UC Davis
UC Davis Previously Published Works

Title
The feasibility of residential microgrids: a hypothetical neighborhood in Davis, California

Permalink
https://escholarship.org/uc/item/4dq2m0z7

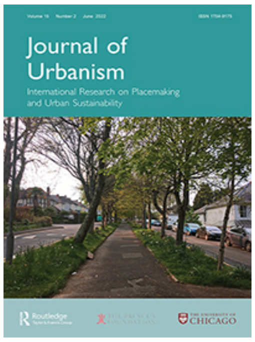
Authors
Mooyman, John
Wheeler, Stephen M

Publication Date
2022

DOI
10.1080/17549175.2022.2116471

Copyright Information
This work is made available under the terms of a Creative Commons Attribution License, availalbe at https://creativecommons.org/licenses/by/4.0/

Peer reviewed



Journal of Urbanism: International Research on Placemaking and Urban Sustainability

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/rjou20

The feasibility of residential microgrids: a hypothetical neighborhood in Davis, California

John Mooyman & Stephen M Wheeler

To cite this article: John Mooyman & Stephen M Wheeler (2022): The feasibility of residential microgrids: a hypothetical neighborhood in Davis, California, Journal of Urbanism: International Research on Placemaking and Urban Sustainability, DOI: 10.1080/17549175.2022.2116471

To link to this article: https://doi.org/10.1080/17549175.2022.2116471

© 2022 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group.

Published online: 05 Sep 2022.

Submit your article to this journal

View related articles

View Crossmark data

Full Terms & Conditions of access and use can be found at
https://www.tandfonline.com/action/journalInformation?journalCode=rjou20

JOURNAL OF URBANISM
https://doi.org/10.1080/17549175.2022.2116471

Routledge
Taylor & Francis Group

OPEN ACCESS Check for updates

The feasibility of residential microgrids: a hypothetical neighborhood in Davis, California

John Mooyman and Stephen M Wheeler

Department of Human Ecology, U. C. Davis, Davis, CA, USA

ABSTRACT
Microgrids create a local electric system partly or completely detached from the grid. Microgrid neighborhoods potentially offer more reliable power, lower costs, zero greenhouse gas emissions, improved air quality, ability to level power demands on the grid, and positive net electricity production. However, until now microgrids have primarily been used for military and institutional projects. To improve understanding of residential microgrid design and performance, we analyze current literature, discuss existing examples, and calculate energy use and cost for a hypothetical microgrid neighborhood in Davis, California. We find that such a neighborhood could easily achieve zero net operating energy status annually for both homes and cars, with a 16-year payback period or 7 years if owners also adopt electric vehicles. Similar results are likely in warm climates globally. If built at scale, microgrid neighborhoods could thus be a main tool to reduce residential GHG emissions and improve energy service resiliency.

KEYWORDS
Microgrid; Zero-Net-Energy; Plus-Energy; neighborhood; sustainable urban design; ecodistrict

Introduction

As the climate crisis grows, Americans are beginning to rethink residential energy systems. One clear need, given the slow pace at which utilities are transitioning away from fossil fuels, is to move towards zero-net-energy[1] or plus-energy homes and neighborhoods producing their own electricity from renewable sources. Another need, given increasingly severe weather and fires, is to improve the resilience of local and regional energy systems. For example, since the late 1990s the Pacific Gas & Electric Company (PG&E) has instituted planned power outages on windy days in northern California to reduce risk of its transmission lines sparking wildfires. In winter 2021 unusually cold weather also led to a widespread grid failure in Texas, while later in that same year Hurricane Ida interrupted power in parts of Louisiana for several weeks. Both events left many residents without power and essential heating or cooling services. Such events indicate that U.S. energy infrastructure needs new, more resilient designs.

Microgrids represent one strategy for improving electric service resilience and creating sustainable local energy systems with zero greenhouse gas emissions from operations. (Some emissions will result from production of system components.) “Resilience” in an engineering context refers to the ability of systems to survive shocks without failing. In

CONTACT Stephen M Wheeler smwheeler@ucdavis.edu

© 2022 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group.
This is an Open Access article distributed under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives License (http://creativecommons.org/licenses/by-nc-nd/4.0/), which permits non-commercial re-use, distribution, and reproduction in any medium, provided the original work is properly cited, and is not altered, transformed, or built upon in any way.

this case, microgrids potentially allow neighborhoods to retain electric power should the utility grid fail due to fires, storms, earthquakes, or other events. Such resilience may have important climate adaption benefits.

The U.S. Department of Energy defines a microgrid as

"a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island mode." (Ton and Smith 2012, 84)

In the US, microgrids have been primarily used to date for military, commercial, or institutional purposes for example, at military sites far removed from civilian power grids. However, within recent years developers have begun exploring residential applications. Recent interest in the residential district as an optimum scale for sustainability oriented urban design (e.g. Condon 2010; Fraker 2013; Ecodistricts 2022) emphasizes the importance of the neighborhood as a scale at which to apply microgrids. The microgrid model is also important to explore given the current move towards all-electric homes and vehicles powered by renewably generated electricity in order to end fossil fuel use.

Microgrid residential neighborhoods offer multiple benefits going beyond similar energy-efficient neighborhoods with renewable energy but homes operating on a stand-alone basis. Since they can operate dynamically as a unit, they can disengage from the grid (for example, if the grid goes down), use their central controller and storage to avoid consuming grid energy (for example, if one unit has high temporary demand), and at times provide the grid with additional power or storage. They also allow sophisticated, zero-GHG energy systems to be provided for an entire neighborhood in a way that would be unlikely if individual building owners had to add such services on their own.

Many challenges confront residential microgrid projects. State laws prohibit them in most places, and investor-owned or public utilities may not wish to support them. It is uncertain in many cases whether renewable energy production can meet microgrid demand, and how such electricity might be stored on a daily or seasonal basis. It is also unclear whether the upfront and operating costs of neighborhood-scale microgrids make sense for developers and residents. Lastly, few examples exist of how microgrid infrastructure might affect site design and interact with other sustainability needs at a neighborhood scale.

Therefore, microgrids hold great promise to meet local electricity needs more sustainably and with greater resilience, but are as of yet little explored, and face many obstacles. To improve understanding of residential microgrid design and performance, we ask, how might typical residential neighborhoods incorporate them, and can they provide sustainable electric power in an affordable manner to help these neighborhoods become net-zero for operating energy while increasing resilience? This question is not primarily one of engineering. The technology behind photovoltaic electricity is well-established, and battery technology is also increasingly well-developed, though cost and technical strategies continue to evolve. The main challenges to microgrid implementation concern design, configuration, planning, economics, and institutions. The lack of built examples is a particular hurdle.

To gain insight into how a typical residential subdivision might incorporate a microgrid, our method was to first review the existing literature on residential microgrids, second to survey current examples, and third to develop a site plan and energy and cost calculations for a hypothetical residential microgrid in Davis, CA.

For the first of these tasks we conducted searches on university databases, Google Scholar, JSTOR, ScienceDirect, and The US Department of Energy website for terms such as "microgrids," "residential microgrids," "microgrid technology," "self-sustained living," "zero net energy communities," and "local energy systems." These searches yielded a small but growing body of literature which we discuss in this paper's second section. They also provided information on current examples, which we expanded from online sources, in particular the Oakland Ecoblock, Whisper Valley, Reynolds Landing, Altus, and Onslow. The third section below discusses these cases with attention to their lessons for other potential residential projects.

