Resilient, Rural, and Revolutionary: Salisbury Square's Direct-Current Affordable Microgrid Community

Preprint

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Resilient, Rural, and Revolutionary:
Salisbury Square's Direct-Current Affordable Microgrid Community

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ABSTRACT

The technology to interconnect buildings with a dedicated direct-current (DC) power distribution network is in place today. What is missing is a turnkey approach to designing a DC microgrid, and the business models allowing such systems to be deployed, owned, and operated at scale. To close this gap, the Salisbury Square Microgrid Development Team, comprising clean-energy experts, has engineered a resilient community DC microgrid for an affordable housing community in Randolph, Vermont.

Nine single-family, occupant-owned residences and 12 multifamily rental units will share locally generated and stored solar energy via a DC power distribution bus capable of operating during extended grid outages. With a DC power distribution network in place, each home will be equipped with high-efficiency DC lighting and appliances, operating alongside alternating current (AC) appliances, even during an islanded mode of operation.

To obtain a comprehensive understanding of what is possible and achievable, the Team collaborated with the local utility, regulatory agencies, a national laboratory, energy-as-service providers, and vendors. The collaborators evaluated microgrid typologies, business models, and energy modeling, and analyzed electrification and resilience. Further, the Team applied the URBANopt^{TM} (Urban Renewable Building and Neighborhood optimization, NREL 2022) software development kit (SDK) to Salisbury Square's single-family and multifamily buildings to validate workflows and identify needs for advanced capability.

This paper addresses the barriers to entry, scalability, and impact on residents and system ownership. It also examines the analysis that informed the design and engineering of the DC microgrid and the opportunities to streamline the process.

Introduction

Communities nationwide face growing challenges related to climate and economic resilience. Although many communities are seeking to reduce emissions through the deployment of energy efficiency and renewable energy measures, they must concurrently respond to the increasing effects of climate change and the growing need for resilience during extended power outages caused by extreme weather and other events. Further, a lack of affordable housing and energy cost volatility (for example, in heating fuels) can add significant burdens to low-income households and communities. Holistic and socially equitable solutions, however, can reduce emissions, strengthen resilience, and improve quality of life.

Advances in heat pump technologies, solar photovoltaics (PV), battery storage, smart electrical panels, and power electronics such as power semiconductor devices with advanced control mechanisms can now make possible the delivery of highly efficient, all-electric buildings with backup power. During typical operation, these buildings can be grid-connected and deliver to their occupants utility bill cost reductions, improved comfort, and superior indoor air quality.

During power outages and when properly designed for backup, they can use stored energy and on-site electricity generation to meet critical loads and maintain safe indoor air temperatures for extended periods. This can be achieved at an individual building level and bring economies of scale and increased use of shared batteries and PV to an entire connected community (Pless et al. 2020, Olgyay 2020). Microgrid technologies that can move between grid-connected and islanded modes make such community-scale strategies possible. DC microgrids particularly can improve the efficiency of the integrated systems by eliminating DC-AC-DC power conversion losses between the PV system and DC-powered equipment and devices in buildings.

The Need: Proof of Feasibility

Even so, there is a need for projects that demonstrate the technical and economic feasibility of such integrated community-scale solutions, while also demonstrating the ability of modeling tools and workflows to be effective for planning and design.

The Response: Affordable Living That Benefits Customers, Utilities, and the Grid

The project this paper showcases is a promising new housing strategy for climate and economic resilience in a type of setting that, nationwide, is home to 20 percent of the population. It is a study of how historical electricity supply methods can be re-purposed to contribute significantly to *affordable living* in today's rural environments. The project also connects the community's technological and social structures, in the context of climate resilience.

This paper discusses the feasibility of a community project that combines net-zero-energy building construction techniques with shared utility resources, producing grid stabilization and load shape benefits. The study examines 21 affordable-housing units, with 9 homeowners and 12 tenants who can operate their own unit-specific nanogrid. The nanogrid comprises small, self-sufficient systems with power generation, controls, and energy storage feeding a community microgrid, with DC systems. The project, Salisbury Square, is a community at a former brownfield in Randolph, Vermont, and is already under way. Figure 1 shows the site plan.

Figure 1. Salisbury Square site plan.

A Community-Scale DC Project as a Climate Resilience and Energy Security Measure

AC, despite its nearly universal application throughout the United States, compels power conversions from high-voltage AC to lower-voltage DC distribution of a building's energy load, particularly the load in a home. AC has been in place for well over 100 years and is most appropriately and commonly used in central power generation and transmission. The past several years, however, have seen an increased use of DC in homes, with an increase in the number and type of household products that require DC power (Pantano et al. 2016).

