

An Evaluation of Microgrid-Based Enterprise Viability

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Executive Summary

The global requirement to meet population housing needs through infrastructure development is at odds with the urgent necessity to mitigate the impacts of climate change. This investigation considers the relationships between built infrastructure and electricity supply by evaluating the viability of microgrid-based enterprises within the context of low- or zero-carbon development solutions. Existing microgrid technologies and emerging building techniques have significant potential to provide viable energy access solutions across multiple use cases and to integrate well into financially attractive business models. To this end, the primary objective of this study was to evaluate the viability of enterprises that seek to develop and deploy microgrids.

Specifically, this study evaluates: the technology, policy, and economic factors that a microgrid-based enterprise must take into consideration; the implications that these factors have for the viability of microgrid-based business models; and the details the models used to conduct the technical and financial analysis. The findings are presented in terms of benefits to both the developer/investor and the end user.

Microgrid components consisting of generation, distribution, storage, and load are discussed, as are a range of microgrid use cases. Issues related to built infrastructure and modular construction, as well as photovoltaic energy generation, are explored more in-depth. Modular construction, or prefabrication, is an emerging construction technology demonstrating decreased costs and development timelines, with greater flexibility in deployment relative to traditional construction methods. Photovoltaic (PV) and battery storage technology mirror some of these aspects of deployment flexibility while functioning as mature technologies with predictable financial parameters, especially within the context of microgrids. Evaluating these technologies through the lens of infrastructure costs, geographically specific time-of-use rates, and stochasticity of demand and power generation will provide the foundations of financially-sound microgrid business models with insights towards feasibility.

Additionally, this study discusses the relevant policy and economics factors that must be taken into consideration by microgrid-focused businesses. Policy and economic feasibility are two key limiting factors for investor interest and business viability. The factors that are discussed (i.e. time-of-use rates, net-metering, costs, and revenues) are some of the essential inputs into the

simulation and modeling that was done in this study. The simulation and modeling were designed to:

- 1) Aggregate and analyze residential and commercial building sector energy use data
- 2) Organize that data relative to the physical characteristics that inform solar and infrastructure development
- 3) Optimize PV and storage solutions for new infrastructure built in locations with geographic and climatological variability
- 4) Reveal the business development considerations required to deploy management platforms

The methods involved in this process required geographic location selection, data collection, and size/cost estimation of both residential buildings and microgrid energy generation & storage systems. Following the selection of the input parameters, the data were run through a series of Python-based software simulations and constrained objective functions. The results were analyzed to determine the financial and operational viability of microgrid developments as modeled in the selected locations of Durham, NC; Rochester, NY; Los Angeles, CA; and Charleston, WV.

The results of this investigation were framed from two perspectives: benefit received by the end user, and the potential ability to recover costs for the developer. From the perspective of the end user, benefit is a function of the cost savings on grid purchase that result from operation of the PV and storage systems over the 25-year time horizon. Our analyses indicate that benefit to the end-user is dependent on location, as PV panels will generate less power in regions with less insolation and lower power prices will make the avoided cost value proposition of a microgrid less attractive. The developer can expect to profit on a project depending on the occupation rates (i.e. rent) they are able to set for each residential unit. Based on our analyses of projected developer cost and recovery rate requirements, microgrid-based business models are viable for developers across all of our selected locations. However, the results of this study indicate that microgrid-based business models are highly sensitive to capital cost variances, and the viability of these businesses is contingent upon a multitude of economic, technological, and policy factors.

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Introduction

Today's macro power grid is dealing with unprecedented challenges related to integrating renewables, grid modernization, and energy efficiency. Electric utilities and energy service providers are grappling with how best to address the issues and are increasingly turning to new technology solutions as a means of maintaining reliability while minimizing costs. Ironically, one of the most promising technological solutions isn't a new concept.

Though the modern macro-scale electrical grid ("the Grid") has been the de-facto source of power for most Americans since Samuel Insull and other industry leaders pioneered the modern electric utility-as-monopoly model in the early 1900's, microgrids have been around since the advent of the lightbulb in the late 1800's. Thomas Edison's Pearl Street Station arguably met all of the criteria for what we would today define as a microgrid¹. However, his small, localized generation model was quickly superseded by larger generation and transmission approaches that scaled well and "encouraged vertical integration and drove down the cost of electricity, fostered universal access, and provided for reliable electric service delivered by a single utility in a given region"². Though the development of our Grid has reflected the power of economies of scale and monopolies during the past century, modern technology advances have begun to make more decentralized approaches increasingly attractive.

This primary objective of this study was to evaluate the viability of enterprises that seek to build business models around the deployment of microgrids. These businesses are highly sensitive to a variety of factors, and companies that are trying to leverage this emerging technology are likely to need extensive technical and analytical capabilities if they hope to be competitive in the marketplace. However, this is true for any emerging energy technology. Microgrids are particularly unique in their threat "to politically powerful incumbent electricity utilities, whether privately or publicly owned. To date, these utilities have helped stall widespread growth of microgrids throughout the United States"³. As such, the success of microgrid-based enterprises will be affected by three primary factors: technology, policy, and economics. These factors are complex and interrelated, and working knowledge of each area is vital if an organization hopes

¹ Wolf, "A Short History."

² David Tuttle et al., "The History and Evolution of the U.S. Electricity Industry."

³ Asmus, Cornelius, and Wheelock, "Microgrids."

to be successful. This report discusses these factors and their implications for microgrid-based enterprises and uses them to establish an understanding of the components of our analysis.

Our analysis was conducted by aggregating datasets across selected locations and evaluating the financial potential of constructing microgrids that paired new construction with solar energy and battery storage technologies. The methodology of this analysis involved the creation of software simulations and financial models. We simulated communities composed of individual residential units, sized the renewable energy generation components for those individual units, and analyzed the financial benefits accrued by each residence's occupants and potential for the microgrid developer to recoup costs. The simulation and model inputs were analyzed over several different scenarios to understand the sensitivity end users and developers have to shifting technoeconomic projection and policy parameters.

To inform decisions made during the creation of this study's models and the framing for this paper, data was collected from energy information agencies such as the U.S. Energy Information Administration, the National Energy Resource Laboratory, and the U.S. Department of Energy. Approaches to photovoltaic array sizing and storage management scheduling were supported by coursework at Duke University's Nicholas School of the Environment⁴. This study is unique in its examination of technology and location-dependent microgrid parameters and their implication for the viability of business models.

Research in this space has looked at a wide breadth of relevant technoeconomic and policy topics. Examinations of microgrid components, trends, and architecture have been conducted by multiple studies. Mariam et al.⁵ performed a comprehensive review of these issues and outlined their findings and their implications for future microgrid trends. Olivares et al.⁶ performed a literature review of current trends in microgrid control technologies and codified their findings in terms of primary, secondary, and tertiary microgrid control levels. Wei et al.'s⁷ systematic research overview of microgrid technologies examined "the typical structure, planning and design, operational control, protection technology, and power quality" of microgrids.

⁴ Courses include Economics of Modern Power Systems, Modeling for Energy Systems, Energy Technology, and Microgrid Seminar.

⁵ Mariam, Basu, and Conlon, "Microgrid: Architecture, Policy, and Future Trends."

⁶ Olivares et al., "Trends in Microgrid Control."

⁷ Wei, Xiangning, and Pengwei, "Overview of Key Microgrid Technologies."

Systematic microgrid literature reviews and technology assessments are complemented by studies that looked at interdisciplinary interactions, such as “The Impact of Policy on Microgrid Economics” by Milis et al.⁸ and “Policy Effects on Microgrid Economics, Technology Selection, and Environmental Impact” by Zachar et al.⁹. Milis et al. found that “current economic analyses indicate that the adoption of renewable energy sources within microgrids is not economically rational”, and Zachar et al. found that “an optimal [system] design is found to minimize the cost of energy supply over a 20-year lifespan” based on an evaluation of a variety of microgrid-related policy decisions. Another interdisciplinary study by Hanna et al.¹⁰ found that a policy framework is needed to ensure that microgrid developments deploy renewables over other existing low-cost energy generation technologies like natural gas-fired power plants. Additional studies have explored microgrid optimization, such as De Clercq et al.¹¹, which conducted technoeconomic modeling to define the “optimal system configuration of a grid-connected power system”, and Sharma et al.¹², which used probabilistic modeling to explore microgrid operation cost minimization and found that software can be used to effectively minimize microgrid costs.

The findings presented in the following manuscript complement the existing literature by evaluating the viability of microgrid-based business models within the context of real-world technology, policy, economic, and built environment constraints.

Technology

The U.S. Department of Energy Microgrid Exchange Group defines a microgrid as “a group of interconnected loads and distributed energy resources [DERs] within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected and island-mode”¹³. Within this broad definition, there are near countless technological permutations for physical construction.

⁸ Milis, Peremans, and Van Passel, “The Impact of Policy on Microgrid Economics.”

⁹ Zachar, Trifkovic, and Daoutidis, “Policy Effects on Microgrid Economics, Technology Selection, and Environmental Impact.”

¹⁰ Hanna et al., “Evaluating Business Models for Microgrids.”

¹¹ De Clercq, Zwaenepoel, and Vandeveldel, “Optimal Sizing of an Industrial Microgrid Considering Socio-Organisational Aspects.”

¹² Sharma, Bhattacharjee, and Bhattacharya, “Probabilistic Operation Cost Minimization of Micro-Grid.”

¹³ Ton and Smith, “The U.S. Department of Energy’s Microgrid Initiative.”

A large part of why microgrids are currently so appealing is this flexibility to meet multiple different needs. However, stability, reliability, and the complexities of integration with the Grid pose significant challenges. As we will see in this section, microgrids have specific key components that are required for successful construction and operation and can be deployed in multiple use cases. We will also examine why we chose to model our microgrid enterprise viability study using solar photovoltaic generation technology, as well as current trends in end load and built infrastructure and the implications they may have for a microgrid-based enterprise.

Microgrid Components

The components of a microgrid serve to create a miniature version of the Grid. Given the scale typically associated with microgrids, as well as their ability to operate in isolation¹⁴ from the Grid, microgrids are reliant on four key groups of components for reliable operation: generation, distribution, storage, and consumption (also referred to as “load”).

Generation

There are a wide range of technologies available for microgrid power generation, all with different attributes (see Table 1). Solar photovoltaics, wind power, hydro power, geothermal energy, and natural gas-fired generators are just some of the options currently used. The power generation technology used is largely dependent on the needs of the microgrid. Solar photovoltaics and wind power systems provide low marginal cost generation but have intermittent and variable energy resources. Typically, this means these technologies either need to be coupled with storage, additional generation assets, or a Grid connection in order to provide reliable power. Other options, like geothermal or hydro power systems, are less intermittent, but still subject to variability that can be problematic for reliability.

Power sources that rely on a consumable fuel, such as a diesel generator, can provide reliable primary or backup power without concern for intermittency or variability. However, depending on the desired attributes or location of the microgrid, the emissions, cost, or availability associated with the fuel may prove a barrier to implementation.

¹⁴ The term typically used to refer to this type of operation is “islanded” or “island-mode”, as mentioned in the DOE definition of a microgrid.

Table 1: Attributes of Common Microgrid Power Generation Systems

Attribute	Solar	Wind	Hydro	Diesel
Availability	Intermittent	Intermittent	Intermittent	On-demand
Output power	DC	AC	AC	AC
GHG emissions	None	None	None	High
Control	Uncontrollable	Uncontrollable	Uncontrollable	Controllable

Source: Mariam et al., 2016

A microgrid’s need for reliability may dictate the power source used. If the microgrid is located in a region with low availability of environmental energy resources, or the potential power supply disruption posed by voltage disturbances caused by fluctuations in cloud cover¹⁵ is an unacceptable or risk (as in the case of a hospital¹⁶), a diesel generator may be the best option for primary (or backup) power. However, if a microgrid is located in a remote location and fuel is either unobtainable on a regular basis or costs too much to transport, the challenges associated with the intermittency and power quality (see Table 2) of renewables may be worth it.

