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Low Cost Community Microgrids by Efficiency and Reduced Availability

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ABSTRACT

The climate crisis currently being faced by humanity is going to increase extreme weather events which are likely to make long-duration power outages for communities increase in frequency and duration. Microgrids are an important part of electrical resilience for connected communities during power outages. They also can have transactive potential to save energy on electric loads through coordinating distributed energy resources. Microgrids are expensive though. Making electric load coverage available nearly 100% of the time given known design basis threats and component failure statistics is one of the largest drivers of cost. Such high availability is non-negotiable for critical applications such as life saving equipment in a hospital but could perhaps be compromised for less critical loads. . This paper documents an analysis that used the Microgrid Design Toolkit and EnergyPlus simulation results with two energy retrofit options exercised. The results show how increasing energy efficiency and reducing availability to 90% and 80% reduced the calculated price of a photovoltaic and battery storage microgrid in a New Mexico neighborhood by 63% and 70%, respectively. A microgrid with 80% availability with 48-hour islanded run-time capability is therefore suggested as a low-cost method for accelerating microgrid infrastructure penetration into the residential sector. Such an "under-built" microgrid will significantly increase resilience even though it will not guarantee energy security for the non-critical applications in residential households. This will in turn accelerate the growth of storage potential across communities providing greater grid flexibility. The results of the study also show how increased insulation applied to the proposed residential community can be less expensive than creating a larger microgrid that carries larger electric loads. The likelihood that energy retrofits are a better investment than a larger microgrid is inversely proportional to availability. Here, availability is a metric equal to the percentage of the demand load served by the microgrid during power outages, not including the startup period.

INTRODUCTION

The present climate crisis requires significant efforts to reduce greenhouse gas (GHG) emissions to mitigate increases in frequency, intensity, and duration of extreme temperature, precipitation, hurricanes, and fires (IPCC, 2021). Such efforts to mitigate anthropogenic effects on climate change must also be accompanied by adaptations (ASHRAE, 2021) in energy infrastructure that increase resilience to extreme events to decrease human suffering and death due to climate change (Vicedo-Cabrera et. al. 2021). Microgrids are a technology that may be a significant part of both climate change mitigation and adaptation. Microgrids do not necessarily provide energy efficiency (EE) for GHG reductions but do give the capacity for innovative, higher resolution control that have large EE potential. For adaptation, islandable microgrids (Petrelli et. al., 2021; Mathiesen et. al., 2021; Broderick et. al., 2021; Dagar et. al., 2021; Kwasinski et. al., 2012) are a key to a more resilient future for power infrastructure (Jeffers et. al., 2020). Unfortunately, microgrids are

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costly and have so far mostly been applied to high consequence applications such as hospital life support (NFPA, 2021) and military command centers (Booth et. al., 2020). Also, these applications are highly dependent on fossil fuels with 60% of 461 microgrids across the U.S. having some dependence on fossil fuel where 45% of generation is dependent on fossil fuels, 10% on renewables 42% on Combined Heat and Power (CHP), and 24% unknown according to the U.S. Department of Energy (DOE) CHP Microgrid Database (CHP-MG-DB, 2021).

The critical missions already serviced by microgrids must not be compromised because human life is likely to be lost should they fail. Therefore, they are created to be available 99-99.99% over the required outage operation time. Here, availability is a metric equal to the percentage of the load energy demand served by the microgrid during power outages, not including the startup period. For example, the 2017 U.S. Navy requirement is 99.9886% availability (Booth et. al., 2020 page 2). This availability must be maintained across the range of Design Basis Threats (DBT) considered in microgrid design. DBTs are events that could disrupt or disable microgrid operations. DBTs can be divided into naturally caused events (Kwasinski et. al., 2012) and human-induced events. Naturally caused DBT include events like earthquakes, hurricanes, tornadoes, and heat waves. Human-induced DBTs include physical attacks, cybersecurity breaches (Gaggero, et. al., 2021), and human errors (Wicaksana et. al., 2021).

Unlike critical applications, the residential sector is likely to cause inconvenience should a microgrid fail during a DBT. This reduction of consequence also makes 100% renewable energy with relatively limited storage a more probable solution. Also, cost is the bottom line for residential developers instead of certainty of operations. This makes implementation of microgrids require a profit on investment. This constraint makes cost reduction the primary barrier for microgrids in the residential sector. One way of reducing costs is to reduce the requirements typical for microgrids for critical loads. A reduction in the duration a microgrid can remain operational and the average availability during that duration for expected DBT's is therefore a good strategy for reducing costs.

