Resilience Hubs

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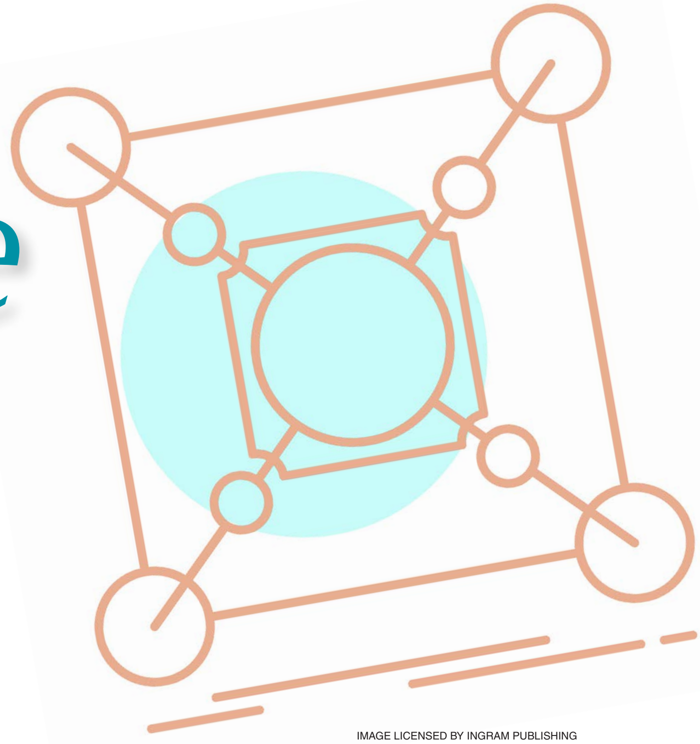

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THE INCREASED FREQUENCY, DURATION, AND intensity of extreme weather events happening around the globe are an immediate threat to the ability of power grids to provide reliable power to customers. In September 2017, Hurricane Maria swept across the Caribbean, causing massive destruction in Puerto Rico, leading to more than 4,000 deaths and more than US$90 billion in damages. The Puerto Rican power system was devastated, with 80% of utility poles and transmission lines downed and only 20% of its generation capacity operable 30 days after the storm. It ultimately took 328 days to fully restore power to the island, marking the largest blackout in the history of the United States and the second largest in the world. In February 2021, three severe winter storms caused the worst energy infrastructure failure in Texas history. Record-low temperatures, ice, and sleet combined to force large-scale generation failure, causing more than 4.5 million homes to go without power and resulting in more than 240 deaths. Limited contingency reserves and few external grid interconnections limited the amount of power that could be imported as the generation went down. The impacts of the storm also reached the electricity markets, where the wholesale price of energy massively fluctuated, peaking at US$9,000/MWh.

Extreme weather events are a threat to the power grid and those who rely on it, but the severity of these impacts can vary significantly for different households across communities. Globally, 2.4 billion people have intermittent power supplies due to unreliable rural power systems. In the United States, 14% of households in indigenous communities do not have access to electricity, and some disadvantaged communities are more likely to experience outages than other communities. Power outages can have disproportionately large economic effects on low-income households, where spoiled food and lost hourly paid income from an inability to work can significantly affect a household's welfare. In some circumstances, lack of access to electricity can even be life-threatening, especially for elderly individuals.

The variation of extreme climate and power system impacts experienced across different communities and customers underscores the importance of community-oriented resilience solutions developed from the bottom up, with constituent needs held paramount. These solutions should aim to correct historic climate and energy injustices that otherwise will likely become more entrenched through the energy transition as resilient technologies become more inaccessible to disadvantaged communities, who often need them the most. This calls for transformative collaboration, bringing communities into a more active role in power system development and operations where local governments and utilities better support their needs. One emerging solution that embodies this ideal is the resilience hub: a grassroots and community-oriented facility designed to provide physical resilience, promote social well-being, and provide flexible and versatile power resources to communities and the grid. This article dives deep into the structure of resilience hubs, analyzing their assets and purpose. It explores a coordinated operational control scheme for a network of hubs to generate maximum benefits for communities, power systems, and other stakeholders and applies it to a test case over Salt Lake City, UT, USA.

Fostering Equitable Access to Resources With Resilience Hubs

A resilience hub is a community facility designed to provide resources, support, and services before, during, and after an extreme weather event to uphold community resilience,

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Bolstering the Grid and Empowering Communities

sustainability, and equity (see Figure 1). Resilience hubs are entirely community serving; they are built at a public location (e.g., a public library), directed by local organizations, and completely accessible to the general public. During severe weather events, they act as secure havens where people, especially those without access to adequate resources, physically relocate for shelter, protection, and access to necessities like power, water, heating and cooling, food, and medical services. During normal conditions, resilience hubs can provide passive benefits to the community by serving as a community energy system or hosting public events. Resilience hubs are designed to have large-capacity smart energy systems that, if leveraged correctly, can be a significant asset to grid resilience and sustainability. Table 1 summarizes some prominent resilience hub projects in practice and under development today.

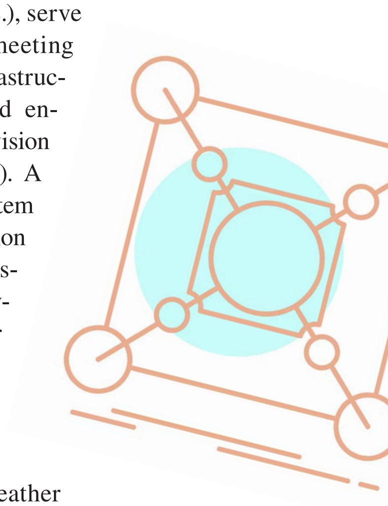
Successful implementations of resilience hubs serve as an asset to their community during *all* times. In addition to addressing immediate needs, resilience hubs can be leveraged to help address long-term challenges related to equitable access to power and other infrastructure by fostering stakeholder collaboration, resource sharing, and community engagement. In addition to providing resilient energy infrastructure, resilience hubs can enable social and economic equity and foster community interconnection. For example, the City of Tallahassee Resilience Hubs run a Grandparents as Parents program that assists and supports grandparents who are the primary caregivers of children through a variety of support programs, legal services, community agency connections, and health screenings. Apart from social services, community-oriented assets can bring significant economic benefits to their communities (Table 1). For example, community solar projects, a popular shared solar business model, not only enhance solar access, but they increase property values and community wealth retention while providing anywhere between 5% and 25% to household monthly energy bill savings. Resilience hubs can follow a very similar approach with their energy assets. Moreover, resilience hubs can empower community health in a myriad of ways. For example, hubs can host community gardens to grow organic produce, hold group fitness classes, and assist in coordinating community medical services, such as free vaccination events. Their renewable energy systems can also decrease local air pollution.