A feasibility study[1] for this partially completed community of Salisbury Square apartments and single-family houses (RACDC n.d.) shows that the community can stand on its own as an energy island during a severe climate event, while also storing and selling back energy to the local utility. Salisbury Square has begun to demonstrate that creating a community net-zero-energy DC microgrid produces benefits to:

- Low-income (cash flow) and low-wealth (assets) households: improved health, building durability, asset creation, and lower ratepayer costs for electricity
- Utilities: shared solar + storage, and improved power resilience via coordinated control of microgrid assets, and predictability in demand response and load shaping
- Grid: lower energy consumption in the residential sector, and demand response and load shape predictability

DC as an Effective Method for Advancing Efficiency and DERs

Highly efficient energy loads—such as those associated with distributed energy resources (DERs)—are typically fed by DC, but are converted to AC under our current electrical system. Low-wealth populations in the United States are often excluded from participating in the benefits of DERs because they can be relatively costly to install. A community-level DC system can help bring DERs within reach for these populations and help close the disparity in access when it comes to cost-effective energy availability, affordability, and delivery (Palaniappan 2019).

The revolution in distributed energy has meant that consumers and small operators can now locally generate, store, and distribute different types of power. This has created complex challenges for the AC-driven grid. Investments in new or upgraded energy infrastructure now address capacity, resilience, and ways to incorporate greater quotas of DERs to meet state and federal clean-energy mandates. With the patchworked drift away from central power generation and transmission, utilities and planners are revising historic use of both AC and DC as a means of transmission and distribution as well as end use loads.

The changing home. The advent of personal computer (PC) use in the 1980s profoundly affected global society, economics, and societal relationships with consumer technology. The PCs' silicon microchips that enable intelligence and computing power at home are natively DC devices, requiring a power supply ("brick") to convert the AC power in the wall to DC power for use on the computer boards. In the last 40 years, the number of devices powered by DC has exploded, involving nearly all consumer electronics, and many HVAC systems, lighting and controls systems, and household appliances. An adapter on any of those products is an AC-to-DC converter and is typically 85 to 90 percent efficient—meaning that one loses 10 to 15 percent of the electricity needed to power the device, because homes have only AC available at the outlet.

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[1] The study, whose report is not publicly available, received funding from the Vermont Low-Income Trust for Electricity, and involved the Randolph Area Community Development Corporation and Green Mountain Power, Rutland's distribution utility. Direct Energy Partners conducted site microgrid analysis and modeling, and Interface Engineering, Inc., specified home distribution and modeling.

Determining the benefits of a community microgrid. The primary objective of the study is to identify and articulate the technical and resilience benefits from DC infrastructure for a community microgrid system. The method is to couple DC solar sources, battery storage, and DC loads from the use of electric vehicles (EVs), lighting, receptacles, appliances, and mechanical equipment. The study also assesses barriers to adoption of the concept.

Taken together, this comprehensive look at DC's potential role in overcoming the limits of AC suggests a new era of participation in DER benefits among vulnerable populations that have been classically excluded from such benefits. The emergence of microgrid DC infrastructure as a reliable method for creating safe-harbor energy islands in severe climate or other events affecting traditional power systems also has broad appeal. That is, scaling DC microgrid installations to populations and utilities, especially in rural areas, can mitigate those regions' chronic risk of prolonged power outages.

Salisbury Square Microgrid Project Characteristics

To our knowledge, Salisbury Square, once it is complete, will be the first primarily DC, net-zero community microgrid in the United States. It is a project of a local affordable housing developer, the Randolph Area Community Development Corporation (RACDC). The housing units and community buildings are constructed to the Efficiency Vermont Certified 3.0 high-performance standards (Table 1). To date, 14 low-income apartment units have been built, and next-phase plans call for the construction of 21 net-zero modular homes and apartments. The plans also specify that second-phase units will be affordable to low- and moderate-income (LMI) households meeting the definition used by the Randolph Area Community Development Corporation: having incomes between 80 percent and 120 percent of area median income. The site will offer pedestrian-friendly walking spaces, EV charging, and network operation of DC nanogrids that feed a community microgrid. Some AC will also be available. Given the extensive field experience of the Team in designing projects and programs for rapid adoption, the project is sufficiently phased and substantial to offer a roadmap for scalability. Further, appliance and equipment manufacturers wanting to expand distribution of their DC products can pilot them for installation and performance tracking. With regard to the local utility, Green Mountain Power (GMP) owns and manages power management hardware and software. The utility and the homeowners can provide and track load management, and safe electricity distribution via digital systems.