Finally, in order to better understand the design, energy, and financial challenges in creating a residential microgrid, we develop a hypothetical example in Davis, California (see Figure 1). This was in part a convenience choice, since we understand the context well, have good local data on residential energy consumption, and have data on a pioneering ultra-low-energy home recently built in conjunction with the University of California, Davis. However, the Mediterranean climate of Davis is similar to that of many other areas in the world in similar latitudes, and so energy generation and usage in this location should be roughly comparable to those other locations. This is a favorable

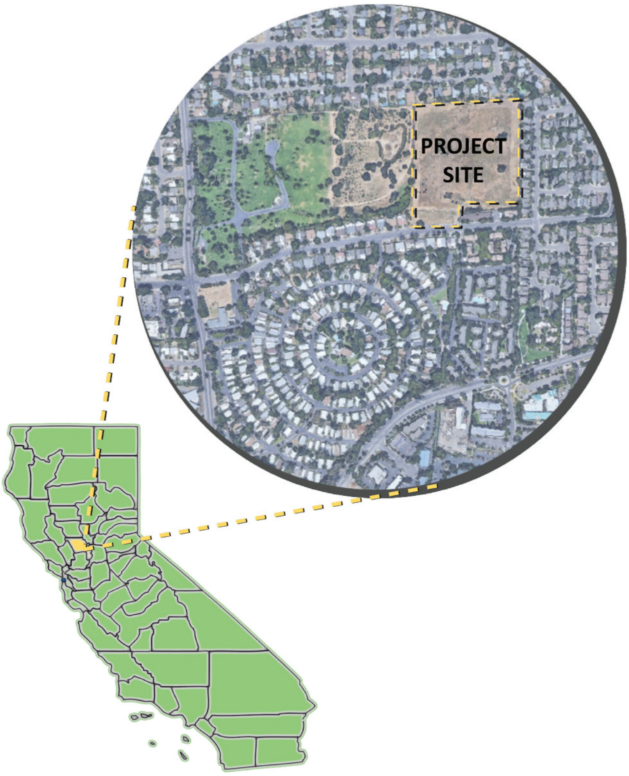


Figure 1. Hypothetical microgrid location in Davis, CA.

environment for such a microgrid, and is likely to be the first type of context in which microgrids might be widely deployed.

Our Davis example helps show how a new neighborhood might be designed to incorporate a microgrid and meet other sustainability goals without adding undue costs for home buyers. Located about 70 miles northeast of the San Francisco Bay Area and about 12 miles east of Sacramento, Davis has a warm Mediterranean climate characterized by hot summers necessitating air conditioning for comfort and cool winters requiring modest levels of household heating. We calculate the new neighborhood's energy use and operating costs based on data from local utilities and developers, as well as operating data from the Honda Smart Home, a demonstration zero-net-energy single-family home built in 2014 in conjunction with the West Village development at U.C. Davis (Honda 2022). We also consider implications of local codes and resident preferences for design of this project.

Finally, in the paper's concluding section we discuss the future potential of residential microgrids in the U.S. and elsewhere, challenges to their development, and possible ways to overcome those challenges.

Background

The residential microgrid model is still in an early stage of development. The small amount of research on this topic, almost all of which is recent, directly reflects this preliminary status.

Hirsch, Parag, and Guerrero (2018) provide an overview of the field. These authors emphasize the important potential role of microgrids in helping meet the "three D" goals of energy systems (decarbonize, decentralize, and democratize). However, they point out that most states have legal frameworks restricting the production and distribution of electricity to franchised electric utilities and, under deregulation reforms of the 1990s, limiting the ability of any single entity to engage in generation, transmission, and distribution of electricity simultaneously. They conclude that if microgrids are to become widespread in the U.S., legal frameworks would need to be rewritten and value in terms of power quality, reliability, and economics would need to be shown to outweigh the costs.

Kristov (2021) argues that societies are ready to embrace "distributed energy resources" (DERs; a broader category that overlaps substantially with microgrids) and that these would reduce costs to society of distribution infrastructure, but that the utility monopolies such as PG&E seek to protect the century-old grid from being replaced. The implication is that state or national governments will need to redefine roles and responsibilities of utilities, or else that the public sector will need to assume control of electricity distribution. Kristov views

> growth of DERs as complementary to, not in conflict with, production and transmission of renewable energy on the bulk system, gradually evolving to a bimodal electricity system that serves customers with varying amounts of local DERs and bulk system supply*(Kristov 2021, 5)*

Linvill, Farnsworth, and LeBel (2021) discuss the need for energy resilience planning at the community scale and focus on challenges of financing. To get such local community efforts off the ground, they argue for higher-level support in the form of funding, technical assistance, demand-side energy conservation and efficiency measures, public/

private collaborations, capacity contracts with utilities, and rate structure reform to support solar, storage, and microgrids.

Churchill (2020) believes microgrids and renewable energy storage to be much needed in California as the state continues to face grid shutdowns due to devastating wildfires. She proposes combining solar power plus battery storage at the individual building level, as well as creating solar-powered microgrids for larger-scale blocks and neighborhoods. In her view electric vehicle batteries would be useful to allow neighborhoods to run entirely off the grid in times of need.

A number of studies address technical aspects of microgrid management. For example, Hirsch, Parag, and Guerrero (2018) discuss the challenge of storing renewably produced electricity on-site for microgrid use. Storage systems that could potentially meet this need include batteries, fuel cells, electrolyzed hydrogen, and kinetic energy storage systems such as flywheels. Rippy (2021) suggests that solid-state battery technologies may be able to address the storage challenge by the late 2020s by improving length of discharge time as well as safety. Hu, Xiao, and Wang (2021) and (Çimen et al. 2021) discuss optimal coordination of loads and storage. Burke (2019) describes successful implementation by Oak Ridge National Laboratory researchers of smart controllers in a 62-unit microgrid neighborhood in Hoover, Alabama. Akter, Mahmud, and Oo (2017) explain the importance of hierarchical energy management systems within the microgrid to efficiently distribute energy. Such systems, which they modeled for a neighborhood of nine houses, communicate with homes, battery storage, and the central grid, directing energy flow to where it is demanded the most. Without systems like this, energy will be distributed inefficiently, leading to less power reliability and more use of the central grid.

Atia and Yamada (2016) modeled power demand and battery storage for a recently constructed 19-unit residential microgrid in Okinawa, Japan under five different scenarios. The model varied electricity price, load uncertainty, energy surplus, storage capacities, and fluctuating generation scenarios. The authors concluded that a microgrid smart controller must be highly flexible in order to account for all these scenarios as well as situations in which energy production and storage fail. Related to this need, Dey and Bhattacharyya (2018) discuss software to manage energy flow, reduce costs, and increase robustness within both connected and islanded microgrids. They concluded that well-tuned software is especially important within islanded (stand-alone) microgrids since utility backup is not available.

Other authors bring economics into the picture. Saviuc et al. (2019) test the economic value and productivity of lithium ion batteries in four hypothetical neighborhood microgrids of eight houses each in various countries across Europe. Such storage systems are usually seen as desirable to increase the percentage of renewably generated electricity consumed, improve the autonomy of end users, and level loads and stabilize the grid for the utility. The authors found that if central grid electricity is low in price and feed-in tariffs are available for locally generated electricity (as in these European Union countries), then storage makes little economic sense. However, if central grid electricity is expensive, feed-in tariffs don’t exist, or tax credits are available for battery purchase, then it becomes economically viable to include battery storage on site.

Wu et al. (2018) analyze the most economical ways households could get power for a microgrid of 20 houses near Harbin, China. They found that the average household in this neighborhood could save 15.6% on its electricity bills with a microgrid structure that primarily receives power from the utility grid, secondarily receives power from photovoltaics, and thirdly receives energy from electrical vehicles sending power back into the microgrid. This scenario is best mainly due to the cheap cost of electricity in the area and the low value of power buyback from the Chinese government. These authors like others highlight the potential use of electrical vehicle batteries as a power source for the neighborhood. Vehicles can be charged during the day when photovoltaic power is plentiful and some portion of their battery capacity then used to power the microgrid at night. This method is much cheaper than purchasing a large battery on site, but is more inconsistent and creates problems in leveling loads. This is an added reason that these authors' preferred scenario focused on receiving most power from the central grid.