An inclusive environment for community participation in local initiatives can help to uproot systems in which communities were formerly passive recipients of projects led by external groups. Therefore, the impacts of resilience hubs are maximized by designing their services to meet the specific needs of community members through engagement, ownership, and operation. For example, resilience hubs developed in the Vibrant Hawai'i initiative have strongly advised hubs to partner with and be operated by trusted community leaders at established community centers (Table 1). Through trusted relationships, resilience hub developers meaningfully engage with community stakeholders to define expectations and identify existing hardships. A good example of this is the Resilient Minneapolis Project's resilience hub, whose community engagement with key stakeholders resulted in achieving specific community-oriented goals (Table 1). It identified the need for the resilience hub's energy system to meet energy needs for 48 h at 50% operations.

Operation Modes of Resilience Hubs Adapt to Meet the Needs of Their Communities

In addition to serving as a shelter and providing reliable power during extreme weather events, a resilience hub is intended to benefit and serve interested stakeholders at all times, though its purpose may change depending on conditions. Their assets make them a powerful tool for ensuring equitable access to energy, but how they should be used and optimized in power system operations will also depend on the conditions under which the resilience hubs are operating, which include normal operation, during extreme weather events, and during recovery, as shown in Figure 2.

1) *Normal operation*: During normal conditions, resilience hubs passively serve the community. Hubs can host community-oriented programs (day care, markets, workshops, events, etc.), serve as open and accessible meeting places, and meet local infrastructure needs (i.e., distributed energy generation or the provision of electric vehicle charging). A resilience hub's energy system can export excess generation onto the local distribution system, participate in peak shaving with intelligent loads, or even provide grid services if it is equipped with inverter-based resources.



2) *During extreme weather events*: During extreme weather events, a resilience hub plays a much more active role in the community as a physical structure where community members can seek support and protection with access to supplies that help meet their basic needs. Resilience hubs are designed to provide

energy services to other nodes on the distribution system during disasters, and they are equipped with multiple generation, storage, and grid-forming capabilities. Hence, there is an opportunity to coordinate energy services between resilience hubs to provide electricity for entire portions of an islanded microgrid or distribution system. Resilience hubs also provide outgoing emergency services, such as dispatched medical support or grid recovery services during extreme events. For example, the San Francisco HUB Program from the Neighborhood Empowerment Network's Neighborhood Emergency Operations Center coordinates resilience hub emergency services during extreme events (Table 1).

3) *During recovery*: Resilience hubs can also facilitate recovery efforts. Because of their central and well-known location in communities, they serve as ideal centers for supply distributions. They also remain open and provide basic services and needs for members of the local community who need support. Resilience hubs equipped with grid-forming inverters can also be crucial assets during blackout restoration efforts.

What Makes a Resilience Hub So Effective?

A resilience hub is a collection of complementary networks of components that promote and foster community resilience, sustainability, and equity, as seen in Figure 3. The defining characteristic of a resilience hub is that it is designed to meet the needs, well-being, and goals of the community it serves. Therefore, no two resilience hubs will look the same. A community-specific mix of available resources, services provided, energy systems, building design, and connected infrastructure is critical in developing a comprehensive resilience hub (Figure 3). Common aspects of existing resilience hubs include robust energy systems and the ability to offer resources and services during times of normalcy and emergency.

Services and Resources

Resilience hubs offer resources and services to their constituents during all modes of operation. During extreme weather events, a resilience hub should have all the resources and services needed to meet the community's basic needs. Otherwise, resilience hubs offer community support through services. For example, resilience hubs in Tallahassee, Florida, offer a variety of services, such as senior fitness programs and recreational activities (Table 1).

Building and Infrastructure

A resilience hub's structure must be resilient to withstand extreme weather events and may utilize sustainable design to promote efficiency and avoid polluting the community. To provide resilience, a hub should have passive survivability features (e.g., modern insulation), risk avoidance (e.g., siting to avoid a floodplain), durability (e.g., an earthquake-proof design), redundancy (e.g., backup electricity generation), and fast recovery systems (e.g., automated energy management systems). For example, Together New Orleans, a nonpartisan coalition of congregations and community-based organizations in New Orleans, has plans to construct resilience hubs designed to withstand the area's increasingly frequent hurricanes so they can provide shelter and emergency services to community members (Table 1).

Resilience hubs must be quickly accessible in the case of a disaster. An ideal implementation in a large urban area includes not a single hub to serve the entire population but rather a network of strategically located hubs that ensures easy relocation for everyone. A good example of this is Together New Orleans's network of neighborhood resilience hubs, which they call Community Lighthouses, which will offer shelter and services within 0.5 mile of all residents during emergencies (Table 1).