Table 2: Power Quality Issues of Common Microgrid Power Generation Systems

Issue	Solar	Wind	Hydro	Diesel
Voltage sag/swell		●	●	●
Over/under voltage		●		●
Voltage unbalance	●			
Voltage transience		●		
Flicker	●	●		●
Current harmonics	●	●	●	
Interruption	●	●		

Source: Mariam et al., 2016

¹⁵ Mariam, Basu, and Conlon, “Microgrid: Architecture, Policy, and Future Trends.”

¹⁶ There are multiple regulations and technical standards that apply to energy reliability and backup power supply at hospitals and healthcare facilities. Though there is some regional variance in codes due to differences in state and municipal laws, others such as NFPA 70 and 110 have broad applicability (Davoudi, “Emergency and Standby Power in Hospitals.”)

Although Table 2 highlights some of the power quality concerns with renewables, modern control and power conditioning systems are at a point where this is less of a concern than it used to be¹⁷. An in-depth evaluation of modern microgrid operational control, topographical design, and power conditioning systems is beyond the scope of this study, but future studies in this space may find value in evaluating how novel approaches to microgrid control and communication can decrease costs or capitalize on niche microgrid customer and use case opportunities. Additionally, depending on the use case (see “Microgrid Use Cases”, below), the carbon-neutral attributes and low marginal cost of generation for renewables may make them significantly more attractive than non-renewable generation sources.

Distribution

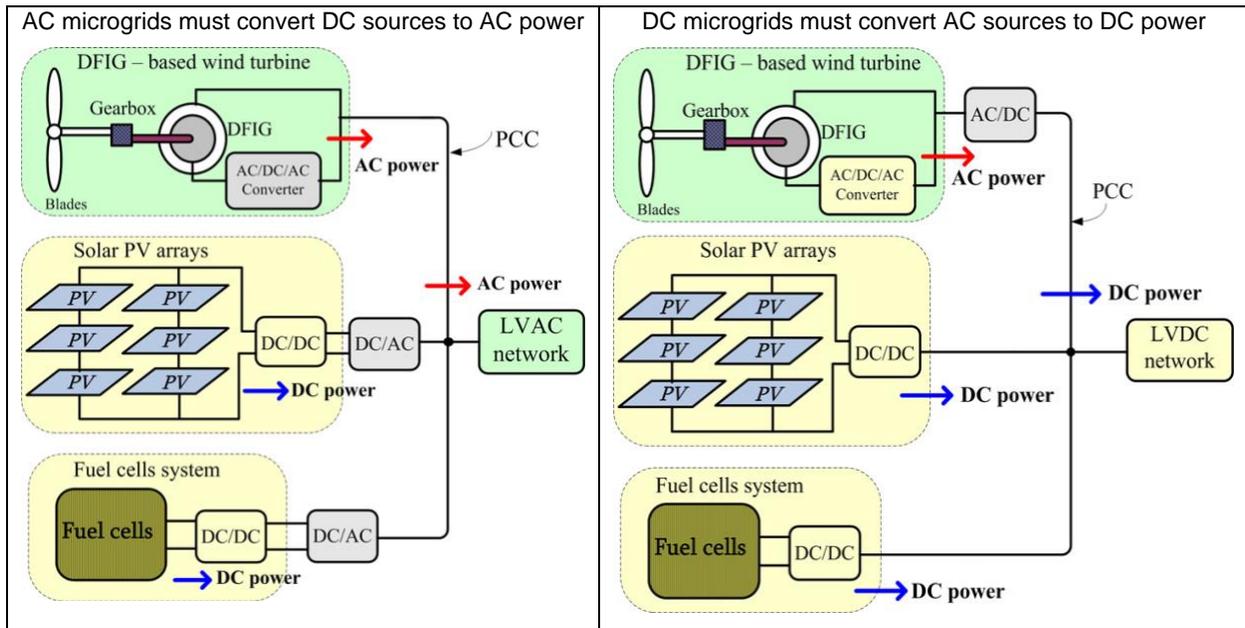


Figure 1: DC vs AC Microgrids (Justo et. al., 2013)

There are two options for power distribution within a microgrid: AC and DC. Whether AC or DC is used is dependent on the generation source and load type. Depending on the design and size of the microgrid, there may be multiple places within a microgrid where power is converted from

¹⁷ Ross, “Chapter IIB-1 - System Electronics.”

DC to AC or vice versa (see Figure 1: DC vs AC Microgrids¹⁸). The electrical design¹⁹ of a microgrid has broader implications for the efficiency of the system as a whole and may be of particular concern for larger systems. Additionally, if the system is intended to be used in connection with the Grid, it will either need to be matched to the Grid frequency or current type.

Storage

Depending on the type and use case of the microgrid, energy storage may or may not be required. Storage comes in many forms (e.g. batteries, fuel cells, flywheels). The type of storage selected will be largely dependent on the generation technology used, the microgrid's need for reliability, and the attributes desired from the storage device(s). Energy storage can perform the following tasks:

- Maintain power balance in the microgrid in the face of voltage, frequency, and load fluctuations
- Improve reliability if the microgrid is reliant on intermittent generation sources, or allow the grid operator greater control over when to dispatch generation sources or connect to external Grid power
- Provide essential services²⁰ for transitioning between islanded and Grid-connected operation²¹

Given the need for at least some level of power 24/7 in most microgrid use cases, storage is an important microgrid component. Indeed, headlines like “Solar-Plus-Storage is Critical to Microgrid Development”²² and “Community Microgrids with Energy Storage: Cost Effective and Clean”²³ highlight the emphasis that is being placed on storage, particularly within the context of solar-powered microgrids. Given the cost decline for solar PV modules we have seen over the

¹⁸ Justo et al., “AC-Microgrids versus DC-Microgrids with Distributed Energy Resources.”

¹⁹ Electrical design extends beyond just AC/DC: in an AC system there are also design parameters related to the line frequency, and both AC and DC systems need to consider the voltage of various parts of the system.

²⁰ Storage systems can act as a buffer between any differences in the characteristics of the microgrid-supplied power and the Grid power. Without this buffer, transitioning between island and Grid-connected operation requires additional electrical components. (Bass et al., “Determining the Power and Energy Capacities of a Battery Energy Storage System to Accommodate High Photovoltaic Penetration on a Distribution Feeder.”)

²¹ Mariam, Basu, and Conlon, “Microgrid: Architecture, Policy, and Future Trends.”

²² Silverstein, “Energy Storage Is Critical to Microgrid Development.”

²³ DeRosa, “Community Microgrids with Energy Storage.”

past decade²⁴, and the projected cost decline for battery storage systems²⁵, it is not unlikely that the majority of the microgrids built 5+ years from now will be solar + storage.

In addition to providing power when the primary generation devices are offline or not meeting demand, storage devices can also provide ancillary services. Ancillary services are additional benefits provided by a storage or generation asset and are typically used to help maintain the stability and reliability of the Grid²⁶. Within the context of a microgrid, ancillary services allow operators to maintain stable system frequency when loads and generation assets come and go and provide voltage support for sensitive loads. Depending on the local Grid policies and connection, these ancillary services can also be used as a source of income for the microgrid owner if the local utility is in need of them and the microgrid was built at a scale that makes this feasible.

The prospect of a Grid connection significantly changes the flexibility and complexity of storage devices attached to a microgrid. Depending on the microgrid power generation sources and the local Grid power rates, deciding when to charge/discharge storage devices can require extensive modeling. If the Grid has a net metering policy and permits bi-directional power flows, there may be opportunities to store low-cost renewable power during certain hours, and discharge to the Grid during other hours. However, the economic viability of this depends on the local policies around microgrids and net metering (see “Policy”, below)

Load

The primary reason a microgrid exists is to provide physical power. The load can vary significantly in terms of whether it needs AC or DC power, its required voltage and current draw, and how sensitive it is to power quality. A microgrid system is almost always designed primarily with the load attributes in mind, and different use cases typically require different design treatments-- a microgrid designed to serve a residential housing load will be almost nothing like one designed to serve an industrial manufacturing facility.

²⁴ Fu, Feldman, and Margolis, “U.S. Solar Photovoltaic System Cost Benchmark: Q1 2018.”

²⁵ Cole and Frazier, “Cost Projections for Utility-Scale Battery Storage.”

²⁶ AEP Energy, “Ancillary Services – Understanding the Basics.”

Microgrid Use Cases

Microgrids have practically unlimited applications. Any electrical load can theoretically operate on a properly designed microgrid, though considerations for cost and feasibility may make many use cases unrealistic. Microgrids offer many benefits, and organizations are increasingly considering them when assessing their energy infrastructure needs. According to the U.S. DOE Microgrid Exchange Group, some of the primary benefits of microgrids are:

- Facilitating integration and adoption of “smart grid” and modernization technologies
- Enabling the adoption and integration of distributed and renewable generation sources to help reduce peak load and improve efficiencies by siting generation closer to loads
- Improving customer participation and engagement via demand-side management and community participation
- Allowing for finer control of power quality and reliability, and helping to ensure energy supply for critical loads²⁷

Microgrids are particularly well-suited to meet the needs of emerging economies. Given the high costs associated with Grid development and/or recovery after natural disasters, microgrids present a viable option for building energy infrastructure that is both reliable and cost effective. For example, Hurricane Dorian destroyed the electrical infrastructure that fed power to the town of Marsh Harbor in the Bahamas. Instead of only rebuilding the diesel power plant and power lines, and risking losing power to their hospital and government center when the next storm hits, the town is building a 15-acre solar + storage facility that will provide reliable and stormproof power for 10% of their load²⁸. This example is only one of many that showcases the flexibility and resiliency value propositions of microgrids. Indeed, there are already many microgrids in existence today, and they can be split into five main categories: residential, commercial & industrial, institutional, off-grid, and military.

Residential

Residential microgrids vary significantly in scale and can be built to serve one or two customers or entire neighborhoods. They can be an effective method of decreasing variable housing costs and increasing economic investment in new construction. Additionally, residential microgrids

²⁷ Ton and Smith, “The U.S. Department of Energy’s Microgrid Initiative.”

²⁸ Whitaker, “Storm-Ravaged Bahamas Rebuilding Its Power Grid with Emphasis on Solar Energy.”

can help reduce overall energy demand, help to manage demand fluctuations, and significantly improve grid resiliency in the event of macro-scale power disruptions²⁹. However, given the challenges surrounding net metering and bi-directional power flows, there are issues associated with regulatory barriers and the development of standards that some observers predict will prevent widespread commercial acceptance in the short-term³⁰.

Commercial & Industrial

Reportedly, the Whiting Refinery in Indiana constructed the first “modern” industrial microgrid in 1955. Since then, many additional commercial and industrial (C&I) microgrids have been built³¹. Though use cases vary significantly, the main reasons C&I customers are reliant on microgrids is to avoid costly plant downtimes or equipment issues associated with unreliable or low-quality Grid power. Given the large generation capacity needed from most C&I microgrids, they can be expensive, and as a result the decision to build one is highly sensitive to technology costs, fuel prices, and operating costs. As such, extensive techno-economic modeling is needed to determine the most effective C&I microgrid design parameters³². The generation and energy storage assets used by a C&I microgrid are highly dependent on the load that needs to be served, and the decision to build one is usually based on a combination of the operational implications and effects on financial margins.

Institutional

Hospitals, schools, and corporate campuses are increasingly turning to microgrids to provide cost-effective, resilient, and low-carbon power. It is estimated that 40% of future microgrid development will be for this use case³³. Recent trends have underscored this, with large tech organizations³⁴, medical centers³⁵, and New Jersey’s second-largest university³⁶ installing microgrids in recent years. Not only does this use case allow institutions to ensure a resilient and reliable power supply, but it also allows them to invest in physical assets that will decrease

²⁹ Thompson, “The Sonoma Community Microgrid Initiative: The Path to Resilience and Sustainability.”

³⁰ Asmus, Cornelius, and Wheelock, “Microgrids.”

³¹ Asmus, Cornelius, and Wheelock.

³² De Clercq, Zwaenepoel, and Vandeveld, “Optimal Sizing of an Industrial Microgrid Considering Socio-Organisational Aspects.”

³³ Asmus, Cornelius, and Wheelock, “Microgrids.”