Table 1. Key prescriptive requirements for each Salisbury Square unit, per Efficiency Vermont Certified 3.0 high-performance standards

Feature	**Requirement**
Maximum window U-factor	U-0.21
Maximum door U-factor	U-0.25
Minimum ceiling R-value	R-60
Minimum above-grade wall and joist R-value	R-32
Minimum below-grade wall R-value	R-20
Minimum exposed floor R-value	R-35
Air leakage (air changes per hour, ACH)	≤ 1.0 ACH50 *or* 0.06 cfm50 / sf surface area

Feature	Requirement
Ventilation	Balanced system, flow rate meets ASHRAE 62.2, sensible recovery efficiency (SRE) ≥ 75%
Water and water heating	WaterSense & ENERGY STAR
Heating and cooling	ENERGY STAR
Lighting	95% ENERGY STAR
Appliances (all)	ENERGY STAR

General Approach to the Project

The typical lifecycle of a microgrid implementation project involves defining project goals and benefits, site selection, design, procurement, implementation, commissioning, and operations and maintenance. This project's fundamental design supports a multi-vendor microgrid platform with interchangeable generation, distribution, and storage assets.

Multi-vendor DC microgrids offer significant benefits. They prevent single-vendor lock-in to a particular microgrid solution and mitigate risks with supply chains of critical microgrid components such as power conversion systems and energy storage systems (ESS).

The key to unlocking multi-vendor microgrids is a modular design with a vendor-agnostic DER controller. It must be built from the ground, up, to ensure interoperability between microgrid components, including PV systems and ESS. This means that the microgrid's operational logic is "software containerized"; if equipment must be replaced, only configuration points specific to the replacement equipment must be changed to make the new microgrid operational. This efficiency has obvious administrative, operational, and functional benefits.

When it is complete, the Salisbury Square project will work closely with GMP to integrate the control system, operation, and maintenance functions. The Salisbury Square project has benefited from partner engagement to reduce soft costs (for example, engineering and commissioning) through well-thought-out project design. Although it is not yet known what the costs of the microgrid and its soft costs are for this residential project, soft costs typically account for 43 percent of commercial / industrial microgrid projects' cost (Giraldez et al. 2018). Project partner Direct Energy Partners reduced these soft costs by using its streamlined system design tool DCIDE (Direct Current Integrated Design Environment).

How the DC Microgrid and Nanogrids Will Work

Nanogrid design. Each home will have its own DC nanogrid, using a DC connection to the community microgrid. The homes' DC loads are lighting, receptacles, HVAC, hot water, and DC appliances. Many of these DC native input devices are not yet widely available. However, the Team[2] has worked directly with several large manufacturers to secure pilot and commercially available devices that have been engineered and manufactured to be powered with DC voltages (380VDC / 48VDC / 24VDC). AC will still support legacy AC devices and some mechanical equipment. Local inverters supply the AC devices.

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[2] The core team for the Salisbury Square project comprised staff from VEIC and Direct Energy Partners. NREL researchers applied the URBANopt advanced analytics platform, in collaboration with the Team, to inform future community-scale modeling capabilities.

Feeding the microgrid from the nanogrids. The community will connect these net-zero energy homes into a single, zero-energy microgrid that offers resilience to homeowners and the utility. The microgrid will involve:

- 157 kW solar capacity, distributed across the homes, apartment buildings, existing community building, and a carport, to produce approximately 184,000 kWh per year
- Modeled energy consumption of the community equal to 184,000 kWh per year
- On-site battery storage offering a combined 980 kWh of use, shared among the homes
- Ownership and management of power management hardware and software by GMP
- Sufficient microgrid capacity to support both a DC service connection and downstream conversion to AC within individual homes
- Microgrid-managed load, with a digital electricity distribution system
- Safe electrical distribution via patented, digital electricity communication, over wire technology
- Microgrid-incorporated battery storage of future EVs

Anticipated benefits from this microgrid-nanogrid structure are:

- Improved asset utilization through shared resources (solar and storage)
- Improved power resilience through optimized and coordinated control of microgrid assets
- Enhanced demand response and load shaping
- Lower costs for ratepayers
- Reduced energy consumption in homes via high-efficiency DC lighting and appliances

Anticipated challenges are:

- DC equipment availability—for example, residential-sized DC main electrical panel
- DC appliance availability—kitchen appliances, washer / dryer, HVAC and hot water
- Additional cost for equipment and appliances
- Contractor familiarity with microgrid and DC electrical codes and wiring
- Owner and tenant adoption, operation, and maintenance of DC net-zero energy home
- Collaboration of property managers and equipment specialists with the local electric utility, to manage the DC microgrid