A resilience hub provides essential services, but complementary

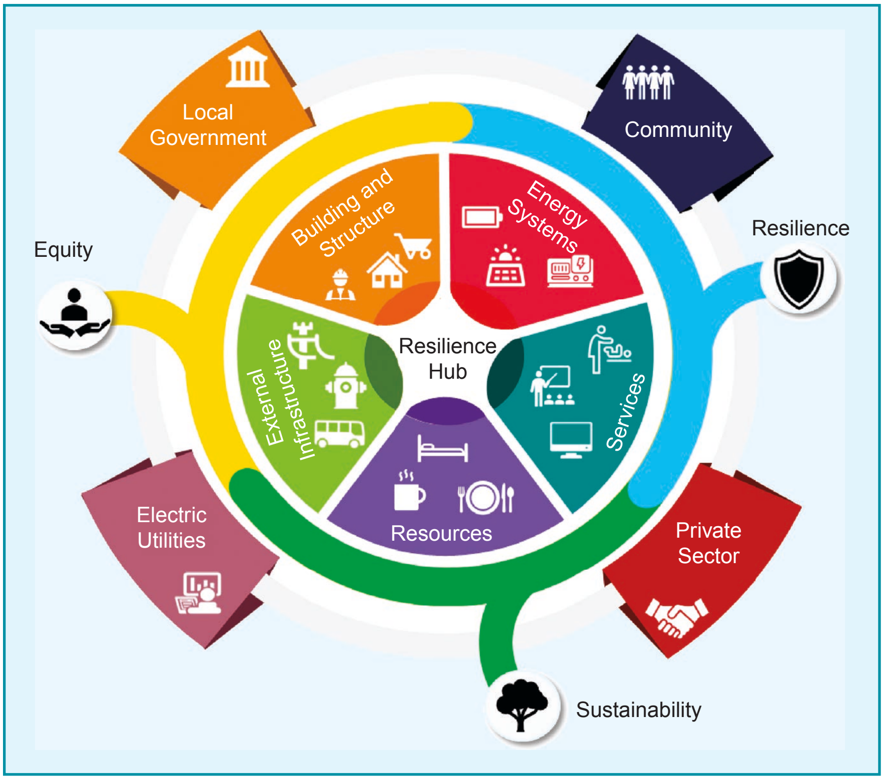


figure 1. The components, impacts, and stakeholders of a resilience hub.

infrastructure is required to maximize the impact of those services. Proper power infrastructure is required to connect a hub to the rest of the local grid in a safe and reliable way. Sufficient transportation infrastructure is required for community members to travel to and from a hub if it is not within walking distance. The hub should also be connected to auxiliary infrastructure, such as water, gas, the Internet, and communications. For example, in addition to resources to meet basic needs, the Vibrant Hawai'i resilience hubs also offer access to computers, the Internet, and public Wi-Fi (Table 1).

Energy System

A resilience hub's energy system is its defining asset. A hub typically has on-site renewable generation, energy

table 1. Sample resilience hub programs in the United States.

Program Name/More Information	Program Structure Details	Program Mission	Program Highlights	Active/ Planned Hubs
Baltimore City Community Resiliency Hub Program https://www.baltimoresustainability.org/baltimore-resiliency-hub-program/	Community trusted locations operated by nonprofit community organizations providing essential resources and support during crisis and outfitted with solar PV power and energy storage	Improve emergency response and recovery services by connecting frontline community organizations with targeted support and resources for underserved neighborhoods and vulnerable residents during disasters	• Robust energy system deployments • Access to renewable energy to disadvantaged communities • Extensive partnerships with trusted community organizations	16/20
Together New Orleans Community Lighthouse https://www.togethernola.org/.	Sites at community and religious centers with solar PV power and energy storage to provide essential resources during power outages	Construct a large network of distributed sustainable energy in public resilience hubs across the state	• Operate hubs at established community centers • Provide access to renewable energy to disadvantaged communities • Practice transformational engagement to uplift community members	3/24
Vibrant Hawai'i Resilience Hubs https://www.vibranthawaii.org/hubs.	Community-centric locations to provide equitable access to resources and host events to meet the unique needs of each site	Empower community members to implement hyperlocal solutions for community resilience	• Partner with trusted community leaders • Utilize place-based and culturally informed strategies • Improve communication between community and government agencies	7/7
San Francisco Neighborhood Empowerment Network HUB Program https://www.empowersf.org/hub/	Network of community organizations to prepare and execute emergency preparedness and response strategies	Help create a local network of community organizations that support daily preparedness and provide critical support during and after extreme events	• Coordinated planning across communities • Practice culturally competent resilience action plans • Provide services during all phases of a disaster	–/12
Resilient Minneapolis Project https://www.energy.gov/communitiesLEAP/minneapolis-minnesota.	Sites to provide communities with emergency resources and improved energy access with community solar PV installations	Use resilience hub spaces to combat environmental hazards like air pollution and soil contamination	• Partner with existing public facilities • Provide diverse community services • Emphasis on senior citizen support	–/3
City of Tallahassee Resilience Hubs https://www.talgov.com/neighborhoodservices/hs-reshub	Augmented recreational and public facilities with enhanced social services and sustainable construction that support emergency preparedness and disaster recovery	Improve neighborhood resilience, preparedness, and sustainability by incorporating critical social services into existing public recreation spaces	• Technical analysis assuring equitable power restoration • Strong community stakeholder dialog • Selling of power generation during normal operations	3/3

PV: photovoltaic.

storage, and backup generation. Solar photovoltaic (PV) power is the most common form of renewable generation at a resilience hub, but there might also be wind, fuel cells, pumped storage hydropower, or others, depending on the hub's regional characteristics. Complemented with energy storage systems, the energy system can be sized to meet the demand of the hub or even sized to serve other critical loads on the adjacent distribution system. The Baltimore City Community Resiliency Hub Program makes this a priority by providing grants to outfit partnering organizations and sites with on-site solar PV power plus storage systems (Table 1). An inverter is also a critical component in a resilience hub, providing an interface between the on-site generation and local distribution system. Resilience hubs can also take advantage of and optimize on-site controllable loads to maximize flexibility.

The resilience hub's energy system can be structured like a community energy system where community members can subscribe to shares of generation and receive discounted electricity rates, thus providing passive economic benefits while enhancing resilience. Community energy systems are already being designed to support low-income accessibility to distributed energy resources (DERs). For example, community energy systems in Colorado provide subscriptions at a reduced price for qualifying low-income households.