³⁴ Weaver, “Apple Energy Deeper Dive.”

³⁵ Francklyn, “Pioneering Kaiser Microgrid Meets Stringent Safety and Reliability Standards and Saves Money Too.”

³⁶ Ellsmoor, “Microgrids Are Powering the Future At MSU.”

their costs in the long run if the cost of power supplied³⁷ from their microgrid is lower than the cost of power from their local electrical utility.

Off-Grid

This use case has the most individual microgrids globally, but amongst the use cases this type has the smallest average system capacity³⁸. These microgrids are typically used in communities that are remote and nowhere near utility-scale transmission or distribution lines, remote research stations, or any other application where power is needed but the Grid is nowhere to be found. Depending on the type of generation used by these microgrids, operation can be expensive. However, fuel management strategies³⁹ and fuel-free renewable generation sources can help reduce costs. Off-grid microgrids offer an attractive option for rural electrification in emerging economies and are a viable solution for improving energy access for the roughly 900 million people without access to electricity⁴⁰. Indeed, many organizations are aware of this and are moving to capitalize on this opportunity; in 2018 annual investment in off-grid energy access broke \$500M and totaled nearly \$1.7B⁴¹.

Military

Microgrids are very attractive for the military given their need for reliable infrastructure in the face of uncertain supply chains, remote locations, and external disruption. Microgrids in this use case manifest themselves in a wide range of designs: diesel generators, miniature nuclear reactors^{42,43}, solar + storage systems, and emerging technologies like airborne wind energy⁴⁴. However, given the breadth of military applications and the strategic implications of reliable power, most of these microgrids have to be designed on a case-by-case basis to ensure that

³⁷ This assumes that the cost of power supplied by the microgrid includes the upfront capital, fixed, and variable costs incurred to produce the power.

³⁸ Asmus, Cornelius, and Wheelock, "Microgrids."

³⁹ Saner and Skarvelis-Kazakos, "Fuel Savings in Remote Antarctic Microgrids through Energy Management."

⁴⁰ Ritchie and Roser, "Access to Energy."

⁴¹ St. John, "Investment in Off-Grid Energy Access Totals \$1.7B Through 2018."

⁴² Scott, "Ship to Shore Power- US Navy Humanitarian Relief?"

⁴³ Technically, nuclear-powered submarines and aircraft carriers are mobile, islanded nuclear microgrids; their nuclear generators provide power to a group of interconnected loads within a discrete boundary and can hypothetically be connected to the Grid to provide power. Interestingly, a non-nuclear US Navy vessel has actually been used to supply power to the grid, but not for almost a century (Wilma, "U.S.S. Lexington Provides Electricity to Tacoma Beginning about on December 17, 1929."). The emerging development of small modular nuclear reactors (SMNRs) is a promising civilian application of technology similar to the US Navy's shipboard nuclear reactors.

⁴⁴ Harris, "The Promise and Challenges of Airborne Wind Energy."

they meet the needs of the men and women who will be using them. Though there are companies that offer “plug-and-play solutions for military bases”⁴⁵, the US DOD has recently taken steps to develop a “standardized, scalable microgrid planning tool” for its installations⁴⁶. Investment and development in this sector are somewhat opaque, given the military’s need for secrecy.

Photovoltaics as a Choice for Generation

Photovoltaics (PV) as a solution for electricity generation in microgrid models is an attractive proposition by virtue of declining capital costs and high deployment flexibility. The National Renewable Energy Laboratory (NREL) reports that in the last 10 years prices per watt DC (Wdc) have fallen on average by 68.9% across residential, commercial, and industrial sizing categories⁴⁷. Recent years have consistently featured the approach of PV to cost parity relative to the capital expenditures of more traditional energy generation options. Existing economic indicators suggest this trend is likely to continue. Additionally, PV panels can be deployed in a wide variety of locations with a range of landscapes due to the relatively low infrastructure requirements of the technology. Generally speaking, any location that has the landscape and structural prerequisites for the development of infrastructure that requires electricity could support collocation of PV modules.

In addition to the falling cost trends, all-in total costs for PV are smaller relative to other renewable energy technologies. As a share of U.S. electricity generation, the primary renewable energy sources used by consumers in 2019 were wind at 7.9%, hydropower at 6.6%, PV at 1.7%, and biomass at 1.4%. Over the next 5 years it’s projected that PV will be the lowest cost option by total levelized cost of energy (LCOE) relative to other major renewable sources. Table 3 below shows that PV will have between approximately 3% and 70% lower cost than wind and hydroelectric. The chart also shows that in the next five years, total system LCOE of PV will be lower than that of natural gas combined cycle plants and combustion turbines⁴⁸.

⁴⁵ Schweitzer Engineering Laboratories, “Keep the Power On.”

⁴⁶ Casey, “USA Braces for Tsunami of Microgrids As Defense Dept. Wades In.”

⁴⁷ Fu, Feldman, and Margolis, “U.S. Solar Photovoltaic System Cost Benchmark: Q1 2018.”

⁴⁸ EIA, “Levelized Cost and Levelized Avoided Cost of New Generation Resources.”

Table 3: Estimated LCOE for New Generation in 2025 (\$/MWH, 2019 USD)

Plant Type	Capacity Factor (%)	Levelized Capital Cost	Levelized Fixed O&M	Levelized Variable O&M	Levelized Transmission Cost	Total System LCOE
Dispatchable Technologies						
Combined Cycle	87	\$7.48	\$1.59	\$26.40	\$1.13	\$36.61
Combustion Turbine	30	\$16.10	\$2.65	\$46.51	\$3.44	\$68.71
Geothermal	90	\$20.36	\$14.50	\$1.16	\$1.45	\$37.47
Non-Dispatchable Technologies						
Wind (Onshore)	40	\$23.51	\$7.51	\$0.00	\$3.08	\$34.10
Wind (Offshore)	45	\$84.00	\$27.89	\$0.00	\$3.15	\$115.04
Solar Photovoltaic	30	\$24.12	\$5.77	\$0.00	\$2.91	\$32.80
Hydroelectric	73	\$28.89	\$7.64	\$1.39	\$1.62	\$39.54

Source: EIA, 2020. “Levelized Cost and Levelized Avoided Cost of New Generation Resources.”

Unlike other renewable energy resources, PV has a certain modularity that matches the prefabrication construction process that will be proposed by this investigation (see “Modular Construction”, below). Solar array building across a development offers a scalability and flexible capacity to more accurately match demand, while limiting the barriers posed by zoning and permitting restrictions relative to a renewable energy source like wind. Compared to the roughly \$1.10 per watt DC emblematic of PV soft costs, which include permitting and inspection⁴⁹, distributed wind resource development requires more than seven times that investment⁵⁰. Lastly, the selected cities under investigation in this paper – Raleigh-Durham, Los Angeles, Rochester, and Charleston (discussed in greater length in the Location Selection section of this paper) – encouraged financial inquiry into solar technology by virtue of their legislative

⁴⁹ Day, “Best Practices in Zoning for Solar.”

⁵⁰ Jimenez et al., “Distributed Wind Soft Costs: A Beginning.”

favorability for PV development. Two of the cities analyzed in this paper are in states that actively promote solar development through state incentives and aggressive climate action plans – Los Angeles and Rochester⁵¹ – while a third resides in a state that features competitive requests for proposals for solar generation capacity from independent power producers as a component of North Carolina House Bill 589⁵².

Policy

Policy impacts how a microgrid can be built, operated, and connected to the Grid. As such, policy is simultaneously a key driver helping to expand microgrid implementation and a barrier to adoption and can have a material effect on the economics of a project. The policies that affect microgrids are diverse and range from net metering and time of use rates to interconnection requirements and service territory rights. Though these policies can have a material impact on the feasibility and viability of a microgrid, there is a remarkable range of policies across the US and the globe. In this section, we will focus on two key US policies that are likely to have a material impact on the viability of new residential microgrids: net metering and time of use rates. While there are a host of additional US policy issues (e.g. franchise rights, PURPA qualifying facility rules, emissions regulations, and reliability requirements)⁵³ that are relevant to microgrid planners, we have omitted them from our discussion and models for feasibility.

Net Metering

Net metering involves taking the difference between the amount of energy a consumer draws from the grid and the amount of energy they produced and fed into the grid from their on-site generation. If the customer produces more energy than they consume in a given period of time, they are typically given a credit on their bill that is equal to the net difference. It is designed to offer financial incentive for DER owners to feed some of the power they generate onto the grid. However, despite the fact that 39 states (see Figure 3: Net Metering Policies in the US⁵⁴) have

⁵¹ Both California and New York have a host of legislative bills and state-level policies that are geared at reducing their state's GHG emissions.

⁵² General Assembly of North Carolina, "GENERAL ASSEMBLY OF NORTH CAROLINA SESSION 2017."

⁵³ Refer to Walsh, "Microgrid Regulatory Policy in the US." and Energy Efficiency Markets, "Think Microgrid: A Discussion Guide for Policymakers, Regulators and End Users." for an expanded discussion of some of the policy issues.

⁵⁴ DSIRE, "Detailed Summary Maps."

net metering rules in-place, there is still a significant amount of discussion around the challenges and benefits of net metering policy.

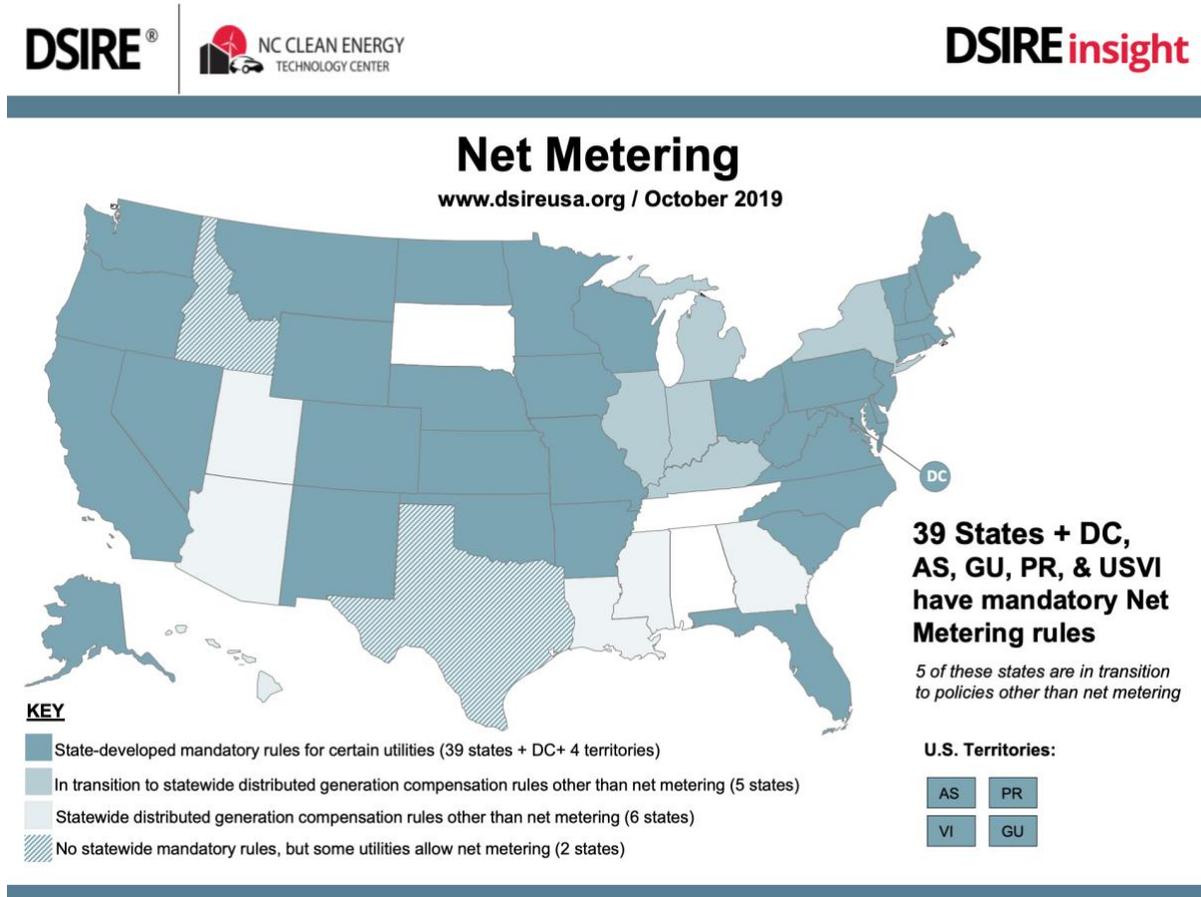


Figure 3: Net Metering Policies in the US (DSIRE, 2019)

Net Metering Challenges

One of the first challenges regarding microgrids and net metering is the variance in net metering policies across different states. The lack of a single unified national net metering policy means that a microgrid developer will have to examine state-level policy on a case-by-case basis. In some cases, “states that lack a standardized net metering tariff structure expose microgrid and DER customers to the possibility of refusal of service from the local utility”⁵⁵. Given this, as well as the interconnection requirements⁵⁶ imposed by federal, state, or local utility regulators, some states may be altogether too difficult for a microgrid developer to break even or build in.