Achieving net zero and energy efficiency with DC loads. The microgrid design of the 9 new homes and 3 four-plex buildings is based on the zero energy modular (ZEM) initiative pioneered by Efficiency Vermont, a statewide energy efficiency utility. The new homes and apartments will be factory built and meet the Efficiency Vermont Certified 3.0 high-performance standard, incorporating high levels of insulation, exceptional air tightness, energy recovery ventilation, ENERGY STAR® lighting and appliances, and water efficiency (Efficiency Vermont 2020; Table 1). The homes are all-electric, fully supporting net-zero-energy microgrid technologies. The buildings feature efficient physical design. The 1-story homes, at approximately 1,100 square feet, have an open floor plan with three bedrooms and one full bathroom. The 2-story homes, at 1,200 square feet, have first floors with living room, dining room, kitchen, bedroom, and full bath. The second floors have two bedrooms and one full bathroom. The homes are filled with natural light and are efficient with their use of space—while providing ample storage. Each home has off-street parking to accommodate two cars, and a circuit to accommodate an EV charging station. The four-plex apartment buildings comprise eight 1-bedroom / 1-bathroom units, and four 2-bedroom / 1-bathroom units. Each apartment and home has independent HVAC and hot water systems that use energy-efficient electric and heat pump compressor-driven technologies for heating, cooling, and domestic hot water production.

The target demographic for home ownership is LMI households making 80 to 120 percent of area median income. Nearly all the homes will be covenanted for permanent affordability to ensure that the community continues to serve the target population and continues to provide affordable home ownership options for area residents.

The technical details of a Salisbury Square unit. The design considers how people live and specifies user-friendly technology whose optimal operation is easy to learn and understand.

An in-home DC nanogrid enables power wiring and equipment selection. The electrical plan, shown in Figure 2, suggests the locations where low-voltage DC cabling (24 / 48VDC) can be run to power lighting and receptacles. Wherever National Electric Code (NEC) requires it, AC receptacles are necessary and can be powered from a dedicated DC / AC inverter.

The topology is largely based on the use of 380VDC for large electrical demand (>100 W), and 24VDC for both lighting and convenience receptacles. This system topology is similar to EMerge Alliance's design for residential applications. Emerge Alliance is an industry association promoting the adoption of DC and hybrid AC / DC technology. The use of 380VDC aligns well with available compressors, fan motors, and the power requirements for larger resistive loads comparable to the 120 / 240VAC used in conventional homes.

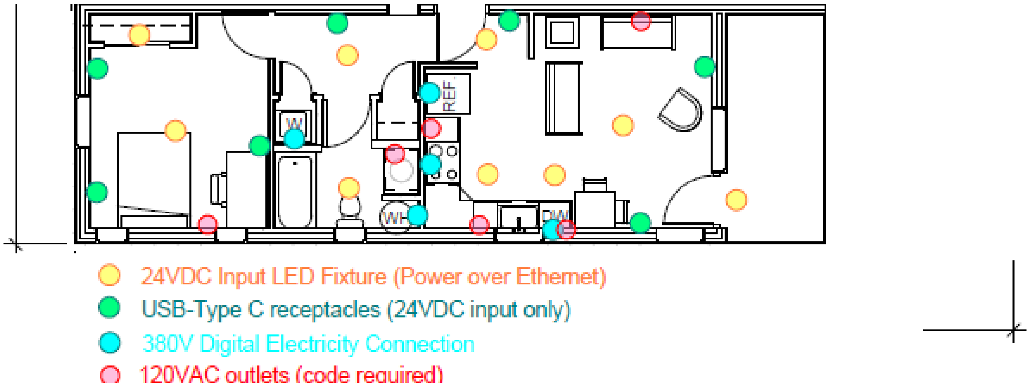

Figure 2. Typical 1-bedroom hybrid AC / DC layout.

The major electricity-consuming devices align with the following categories:

- Lighting and convenience receptacles
- Large appliances
- HVAC
- Domestic hot water equipment
- EV charging

Lighting and convenience receptacles. The study has proposed a Power-over-Ethernet (PoE) system to provide low-voltage lighting and convenience USB-C charging, relying on a <60VDC distribution over CAT6 cables. PoE standards have evolved quickly in the past decade; the latest approved standard supports up to 90W of connected load per cable.

A dedicated lighting and convenience receptacle PoE switch can drive LED lighting and USB-C charging receptacles. Several vendors have created power sourcing equipment for this application, but few have considered the needs of homeowners, who are not enterprise-type corporate clients. For convenience receptacles, the Team has proposed combination USB-A and USB-C receptacles that support USB charging for phones and tablets or plug-in USB input floor lamps and consumer electronics. These types of DC input receptacles are commonly available for industrial and automotive / yacht markets, but not necessarily for residences, where receptacles are installed in junction boxes behind drywall.