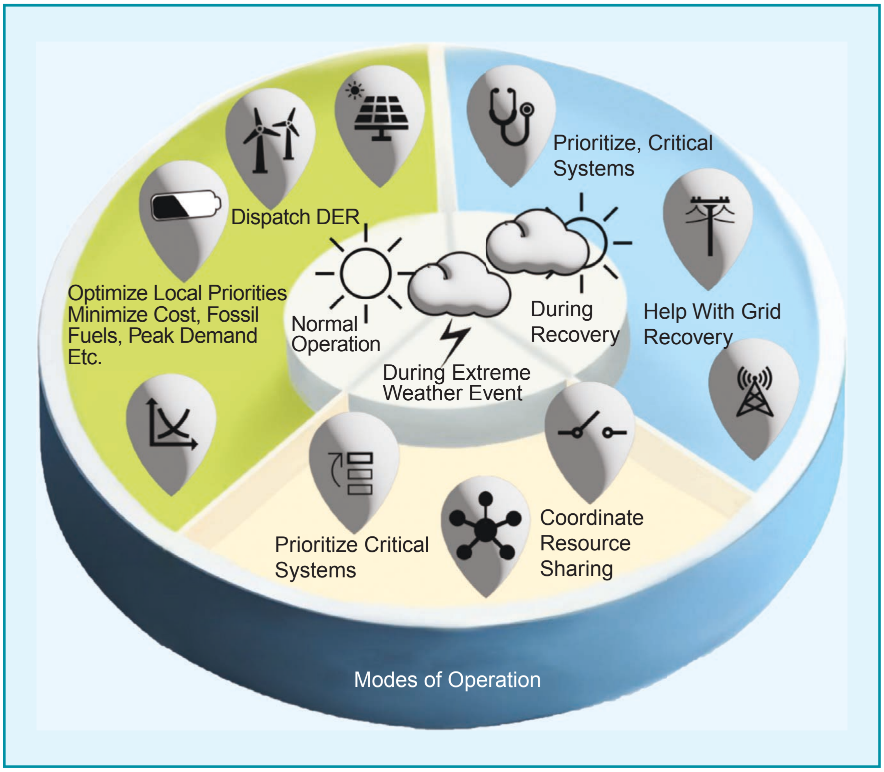


figure 2. Resilience hub energy system functions during different modes of operation. DER: distributed energy resource.

Grid Interaction

Resilience hubs offer a number of immediate and long-term benefits to the communities they serve. If implemented correctly, they can also be an asset to power system operation by offering a controllable,

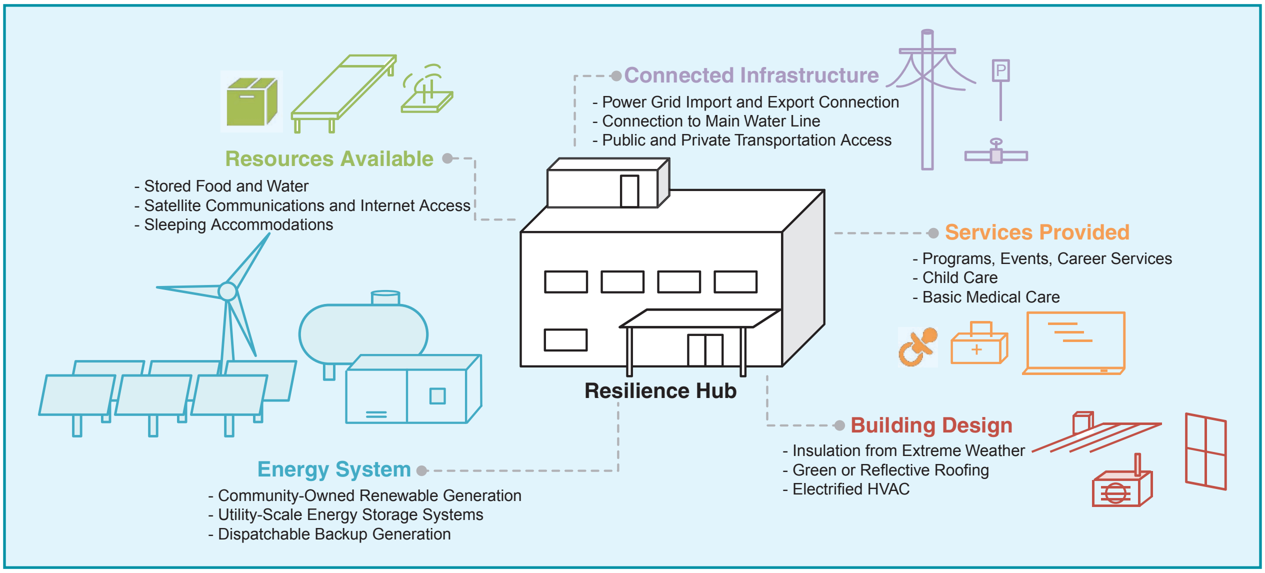


figure 3. A resilience hub has a robust energy system and available resources, provides services, connects to local infrastructure, and has an innovative building design. HVAC: heating, ventilation, and air-conditioning.

sustainable, flexible, and high-capacity resource as summarized in Figure 4. Resilience hubs can offer the following:

- ✔ *Enhanced resilience and critical load backup*: During outages, they can provide backup generation for critical loads neighboring the hub, like medical centers. A resilience hub equipped with a grid-forming inverter can assist in outage restoration in neighboring feeders using automated switching coordination. In other situations, a resilience hub may dispatch mobile energy storage systems.
- ✔ *Provision of flexibility and market participation*: Dispatchable energy generation and flexible load at a resilience hub can be aggregated to provide flexibility in local or wholesale electricity markets. Similarly, if the resilience hub has sufficient energy storage capacity, it can provide up and down regulation and reserves in ancillary service markets.
- ✔ *Increased renewable integration*: The renewable generation at a resilience hub can contribute to a utility's or community's renewable integration goals, procuring renewable energy credits. This may motivate a local utility to invest in the resilience hub.

The extent to which a resilience hub is an asset to the local power system depends on local utility, system operator, and community preferences. So, while resilience hubs are designed to support local needs, and specific resources can vary between hubs, coordinating these resources optimally has the potential to improve their benefit and the overall resilience of the community and power system. Depending on the ownership and financial structure of the resilience hub, any one or a combination of these grid interactions can generate revenue to offset installation and operating costs. This provides holistic benefits, improving the economics of the hub while also acting as an asset to the local power system.