Wang et al. (2019) assessed payback periods for a commercial microgrid located in Town Island, Hong Kong and tested the global warming potential of microgrids powered by diesel generators and grid extensions. Monitoring this real-world microgrid they found its payback period to be 9.2 years which is about average compared to other microgrid projects across the globe. They also concluded that the global warming potential of their microgrid increases 4.3 times when using a diesel generator and 7.8 times when using a grid extension, leading them to conclude that microgrids can provide superior lifecycle environmental performance and better economic incentives than current power options.

Existing examples

We are able to identify only a few pioneering built examples of residential microgrids, and data from these is limited. Most of these examples are recent or still under construction.

A pilot project funded by The California Energy Commission to test a microgrid retrofit within a low-to medium-income community, the Oakland Ecoblock is being created by researchers affiliated with the University of California, Berkeley. The goal is to explore ways to reduce GHG emissions of existing homes in line with California's goal of 40% GHG reductions below 1990 levels by 2030. The project is adding photovoltaic power, battery storage, energy-efficient appliances, a smart controller, and rainwater collection to 27 homes whose moderate-income owners would benefit most from reduced utility costs but otherwise could not afford the retrofit. The microgrid model is expected to lower electricity usage by 80%, eliminate natural gas use, save up to 70% on water consumption, and reduce CO2 emissions by 90%. Challenges found to date include lack of participation from residents, multidisciplinary team coordination, and overall cost (Salem 2018; Barr et al. 2019, 305–328; Ecoblock 2022). The Oakland project is ongoing, but clearly retrofitting a microgrid into an existing neighborhood is difficult because of the physical difficulty of working with existing infrastructure and because of the large number of stakeholders. However, the team notes positive developments such as the growing willingness of the utility to work with microgrids (Chung 2021). Under current regulatory framework, utility companies like PG&E have full operational authority over multi-customer microgrids, making them difficult to develop.

The Blue Lake Rancheria tribe in Humboldt County has developed another California microgrid with financial help from The California Energy Commission for purposes of emergency preparedness, power reliability, emissions reductions, and economical benefits. The microgrid connects facilities such as a gas station, hotel, American Red Cross disaster shelter, casino, and houses. Including 0.5 MW of ground mounted solar panels and 1 MWh of battery storage, this project has achieved 25% energy cost savings and reductions of 195 metric tons of CO2 per year. During the 2019 wildfires Blue Lake Rancheria was able to maintain power for homes, customers, and the emergency facility when the grid was unavailable. Lessons from this example include the benefits of developing such a project in stages, training personnel in microgrid maintenance, and hiring a project manager with both engineering and communications expertise (Narum, Ganion, and Carter 2016, 1–10).

Whisper Valley in Austin, Texas is a newly constructed neighborhood with 237 homes, community gardens, parks, walking trails, an elementary school, and retail buildings all powered by a centralized microgrid. The all-electric community employs ground-source heat pumps for heating and cooling as well as photovoltaics and smart appliances. With a relatively large-scale microgrid like Whisper Valley, many costs can be reduced due to economies of scale. Installing infrastructure upfront, using the same joint trenching for utilities, and purchasing in bulk all helped reduce costs. The developers were able to price homes between $200,000 and $400,000, about $50,000 below market for Austin. This microgrid has reached zero-net-energy status while providing its residents with a stable power source during many challenges (Hilde 2017). In February 2021, Texas was hit by an extreme snow storm that caused the state grid to fail, left millions of people without electricity in freezing temperatures for days, and killed over 200 Texans. During this time, Whisper Valley was able to operate separately from the main grid, providing heat and power to the homeowners and people in need.

Oak Ridge National Laboratory with funding from the US Department of Energy has lent its expertise to two microgrid neighborhoods in the southeastern United States named Altus and Reynolds Landing. The Reynolds Landing microgrid neighborhood in Alabama consists of 62 houses made 35% more energy efficient than typical homes in the state through the use of smart thermostats, triple pane windows, air-source heat pumps, and a tight building envelope. These efficiency steps are complemented by 400 kilowatts of ground-mounted photovoltaics, a 600-kWh battery, and a 400-kilowatt natural-gas generator. The Altus microgrid neighborhood in Georgia consists of 46 smart townhomes using 39% less energy than comparable newly constructed homes. In both developments Oak Ridge is testing energy savings of technologies such as automated window shades, highly efficient light fixtures, and heat pump water heaters. It is also monitoring power supply and demand performance to optimize the microgrids. Researchers have found that peak loads can best be reduced by educating homeowners to use scheduled thermostat settings, integrating water heaters into air-source heat pumps to better utilize excess heat, and installing HVAC optimizers that can more efficiently meet temperature needs (Gerdes 2019; Office of Energy Efficiency & Renewable Energy 2019).

In Western Australia, the small, remote town of Onslow now receives 100% of its electricity from its newly installed microgrid. With the collaboration of PXiSE Energy Solutions, Horizon Power, and all community members, the town installed an 11 MW photovoltaic system to meet a daily peak load of 4 MW which was funded by Australia's federal government. Two 1 MW battery storage systems allow the town to reduce natural gas consumption by more than 55,000 gigajoules, lower utility costs, improve reliability, and reduce carbon dioxide emissions by 820 tons per year. After load tests and a couple months of operation, this project was deemed a success by the Government of Western

Australia, which hopes to adapt similar rural neighborhoods into microgrids (Proctor 2021).

In the state of Manipur in northeast India, an estimated 45% of rural households do not have electricity. Extending the grid to rural communities is not feasible in this context, so microgrids have been pursued as an alternative. In Manipur microgrids have been implemented for 112 villages providing 3,026 homes with electricity. This has increased disposable income while reducing the need to burn kerosene for energy. To overcome maintenance challenges, members of each household were given user manuals and basic training on how to handle, operate, and maintain their systems. Some villagers also received 1 month of microgrid repair technician training. Such educational programs helped get all village members involved and excited about this technology, ensuring that residents would take ownership of their microgrid and value the service it is providing. The average payback period for each household is 5 years, and if the microgrid is well maintained it should last 20 years before components like the PV system must be replaced (Aggarwal et al. 2014, 29–63).

The above examples show that microgrid neighborhoods are feasible in a number of contexts. In addition to energy-efficient buildings with photovoltaics, they include a centralized smart controller, centralized battery storage, and the wiring necessary to connect all of these elements. Some microgrids include additional components, such as centralized photovoltaics, a fossil-fuel-powered backup generator, and further efficiency upgrades for structures. None of these elements are particularly difficult or time-consuming from an engineering perspective. Nor are there barriers to such installation at a large scale. Large, master-planned communities are routinely wired for purposes such as telephone and internet currently, and large photovoltaic and battery installations are increasingly common. A variety of microgrid controllers are on the market. If regulatory hurdles can be overcome and large-scale developers appropriately trained and incentivized, microgrids can potentially extend their benefits to large quantities of housing in the near future.

However, most of the successfully operating examples above do not produce 100% of their net energy on-site, a goal desirable for climate change mitigation purposes. Also, little information is available about the economics of most projects as well as the amount of storage that would allow them to operate independently for extended periods. Lastly, little information exists about how a new microgrid neighborhood might be designed for a U.S. suburban context while meeting other sustainability needs such as for increased residential density, affordability, shared open space, varied unit sizes for a diverse population, and emphasis on bicycle and pedestrian transportation.