⁵⁵ Walsh, “Microgrid Regulatory Policy in the US.”

⁵⁶ Generally, FERC is responsible for regulating all transmission-level interconnections, while states are responsible for regulating all distribution-level interconnections. As such, interconnection requirements

Table 4: Examples of Net Metering Capacity Regulation

State	Capacity Size Limit/ Rule
Arizona	125% of customer's total connected load
Massachusetts	10 MW
New Jersey	No limit
New Mexico	80 MW
Ohio	No limit
South Carolina	20 kW
Virginia	20 kW
Wisconsin	20 kW

Source: NCSL, 2017

Additionally, there may be microgrid capacity size limits imposed through the net metering or other regulatory⁵⁷ policies. Capacity limits can vary significantly within and between States, and can be based on utility type, customer type, technology and system type, and net metering method. Nearly 50% of the States that have net metering policies allow net metering up to 1 or 2 MW, and the other States have a wide range of capacity rules⁵⁸:

Net Metering Benefits

Despite the challenges, net metering does have some positive attributes. By incentivizing customers to sell their excess generation onto the Grid, utilities and regulators are able to help these customers decrease their electric bills and accelerate the time to payback for their energy generation system. Additionally, net metering is relatively straightforward to deploy, doesn't require any changes to existing retail power rates, and can often be implemented using existing

vary significantly state to state, and can have broad changes regarding size criteria, process and timeline, fees, insurance, and design and operating requirements. (Rolufs, "Missouri Microgrid Interconnection Requirements.")

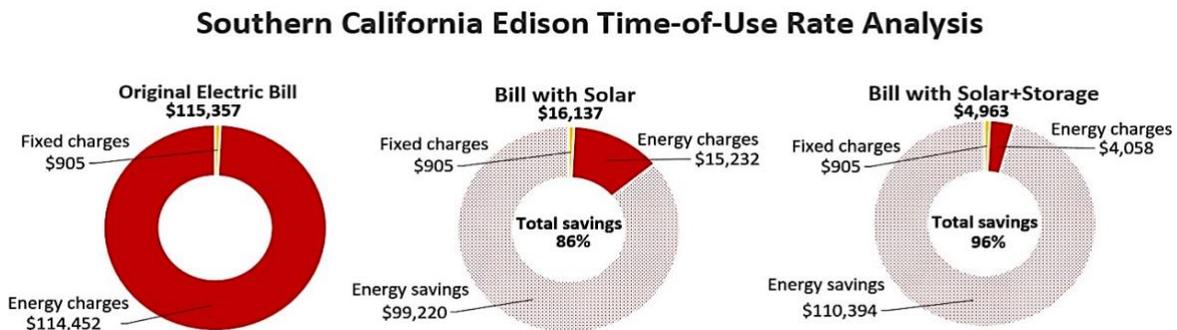
⁵⁷ A prime example of a regulatory policy that affects microgrid sizing is PURPA. PURPA outlines the provisions that enable an electrical generation station to become a "qualifying facility" (QF), which grants the facility key exemptions and rights needed to sell power into the grid (e.g. interconnection rights, exemption from being regulated like a utility, exemption from FERC approval). While microgrids can be designated as a QF in some locations, there are significant variations across states in how PURPA is implemented. (Attanasio, "A PURPA Roadmap for Microgrids.")

⁵⁸ NCSL, "State Net Metering Policies."

metering infrastructure⁵⁹. Additionally, net metering can be a useful tool for utilities which are struggling with daytime demand peaks. By offering net metering as an incentive for customers to install DERs, the utility can potentially lower some of these peaks⁶⁰, and avoid having to source this power in real-time and at higher rates from a capacity market. Furthermore, net metering can be combined with variable time of use rates to help incentivize and regulate behind-the-meter generation and storage devices.

Time of Use Rates

Time of use (TOU) rates are a tool that utilities use to signal to consumers when to use more or less energy. Typically, TOU rates involve the utility setting a higher retail power price during daytime peak demand hours, and lower rates during time periods when demand is lower; they can also vary seasonally. As of 2017, 14% of all US electric utilities offered a TOU rate option, and only had 3% of their customers enrolled in the rate class⁶¹. However, as the economics of DERs continues to evolve, we will likely see additional customers shift to TOU rates. Coupling DERs with behind-the-meter storage when there is a TOU rate structure available has been shown to have significant financial upside by virtue of the ability to perform rate arbitrage. As shown in Figure 4 below, the incremental addition of solar and storage technologies for a large low income, multi-family residential building boosted savings and improved the time to payback for the installation of the solar and storage systems and mitigated risks to low-income ratepayers posed by TOU rates⁶².



Source: Geli/ Clean Energy Group, 2016

Figure 4: The Effect of TOUs on Residential Electricity Bills (Mullendore, 2017)

⁵⁹ NREL, "Net Metering."

⁶⁰ SEIA, "Net Metering."

⁶¹ Hledik, Faruqui, and Warner, "The National Landscape of Residential TOU Rates: A Preliminary Summary."

⁶² Mullendore, "Time-of-Use Means It's Time for Storage."

Within the context of a Grid-connected solar + storage microgrid, TOU rates make the decisions around when to charge and discharge the storage system much more complicated—Grid power price variability coupled with variable (but free) behind-the-meter solar power availability requires extensive optimization to minimize costs and battery wear-and-tear while maintaining reliability. However, if the microgrid is also able to take advantage of net metering, there may be significant opportunities for arbitrage. When correctly capitalized, these opportunities can have a sizable impact on the economics of the microgrid.

Economics

The economics of microgrid business ventures are largely dependent on two primary factors: the costs associated with their installation, operation, and upkeep, and their ability to earn revenue. As such, the decision to build a microgrid is typically based heavily on the estimated costs of the project and the cash flows the owners will be able to capitalize on for a return.

Costs

The largest cost component of a microgrid is the generation system, followed closely by the site construction and engineering costs (see Table 5 below). These costs can range significantly depending on the size of the microgrid, the technology used, and the regulatory requirements for interconnection. Due to the breadth of considerations microgrid developers must take into consideration, it is rare for a microgrid design to be perfectly replicable. Depending on the complexity of the system and, the engineering and modeling needed to develop a larger microgrid can range from \$10,000 to over \$1M⁶³.

As technology costs decline, the economics of a microgrid changes significantly. A 2018 study that examined 16 different microgrid use cases across 17 US locations found that at high technology costs solar microgrids were only cost-effective in 43.8% of cases, and solar + storage was cost-effective in 8.5% of cases. At a “stretch” low technology cost solar microgrids become cost-effective in 84.2% of cases, and solar + storage was cost-effective in 40% of cases⁶⁴. Given the recent and projected cost declines for DERs and battery storage, it is likely

⁶³ National Academies of Sciences, *Microgrids and Their Application for Airports and Public Transit*.

⁶⁴ McLaren et al., “Identifying Critical Factors in the Cost-Effectiveness of Solar and Battery Storage in Commercial Buildings.”

that the “stretch” low technology costs won’t remain that way for much longer. If this proves to be true, the economic outlook for solar + storage microgrids will continue to improve. However, it should be noted that the relative costs associated with a microgrid vary significantly across different use cases (see Appendix A: Total Microgrid Cost per MW Across Use Cases).

Table 5: Relative Cost Ratios of Microgrid Components

Component	Cost Ratio	Description
Energy Resources	30 - 45%	Energy storage; controllable loads; distributed generation
Switchgear Protection and Transformers	20%	Switchgear utility interconnection
Communications and Control	10 - 20%	Standards and protocols; control and protection technologies; power electronics; SCADA systems
Site Engineering and Construction	30%	System design and analysis; integration; testing and validation
Operations and Markets	5 - 15%	Operations and maintenance; market acceptance and costs

Source: National Electrical Manufacturers Association, 2016

Additionally, the equipment required for utility interconnection (“Switchgear Protection and Transformers” in Table 4, above) can be a significant cost component for a Grid-connected microgrid. However, this varies significantly depending on the regional regulatory and utility requirements. Microgrid technologies are still relatively new, and there are few regulatory standards that apply to microgrids as standalone, self-contained assets⁶⁵.

The operational and maintenance (O&M) costs of a microgrid refer to any costs that are incurred as a result of operating the microgrid or performing and maintenance on it. These costs can vary significantly and would look very different for a diesel generator-powered microgrid and a solar + storage microgrid. Modern microgrid designs that rely heavily on renewables typically have lower (if any) fuel costs, but their control and optimization systems can require expensive overhaul and maintenance. Tests of emerging microgrid control technologies have been shown to lower operational costs and streamline integration of renewables⁶⁶, and novel approaches to software modeling and optimization⁶⁷ have potential to minimize operating costs.

⁶⁵ NEMA, “Powering Microgrids for the 21st-Century Electrical System.”

⁶⁶ Eto et al., “The CERTS Microgrid Concept, as Demonstrated at the CERTS/AEP Microgrid Test Bed.”

⁶⁷ Sharma, Bhattacharjee, and Bhattacharya, “Probabilistic Operation Cost Minimization of Micro-Grid.”

Revenues

Given the variety of microgrid use cases, there are a number of microgrid revenue models. However, the various types of revenue models can be grouped into three main categories: customer-owned, microgrid-as-a-service, and pay-as-you-go⁶⁸:

Table 6: Microgrid Revenue Models

Revenue Model	Description
Customer-Owned	In this model, the customer buys the microgrid outright (maintenance, operation, and service contracts notwithstanding). The majority of the financial risk falls on the customer. This type of microgrid is the most common today.
Microgrid-as-a-Service (MaaS)	MaaS models are relatively new but are emerging as a viable microgrid model for utilities. MaaS operates via a contractual partnership or agreement between the operator/owner and service beneficiary and provides flexibility for entities which may need more access to equity or debt financing.
Pay-as-You-Go (PAYG)	The PAYG model is most applicable to developing economies and small-scale microgrids. This model is reliant on a customer base who needs small but regular access to power, and pairs well with small-scale solar + storage installations.

Source: Borghese et al., 2017

Though these business models are all technically viable, current regulatory and utility policy is a barrier to implementation in some locations. The owner of the microgrid, its size, and its revenue model all have implications for the rate structure, facility classification, and interconnection agreement⁶⁹. Additionally, depending on where the microgrid is built, net metering and TOU rates may have serious implications for the ability of the microgrid to earn revenues (or avoid costs) via excess generation or battery-based arbitrage. However, the Federal Energy Regulatory Commission (FERC) recently passed a new rule that will “remove barriers to the participation of electric storage resources in the capacity, energy and ancillary services markets”⁷⁰. This rule will help to streamline the ability of microgrids to leverage storage assets as sources of revenue and may prove to substantially alter project economics. Given the nascency of microgrids as market participants, the outlook for microgrid revenue streams is promising but complex. As peer-to-peer (P2P) markets, blockchain-based platforms, and virtual power plants become more mature, it is likely we will see novel approaches to microgrid revenue models.

⁶⁸ Borghese, Cunic, and Barton, “Microgrid Business Models and Value Chains.”

⁶⁹ Falber and Feller, “The Top 6 Legal Factors Holding Back Microgrids.”