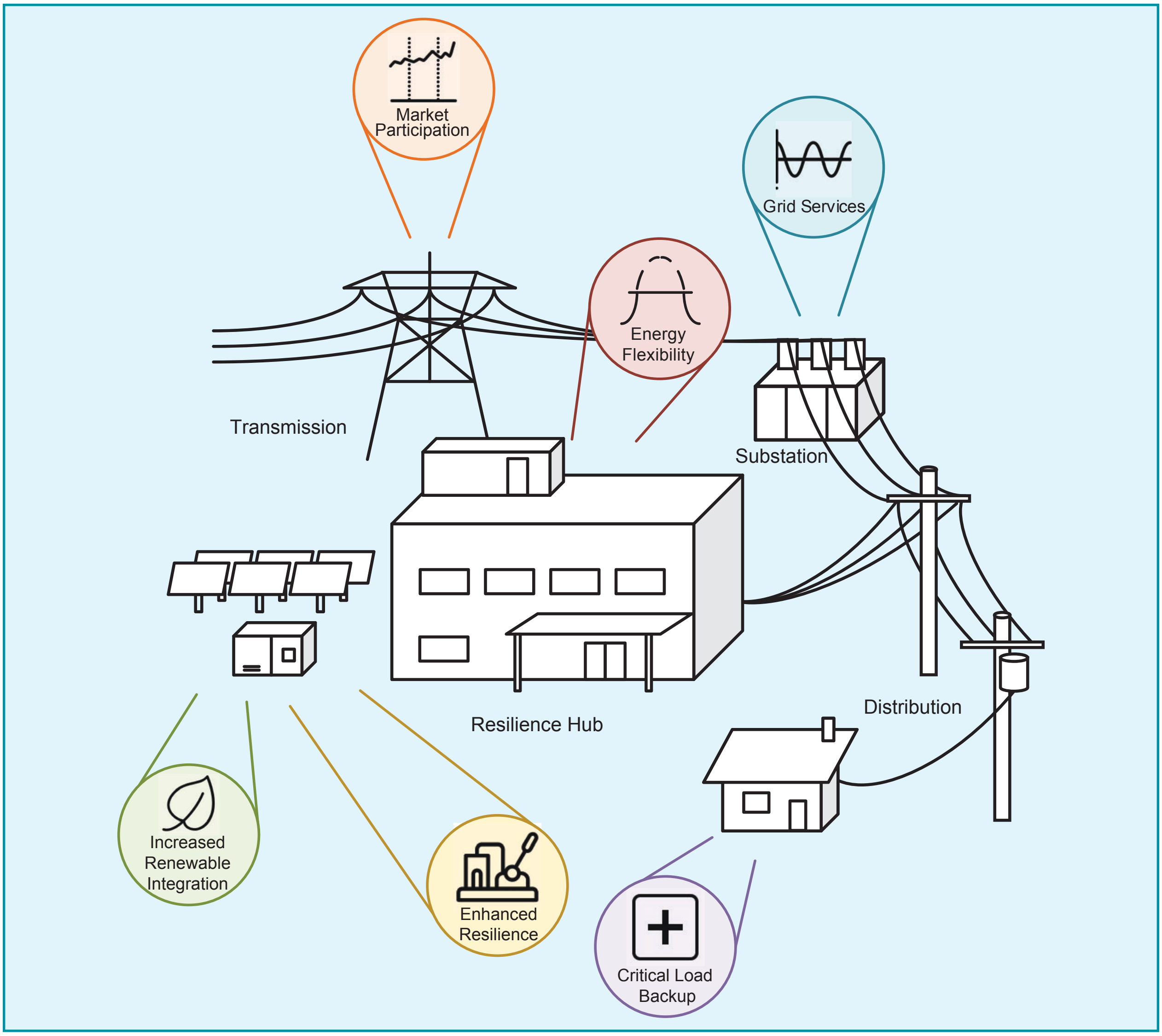


figure 4. Resilience hubs provide enhanced resilience and critical load backup, participate in wholesale electricity markets and ancillary services, and increase renewable energy integration.

Coordinated Operation of Networked Resilience Hubs

Providing resilient and reliable power is a core tenet of a resilience hub as all other resources and services rely on power to operate. A resilience hub's energy system must be optimized during all modes of operation such that there are adequate resources available during extreme weather events, the highest priority systems receive sufficient power, the hub's generation capabilities and grid support functionalities are fully leveraged, and all community members benefit from the hub's clean energy in a way that mitigates inequity. Because resilience hubs ideally operate as a network where multiple hubs exist across a large area and each serves its local community members, there is an opportunity to incorporate a coordinated operation scheme among the hubs.

Coordinated operation schemes can provide a plethora of added benefits to resilience hub stakeholders (especially community members relying on the hubs), including increased resource access, better system stability, enhanced resilience, economic collaboration, reduced costs, and increased social welfare. Here, we provide the concept of an intelligent hierarchical operation scheme for interconnected networked resilience hubs designed to enhance system resilience and overall stakeholder benefits.

Intelligent Hierarchical Operation of Networked Resilience Hubs

In modeling the control framework for resilience hubs, each hub and its collection of DERs and grid service providers are aggregated into a single node with a net real and reactive power demand and generation capacity. The purpose of coordinated resilience hub operation is to optimize the scheduling of each resilience hub in a computationally efficient and coordinated way that reflects the priorities of each local resilience hub's community while also ensuring the stability and resilience of the whole system.

The coordinated operation of networked resilience hubs can be implemented using a two-stage intelligent hierarchical scheme in which local resilience controllers (LRCs), designed to reflect community priorities, make local decisions about resource scheduling for each hub and then send their decisions to a central resilience controller (CRC) that makes adjustments to coordinate their operation subject to grid constraints. This model creates a computationally efficient and scalable control scheme that can be adapted to the needs of each community while guaranteeing stability, maximizing resilience, and addressing energy inequities among communities. A coordinated control scheme is depicted in Figure 5, and the LRC and CRC are discussed next.