A hypothetical microgrid neighborhood in Davis, CA

To shed further light on the technical and financial feasibility of residential microgrids in the U.S. context, we designed a hypothetical microgrid neighborhood that we named the Chiles Microgrid on a vacant, 12-acre parcel of land in Davis, California [See Figures 1 and 2]. The site is zoned for planned-development medium-density residential use and is within walking and biking distance of downtown Davis (approximately 1.25 miles). This size of site, allowing 40–120 units of housing at typical suburban densities, is similar to many available to developers for small-to-midsized residential subdivisions in an existing urban region. It is smaller than the large master-planned communities often built on greenfield land at the

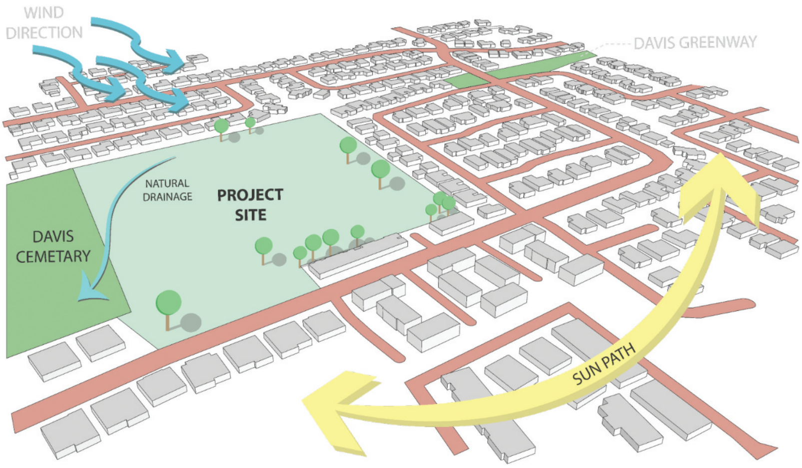


Figure 2. Project site analysis.

metropolitan fringe, but typical of smaller parcels left over after the first wave of development, and similar in size to the redevelopable parcels offered by defunct shopping centers, old industrial properties, or surplus school sites. That being said, site size is unlikely to matter greatly in terms of suburban microgrid design, which in most cases would use the same basic elements. For urban sites, on the other hand, high density can make it difficult to have sufficient photovoltaic production for a zero-net-energy (ZNE) microgrid since the ratio of roof and parking square footage for photovoltaics to units would be lower.

In addition to the microgrid infrastructure, we sought to meet likely sustainability goals for the site such as maximizing housing density within a suburban context, ensuring affordability, reaching zero net operating energy, improving street and path connectivity, increasing shade cover, supporting local wildlife, honoring site history, and providing open space. We aimed to provide both resilience, in the sense of having a neighborhood that could operate for several days islanded from the electric grid, and sustainability, in the sense of a zero-net-energy development that enhanced many aspects of long-term social and ecological well-being.

We included 144 units on the site, a gross housing density of 12 units per acre. This density is approximately triple that of surrounding single-family-home neighborhoods, but not unrealistic in this suburban context given that heights of up to 38 feet are allowed as a conditional use under current zoning. In line with historic neighborhood form, we included 28 1,400-square-foot two-story, two-to-three-bedroom detached houses, but added accessory 600-square-foot dwelling units to these lots. We also included 16 2,500-square-foot three-story row houses with four bedrooms for larger families, and 40 three-story stacked townhouses with a 550 square foot one-bedroom unit on the bottom floor and 2,600 square foot three-to-four-bedroom units on the upper floors (See Figures 3 and 4). This variety and number of housing units allows the development to respond to severe housing shortages in the State of California and City of Davis, an important sustainability need, providing a number of relatively large units to meet the needs of families in this

Figure 3. Hypothetical microgrid neighborhood layout.

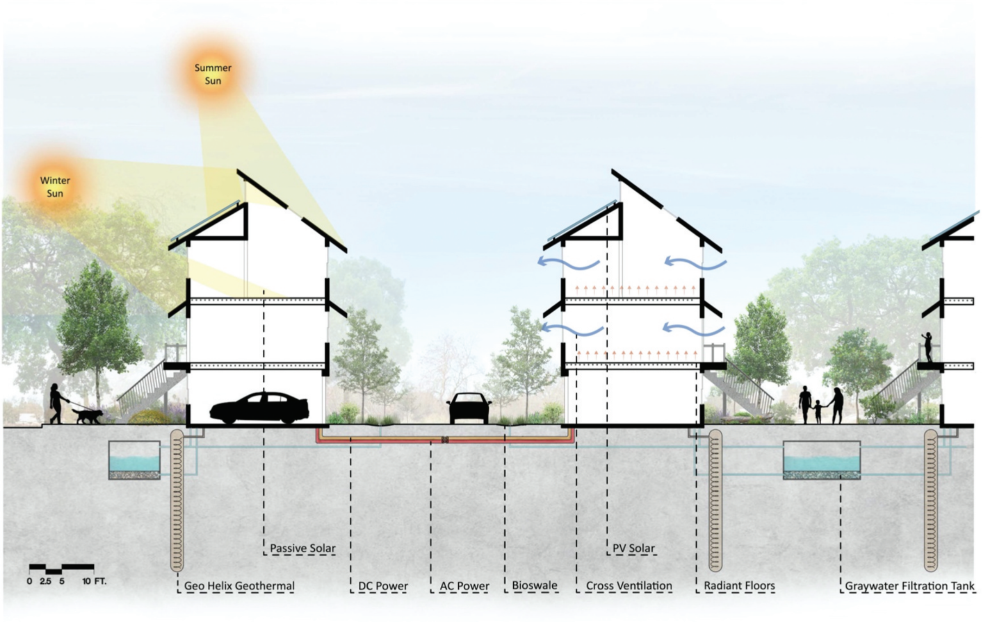


Figure 4. Hypothetical microgrid neighborhood block section.

suburban location and a variety of for-sale and rental options to meet the needs of a diverse housing market. In line with sustainable neighborhood design principles, we also included a neighborhood park and connections to surrounding streets and bike routes.

Using passive solar design principles, we oriented structures with long roof surfaces facing south and then covered south-facing roofs with photovoltaics except for a three-foot setback for fire and safety personnel access. In this way we were able to accommodate 32,475 square feet of panels on homes and over parking, yielding 648 kW of electricity production capacity, an average of 4.5 kW per unit. Three 1,050 kWh lithium-ion batteries on site store electricity to level the daily load between peak energy production in the afternoon and peak usage in the evening, and would be capable of powering all 144 units for up to two days in the absence of power from the grid or photovoltaics. (Even on cloudy days photovoltaics produce some amount of electricity, so stored power would likely last longer.) This short-term battery storage has potential benefits for both the utility – avoiding swings in demand – and the neighborhood, allowing it to stay islanded a larger percentage of the time, especially when grid electricity may be most expensive. It is substantially larger than the neighborhood would likely have if individual homeowners acquired batteries. A Tesla PowerWall (the most common battery type currently) holds 13.5 kWh. If all 144 units had such batteries, total storage would be 1,944 kWh, only about 62% of this centralized battery storage. Managing our power load distribution is a smart controller inside a small secure 100 square foot building located next to the batteries. This computer allocates power where it's needed within the community and provides data on the microgrid that can help identify problems or inform us how well the system is operating.