Large appliances. One of the most energy-intensive aspects of a residential single-family home is its large-appliance loads. This project has specified all-electric equipment. Appliance electrical loads can be subdivided into categories of resistive appliances (ovens, dishwashers, electric heaters) and non-resistive appliances (refrigeration compressors in refrigerators / freezers, microwaves, induction stovetops, washing machines, and heat pump clothes dryers). Resistive loads can be met with DC input power comparable to AC input.

Most non-resistive load appliances already use DC power downstream of incoming AC filters and inverters to clean up the utility power before being routed through appliance control and power boards to drive motors, compressors, and other appliance electronics. For these non-resistive load appliances, converting the equipment to accept DC input is largely a simplification of the existing electronics.

Because appliance manufacturers are increasing equipment energy efficiency and providing more Internet of Things smart home integrations, the electronics inside residential appliances are largely migrating from AC to DC. Appliances not currently accepting a DC input could be adapted to accept either AC or DC input at similar voltage ranges. EMerge Alliance is advancing dual AC / DC input appliances, which would help manufacturers and consumers avoid splitting the market.

HVAC. The project will use cold-climate air source heat pump systems with one outdoor condensing unit and an appropriately sized indoor ducted fan coil unit. Many new air conditioning systems invert incoming AC power to DC for use in powering the system's DC motors and compressors. A traditional AC installation would have a 230VAC power supply, which would feed the outdoor condensing unit and the indoor fan coil units.

The DC alternative provides a 380VDC connection to the outdoor unit to run the fan motors and compressor with no inverter, whereas a voltage-changing DC-to-DC converter would step down this 380VDC to safe line voltage of <60VDC, taken off the main control board of the outdoor unit to feed the indoor fan coil units.

The project's proposed Zehnder central energy recovery ventilator (ERV) system has a backup electric resistive heating element. The accompanying fan motor and power supply would be re-selected to be 350VDC input, with a small DC / DC voltage converter to step down 350VDC for the control board at 12VDC.

Domestic hot water equipment. The project will use heat pump water heaters with a 380VDC connection. The HPWH converts low-temperature to high-temperature water using two heat exchangers, a condenser, and an evaporator. Working like a refrigerator in reverse, a stand-alone air source heat pump water heater extracts heat from the surrounding air in the conditioned living space and transfers it, at a higher temperature, to heat the water in a storage tank. Although at least one heat pump water heater with an outdoor heat exchanger (Hx) is commercially available, a unit with indoor Hx was selected in this application due to it having substantially lower initial equipment costs.

EV charging. Each home has off-street parking to accommodate two cars, and a circuit to accommodate an ENERGY STAR charging station for an EV. Two charging stations will also be located at the 6-car solar carport.

Utility Considerations

The proposed project, involving more than 20 households and related common spaces, opens considerations for the local utility. The primary effects on GMP, from this kind of community, relate to (1) bigger utility loads because of the introduction of microgrids, (2) benefits from occupant self-sufficiency with renewable sources of power, and (3) reduced numbers of urgent outage responses because of island resilience characteristics.

To gauge the effects on utilities and the grid, the Team created five scenarios to test the feasibility of the project's completion as a DC microgrid community.

Modeling for Optimal Specifications—Five Scenarios

The Team evaluated five microgrid design scenarios utilizing an internal simulation modeling software, DECIDE, for alignment with project objectives, concluding that a centralized energy storage system powering the site-level DC microgrid and indoor DC nanogrid provides the best balance among economical and performance tradeoffs for this project.

- **Scenario 1.** Traditional AC architecture: AC site infrastructure with indoor AC power distribution
- **Scenario 2.** DC nanogrid per house: AC site infrastructure with indoor DC nanogrid
- **Scenario 3**. Centralized storage: DC site infrastructure with indoor DC nanogrid and centralized storage powering the site DC microgrid
- **Scenario 4.** Distributed storage 1: DC site infrastructure with indoor DC nanogrid, in which all homes interfaced to a common DC bus *without* an intermediate DC-to-DC converter
- **Scenario 5.** Distributed storage 2: DC site infrastructure with indoor DC nanogrid, in which all homes interfaced to a common DC bus *with* an intermediate DC-to-DC converter

Results of the Simulations and Their Contexts

The objective of the cost-benefit analysis was to quantify the benefits of adopting a community-level, low-voltage direct current (LVDC) microgrid to complement the existing AC infrastructure and facilitate a high presence of DERs—solar PV, EV charging infrastructure, and battery storage—that could supply energy-efficient loads (HVAC, LED lighting, and EVs). The benefits address savings in power conversion capacity and gains in power conversion efficiency, compared to a modern AC distribution network architecture featuring the same distributed assets. The power conversion efficiency is expressed in kWh / annum, and directly relates to the annually recurring operational expenditure (OPEX). The power conversion capacity is expressed in kW installed power and directly correlates to the upfront capital investment (CAPEX). The analysis's objectives addressed the following questions:

1. What is the degree to which a DC microgrid increases the power conversion efficiency of the system, compared to its legacy AC counterpart?
2. What is the degree to which a DC microgrid reduces the overall installed power conversion capacity, compared to its legacy AC counterpart?
3. What are the benefits of adopting a community-level microgrid, as opposed to a home-level DC microgrid architecture?
4. Is it beneficial to deploy a community-level hybrid AC and DC distribution architecture?
5. How does DC microgrid architecture affect the asset ownership model that considers homeowners and utility?