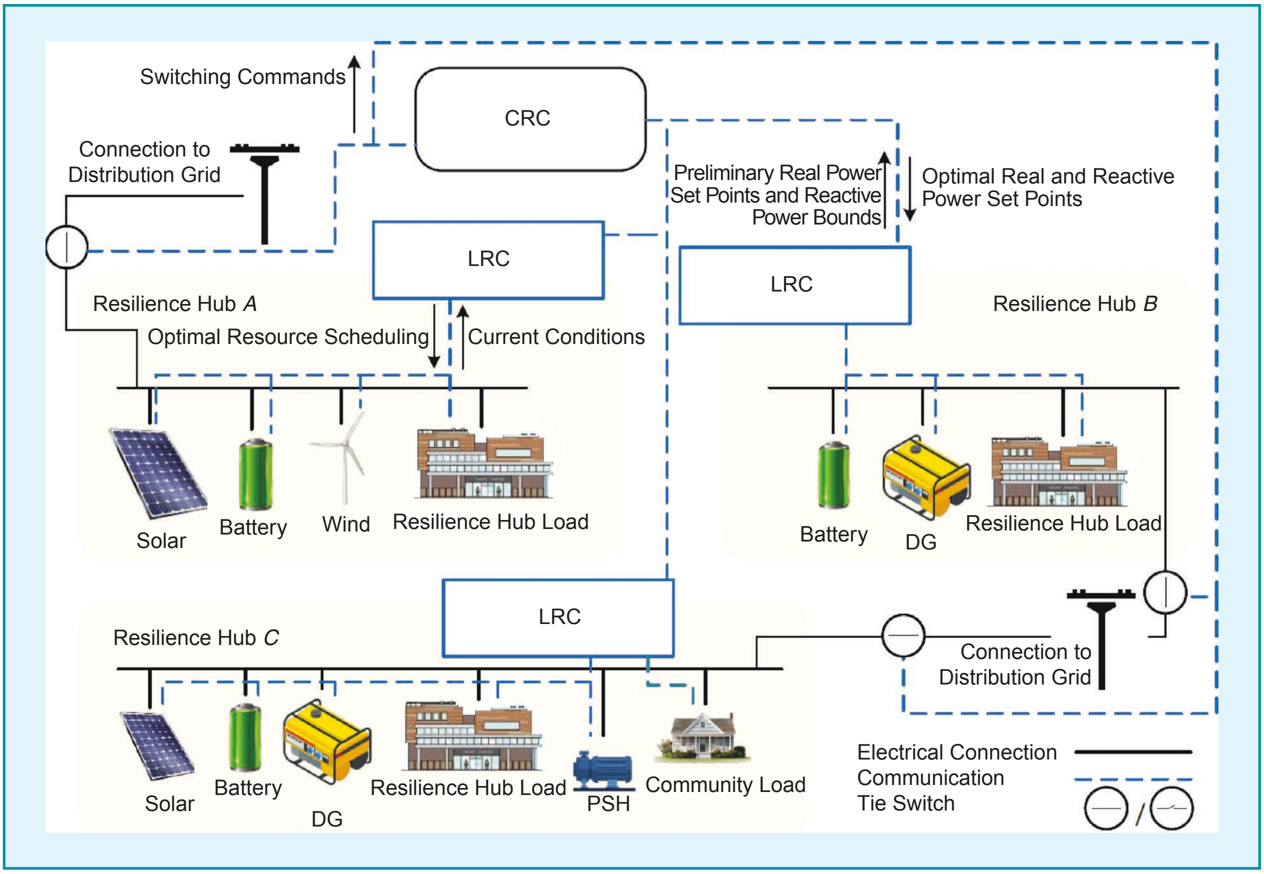


figure 5. A framework for intelligent hierarchical operation of networked resilience hubs. PSH: pumped storage hydropower; DG: distributed generation.

> During extreme weather events, it is possible that the CRC will need to disconnect one or more of the hubs in the network, operating them in an islanded mode.

Local Resilience Controller (LRC)

An LRC aims to make near-optimal decisions for operating the resources of resilience hubs based on local needs and priorities. The LRC may be designed using an optimization or an artificial intelligent model, such as deep reinforcement learning (DRL). The inputs to the LRC include real-time information about the current energy storage, distributed generation capacity, critical and noncritical load demand, and flexibility of the resources in the hub. The agent then uses this information to make real and reactive power scheduling decisions for all of the resources in the hub. Many scenarios can be generated to train the LRC agents; however, the uncertainty involved in knowing the exact scenarios, or states, in which the agents will need to operate means they need to be able to generalize their decision making to never-before-seen states, making DRL a practical choice. The set points determined by the LRC are then sent to the CRC. The CRC adjusts the real power set points if needed, determines the optimal reactive power set points, and sends them back to the LRC, which then directly controls the hub's resources. While the CRC's optimization model ensures the optimality and feasibility of the control decisions, a DRL-based LRC agent provides computationally efficient near-optimal set points and scalability for large-scale implementation.

For a given network of resilience hubs, the DRL agent operating the LRC should be trained to reflect the energy management best suited for the area, given the climate, types of extreme weather events it needs to prepare for, and historical energy and social injustices it aims to correct. Thus, the LRC operation objectives might be determined differently, but all LRCs should be designed to ensure that a threshold energy storage is maintained at all times in case of extreme weather events, especially for resilience hubs designed to be disconnected from the main grid during blackouts.

Central Resilience Controller (CRC)

The initial decisions made by the LRC are then sent to the CRC, which oversees the coordinated operation of networked resilience hubs and is designed to maximize resilience and power served during extreme weather events and ensure that grid stability constraints are met. The CRC determines if the real power set points are feasible given the current status of the network's interconnections and each hub's connection to the local grid. It also solves optimal reactive power set points based on power flow constraints and sends them back to the LRC. This ensures the feasibility of the solutions to satisfy the power flow constraints of the distribution system. The CRC solves a reduced-order optimization model that treats each resilience hub as a node in a distribution circuit with a net demand and generation capacity based on real-time conditions. The CRC is designed to operate during all three resilience hub modes to ensure that grid constraints are not violated during normal operation and to maximize hub demand served by coordinated operation during a disruptive event and recovery. Because the CRC is making decisions in real time, the problem must be solved quickly. If the CRC were to make constrained decisions about every resource in the resilience hub network, the computational complexity would be high. Using the LRC to make near-optimal decisions and treating each resilience hub as an aggregated node in the CRC optimization will reduce the complexity and allow the hierarchical control scheme to make effective real-time decisions.

Because the resilience hubs are electrically connected via the distribution network, the CRC can optimally configure these connections to maximize the number of energized hubs in the network and facilitate optimal and coordinated resource scheduling across them. During normal operations, the hubs will largely operate connected to the distribution system, and their operation is coordinated across the full resilience hub network. During extreme weather events, it is possible that the CRC will need to disconnect one or more of the hubs in the network, operating them in an islanded mode. The CRC will optimally adjust local generation set points to utilize resources in the network to maximize the available energy over an extended time horizon in the case of prolonged outages.

Applying the Intelligent Hierarchical Operation Scheme to Networked Resilience Hubs Across Salt Lake City

To demonstrate how the coordinated operation might take shape and discuss the potential benefits of the implementation, a hypothetical network of resilience hubs across Salt Lake City, Utah, is utilized, where each hub is designed to meet local needs, and the hubs are interconnected through the distribution network. Figure 6 shows three maps of Salt Lake City, each displaying U.S. Census Bureau census tracts. Eight resilience hubs are placed at public libraries in neighborhoods across Salt Lake City, as shown in Figure 6(a). The hubs labeled as A through H in Figure 6(a) correspond to resilience hubs located at public libraries in the Rose Park, Capitol Hill, Avenues, Foothill, Downtown, Poplar Grove, Glendale, and Sugar House neighborhoods, respectively. Each hub serves its local neighborhood, and all are interconnected with one another through the distribution network with redundancy. Each hub is controlled by an LRC, which sends data to and receives coordination control commands from the CRC. Figure 6(b) is the map of the average household income per census tract across Salt Lake City, and Figure 6(c) is a map of the urban heat island effect across the city [the data for Figure 6(c) are based on the CAPA/National Oceanic and Atmospheric Administration Heat Mapping Campaign, 2023].