We designed an all-electric neighborhood, something that will soon be required by California building code in order to reduce methane-related GHG emissions. We also used a number of strategies to lower energy use, including passive solar architecture, geohelix geothermal heat pumps, smart appliances, cross ventilation, and whole-house exhaust fans to bring in the cool evening air of the Davis summer climate. These were the least costly and most sustainable ways to reduce energy load. Passive solar design principles have been modeled locally by the well-known Village Homes community in Davis (Corbett and Corbett 1999), and include east–west orientation of structures to maximize south-facing windows letting in winter sunshine, shading of windows to keep out summer sun, strategies to increase ventilation for summer cooling, and thermal mass to retain interior heat or cool during the daily cycle. The geohelix method was developed and piloted by local energy expert Dick Bourne and used in the Honda Smart Home and the Parkview Place LEED-Platinum apartment project in Davis to save cost compared to deep-bore ground-source heat pumps. It uses a spiral-tubing method with bores 9 feet apart, 2 feet wide, and 21 feet deep (Bourne 2015).

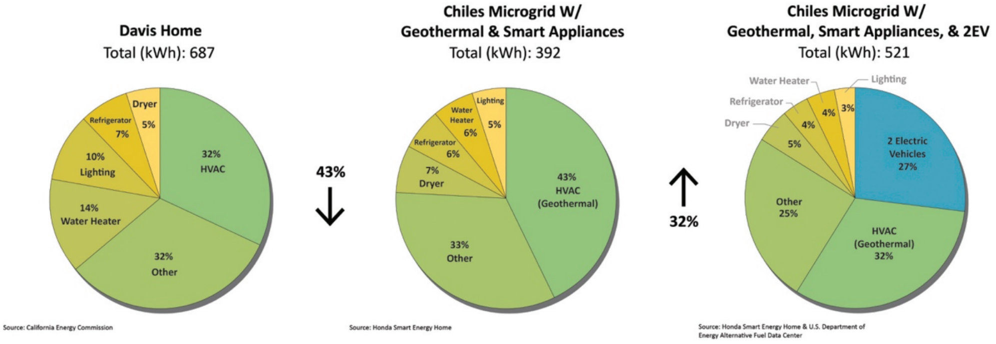
Affordability was a prime concern in designing this microgrid neighborhood. A new development allowed us to take advantage of economies of scale in purchasing items; to combine trenching for water, electrics, fiber, and the ground-source heat pumps; and to have construction proceed efficiently in phases. We assumed continued existence of federal tax credits for solar, which make photovoltaics more affordable. We developed a 15-year cost plan for components like the batteries and the smart controller. Prices will undoubtedly change, but as of 2021 we estimated the cost of photovoltaics for the neighborhood to be $1,814,400, battery cost to be $1,968,750, the geohelix geothermal heat pump technology to be $123,840 (based on Bourne 2015), and the microgrid smart controller to be $470,000.

Since actual residential electricity production and consumption depends on factors such as local latitude, climate, and weather, we grounded our analysis on four years of actual monthly energy data from the Honda Smart Home, an experimental ZNE single-family home located in Davis. This structure built in 2014 is quite similar to the units we envision for the Chiles Microgrid, and like our units incorporates energy-efficient appliances, ground-source heat pumps, and an electric vehicle (Koenig 2021). We also compared our estimates to average Yolo County household energy consumption data compiled by the California Energy Commission (Palmgren 2021, 3–8). These data show that the average home in the county consumes an average of 687 kWh per month, with additional natural gas energy used for heating, hot water, and cooking. However, California's building energy code now requires vastly more energy-efficient construction than used for existing homes built mainly during the second half of the 20th century, so we believe the Honda Smart Home offers a more accurate comparison. We also used one of our own homes (Wheeler's) for additional ground-truthing comparison. This retrofitted 1978 house is all-electric and plus-energy for both the structure and the electric vehicle.

Results and discussion

Using the above data sources and adjusting for unit size, we calculated average home energy consumption for new units in our all-electric neighborhood to be about 392 kWh per month. Given the motor-vehicle-oriented lifestyles of California, we assumed that households would each drive two electric vehicles (EVs) traveling some 10,000 miles apiece annually, bringing the average monthly household electricity usage to 521 kWh (Voelcker and Kurczewski 2021). Total energy consumed by the entire development would thus average 75,024 kWh per month (see Figure 5). Summer and winter would be peak demand periods due to heating and cooling needs; spring and fall would have as much as 20% lower demand.

Again using production data from the Honda Smart Home and adjusting for installation size, we calculated that Chiles Microgrid photovoltaic production would average 92,244 kWh monthly (more in summer months, less in winter months). The neighborhood would thus be able to generate a surplus of electricity on an annual basis (see Figure 6). Onsite photovoltaic production would more than meet neighborhood needs for all



Source: California Energy Commission

Source: Honda Smart Energy Home

Source: Honda Smart Energy Home & U.S. Department of Energy Alternative Fuel Data Center

Figure 5. Hypothetical neighborhood unit monthly energy calculations.

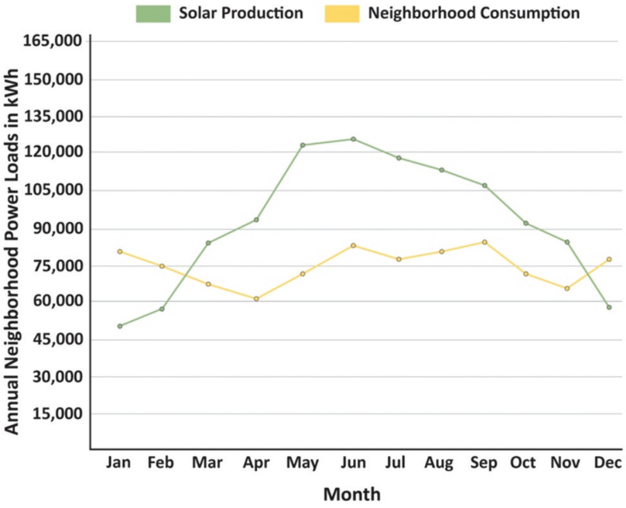


Figure 6. Hypothetical neighborhood energy consumption.

months except December, January, and February. On a daily basis, battery storage would provide sufficient capacity for nighttime demand except during the winter period.

Rather than seek a bare sufficiency of electricity produced on-site, our strategy was to maximize photovoltaic production given the extent to which PV prices have fallen, state policy promoting renewable energy production, the need to offset embodied energy in building construction, and general needs to maximize renewable energy given the climate crisis. With this relatively high level of photovoltaic capacity, the neighborhood could be islanded for much of the time both on a daily basis and an annual basis. The exceptions are for daily periods during warm weather in which the microgrid would feed surplus power back into the grid, and for winter periods during which the microgrid would run a daily deficit without grid power. The neighborhood thus meets our resiliency goal, being able to go for many days during most months of the year without grid power.

The amount of battery storage in our neighborhood was more than sufficient to meet evening and nighttime resident energy needs during most months of the year. This storage can also help level utility loads on a daily basis – storing electricity when the grid has surplus energy (such as from photovoltaic installations at midday), and then feeding power into the grid when more electricity is needed. This type of utility load leveling is much needed given the rise of solar and wind power installations with intermittent production, and has led to increasingly sophisticated schemes under which utilities contract with local businesses, microgrids, and EV owners to store energy or reduce demand when needed (Günter and Marinopoulos 2016).

However, the battery bank in our neighborhood is not nearly enough to eliminate seasonal reliance on the grid, storing electricity produced in warm weather for winter use. For that purpose, much larger long-term storage would be needed. If this were possible, then the neighborhood would never be a net daily consumer of grid electricity, and would connect to the grid primarily to contribute surplus energy or to assist in leveling grid loads.