Assumptions. Analysts performed all simulations with a 1-hour time resolution, making several assumptions about CAPEX and OPEX, such as:

- **Voltage**: nominal DC voltage: 380VDC; AC voltage: 240 / 120VAC
- **CAPEX:** on power conversion equipment, excluding installation costs of supplementary equipment
- **EV:** The 6-car solar canopy will accommodate 4 EVs with 7.6kW capacity EV chargers; EV chargers operate at full load for 8 hours / weekday and are idle for 16 hours. The community's individual charging profiles are scheduled to flatten the total charging profile.
- **Solar:** All rooftop solar generation occurs at the same time.
  HVAC: The individual HVAC load profiles are spread over time to alleviate power peaks on the grid.
- **Lighting, ventilation, and appliances**: Powered simultaneously in all dwellings
- **ESS:** capacity of 300kWh with a C rate equal to 0.52. This corresponds to the median C rate of commercially available storage systems.

The models exclude labor costs, grid constraints, standby power, and standby losses.

Resilience. A microgrid architecture improves the resilience of the community because it can create an energy island. Islanding allows the community to operate on its own when powered by on-site generation and the back-up power from the centralized, community-level energy storage system. That system aggregates solar and grid power and centrally distributes stored energy. Due to the design of the central power distribution system, the microgrid is capable of sharing power among the dwellings. That is, although the utility maintains the grid for back-up power, community members generate, store. and trade energy via an energy management system.

Minimum power conversion hardware. Beyond resilience, a DC microgrid architecture lessens the requirements for converters and inverters. Fewer electronic components in the chain among generation, storage, and loads yield higher efficiency and space savings, and lower CAPEX.

Incentive support from the utility, possible rate design changes. GMP incentivizes energy storage by a dedicated support scheme. In return, the energy storage can be dispatched by the utility. Typically, the battery needs to provide peak power for three hours. The peak power capability of the battery storage determines the subsidy. Consequently, the power conversion equipment needs to be capable of handling that battery power. In any DC architecture, the AC / DC converters need to send the battery power back to the grid.

Microgrid community technical needs (central technical room). A DC microgrid architecture requires a central technical room for the AC / DC power conversion equipment, connecting to the utility, optimizing for minimizing the total cost of ownership.

Results

The Team used the scenario modeling to determine optimal outcomes in the context of resilience requirements, minimizing power conversion, and communal space requirements for the housing community. The Team then determined the concept's next steps, particularly with scalability in mind. They considered the tools available to most planners, whether operating in rural or semi-rural areas, or in suburban and urban settings.

Resilience Requirements Must Be Met with Prioritized Battery Storage

Battery storage, a key to resilience during an electrical power outage, must be adequate to meet resilience criteria. The Team determined that the level of adequacy is independent of the selected system architecture. That is, if the community suffers a power outage from a local utility event, or even an outage of the community microgrid, each dwelling unit's battery storage will be a backstop to ensuring occupants still receive power. Thus, battery storage must be prioritized as an irreducible essential for adequate system architecture. Further, high-efficiency DC architecture with demand management extends the community's off-grid operation, since every gain in system-level efficiency means more power can be dedicated to running equipment, rather than being assigned to system-level losses.

The Importance of Minimizing Power Conversion

To reduce energy losses from conversions to DC power, the Team prioritized accurately sizing the power conversion hardware for each system architecture, via valid and reliable calculations for power conversion losses. A further aim was to minimize the power conversion hardware in the system ro reduce cost and increase reliability, while still meeting all known system situations and constraints (battery charging during peak, AC / DC utility interface converter capability, and power conversion capacity, for example).

Determining Communal Space Requirements

Because Salisbury Square occupants share community spaces and are in a cooperative living environment, determining the energy requirements for common spaces was and continues to be necessary for optimal community effectiveness. Given the known system constraints, the Team determined that optimal site architecture for wire distribution should involve hybrid AC / DC distribution.