⁷⁰ FERC, “FERC Issues Final Rule on Electric Storage Participation in Regional Markets.”

End Load and Built Infrastructure

Microgrid management offers an opportunity to more granularly analyze consumer power use to predict user needs and opportunities in service efficiency. Residence size and technology that make up the use characteristics of a load are effective predictors of electricity consumption at a particular location. Pairing historical weather patterns with those parameters can approximate the generation capacity required at that location, which helps determine the capital costs of development.

Analyzing these relationships offers a business opportunity that addresses problems and trends observable in today's housing and electricity markets. For example, over the next 25 years Durham is projected to need 2,000 new housing units annually to keep up with current city population growth⁷¹. Building construction addresses the maintenance and support of the housing market but does not consider the potential impacts on the electricity market. The influx of new Durham residents will require expansion of generation capacity and necessitate consideration of the Grid's ability to effectively support this growth in electricity demand. One of the most glaring opportunities for infrastructural advancement to meet the changing population landscapes around Durham, and many places around the world, is the detailed analysis of the relationships between housing and Grid developments.

The Energy Information Administration (EIA) provides detailed historical records of the annual energy usage from the residential and commercial building sectors in the United States. EIA records organized by building size and general load characteristics provide a repository for energy generation and end use data that elucidates relationships when considering the growth of those industries⁷². Each square foot of extant housing suggests a per-kWh end use that needs respective generation capacity. Historical data also supports projection of electricity consumption by end use and intended building use⁷³. Financial projections for growth of new housing developments can use this information to simulate investment parameters necessary to support this growth with an accuracy based on physical and financial assumptions. This investigation relies on groups of assumptions detailed throughout this paper. Creating a model

⁷¹ Willets, "To Keep Up with Growth, Durham Needs to Add Two Thousand Housing Units a Year. Its Rules Are in the Way."

⁷² EIA, "Residential Energy Consumption Survey (RECS) - Data."

⁷³ EIA, "Commercial Buildings Energy Consumption Survey (CBECS) Data."

that could seamlessly incorporate these factors was an important part of this programmatic undertaking. In order to build a program that accepted user input when prompted by the underlying code, this analysis relied on Python to organize and manipulate data, as well as simulate the physical and financial characteristics of the locations and infrastructure involved.

Modular Construction

Merging built infrastructure and renewable energy investment presents a challenging financial landscape considering the high capital intensity of these two industries. Cost recovery is considered over multi-year time horizons, making financial projection contingent on the risks associated with future revenues and market conditions. One key technological and infrastructure sector development that makes a business model that merges energy deployment with construction a more attractive financial proposition is the emergence of modular construction, or prefabrication. Modular construction offers a lower-cost and less time-intensive alternative to traditional on-site construction practices. Modularity refers to the standardized design and manufacturing of building components prior to their transport to building sites.

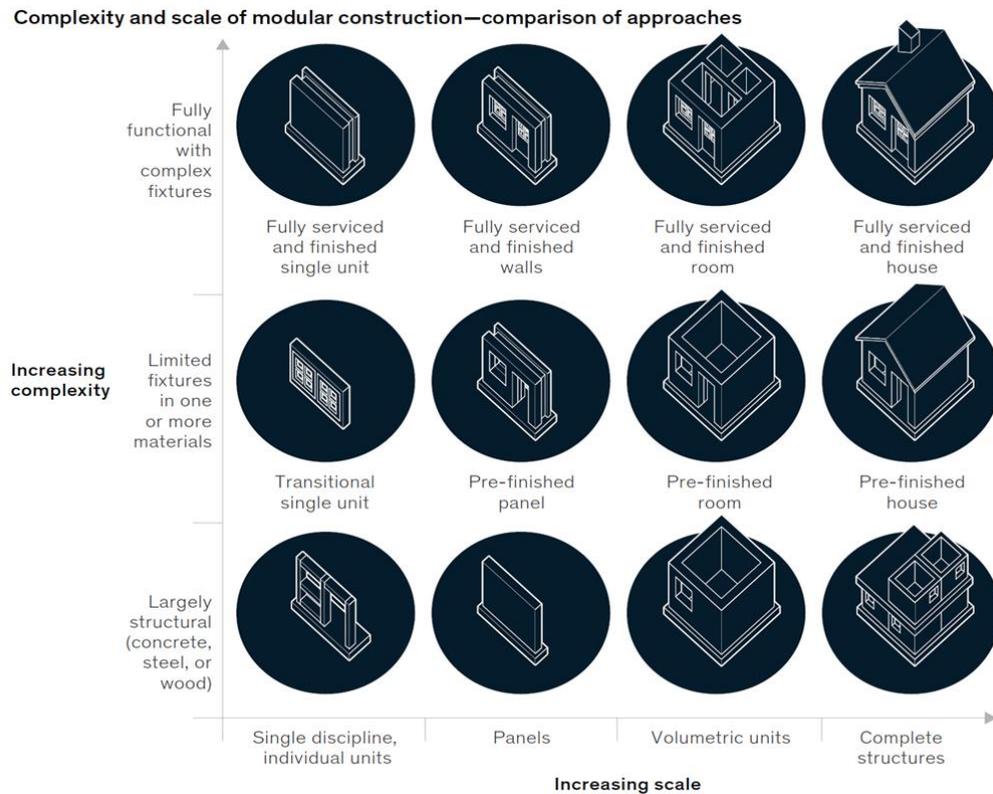


Figure 2: Approaches to Modular Construction Production (McKinsey, 2019)

This approach offers substantial flexibility in the ways in which materials are managed in construction processes, control over the environments in which construction takes place, and quality control of the infrastructure in question throughout the product life cycle⁷⁴. Figure 2 illustrates some of the common variations in prefabrication components transported from construction facilities to desired locations for on-site assembly.

The U.S. construction market is projected to reach a market capitalization of roughly \$1.8 trillion by 2023, demonstrating a residential construction compound annual growth rate (CAGR) of 9.1%, almost double that of the industry as a whole⁷⁵. In this high-growth sector, modular construction is considered a promising solution for new construction projects at decreased cost. These cost savings are realized through waste minimization, high operational throughput, and controlled work environments emblematic of factory construction. Between the U.S. and Europe, modular construction projects report cost savings of 20% with a development timeline up to 50% shorter than that of traditional on-site construction projects⁷⁶. Off-site building component construction supports the concurrent preparation of site-foundations. This off-site building process most commonly takes place in a controlled factory or industrial warehouse environment indifferent to the weather disruptions that often slow the building process. The design process and uniformity of production support substantial decreases in time and financial expenditure as well⁷⁷.

The modular construction process develops building components at various stages of progress towards the end product. Off-site construction can produce panels that are assembled as the walls, floor, and roof on-site, volumetric shells that serve as individual rooms that aggregate to produce a completed structure or completed building models that simply need transport to the end location. The transportation parameters (e.g. distance to site and off-site construction capacity) dictate which parts of the design are manufactured off-site relative to those saved for on-site assembly, but this flexibility ensures overall decreases in construction duration.

⁷⁴ Mark Lawson, *Design in Modular Construction*.

⁷⁵ BusinessWire, "United States Construction Industry Databook Market Size & Forecast 2014-2023, Q3 2019 Update - ResearchAndMarkets.Com."

⁷⁶ Bertram et al., "Modular Construction: From Projects to Products."

⁷⁷ Smith and Timberlake, *Prefab Architecture*.

Assessing Microgrid Enterprise Viability

Methods & Approach

The breadth of factors contributing to the development and efficacy of microgrid solutions requires a disciplined approach to analysis. With this in mind, high-level distillation of the most relevant contributors to microgrid cost was the priority of the early stages of this investigation. Ability to operate at various scales and inherent impacts on carbon reduction relative to more carbon intensive generation fuels (e.g. coal) make renewable energy technology a clear solution for the generation source for the microgrid model. PV modules feature sizing and pricing modularity that make them a convenient subject for an evaluation of the financial feasibility of microgrid scaling. As discussed previously, intermittency is a key limitation of PV and other renewable options, which encouraged the thorough analysis of storage options in this investigation. Ultimately the purpose of any microgrid is the provision of electricity and power services to a given area or region, making built infrastructure a critical component of any evaluation of microgrid efficacy, use potential, and financing. Understanding the scope of considerations for these three components – PV, storage, and built infrastructure – offers a functional foundation for the analysis of possible business cases for scalable microgrid deployment.

Analytical Process

Economic and financial feasibility are two of the limiting factors for investor interest in microgrid development, making cost simulation an essential first step to drafting a compelling business case. Residential housing construction and renewable energy technology expansion are mutually entwined industries experiencing growth in today's markets, suggesting a market niche for tools intended to optimize efficiency in their deployment. Colocation of distributed energy resources with new construction has the potential to address the needs of electricity service providers while creating methods for more detailed user data analysis. Energy industry professionals, such as Duke University's Energy Manager Casey Collins, believe that granular

electricity end user data collection and analysis are the future of the electricity sector and Grid management⁷⁸. The following methodology details a programmatic approach designed to:

- 1) Aggregate and analyze residential and commercial building sector energy use data
- 2) Organize that data relative to the physical characteristics that inform solar and infrastructure development
- 3) Optimize PV and storage solutions for new infrastructure built in locations with geographic and climatological variability
- 4) Reveal the business development considerations required to deploy management platforms⁷⁹

Simulating the characteristics of housing components and energy systems relies on data aggregation across a collection of energy consumption and expenditure, infrastructural, and national power sector databases. The EIA provides data on the residential and commercial building population in the US, their collective square footage, and electricity use in relation to end use in kWh^{80,81}. Using this data, this investigation was able to find the typical kWh consumed per square foot organized by type and size of the building in question. The Residential Energy Consumption Survey (RECS) and Commercial Building Energy Consumption Survey (CBECS) offered the consumption of energy by specific end-use categories (e.g. lighting, space heating, and refrigeration) and building use type (e.g. office and medical facility)^{82,83}. Aggregation of this data allows a program to approximate the expected load of a structure with a technological profile represented by end use parameters. From the perspective of modular construction and modular generation outfitting, a developer could accurately pair a new structure of predetermined use and size to a solar array of matching generation capacity.

⁷⁸ Pratson, Insights from Duke University Nicholas School of the Environment course EOS 792S (Microgrid Seminar).

⁷⁹ These management platforms provide microgrid system oversight and financial projections, and ideally will be comparable to existing standard platforms used by projects and firms in the microgrid space

⁸⁰ EIA, "Commercial Buildings Energy Consumption Survey (CBECS) Data."

⁸¹ EIA, "Residential Energy Consumption Survey (RECS) - Data."

⁸² EIA.

⁸³ EIA, "Commercial Buildings Energy Consumption Survey (CBECS) Data."

Location Selection

To adequately pair the solar array to new infrastructure, this investigation employs capacity optimization. The initial consideration when deciding PV potential is the location. Geographical location determines the historical datasets needed to estimate global horizontal irradiance (GHI) and solar insolation in a certain area over a year. GHI is a measure of the total amount of shortwave solar radiation received by a surface horizontal to the ground⁸⁴. NREL compiles an extensive database that provides Typical Meteorological Year (TMY) data for most major cities in the US. TMY data is a collection of meteorological characteristics representative of the typical characteristics experienced by a specific location in a given year⁸⁵. This paper selects several locations with a variety of climatological and regulatory profiles as subjects for this investigation – Durham, NC; Rochester, NY; Los Angeles, CA; and Charleston, WV. These locations offer a range of climatological, policy, and public perception of renewable energy and climate impacts variations and were selected in an effort to provide a robust range of considerations for analysis. Durham provides insight to a highly regulated energy industry with a rate structure intended to support a regulated monopoly. Durham also provides climate variability in a location with mild winters, hot summers, and increasingly severe incidences of natural disasters – North Carolina is categorized as having a high frequency of billion-dollar weather disruption events over the last 40 years⁸⁶. In addition, though NC ranks in the top 10 states in electricity generation, the state consumes more energy than it produces⁸⁷. These characteristics paired with the growing population detailed earlier in this paper suggest a market favorable to innovative approaches to infrastructure and power generation.