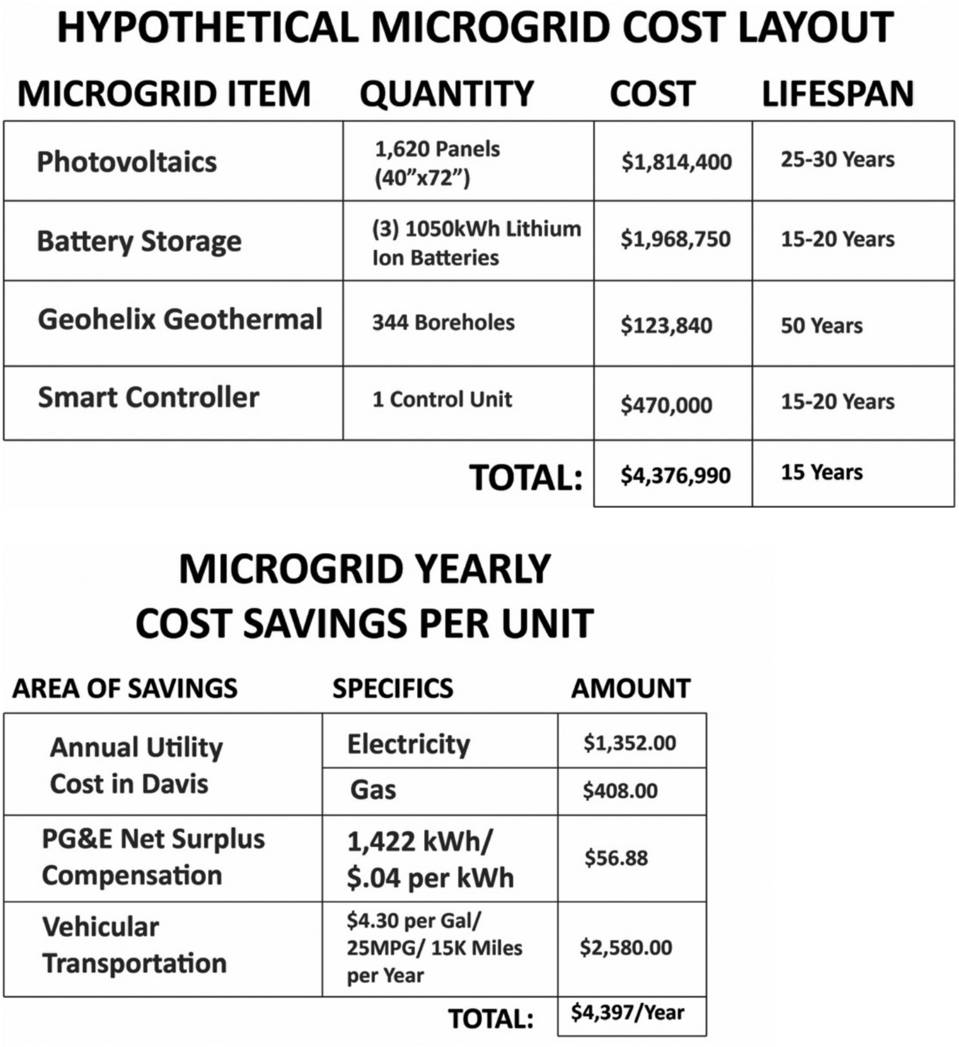
Proven and economical technologies to provide long-term energy storage do not yet exist at the neighborhood scale. Research into flywheel systems and in-ground thermal storage is ongoing, but long-term storage appears most feasible at the utility scale, where utilities have access to techniques such as pumped-water storage using existing reservoirs. If such long-term energy storage were available at either local or grid scales, then renewable energy generated by photovoltaic systems during sunnier months of the year could be effectively stored for winter use. Microgrids or individual property-owners might then be able to operate independently of the grid for much or all of the year.

In terms of economics, we found that photovoltaic and microgrid components would add $4,376,990 to overall construction costs for the Chiles Microgrid – an average of $30,396 per unit for the 144 units. This is a large additional cost, but is offset by energy savings over time, and by selling excess power to the utility. Under PG&E's current net metering program, the neighborhood would be reimbursed about $8,191 annually for selling excess power back to the grid. (The utility's reimbursement rate is under $0.04 per kilowatt hour. However, net metering policy is in flux in California and future revenues could be higher or lower.) This is not a large amount; avoided costs for grid electricity, methane, and vehicle fuel are far more significant. Since the average Davis household currently spends about $1,796 annually on electricity and methane (Palmgren 2021, 3–8), it would take microgrid owners about 16 years to recover their initial extra investment compared with purchase of an average home in the same city. If owners switched to electric vehicles at the same time, their payback period would be 7 years. (See Figure 7). After that period, homeowner costs for energy supply would be essentially zero, with payments only needed for grid access and repairs or improvements to the microgrid system.

These payback periods show that the Chiles Microgrid will be economical for homeowners, especially considering that their extra up-front investment increases the value of the home as well. In comparison the Town Island, Hong King, microgrid case study had a payback period of 9 years, and other examples are similar. In locations that receive fewer sunlight hours per year, the payback period will be longer due to the less productive PV system and stronger reliance on the main grid.

Additional steps could help homeowners of modest means cover the upfront costs of the microgrid. For example, public sector agencies could institute a Property Assessed Clean Energy (PACE) program, through which an agency finances the microgrid program up front, with homeowners paying back the investment over a set period of time in lieu of energy supply payments made to a utility (U.S. Department of Energy 2021).

The exact economics of such a residential microgrid would depend on the local utility's rate structure, the cost of energy alternatives such as fossil fuel-generated electricity and gasoline for vehicles, and government policy regulating utilities and subsidizing desirable energy practices. These variables are subject to change over time. Particularly important are the rate at which the utility would reimburse the neighborhood for electricity contributed back to the grid, any incentives available for photovoltaic installation or battery storage, whether and how much the utility would pay the microgrid for the ability to temporarily use its batteries to address grid load-leveling issues, and future cost of grid electricity, photovoltaics, battery storage, and microgrid controllers. Feasibility would also depend on the ease and speed with which the utility would approve and connect the microgrid.



HYPOTHETICAL MICROGRID COST LAYOUT

MICROGRID ITEM	QUANTITY	COST	LIFESPAN
Photovoltaics	1,620 Panels (40"x72")	$1,814,400	25-30 Years
Battery Storage	(3) 1050kWh Lithium Ion Batteries	$1,968,750	15-20 Years
Geohelix Geothermal	344 Boreholes	$123,840	50 Years
Smart Controller	1 Control Unit	$470,000	15-20 Years
	TOTAL:	$4,376,990	15 Years

MICROGRID YEARLY COST SAVINGS PER UNIT

AREA OF SAVINGS	SPECIFICS	AMOUNT
Annual Utility Cost in Davis	Electricity	$1,352.00
	Gas	$408.00
PG&E Net Surplus Compensation	1,422 kWh/ $.04 per kWh	$56.88
Vehicular Transportation	$4.30 per Gal/ 25MPG/ 15K Miles per Year	$2,580.00
	TOTAL:	$4,397/Year

Figure 7. Hypothetical neighborhood cost analysis compared with an average conventional household in the same city.

Our bottom-line finding is that with current technologies and economics a residential microgrid appears able to meet the annual energy needs of both homes and electric vehicles for a neighborhood in a Mediterranean climate, and able to do so in a way that is carbon-free in terms of operating energy, affordable from the residents' perspective, and consonant with other sustainable neighborhood design goals. This finding goes beyond evidence from most of the other microgrid examples mentioned earlier. Those do not aim for zero-net-energy or plus-energy status, do not consider sustainable neighborhood design goals holistically, and/or do not have detailed data available. Although the specifics of our modeled neighborhood are those of its location in California, the fact that it would be likely to generate a sizeable net annual surplus of energy shows that such a neighborhood would likely achieve its goals in settings that are somewhat different in terms of climate and institutional environment. The fact that prices of photovoltaics and battery storage are likely to decline over time makes the model all the more robust.