Salt Lake City serves as a compelling test location as clear spatial correlations exist between income level and urban heating effects. Extreme heat poses a significant threat to Salt Lake City and is expected to become significantly more frequent as climate change persists. Neighborhoods in Salt Lake City at higher elevations (census tracts on the east side of the city) typically experience more moderate heating effects and also have higher average household incomes. Lower-income census tracts in central Salt Lake City face the largest urban heating effects. Moreover, low-income households are more likely to be less weatherized, making them more susceptible to extreme heat.

The inequitable impact of heat waves in Salt Lake City signals the importance of reducing power outages for the more vulnerable communities. In the presented resilience hub network [Figure 6(a)], hub *E*, in the Downtown neighborhood, would likely serve as a community cooling center during extreme heat events. Operating as a cooling center increases electricity demand, so the CRC may leverage resources from neighboring hubs, allowing excess generation to meet hub *E*'s increased demand. Since hub *E* is

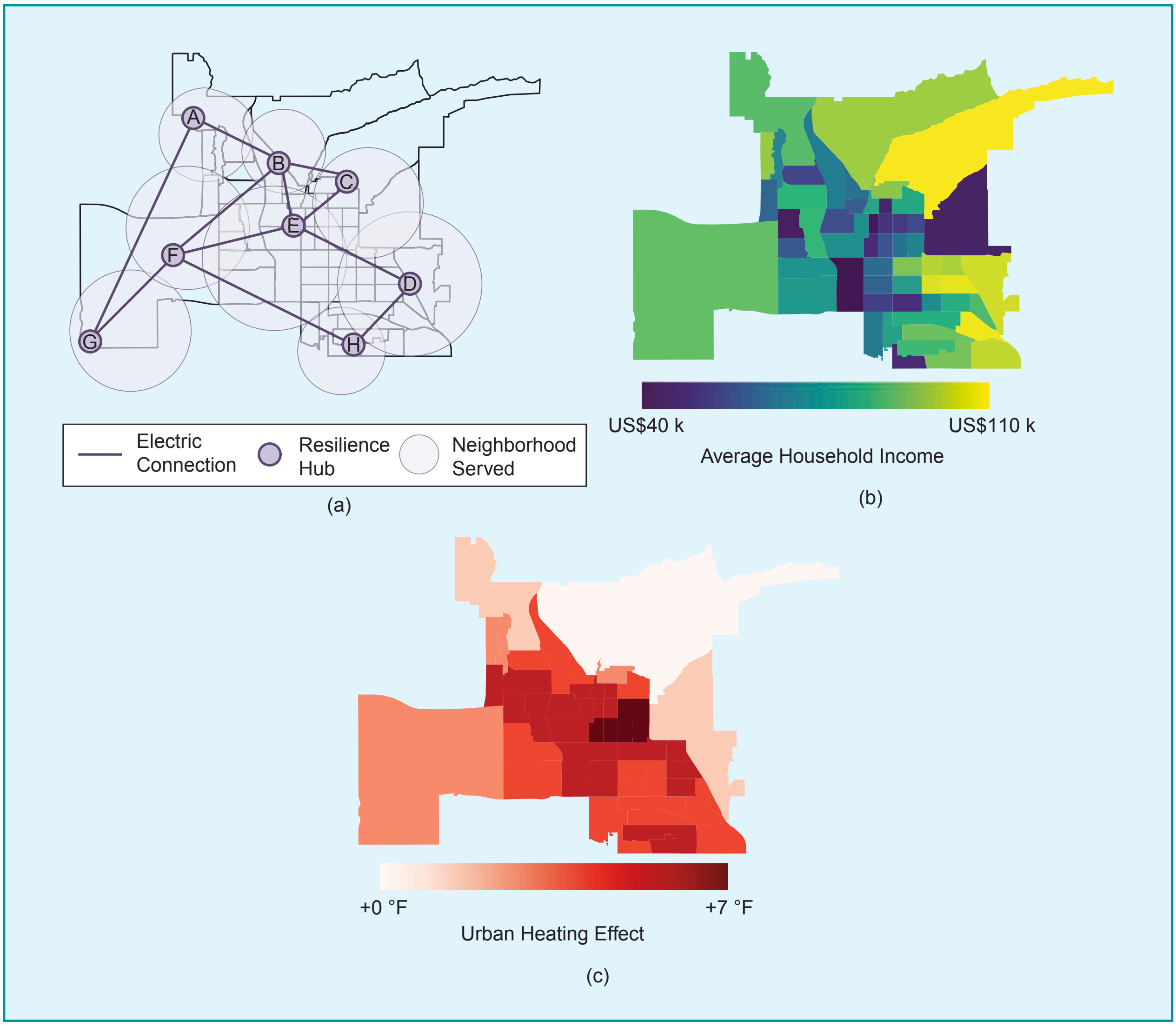


figure 6. Maps of Salt Lake City census tracts. (a) Hypothetical resilience hub network at existing public libraries serving eight neighborhoods and electrically connected via the distribution network. (b) Average household income per census tract. (c) Average increase in temperature from urban heating effect.

> The CRC may direct a neighboring hub to charge its energy storage to serve as a contingency for resilience hub E if it were to experience an outage.

providing critical community services, it will also maintain a sufficiently high state of charge for its energy storage systems in case of an outage. Through intelligent coordinated operation, the networked resilience hubs' energy assets can be leveraged to reduce the impacts of extreme weather events equitably.