Rochester features harsh, long winters with a trend in regulatory policy favorable to the expansion of renewables. New York's plan to Reform the Energy Vision (NYREV) is one such example. NYREV is an ambitious proposal to implement a climate action plan to achieve an 85% carbon emissions reduction by 2050. Per the proposal, the target reduction will be supported by 100% clean energy in electricity generation by 2040, 9 GW of offshore wind capacity installed by 2035, 6 GW of distributed solar installed by 2025, and 3 GW of storage capacity installed by 2030⁸⁸. This state priority closely matches the goals of this paper.

⁸⁴ NREL, "Solar Resource Glossary | Grid Modernization."

⁸⁵ NREL, "NSRDB: 1991- 2005 Update: TMY3."

⁸⁶ Energy.gov, "Economic Benefits of Increasing Electric Grid Resilience to Weather Outages."

⁸⁷ EIA, "North Carolina - State Energy Profile Analysis."

⁸⁸ NY.gov, "REV Initiatives."

However, the harsh and long winters of Rochester and New York more broadly limit the potential of solar output in the state: sunlight is limited in NY. Additionally, a location like Rochester that is often cold has more cost incentive to expand natural gas use as a more cost competitive alternative for housing needs like space heating and cooking than added PV capacity to serve as a replacement for those specific uses. This is particularly relevant considering the fact that space heating accounts for roughly 41% of residential energy consumption⁸⁹. This investigation evaluates the financial landscape of both natural gas and PV to identify the least-cost strategies for meeting end-use load.

Open Energy Information (OpenEI) data provides hourly natural gas use behaviors, making gas cost parameters a straightforward addition to this cost analysis⁹⁰. Given the historically low cost of domestically sourced natural gas as a function of hydraulic fracturing and extensive transportation pipeline network, understanding the economic impacts of this primary energy source is integral to the completion of a comprehensive financial analysis⁹¹.

Los Angeles, CA is characterized by year-long sunshine and climate policy favorable to the growth of solar and storage technology. ToU rates are structured to create a competitive market for traditional and renewable primary sources relative to their levelized cost of electricity, while legislation supports the generation potential for storage technology⁹². California's Solar Mandate, legislation requiring all new housing construction to collocate solar generation technology, is scheduled to take effect in 2020 and may soon require renewable technology to have supporting storage capacity⁹³.

Finally, Charleston, WV is an unregulated market with an electricity grid supported primarily by coal; coal supplied 92% of the state's net electricity generation in 2018⁹⁴. WV is specifically facing growth in its housing market as a feature of urban sprawl from the Washington D.C. metropolitan area, signaling ample opportunity for industry support in housing development. Given the impacts of climate change, any future regulation requiring decarbonization of energy mix could also significantly impact the energy and housing markets.

⁸⁹ EIA, "Residential Energy Consumption Survey (RECS) - Data."

⁹⁰ OpenEI, "Residential Load Datasets."

⁹¹ OpenEI, "Energy Information and Data."

⁹² EIA, "California - State Energy Profile Overview."

⁹³ Thoubboron, "California Solar Mandate."

⁹⁴ EIA, "West Virginia - State Energy Profile Overview."

Data Collection

NREL's TMY database offers hourly meteorological data for a year based on location. To easily orient this data for optimization processing, this investigation organizes the solar insolation data by month and averages each hour of every day to build a resource profile typical of an average day. Building the end-use load profile for each housing structure mirrors this process. End user load construction relies on representation of each hour of every day from the various locational dataset as a percentage of the total energy use in that day. Matching 24 percentage values of each day from datasets allows the program model to overlay that profile with the total end uses constructed based on the simulated technological variability of residential units across different scenarios. Collecting those percentage values over certain parts of the datasets allowed this investigation to then simulate what a load would be across certain seasons and months in every location of interest.

OpenEI, hosted by the US Department of Energy (DOE), provides annual hourly end-use data based on load profiles of sample houses⁹⁵. These sample houses are organized based on regionally specific use categories and construction characteristics. The four cities under investigation cover three different climate zones as specified by the DOE: cold, mixed-humid, and hot-dry⁹⁶. The base housing load model reflects a housing size of 2,696, 2,546, and 2,000 square feet respectively, all with three bedrooms, one bath, and one story. This investigation focuses exclusively on the base housing load data from OpenEI because the end-use categorizations already account for the variability in energy intensities under a range of development scenarios. Refer to Appendix B (Building Specification for OpenEI Base Load Datasets) a more detailed representation of the organization of these sample housing specifications.

To offer sensitivity in this investigation's analysis, this hourly load data was matched with end-use technological characteristics designated as low, medium, and high energy use. For the purposes of this investigation, low energy use is reflected by a load composed of lighting, space heating, water heating, refrigeration, and light additional appliance use (i.e. internet router and a small tv). Base, or medium, energy use adds air conditioning and increases appliance use to incorporate more small electronics, such as larger television models and microwaves. High energy use categories expand the load profile to include a larger variety of kitchen appliances,

⁹⁵ OpenEI, "Energy Information and Data."

⁹⁶ EIA, "About the Commercial Buildings Energy Consumption Survey (CBECS)."

washing and drying machines, and electronic device categories featured in an average U.S. home (e.g. gaming systems and multiple desktop computers). The rationale for this end-use delineation was to consider the potential use profiles of more remote locations in addition to those more classically associated with wealthier, urban lifestyles.

PV sizing

Manipulating this raw data into monthly, hourly averages provided data that could be analyzed across monthly and geographically specific comparisons. To determine the PV capacity for the simulated structures in these four locations, this investigation formulated a linear program (LP) composed of an objective function that minimized the cost of the required solar energy technology infrastructure contingent on constraints that matched PV generation to load data for every hour of the average day, limited the footprint of the optimal solar array to that of the total square footage of the residential unit based on industry standards for the watt of installed capacity per square foot of a typical solar module, and non-negativity of optimal capacity using Python programming language. The complete objective function and constraints are recorded in Figure 5. This model uses the EIA rate structure in dollars per installed Wdc to evaluate capacity potential: a residential rate of \$2.80/Wdc and a commercial rate of \$1.85/Wdc for PV arrays or a collection of arrays that exceed 10 kW of installed capacity⁹⁷.

<p>Objective Function:</p> $\min z = \sum_t^T P_D * C_{PV} \quad \forall t$ <p>Constraints:</p> $PV_{size} \leq FP_{Total}$ $PV_C \geq 0$ $PV_C \cdot DR \cdot PSH \cdot \eta_{inv} \cdot \eta_{pv} \geq \sum_t^T P_D$	<p>P_D = Demand</p> <p>C_{PV} = Cost of PV</p> <p>PV_{size} = PV Array Square Footage</p> <p>FP_{Total} = Residential Unit Square Footage</p> <p>DR = Solar Panel Derating</p> <p>PSH = Peak Sun Hours</p> <p>η_{inv} = Inverter Efficiency</p> <p>η_{pv} = PV Panel Efficiency</p>
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Figure 5: PV Sizing Optimization Equations

⁹⁷ Fu, Feldman, and Margolis, "U.S. Solar Photovoltaic System Cost Benchmark: Q1 2018."

Residential Construction Costs and Sizing

To further evaluate the scope of contributing costs, this investigation analyzes the cost per square foot of modular housing units based on a variety of case studies. Based on reporting from modular construction firms with a portfolio representative of the scaling impacts of preconstruction, a low-cost construction range is any cost lower than \$160 per square foot, medium-cost range is between \$161 to \$210, and high-cost is greater than \$210⁹⁸. Relative to the location-specific housing prices per square foot in the RDU area, this construction breakdown is representative of the current US housing market trends⁹⁹.

Standard construction models were used to model the community of houses simulated in this investigation. The consumption and expenditure data collected from EIA divided end-use consumption by the number of occupants in each residential unit, providing a convenient energy end-use delineation to simulate familial units. Standardization of housing units paired each familial unit to a construction model to best orient the simulated load information. The housing models were segmented into four units that presented a variability representative of residential construction strategies used in the US. The smallest model in each development is 650 square feet, the next smallest is 1,000 square feet, the penultimate model is 1,350 square feet, and the largest model is 1,800 square feet. The model simulation limits the number of occupants for the smallest unit considering 650 square feet is not typically large enough to house more than three or four people. Based on simulation design, if the model unit selected to add to the community is fewer than 800 square feet, then no more than four people could be assigned to that unit.

Storage Sizing

Energy management determined by the battery storage deployment plays a significant role in this investigation as it relates to the potential financial savings for the end user and the costs incurred by the developer. The usable energy capacity and scheduling of power support for the residential unit in question have the potential to substantially offset the electricity draw from the Grid while being oriented to supply power to the home at the most opportune times. To that end, this investigation selected three of the most widely used battery storage options on the market – the SunPower Equinox, the LG Chem RESU, and the Tesla Powerwall – and employed storage

⁹⁸ Smith and Timberlake, *Prefab Architecture*.

⁹⁹ Zillow.com, “Real Estate, Apartments, Mortgages & Home Values.”

optimization linear programming to determine how best a storage system could impact residential interactions with the Grid.

The three storage options chosen for this investigation were picked based on their usable battery capacity. From a low, medium, and high battery categorical designation, the Solar Equinox assumes the low-level capacity role with an energy capacity of 6.5 kWh, the LG Chem RESU is the medium-level capacity unit with 9.8 kWh, and the Tesla Powerwall is the high-level unit with 13.5 kWh^{100,101,102}. Variability in capacity sizing and technical specifications offered this investigation the ability to include added sensitivity to the model simulation beyond the characteristic variability of the location and the housing unit type. Additionally, the developer cost incurred relative to the economic benefit of renewable technology for the end user is impacted specifically by the residential battery's ability to offset Grid usage.

With the battery types identified, determining probable battery dispatch scheduling relative to electricity rates and PV generation for each home was the next step in evaluating financial outcomes. A linear programming model (LP) works to pass the predetermined parameters through an objective function and set of constraints to provide a range of decision variable values optimized to meet the features of the PV and storage system. This particular LP, designed to optimally manage power battery scheduling, minimizes grid purchases while operating within the limitations of battery technology. The battery system meets individual residential unit load demand through a combination of PV system electricity generation in a given hour, charge and discharge scheduling from the PV system to the battery and from the battery to the necessary loads, deferred energy capacity that cannot be used by the residential unit or stored in the battery, and Grid purchases. The physical and programmatic limitations of the battery specify that the battery must maintain a state of charge (SOC) that is an additive value of the state of charge in the previous time period and the charge or discharge that occurs in the current time period, maintains a charge capacity in a given time period that is less than PV generation (to ensure the battery is charged from the PV array alone), prevents negative Grid purchase values (so that the system isn't supplying excess electricity to the grid), and does not violate the minimum or maximum battery charge capacity. For the benefit of using a platform capable of processing the range of decision variables over the predetermined time period for

¹⁰⁰ SunPower, "Solar Battery Storage for Homeowners - Product Brochure."

¹⁰¹ GoGreenSolar, "LG Chem RESU 9.8 KWh Lithium Ion Solar Battery Backup Solar Battery."

¹⁰² Tesla, "Tesla Powerwall."

this investigation, this LP model employs Python. The complete objective function and set of constraints for the LP can be viewed in Figure 6 below.

	Constraints:
	$P_{g,t}^i = P_{dem,t}^i - P_{PV,t}^i + P_{C,t}^i - P_{D,t}^i + P_{def,t}^i, \forall t \in T, \forall i \in I$
	$SOC_t^i = SOC_{t-1}^i + \frac{P_{C,t}^i \eta \Delta t}{Q_i} - \frac{P_{D,t}^i \Delta t}{Q_i \eta}, \forall t \in T, \forall i \in I$
Objective Function:	$\sum_n P_{C,t}^i \leq \sum_n P_{PV,t}^i, \forall t \in T$
$\min z = \sum_t^T (C_T \cdot P_{g,t})$	$\sum_n P_{g,t}^i \geq 0, \forall t \in T$
	$SOC_{min}^i \leq SOC_t^i \leq SOC_{min}^i, \forall t \in T, \forall i \in I$
	$P_{ch,min}^i \leq P_{ch}^i \leq P_{ch,max}^i, \forall t \in T$
	$P_{disch,min}^i \leq P_{disch}^i \leq P_{disch,max}^i, \forall t \in T$

Figure 6: Battery Storage Management Equations

NREL's battery pricing benchmark provided current cost parameters for energy storage units and a range of future cost projections that reflect various market scenarios. To add sensitivity in battery pricing to this investigation, low, medium, and high battery cost scenarios were incorporated into the simulation – \$271, \$310, and \$350 per kWh installed capacity respectively.