However, the problem remains that microgrids are not legal in the state of California. Section 218 of the state code requires that any entity wishing to sell energy to more than two contiguous parcels become a regulated electrical corporation. It would then be subject to state regulation intended to ensure that the utility is meeting public customer service expectations, public safety standards, and just and reasonable terms and conditions of utility service (Public Utilities Code §§ 451, 454 and 728). Rules developed by the state's investor-owned utilities (PG&E Electric Rule 18, SCE Electric Rule 18, and SDG&E Electric Rule 19; collectively known as Rule 18/19) also govern the supply of electricity to separate premises and prohibit one premise from supplying electricity to a different premise. The state's Public Utilities Commission has justified such restrictions as necessary to protect the safety and reliability of the grid, but such a rationale is increasingly seen as outdated and overly protective of utility dominance of the market (e.g. Pullins and Westerman 2021). Lawmakers have sought to exempt microgrids from these restrictions through legislation (e.g. Sen. Henry Stern's S.B. 1339 in 2018), but finding a solution that both the state government and PG&E agree upon has been difficult. As it currently stands, California residential microgrids can only be approved as pilot projects similar to the Oakland Ecoblock, with heavy supervision.

Many other states already have a legal framework to support microgrids, and the US as a whole has been making headway towards standardizing and supporting microgrids. The CLEAN Future Act introduced in the US Congress in 2021 (H.R. 1512) proposed to set aside 1.5 billion dollars to fund future microgrids. Within this Act $50 million would be used as grants for microgrid technical assistance. Such developments provide hope that institutional hurdles to microgrids can be overcome with time.

Conclusion

Interest is growing worldwide in the microgrid model of a neighborhood-scale electric system that can connect or disconnect from the utility grid. Such a model potentially offers greater resilience and sustainability compared to the conventional electric power system, and is especially important to explore given the current move towards all-electric homes and vehicles powered by renewably generated electricity in order to end fossil fuel use.

Recently constructed pilot projects show that microgrid neighborhoods are feasible in multiple worldwide locations. However, few of these examples aim to produce as much energy as they consume, and very little performance and economic data is yet available. To shed light on the feasibility of a zero-net-energy or plus-energy residential microgrid neighborhood, we designed a hypothetical microgrid neighborhood of 144 units for a site in Davis, California. Our design sought to show how other sustainability dimensions such as increased density, affordability, varied unit sizes, bicycle and pedestrian friendliness, and shared open space might also be incorporated into a zero-net-energy or plus-energy microgrid development within an existing suburban context.

Using data from the nearby Honda Smart Home, our analysis shows that the model neighborhood could produce 23% more electricity than it consumes for buildings and vehicles on an annual basis, and that daily electricity needs of these homes and vehicles could be amply supplied by rooftop photovoltaics for 9 out of 12 months of the year. The microgrid's batteries reduced need for grid electricity by storing daytime energy for nighttime use. At many times of the year this storage completely met community needs. During the summer (with a net daily surplus of photovoltaic electricity) and winter (with a net daily deficit) the neighborhood benefitted from exchanges with the grid. If long-term energy storage becomes available, a neighborhood such as this one would have even greater ability to balance its own energy needs internally throughout the annual cycle without relying on grid exchanges.

The payback period for the additional microgrid cost of $4,376,990, an average of $30,396 per unit, was 16 years. This period can be reduced to 7 years if the owner utilizes their excess generated energy to power an electric vehicle instead of purchasing gas. After that time, residents would essentially be receiving no-cost energy. Although longer than for some other examples mentioned earlier, perhaps due to the higher cost of construction in the state, this payback time still shows a high level of economic feasibility. Public policy (in the form of rebates, tax credits, or PACE loans) could further reduce this payback period and/or assist homeowners with up-front microgrid costs.

In climates with less solar radiation or those requiring greater use of electricity for heating or cooling the payback period would be longer. However, the fact that our model neighborhood is plus-energy shows that it should be possible to still meet many if not most energy needs internally without much extra cost. Additional photovoltaics might further reduce the need for any grid energy.

We thus find that the zero-net-energy residential microgrid model is likely to be highly feasible in suburban locations with a relatively mild climate. Such microgrids would add value in terms of power quality, reliability, economics, grid operations, and reduced GHG emissions. Because of its battery storage the microgrid strategy also addresses one key problem currently by levelling the daily load on utilities when all homes have photovoltaics.

Although exact configurations would vary for different geographical locales, such residential microgrids could go a long way towards meeting global needs for carbon-neutral communities given the growing climate crisis. If built at scale, microgrid neighborhoods could thus be a main tool to reduce residential GHG emissions and improve energy service resiliency. There is, however, an urgent need for institutional reform to make such developments legal in all jurisdictions, and to provide the appropriate incentives for microgrid success. Policymakers should first of all legalize microgrids in places where they are not currently allowed, if necessary working with utilities to increase their acceptance of this model. They could then make technical assistance, financing, rebates, or tax credits available for microgrids, in the same way that these mechanisms have been used to promote residential energy efficiency, photovoltaics, and electric vehicles. Some of these tools might be aimed at developers of microgrid neighborhoods; others might be used to incentivize buyers of homes in those neighborhoods, or to incentivize residents of existing neighborhoods to undertake conversion to microgrid status. Finally, basic research is still needed into long-term energy storage options so as to allow excess photovoltaic electricity from summer months to be stored for winter use. It is not clear whether this is best done at a local scale or at a utility scale, and how it might be incentivized at either level. Better understanding of those subjects is an important missing piece of the microgrid puzzle currently.

Note

1. We use "zero-net-energy" and "plus-energy" to refer to the energy used to operate buildings. These expressions do not include the embodied energy in building materials and construction. That energy should of course be considered as well, but involves a different set of analyses.

Acknowledgements

The authors would like to acknowledge very useful comments from Lorenzo Kristof, Richard Bourne, Carl Linvil, and three anonymous reviewers.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

There are no funding details to declare.

ORCID

Stephen M Wheeler http://orcid.org/0000-0002-5293-3254

References

Aggarwal, V., A. Fahey, H. S. Freymiller, C. C. Huang, S. Li, S. Moilanen, C. Onda, N. Ratledge, S. Speirs, and J. Wong 2014. Clean Energy Solutions Center: *Rural Energy Alternatives in India: Opportunities in Financing and Community Engagement for Renewable Energy Microgrid Projects*. Clean Energy Solutions Center | Rural Energy Alternatives in India: Opportunities in Financing and Community Engagement for Renewable Energy Microgrid Projects. https://cleanenergysolutions.org/resources/rural-energy-alternatives-india-opportunities-financing-community-engagement-renewable

Akter, M., M. Mahmud, and A. Oo. 2017. "A Hierarchical Transactive Energy Management System for Energy Sharing in Residential Microgrids." *Energies* 10 (12): 2098. doi:10.3390/en10122098.

Atia, R., and N. Yamada. 2016. "Sizing and Analysis of Renewable Energy and Battery Systems in Residential Microgrids." *IEEE Transactions on Smart Grid* 7 (3): 1204–1213. doi:10.1109/tsg.2016.2519541.

Barr, Z., N. Bourassa, J. Bowie, and R. Brown 2019. Accelerating the Deployment of Advanced Energy Communities: The Oaklandwe EcoBlock - a Zero Net Energy, Low Water Use Retrofit Neighborhood Demonstration Project. California Energy Commission. https://www.energy.ca.gov/publications/2019/accelerating-deployment-advanced-energy-communities-oakland-ecoblock-zero-net

Bourne, Dick. 2015. The Parkview Place NZE Apartment Project, Davis CA. Presentation to the California Geothermal Heat Pump Association. 4 23 2015. https://www.youtube.com/watch?v=pl7zTbdZxOc .

