, or at least low emissions, resilience or emergency generation equipment.

6.5 Conclusions

While LDES technologies are necessary to decarbonize the energy system, they also introduce their own particular safety, reuse, and production concerns. Li-ion batteries generally present the most significant concerns, though they are the best established and have fire suppression systems associated with them. Some novel technologies like Fe-Air, Fe-flow, hybrid zinc, and TPV seem to present lower material-related risks; however, this could simply be the result of the limited commercial experience with these technologies. Li-ion has established recycling supply chains, though recycling is far from universal and carries its own environmental justice issues.

In addition to the development of new, safer, and cheaper long-duration storage technologies is critical that research on safe and non-toxic recovery and reuse of materials in batteries be adequately funded. In parallel, the integration of safe and economical recyclability as an integral feature in the design of and construction of storage systems should be promoted. That would make battery recycling a routine aspect of storage rather than a toxic afterthought that is shunted to the Global South or to overburdened communities in the Global North. Finally, recycling is unlikely to become safe and non-toxic on its own as stringent regulations are needed in addition to technology development. Indeed, as occurred with pollution control from automobile tailpipes, regulations will help spur new and more environmentally just innovations in LDES technologies.

[117] Krieger, Casey, and Shonkoff 2016

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8. Brief glossary of terms

Energy Capacity – Commonly measured in kilowatt-hours (kWh), energy capacity is the amount of electrical energy stored within a battery or other storage device; it is also represented by the amount of time (hours) at which the rated power output can be sustained without recharging.

Power Output or capacity – Commonly measured in kilowatts (kW), power output is the *rate* at which energy can be exported; the higher the value, the larger the electrical demand that can be supplied. An important caveat for some energy storage is that power output (battery discharging) can be different from power input (battery charging), or the rate at which energy can be stored into the battery.

Roundtrip efficiency (RTE) – Commonly expressed as a percentage (%), roundtrip efficiency is the amount of exportable energy by a storage system as a fraction of the energy input into the system after conversion inefficiencies (i.e., losses) are accounted for. Note: There are losses both when the storage system is charged and when it discharges. We report AC electricity to AC electricity roundtrip efficiency. We have not included leakage losses during storage.

Technological Maturity – Qualitative measure used to reflect our consideration of the current state of development. We use the technology readiness level to describe maturity. Note: A commercial product will be at a technology readiness level of 9, a late-stage prototype will be an 8, and an early beta prototype will be at a 7. Lower technologies readiness levels reflect technologies still under development; they are not considered here, but many are being explored and hold potential to come to market in the coming decades.