Financial Projection Parameters

Expanding the evaluated scenarios over a selected time horizon offered this investigation insight into the benefits accrued by the product end user and the costs incurred by a developer willing to undertake this approach to microgrid construction. To both set a time horizon representative of built infrastructure use and capture the multiple replacement timelines emblematic of renewable energy technology, the financial projections for each scenario occur over 25 years.

The projected lifespans of PV arrays and battery storage systems can vary, but most PV products can expect to maintain useful electricity production efficiencies for roughly fifteen to twenty years, while battery units are most likely to maintain charge efficiencies for five to ten

years^{103,104}. To model somewhat conservative renewable technology lifespans, this investigation selected a 15-year replacement time horizon for the PV system and an 8-year replacement time horizon for the battery system. NREL's cost benchmarking reports for PV and storage technology provided projections on the cost fluctuations anticipated over the replacement timelines captured by these simulations. The NREL projection for residential solar on new construction under less aggressive timelines is a 39% reduction by 2030¹⁰⁵. NREL projects a 45% reduction in storage system costs over that same time horizon under the mid-range cost decline scenario¹⁰⁶. This investigation used mid-range, less-aggressive cost projections in PV and storage cost decline to incorporate more conservative costing mechanisms in financial analysis.

Given the variability in projected cost for the microgrid components considered in this analysis, simulating a range of scenarios was apposite to understanding the future potential of a project of this nature. To match the low, medium, and high cost projections presented by contributing resources, low, medium, and high cost scenarios were evaluated with the addition of a scenario that reflects low cost of energy technology investment with high renewables penetration. The low-cost scenario features a contributing construction cost of \$150 per square foot and \$271 per kWh of battery energy capacity with the Solar Equinox residential battery. The medium scenario has a respective construction and battery cost component of \$200 per square foot and \$310 per kWh for the LG Chem RESU, and the high cost scenario features \$250 per square foot and \$350 per kWh for the Tesla Powerwall. The low, medium, and high energy end-use consumption scenarios detailed earlier in this paper match the cost categorizations here.

The low component cost and high renewable penetration simulation was designed to reflect a scenario in which renewable energy technology is relatively inexpensive, but energy policy is favorable regarding renewable development incentives. This scenario pairs \$150 per square foot construction and \$271 per kWh with the high-capacity Tesla Powerwall under a medium energy end-use consumption profile. This scenario provides insight to the potential for a residential development to not only provide energy to the individual housing units, but also determine how much energy could be available to provide grid support under favorable legislative and market circumstances.

¹⁰³ Smith et al., "Life Prediction Model for Grid-Connected Li-Ion Battery Energy Storage System."

¹⁰⁴ Jordan and Kurtz, "Photovoltaic Degradation Rates-an Analytical Review."

¹⁰⁵ Cook et al., "Cost-Reduction Roadmap for Residential Solar Photovoltaics (PV), 2017-2030."

¹⁰⁶ Cole and Frazier, "Cost Projections for Utility-Scale Battery Storage."

Results

The results of this investigation were framed from two perspectives: benefit received by the end user, and the potential ability to recover costs for the developer. From the perspective of the end user, benefit is a function of the cost savings on grid purchase that result from operation of the PV and storage systems over the 25-year time horizon. The developer can expect to profit on a project depending on the occupation rates (i.e. rent) they are able to set for each residential unit. The comparison of net present costs (NPC) between the control case – each residential unit purchases all of their energy consumption needs from electricity and gas utilities – and the scenarios in which the residential units have access to renewable energy technology determine the financial benefit for the end user. The rate per residential unit required to meet the NPC for development of the entire community over the 25-year period reflects the earning potential for the developer.

In Raleigh-Durham, Los Angeles, and Charleston, more than half of electricity bill purchases were offset by investment in PV and storage technology in each community. Raleigh-Durham experienced a 64.15% average decrease across all scenarios, Los Angeles renewable energy investments decreased residential electricity bill by 65.4%, and Charleston saw a 67.89% decrease across all scenarios. The higher ToU rates in Raleigh-Durham and Los Angeles resulted in higher electricity bills year-round, with costs peaking in the summer months. Charleston followed a similar electricity bill peaking scheduling – rising in the summer months and falling again approaching winter – but as a result of the lower electricity rates in comparison to RDU and LAX, the electricity bills were lower on average. In the colder months of the year this suggested that the cost savings from PV and storage technology were not great enough to justify the expense, but the disparity between solar resource availability in the summer compared to the winter months supported much greater renewable technology utilization in the summer. In certain housing cases in the Charleston community during some monthly periods, PV and storage use decreased the spend on electricity purchased from the Grid by as much as 91%. Figure 7 illustrates the resulting electricity bill offset of a sample house, Residential Unit 14, in Charleston.

In Rochester, a combination of low electricity rates and lower solar resource availability resulted in Grid offsets that didn't hold the same financial motivation as the other three locations. Across

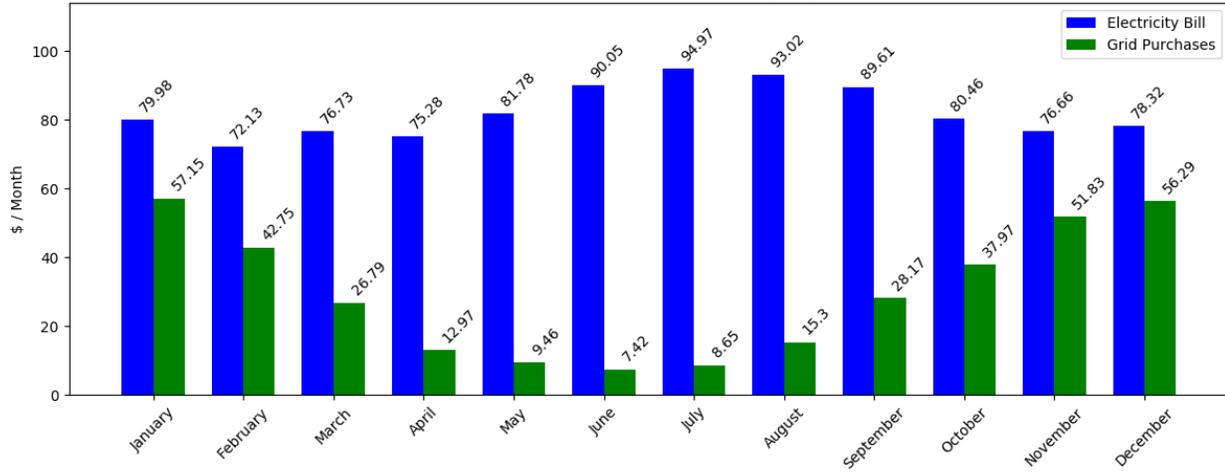


Figure 7: Sample Electricity Bill vs Purchases from the Grid with Solar + Storage for Residential Unit 14

all scenarios, investment in PV and storage technology reduced end user electricity bill spend by 45.27%, as much as 20% lower than the reductions experienced in the other locations. In addition, over the course of the year the electricity bill fluctuations between winter and summer months were not as pronounced: even with solar resource availability peaking in the summer, the corresponding electricity offset is not as stark. A complete breakdown of the changes experienced in average electricity bill spend relative to the control scenario for each community is listed in detail in Table 7 below.

Table 7: Cost Reduction of Solar + Storage Use Relative to Solely Grid Purchases (% Change)

Scenario	RDU	LAX	ROC	CRW
Low	-58.31%	-57.27%	-39.43%	-62.57%
Low – High Tech	-79.90%	-87.50%	-61.45%	-82.36%
Med	-57.75%	-55.84%	-39.11%	-61.96%
High	-60.63%	-61.01%	-41.09%	-64.67%

The NPC approach used in this investigation provided a convenient way to annualize the cost of PV and storage technology for each unit across the technology lifetimes: 15 years for PV and 8

years for storage. The addition of the PV and storage components of each development effectively acted as a rent premium at a set rate to pay off the system over the useful lifetime. Raleigh-Durham's highest annual spend scenario on renewable energy technology as a percentage of base case electricity purchases is the Low Cost – High Technology scenario at 2.49%, while its lowest percentage came from the Low scenario at 1.55%. Each location followed this delineation, a Low Cost – High Technology ceiling and Low-Cost floor for PV and storage annualized rate, but the ranges of each show the impacts renewable technology investment can have on the financial futures of residences.

Between these two scenarios that composed the upper and lower bounds of ratio of renewable energy to control case electricity spend, Los Angeles spent at most 2.08% and at least 1.55% of its control electricity bill on annualized PV and storage payments, Rochester spent 5.39% at most and 3.30% at least, and Charleston spent 3.70% at most and 2.32% on the lowest end. Given the narrow electricity bill payment relief experienced by residential units in Rochester and Charleston with PV and storage, these higher rates of annualized payments for renewable technology could eliminate any benefit received by lower electricity bills over time.

To that end, evaluating the net benefit to the end user over the complete time horizon was essential to understanding the benefit received by each community for investing in renewable energy technology. The NPCs for each unit and the entire community were compared across scenarios to determine which locations and scenarios received financial benefit as a result of the addition of PV and Storage. A complete breakdown of those results is illustrated in Table 8. Whether or not the community received benefit to the end user through the addition of PV and storage is recorded by a "Yes" or "No" and paired with a percentage that signifies the difference in cost savings relative to the control case; positive numbers indicate savings relative to purchasing energy from the Grid over the time horizon and negative numbers reflect additional spend over the Grid-only scenarios. Zeros indicate a difference that was less than a tenth of one percent.

Table 8: End User Benefit by Location and Cost/Building Scenario

Scenario	Raleigh-Durham, NC		Los Angeles, CA		Rochester, NY		Charleston, WV	
	End User Benefit?	% Difference	End User Benefit?	% Difference	End User Benefit?	% Difference	End User Benefit?	% Difference
Low Cost	Yes	3.30%	Yes	4.91%	No	-0.22%	Yes	1.49%
Low Cost - High Tech	Yes	4.18%	Yes	8.70%	No	-3.0%	No	0%
Medium Cost	Yes	4.48%	Yes	6.61%	No	-0.77%	Yes	1.80%
High Cost	Yes	2.07%	Yes	3.96%	No	-1.7%	No	0%

This analysis reveals a range of end-user outcomes across locations and scenarios. Rochester receives no financial benefit across any of the scenarios over the 25-year time horizon from investing in renewable energy technology. The rationale for this simulation’s results in Rochester is revealed by evaluating the individual units in other locations across scenarios. In Charleston, end users incur financial benefit in the Low Cost and Medium Cost scenarios: simulations with lower installed energy technology capacities relative to technology costs. When evaluating the NPC received by each individual unit, it becomes clear that whether or not the community receives financial benefit is driven by the number of high-energy-intense homes in the area. For example, Charleston’s Residential Unit 4 experiences added cost from renewable technology investment when compared to the control over the time horizon in the Medium Cost scenario by roughly 1.2%. Residential Unit 4 is 650 square feet and occupied by one individual.

These physical characteristics paired with a medium technological energy load results in a unit that uses 18.5 kWh on an average day over the course of the year. To put that in context, this same unit in Los Angeles with the same physical and energy use characteristics experiences cost savings over the time horizon by 5.4% when outfit with PV and storage. For Charleston’s larger and more energy intensive residences, however, the end user can expect to save over the time horizon. In the Medium Cost scenario, Residential Unit 17 receives a benefit of 2.4% in cost savings as a function of its larger size (1,350 square feet), high load categorization, and higher average daily energy use (46.9 kWh). This same unit experiences cost savings of 6.9% in LA.