Burke, J. J. 2019. Real Communities Test Ornl Microgrid Controller: Ornl. Oak Ridge National Laboratory. https://www.ornl.gov/blog/real-communities-test-ornl-microgrid-controller.

Chung, Eunice. 2021. Power Distribution for the Oakland Eco-Block: A Conversation with Sasha von Meier. https://ecoblock.berkeley.edu/blog/power-distribution-for-the-oakland-ecoblock-a-conversation-with-sascha-von-meier/.

Churchill, S. 2020. Report: Resilient Clean Energy for California. Vote Solar. https://votesolar.org/report-resilient-clean-energy-for-california/.

Çimen, Halil, et al. 2021. "An Online Energy Management System for AC/DC Residential Microgrids Supported by Non-Intrusive Load Monitoring". *Applied Energy* 307: 118136. doi:10.1016/j.apenergy.2021.118136.

Condon, Patrick. 2010. *Seven Rules for Sustainable Communities*. Washington, D.C: Island Press.

Corbett, Judy, and Michael. Corbett. 1999. *Designing Sustainable Communities: Learning from Village Homes*. Washington, D.C: Island Press.

Dey, B., and B. Bhattacharyya. 2018. "Dynamic Cost Analysis of a Grid Connected Microgrid Using Neighborhood Based Differential Evolution Technique." *International Transactions on Electrical Energy Systems* 29 (1). doi:10.1002/etep.2665.

Ecoblock. 2022. Web resource available at https://ecoblock.berkeley.edu/about/.

Ecodistricts. 2022. The Ecodistricts Protocol. Available at https://ecodistricts.org/protocol/.

Fraker, Harrison. 2013. *The Hidden Potential of Sustainable Neighborhoods: Lessons from Low-Carbon Communities*. Washington, D.C: Island Press.

Gerdes, J. 2019. Welcome to Reynolds Landing: An Alabama Community Spearheading the Grid EDGE TRANSITION. Greentech Media. https://www.greentechmedia.com/articles/read/alabama-reynolds-landing-microgrid-grid-edge

Günter, Niklas, and Antonios. Marinopoulos2016Energy Storage for Grid Services and Applications: Classification, Market Review, Metrics, and Methodology for Evaluation of Deployment Cases*Journal of Energy Storage*8266–23410.1016/j.est.2016.08.011

Hilde, T. W. 2017. Green Infrastructure for Disaster Resilience: Exploring Connections with Scenario Planning. The University of Texas at Austin. Retrieved September 22, 2021, from https://urban.csuohio.edu/sites/csuohio.edu.urban/files/Green%20Infrastructure%20for%20Disaster%20Resilience%20Exploring%20Connections%20with%20Scenario%20Planning.pdf .

Hirsch, A., Y. Parag, and J. Guerrero. 2018. "Microgrids: A Review of Technologies, Key Drivers, and Outstanding Issues." *Renewable and Sustainable Energy Reviews* 90: 402–411. doi:10.1016/j.rser.2018.03.040.

Honda.2022. Honda Smart Home US. https://www.hondasmarthome.com.

Hu, Maomao, Fu Xiao, and Shengwei Wang. 2021. "Neighborhood-Level Coordination and Negotiation Techniques for Managing Demand-Side Flexibility in Residential Microgrids." *Renewable and Sustainable Energy Reviews* 135: 110248. doi:10.1016/j.rser.2020.110248.

Koenig, M. 2021, March . Honda Smart Home US. Retrieved October 25, 2021, from https://www.hondasmarthome.com/.

Kristov, L. 2021. *Opening Comments of the Climate Center on the Order Instituting Rulemaking to Modernize the Electrical Grid for a High Distributed Energy Resources Future*. Sacramento, California Public Utilities Commission: *Before The Public Utilities Commission Of The State Of California*.

Linvill, C., D. Farnsworth, and M. LeBel 2021, July. Solar and Resiliency: Integrative Financing Strategies for Solsmart Communities. SolSmart. https://solsmart.org/resources/solar-and-resiliency-integrative-financing-strategies-for-solsmart-communities/

Narum, D., J. Ganion, and D. Carter 2016. Developing a Low-Carbon Microgrid on Tribal Lands: A Case Study. Humboldt State University. https://www.bluelakerancheria-nsn.gov/wp-content/uploads/2017/08/11_459.pdf

Office of Energy Efficiency & Renewable Energy. 2019. Georgia Power Unveils Atlanta's First Smart Neighborhood. Energy.gov. https://www.energy.gov/eere/buildings/articles/georgia-power-unveils-atlantas-first-smart-neighborhood.

Palmgren, C. 2021. *2019 Residential Appliance Saturation Study*. California Energy Commission. Retrieved September 28, 2021, from https://www.energy.ca.gov/data-reports/surveys/2019-residential-appliance-saturation-study.

Proctor, D. 2021. Communities Benefit from Microgrid Milestones. POWER Magazine. https://www.powermag.com/communities-benefit-from-microgrid-milestones/ .

Pullins, Steve, and John Westerman. 2021. "Opinion: Microgrids Can Reduce Fires and Blackouts in California. Why Aren't We Using Them?" *The San Diego Union-Tribune*, 9 1 2021. https://www.

sandiegouniontribune.com/opinion/commentary/story/2021-09-01/california-wildfire-utility-microgrid-blackouts

Rippy, Kerry. 2021. "These Three Energy Storage Technologies Can Help Solve the Challenge of Moving to 100% Renewable Electricity." *The Conversation*, 10/26/21.

Salem, A. 2018. February 12, 2018: Cities of the Future: Ecoblock Project to Make Oakland Neighborhoods Emission-Free. Retrieved February 12, 2021, from https://ced.berkeley.edu/events-media/news/cities-of-the-future-harrison-frakers-ecoblock-project-to-make-oakland-neig

Saviuc, I., H. Peremans, S. Van Passel, and K. Milis. 2019. "Economic Performance of Using Batteries in European Residential Microgrids Under the Net-Metering Scheme." *Energies* 12 (1): 165. doi:10.3390/en12010165.

Ton, D., and M. Smith 2012. The U.S. Department of Energy's Microgrid Initiative. Retrieved February 23, 2021, from https://www.sciencedirect.com/science/article/pii/S1040619012002254

U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. 2021. Property Assessed Clean Energy Programs. Retrieved October 17, 2021 from https://www.energy.gov/eere/slsc/property-assessed-clean-energy-programs.

Voelcker, J., and N. Kurczewski 2021. *How much does it cost to charge an electric car?* Kelly Blue Books. Retrieved October 19, 2021 from https://www.kbb.com/car-news/how-much-does-it-cost-to-charge-an-ev/.

Wang, R., C.-M. Lam, S.-C. Hsu, and J.-H. Chen (2019, May 11). Life Cycle Assessment and Energy Payback Time of a Standalone Hybrid Renewable Energy Commercial Microgrid: A Case Study of Town Island in Hong Kong. Applied Energy. Retrieved May 4, 2022, from https://www.sciencedirect.com/science/article/abs/pii/S030626191930844X#: :text=Energy%20payback%20time%20of%20the,years%2C%20shorter%20than%20other%20options.&text=Solar%20panel%20is%20shown%20to,impactful%20compared%20to%20wind%20turbine.

Wu, X., Z. Wang, J. Du, and G. Wu. 2018. "Optimal Operation of Residential Microgrids in the HARBIN AREA." *IEEE Access* 6: 30726–30736. doi:10.1109/access.2018.2833143.