Comparing System Architecture in Deciding on Optimal Specifications

The Team also determined the usefulness of comparing system architectures for optimal effectiveness, using the following considerations:

- Ensure batteries can be fully charged and are available for utility dispatch during peak hours (1 pm to 9 pm).
- The AC / DC utility interfacing converters and DC-to-DC community-interfacing converters should be capable of handling the requested power from the utility.

The Potential for Scalability

A Model for Developers

As promising and as advanced as the planning is for Salisbury Square, the Team is fully aware that its own research has brought to light the need for further investigation—particularly in the context of the project's potential for scalability. For example, the following approach will inform other community developers:

- Determining the numbers of affordable housing units ready for renovation or replacement, nationwide, to identify ready markets for the DC microgrid concept
- Determining the extent to which this model can work in small (< 4 units) and large multifamily buildings; such knowledge will inform both power and system architecture needs, and give developers an understanding of how best to approach existing communities for outreach on the concept
- Understanding the full scope of utility readiness factors (presence or absence of net metering options, clean-energy generation sources, energy efficiency programs, and incentives, for example)

District-Level Energy Modeling

For nearly 50 years, the U.S. Department of Energy (DOE) has supported initiatives for creating whole-building energy modeling (BEM) software and standards (DOE 2022). Among many potential uses, BEM tools can compare energy use among energy efficiency programs and design choices, green building organizations, and code, to determine compliance or financial incentives for new and retrofit buildings. Researchers use BEM to estimate effects of policy changes or for planning on how to achieve a goal at the individual building level and for communities. However, BEM tools have been largely constrained to individual building analysis and are not capable of simulating community- or district-level energy flows that buildings draw from and push to DER—and the interaction of those components with each other and with the utility grid. The URBANopt platform, under development by the National Renewable Energy Laboratory (NREL), Lawrence Berkeley National Laboratory, and other university and industry partners, discussed in more detail below, is helping provide this advanced functionality.

To make an impact well beyond Salisbury Square, it is important that analysis workflows for this pilot are replicable for other projects across the country. An open-source software development kit (SDK), URBANopt is intended to support and enable commercial software user-facing interfaces that can serve different purposes and levels of detail. It needs to be easy to learn, well documented, reliable, transparent, and robust in capability. NREL plans to take what was learned through this exercise to inform future capability in URBANopt. The "Bring your own HPXML" functionality, for example (see next section), has been added and documented in the released version of URBANopt. The URBANopt team identified some capabilities as areas of possible future work that would add value to projects similar to Salisbury Square. These are:

- More advanced modeling of passive survivability during power outages
- Distinct modeling in BEM of AC vs. DC building loads and their connection to the grid and microgrids
- Modeling of EV in backup power for buildings
- Time-dependent PV de-rating to show impact on generation profile shape for snow.

The Role of URBANopt

Because of the variety of applicable urban analysis types, URBANopt has modular software architecture supporting multiple engines that work together for a more complete district- and community-scale analysis. For BEM, URBANopt relies on the EnergyPlus^{TM} engine via OpenStudio$^{(R)}$. VEIC partnered with NREL on the Salisbury Square project to pilot URBANopt and provide a real-world use case to evaluate and refine the platform's capabilities.

Like many BEM tools, URBANopt can use simplified inputs and extrapolate the data required for an EnergyPlus simulation. For modeling commercial buildings, URBANopt leverages the OpenStudio Standards Ruby Gem, which has standards and vintage-specific building characteristics and modeling logic for construction, internal loads, and HVAC systems. Commercial building internal loads are modeled as building and space-type specific-area normalized power densities. Residential and multifamily modeling in URBANopt takes a more fine-grained approach with flexibility to better represent specific community and occupant behavior. This is accomplished by modeling individual housing units or single-family homes as a Home Performance eXtensible Markup Language (HPXML) model. This represents individual appliance loads and schedules that can change, independent of each other, which would be much more challenging if internal loads for an apartment was represented as a single W/area value.

HPXML encompasses two open data standards that codify residential building input and modeled output data, and how those data are transferred across software platforms. HPXML is a key underpinning of several software tools and data platforms (Building Performance Association 2022). NREL has used HPXML with the recently developed OpenStudio-HPXML (NREL 2019) workflow to generate an EnergyPlus simulation input files using an HPXML building description file. The OpenStudio-HPXML workflow comprises measures that generate an HPXML file and smooth or stochastic occupancy schedules, translate the HPXML to an OpenStudio Model (OSM), run an EnergyPlus simulation, and generate output reports. This workflow has been adopted by private-sector software tools, helping bring consistency to the residential energy modeling industry.

The most common URBANopt residential workflow is to auto-generate HPXML's models from high level community or building level data stored in an URBANopt GeoJSON file. To support the customization required for this pilot, the URBANopt team created a "Bring your own HPXML" function in URBANopt that allowed custom detailed housing unit-level data to be incorporated into the district-level modeling platform.