The end user results suggest that electricity rates and end user energy intensity are the driving factors of the benefits received by residential renewable energy technology investment. Raleigh-

Durham and Los Angeles are both locations with a higher average electricity spend than either Rochester or Charleston, which drives the benefit received by the consumer. When evaluated on a residence-by-residence basis, it is clear that in order for an end user to experience any benefit in those locations with lower electricity rates and less variability in tiered pricing, they would have to be a high-use load with larger physical construction attributes. Lower solar resource availability as a factor of end user benefit from PV generation can also be overcome by rate structure and energy use intensity. That is to say this investigation suggests that in order to receive end user benefit in lower solar resource intense geographical regions, electricity rate structure and end user behavior dictate renewable energy investment outcomes.

Positive developer perspective on the viability of a project of this nature hinges on its ability to recover the cost from construction of such a community development. This cost recovery depends on the rate setting required to payback investment over the life of the project and whether that rate reflects competitive market value. To determine the total costs for the developments detailed in this analysis, this investigation determined the NPC for the developer incurred through initial upfront investment for construction and renewable energy technology, as well as predicted energy technology replacement according to the predetermined lifespans of PV and storage components.

The Medium Cost scenario set a benchmark for the financial reality of developer costs for a combined built infrastructure and energy development project. The combination of medium to high-use energy intensities and market-standard costing for technological components made it an ideal litmus test for development potential relative to the extreme scenarios across locations. Under the same financial parameters used for determining long-term cost considerations for the end-user – 15-year PV replacement, 8-year storage replacement, 25-year time horizon – the NPC analysis revealed that a developer can expect to pay approximately \$7,000,000 for a development of 30 residential units outfit with PV and storage components. Table 9 shows a financial breakdown of the monthly rates a developer would need to set to cover the cost of development over the time horizon and the cost of each unit for purchase by an end user.

Table 9: Projected Developer Cost and Recovery Rate Requirements in Medium Cost Scenario

Location	Total Developer Investment	Avg. Break-Even Rent	Avg. Break-Even Electricity Bill	Avg. Monthly Rate per Residential Unit	Avg. Total Cost Per Residential Unit
Raleigh-Durham	\$7,039,166	\$727.73	\$54.40	\$782.13	\$234,639
Los Angeles	\$7,071,186	\$727.73	\$57.96	\$785.69	\$235,706
Charleston	\$6,981,788	\$727.73	\$46.92	\$774.65	\$232,393
Rochester	\$6,991,313	\$727.73	\$49.08	\$776.81	\$233,044

As a baseline for expected costs, this analysis suggests there is some financial benefit for a developer in undertaking such a project. The U.S. national average for monthly rent in 2018 was \$1,405¹⁰⁷, though the median rental rates by location investigated in this analysis vary widely. Market comparisons for a one to two bedroom housing unit, which reflects the sizing of the residential units analyzed in this investigation, show that renters in Los Angeles can expect to pay an average of \$2,545¹⁰⁸, Rochesterians can expect to pay \$1,058 on average¹⁰⁹, renters in Raleigh-Durham would pay \$1,202 on average^{110,111}, and a renter in Charleston could set \$671 per month as a benchmark¹¹². Based on the rent required to recover costs revealed by this investigation’s simulations and the average rental rates exhibited by the markets in each of the evaluated locations, a developer can expect to be able to set competitive rates for new microgrid developments that both recover cost over the time horizon and generate profit.

The market viability for ownership of each residential unit based on the recovery rate for the developer is highly dependent on location. The Medium Cost scenario set the price per square foot of development at \$200 and pricing per square foot between the four states under investigation varies widely. The median price per square foot in West Virginia is \$98, North Carolina median housing sale price is \$135 per square foot, New York housing market sells at a

¹⁰⁷ Layne, “U.S. Housing Rents Hit Record-High Average of \$1,405 per Month.”

¹⁰⁸ RENTCafé, “Average Rent in Los Angeles & Rent Prices by Neighborhood.”

¹⁰⁹ RENTCafé, “Average Rent in Rochester & Rent Prices by Neighborhood.”

¹¹⁰ RENTCafé, “Average Rent in Raleigh & Rent Prices by Neighborhood.”

¹¹¹ RENTCafé, “Average Rent in Durham & Rent Prices by Neighborhood.”

¹¹² Salviati, “April 2020 United States Rent Report - Apartment List.”

median price of \$205 per square foot, and California housing listings set a median sale price of \$324 per square foot¹¹³. As discussed in the Modular Housing section of this paper, cost per square foot depends on design, transportation, oversight cost, and a host of other construction parameters, signaling that success in lower cost construction markets (e.g. West Virginia and North Carolina) hinges on cost minimization across the development pipeline.

Discussion

This program model offers useful insight into the range of considerations a developer might take in pursuing a microgrid development strategy that merges built infrastructure and renewable energy technology. Cost breakdowns and financial potential are the key components of investor interest in new projects and though the initial simulated outcomes reflect financial benefit for the end user and the developer, the model is only as good as its inputs. Future iterations of this investigative program should include more variability in residential load curve construction, increased sensitivity in community construction parameters, and more granular financial inputs that more accurately reflect real-world investment scenarios such as land prices, taxes, and the potential return on similar construction projects that omit any microgrid components.

The process of load curve construction in this investigation was limited by data availability. OpenEI provides data for sample houses in various locations as a representation of the average house, but doesn't provide categorical subsets of load curves. Future implementations of this analysis should include hour-by-hour load curve behavior differences across residential units in a given community. For example, understanding the interactions between homes in a community in which some people are home during the day and working at night rather than uniformity in a standard day-time work day would better inform PV sizing and storage charge behaviors to match realistic variability. Having several typical behavioral use cases for residential energy load over the course of a day would strengthen future programmatic sensitivity.

Though this investigation evaluates low, medium, and high construction cost scenarios, real-world development considerations rely heavily on materials used and site-specific characteristics. For this program to improve its utility in more realistic situations, construction

¹¹³ Hoffower and Brandt, "How Much It Costs to Buy a House in Every State, Ranked - Business Insider."

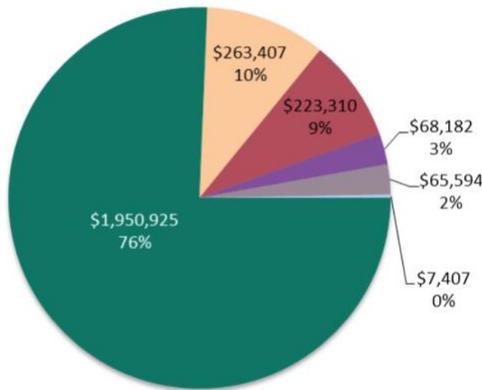
costs per square foot should be more directly dictated by construction materials used, site development preparation commonly experienced during new construction, and machinery and building component transportation. Additionally, consideration of some of the physical characteristics and limitations of electrical systems could be added to inform additional community power system attributes. Ensuring distribution systems can handle the power flow required to meet community needs and potential orchestration of power sharing would further improve the financial viability of development and benefits incurred by the end user.

Financial outputs for investors and end users would also benefit from an analysis of different time horizons, technological lifespans, and future cost decreases in technological components. This financial analysis held each of the aforementioned parameters static, but future financial programming should evaluate the cost and investment threshold over different timelines with a variety of cost projection considerations.

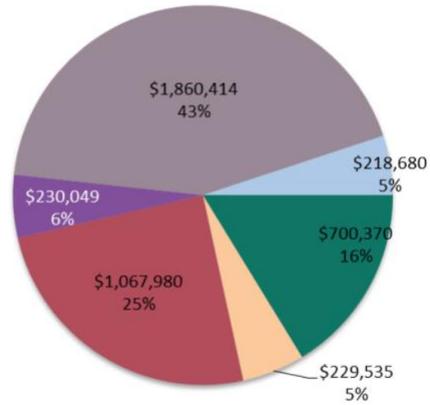
This investigation ultimately reveals that there may be financial benefit for developers to consider new construction beyond simple residential construction. Pairing renewable energy technology with new built infrastructure could generate long-term value for end-use consumers, give more people flexibility in how they would like to engage in electricity consumption with regard to generator type, create profitable projects for a firm's development portfolio, and inspire new mechanisms to support the Grid. Moving forward, future investigations of this nature should consider partnering with firms to process information and data that more accurately reflects real world scenarios. This investigation has undergone a generalizable process that incorporates sensitivity analysis into certain parts of its model structure, but would benefit substantially from a higher degree of specificity. Expanding on this program to accept user input may also provide a means to record and analyze end-user behavior. Engaging individuals and families through survey methods would be a functional avenue for passing data through the program that more accurately reflects realistic scenarios. Further programmatic improvements would ultimately strengthen this model's use as a tool and reveal additional business opportunities for developers while enhancing the potential for greater end-user benefit.

Appendix A: Total Microgrid Cost per MW Across Use Cases

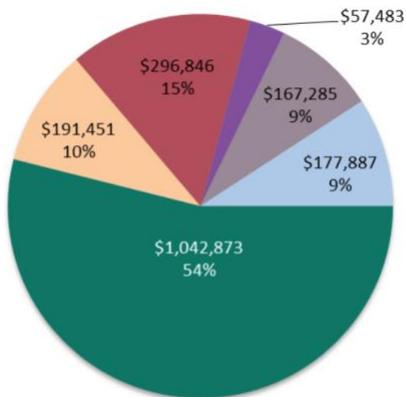
Campus/Institutional - Cost per MW by Component



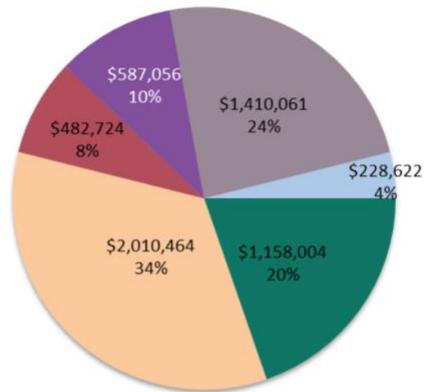
Commercial/Industrial - Cost per MW by Component



Community - Cost per MW by Component



Utility - Cost per MW by Component



■ Conventional Generation
 ■ Renewable Generation
 ■ Energy Storage
■ Controls
 ■ Soft Costs
 ■ Additional Infrastructure

Source: 114

114 Giraldez Miner et al., "Phase I Microgrid Cost Study."

Appendix B: Building Specifications for OpenEI Base Load Datasets

Selected Building Fuel Types					
	Very Cold/Cold	Mixed-Humid	Mixed-Dry/Hot-Dry	Hot-Humid	Marine
Space Heating	Natural Gas	Natural Gas	Natural Gas	Electric	Natural Gas
Air Conditioning	Yes	Yes	Yes	Yes	No
Water Heating	Natural Gas	Electric	Natural Gas	Electric	Natural Gas

Source: OpenEI Residential Load Datasets

Selected Building Structure Types					
	Very Cold/Cold	Mixed-Humid	Mixed-Dry/Hot-Dry	Hot-Humid	Marine
Total Size (ft. ²)	2696	2546	2000	2023	2090
Urban and Rural	Urban	Urban	Urban	Urban	Urban
Metropolitan and Micropolitan	Metro	Metro	Metro	Metro	Metro
# of Floors	1 Story	1 Story	1 Story	1 Story	1 Story
Major Outside Wall Material	Siding (Aluminum, Vinyl, Steel)	Siding (Aluminum, Vinyl, Steel)	Stucco	Brick	Wood
Major Roofing Material	Ceramic or Clay Tiles	Ceramic or Clay Tiles	Ceramic or Clay Tiles	Ceramic or Clay Tiles	Ceramic or Clay Tiles
Foundation/Basement	Basement	Concrete Slab	Concrete Slab	Concrete Slab	Crawlspace
Bedrooms	3	3	3	3	3
Full Bathrooms	1	1	2	2	1
Half Bathrooms	None	None	None	None	None
Basement Single-Family Homes	Yes	No	No	No	No
Finished Basement	No	N/A (No Basement)	N/A (No Basement)	N/A (No Basement)	N/A (No Basement)
Type of Glass in Windows	Double-Pane Glass	Double-Pane Glass	Single-Pane Glass	Single-Pane Glass	Double-Pane Glass

Source: OpenEI Residential Load Datasets

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