Not all of the resilience hubs in this network would have the same energy system resource portfolio. Some hubs' locations are better suited for high-capacity solar PV generation, while others may rely more on wind or other distributed generation. They will also have varying inverter and storage capabilities. Consider the case where the same heat wave scenario happens and resilience hub *E* does not have an onsite energy storage system. The CRC may direct a neighboring hub to charge its energy storage to serve as a contingency for resilience hub *E* if it were to experience an outage. During times of normalcy, the resilience hubs could also operate as a virtual power plant with the CRC aggregating generation and bidding into electricity markets to generate additional revenue for the resilience hub network. Similarly, the CRC could operate a local power pool over the resilience hub network where hubs could trade generation or demand with one another. Depending on the ownership structure of the resilience hub network, a virtual power plant or local power pool may provide economic and operational benefits to the local grid operator.

It is important to acknowledge that two communities, both served by their respective local resilience hubs, may still suffer disproportionate energy and climate burdens and a lack of resources. The intelligent coordinated operation scheme for networked resilience hubs would provide multiple benefits to the communities and power system operators in the Salt Lake City resilience hub network. By leveraging coordinated operation and optimized power system dispatch, it can spread resources across the resilience hub network. Resilience hubs ensure power needs are met where they are needed most, supporting system stability, maximizing the number of energized hubs during outages, and simplifying resilient demand-side resource integration so that the hubs can be an asset to grid operators and communities alike.

Resilience hub networks are region specific. In Salt Lake City's scenario, socioeconomics, demographics, climate, and existing infrastructure influence the design of a resilience hub network. All resilience hub networks should be informed by existing inequities throughout a community and utilize their functionalities to remediate them.

Who Benefits From Sharing Resources Among Resilience Hubs?

Resilience hubs become even more effective through coordinated operation schemes. They facilitate a system where resources are not only pooled but also strategically managed to ensure they are used efficiently and effectively. This approach mirrors the core tenets of the sharing economy, where optimal coordination leads to greater overall benefits.

Resilience hubs embody community energy resilience and sustainability, serving as a nexus for stakeholder collaboration and engagement. They are most impactful through structured participation from private and public sectors aimed to maximize community support. Stakeholders, including local governments, utility companies, and private organizations (Figure 1), play essential roles in the effectiveness of resilience hubs, and coordinated operation holds added benefits for everyone.

At the heart of resilience hubs is the community, which is crucial as a possible owner, participant, and primary beneficiary. Community engagement is vital for setting priorities, planning, operating, funding the hubs, and ensuring solutions are inclusive, equitable, and tailored to local needs. The intelligent hierarchical operation scheme allows individual hubs to determine their own scheduling and management priorities while participating in centralized optimal coordination that improves overall resilience and stability. Allowing coordinated operation among communities has the potential to mitigate inequities by improving resource accessibility and flexibility.

For local governments, active participation in a resilience hub network bolsters economic resilience within communities. Local governments can foster long-term stability and growth by promoting sustainable practices and mitigating the economic impacts of crises. Utility companies, as integral partners, can experience improved grid stability, increased controllability, and reduced system failures through their involvement in resilience hub operations, which in turn benefits all stakeholders reliant on these services. The private sector's contribution of funding and expertise enhances the effectiveness of resilience hubs and cultivates positive community relations, potentially leading to an increased market presence and the leveraging of tax incentives. By actively engaging in resilience hub development and fostering intelligent hierarchical operation in a network, stakeholders reap tangible benefits that contribute to overall community resilience and well-being.

Ownership of a resilience hub is often directly intertwined with the hub's financing. Community, public, or municipal ownership is typically ideal as it naturally guides the resilience hub to meet the unique needs of its constituents. This is the case in many resilience hub implementations today as they are developed in publicly owned facilities (e.g., public libraries). However, implementing a resilience hub can include high upfront costs, requiring entities outside the community to support development. Generally, resilience hubs have finance models similar to those of traditional community energy systems where third-party organizations (the local government, utility company, or private corporations) may cover the upfront system implementation costs in return for partial or full ownership of the asset(s) and receive tax benefits. Nonetheless, resilience hubs are often an excellent candidate for state and federal funding. For example, grants from the Maryland Energy Administration finance the majority of solar PV and energy storage assets for the Baltimore City Community Resiliency Hub Program. On the federal level in the United States, the Inflation Reduction Act has appropriated funds for several agencies to support community resilience (Table 1). It is also common for nonprofit organizations to support resilience hubs through grants and donations. The upfront costs of the Together New Orleans Community Lighthouse project are partially supported by local nonprofit organizations (Table 1).

Electric utilities may also have interest in getting involved in the operation and ownership of a resilience hub or some of its assets. A utility may take on the capital expenditure associated with portions of a resilience hub in return for complete or partial ownership and control over energy assets. Alternatively, the hub may generate revenue from a power purchase agreement with a local utility to supply generation. Utilities may also receive additional incentives through tax benefits for supporting resilience hubs. Independent from a utility, a network of resilience hubs may operate as a virtual power plant, where revenue from participating in wholesale electricity markets and providing ancillary services can offset installation and operating costs. The resilience hub may also procure revenue like a community solar program, where local community members can subscribe to shares of the hub's electricity outputs for reduced electricity rates.

Ownership structures and financing models should ultimately be designed to the community's benefit. If funding of a resilience hub results in increased electricity utility rates or the withdrawing of funding from other essential services in the community, it may not be the best community resilience solution. A resilience hub should only ever serve as an asset to its community; it should not exacerbate any previous or existing hardships. Considering this, funding is often one of the largest challenges in implementing a resilience hub. Third parties may be able to assist in overcoming this financial barrier, but they must do so without compromising comprehensive community engagement. Some communities may be less eager to adopt a new "community" asset from a third party. There have been many instances in which entities put on very limited community engagement programs, simply to meet a requirement, rather than to collect feedback from stakeholders. Inequitable distributions of resilience across communities are often a by-product of long-term systemic and institutional failures, anchored by a neglect of community engagement. Remediating decades of injustices requires comprehensive strategies in dozens of aspects of society. Considering this, it is critical to acknowledge that resilience hubs are only one tool of many in instituting just and equitable resilience throughout communities.

Resilience hubs offer a transformative approach to building stronger, more sustainable communities by fostering collaboration, equity, and resilience among diverse stakeholders. Coordinating networked resilience hubs via an intelligent hierarchical operation scheme allows for greater flexibility and resource accessibility between communities. It has the potential to further increase overall system resilience and mitigate energy injustice. Through concerted efforts and strategic investments, resilience hubs have the potential to not only enhance grid resilience and mitigate the impacts of crises but also to pave the way toward a more socially resilient and equitable future for all.

For Further Reading

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