For Salisbury Square, the authors used the OpenStudio-HPXML workflow to generate HPXML housing unit description files for analysis in URBANopt. The workflow was run in

OpenStudio's Parametric Analysis Tool (PAT). The team then generated an HPXML file for each housing unit. Each file has provided high-level unit characteristics such as size, floors, and orientation. Detailed inputs were effective R-values for each assembly— accounting for nominal insulation values, framing factors, and installation quality; air leakage rates; primary and back-up mechanical systems; and large appliance and lighting details. The HPXML also accounted for unit location within a multifamily building and proximity to neighbors, including adiabatic surfaces and shading impacts. URBANopt combined the resulting OpenStudio Models (OSMs) representing each unit within a multifamily building into one OSM, run through EnergyPlus as a single building model. This has been done in parallel for all buildings in the district (Figure 3), with results passed to district-level reporting.

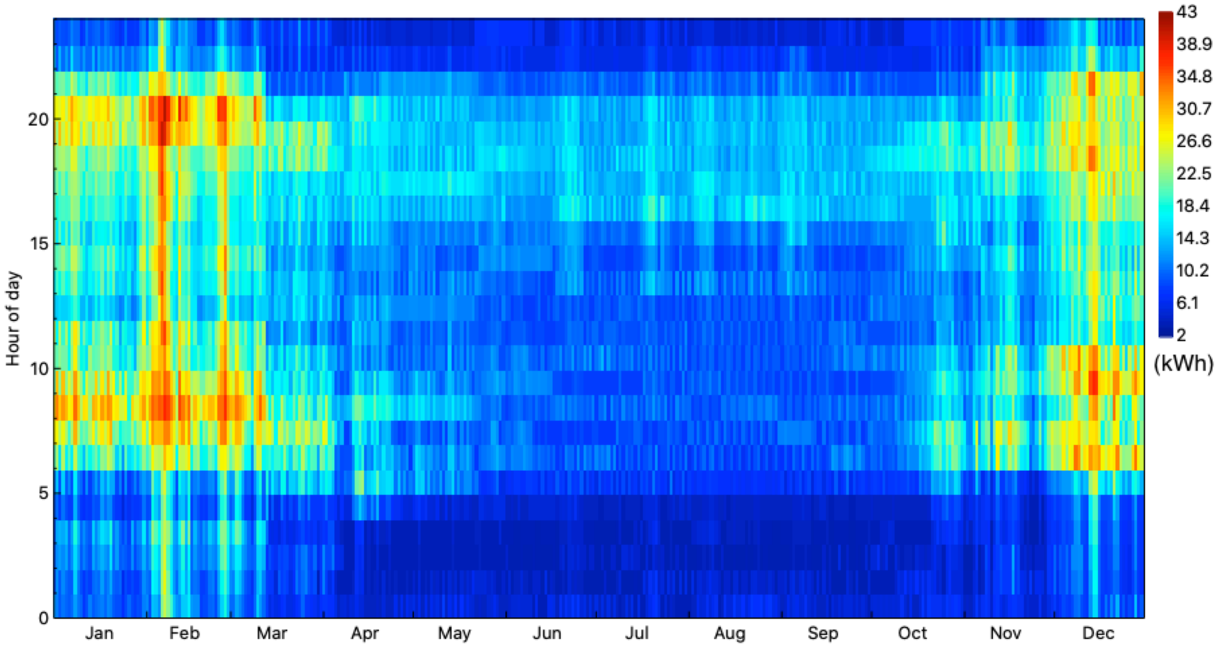

Figure 3. URBANopt-generated hourly annual energy consumption (kWh) for new Salisbury Square Buildings.

Conclusions

The Team has determined that Salisbury Square is an appropriate setting for a DC microgrid community. As modeled, the Team is confident that, when completed in 2024:

- Occupants of this affordable housing community will receive substantial protection from catastrophic power losses, while being given the opportunity to build wealth from assets associated with net-zero housing and EV ownership.
- Utilities will benefit from the design's ability to stabilize grid resources.
- Manufacturers of DC-powered equipment will identify new residential markets for expansion of their products.
- Environmental benefits will accrue through the use of clean energy.

The Team also recognizes that although Salisbury Square is in a rural area, its potential for scalability ranges to suburban and urban areas. The energy security benefits such an "energy island" can accrue to its member-occupants are substantial, both in insulation from short-term catastrophic power events and in long-term asset growth for homeowners. Thus, as a sustainable community model that capitalizes on a growing trend toward DC-powered residential buildings, Salisbury Square is on the ground level for a promising future of DC microgrid communities.

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