Satistics from the United States Energy Information Administration (EIA) on outages indicate that a time duration of 48 hrs will overcome problems for the great majority of outages (EIA, 2018). The Institute of Electrical and Electronics Engineers provide standards for two indices for duration and frequency of outages called 1) The System Average Interruption Duration Index (SAIDI) and the System Average Interruption Frequency Index (SAIFI). SAIFI is defined as the total number of customer interruptions divided by the total number of customers served. SAIDI is defined as the sum of all customer interruption durations divided by the total number of customers served. In 2018 NM had SAIFI ranging from 0.574 to 3.82. SAIDI ranged in 2018 from 12 min to 763 min. This data indicates that 48 hr is well above the average consumers power interruption duration. It should be noted that the data surveyed here do not help indicate what kind of major interruptions are likely to occur to the grid in the future. As a result, this study analyzes a microgrid applied to a planned NM neighborhood that is designed to have storage and generation capacity for 48 hr. This number is intended to be significantly below critical load requirements such as in 1) the Occupational Safety and Health Administration (OSHA) and National Fire Protection Association (NFPA) requirement of 96 hr for hospitals (NFPA, 2021) or 2) the U.S. Department of Homeland Security Federal Emergency Management Agency's Federal Continuity Directive 1 which requires 720 hr for critical loads (DHS, 2017).

A target for availability was harder to justify. This work proposes 80% availability loosely based on the 80-20 rule or "Pareto principle" (Wikipedia, 2021) where it is assumed the majority of resilience problems are solved by a system with less availability. Here, the scale is not linear and 80% availability represents reaching the 20% threshold of cost input that produces 80% of possible increases to resilience while critical application availabilities such as 99.9% represents the remaining 80% of costs that only produces 20% more increase of resilience. This paper tests the hypothesis that these loosened requirements (80% availability for 48 hr) will reduce microgrid price significantly while greatly increasing resilience of a neighborhood with no microgrid Such a 48 hr window will eliminate almost all normal power outages.

The New Mexico neighborhood analyzed will be constructed on the west side of Albuquerque (latitude = 35.17, longitude = 106.71) on 11.2 acres (4.5 hectares). Tentative plans hope to make the community fully connected with a DC microgrid, micro-water network, and thermal bridge between the triplex units. The compact development will consist of 100 passive-solar triplexes, broken into 5 phases of construction of 20 triplexes each. Besides rooftop space, additional land is available for renewables, battery storage, and micro-network infrastructure with access to the community through a service entrance that doesn't require entering the neighborhood. Each 1000 ft^2 (93 m^2) unit will have low-e window glazing and high-quality continuous insulation to eliminate thermal bridges. They will feature tile or brick floors and internal courtyards to create thermal sinks that dissipate summer heat to reduce peak air-conditioning loads to less than 1-ton (3.5 kW) per triplex unit.

METHODS

The study combined results from the EnergyPlus (DOE, 2021; Mazzeo et. al., 2020) residential multi-unit proto-type models with an analysis using the Microgrid Design Toolkit (MDT) (Hossain-McKenzie et. al., 2019; Suk and Hall, 2020; Eddy and Gilletly, 2020). For EnergyPlus, the residential multi-unit prototype models (DOE, 2020) with the following attributes were used: 1) On-slab; 2) Electric heating (EL), air-source heat pump (HP), or natural gas configurations (NG); 3) American Society for Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) climate Zone 4B (ASHRAE, 2013); and 4) Meet the 2018 International Energy Conservation Codes (IECC, 2018). These models were altered from the Baseline (BL) EnergyPlus models into two new configurations to evaluate the microgrid cost effects for EE measures: 1) Maximum Insulation (MI) and 2) Maximum Insulation with limited HVAC (ML). The cases are described in detail in Table 1 and are included to provide tradeoff between microgrid Distributed Energy Resource (DER) investment and building energy retrofits (Stadler et. al., 2014). Typical Meteorological Year Revision 3 (TMY3) data for the Albuquerque airport was used in the analysis (Wilcox and Marion, 2008). A neighborhood scale result was obtained by linearly scaling the square footage of the model to the scale of the neighborhood.

The MDT software takes a novel approach in comparison to other tecnoeconomic microgrid analysis tools (Cuisinier et. al., 2020; Suk and Hall, 2020). MDT allows a user to input 1) Electric loads, 2) Generation Assets, 3) DBTs, 4) Optimization parameters, and 5) Reliability definitions. It enables development of complex networks of electric grid elements such as busses, transformers, and switches connected to electric loads driven by buildings or other infrastructure. These elements can be fixed or can be made to include many design alternatives. For example, a generation node can be given the option of having generation from several different technologies and amounts of each technology deployed. Another node can be a single unaltered electric component such as a transformer. All combinations of design alternatives in MDT provides a search space to evaluate cost to implement a microgrid versus its performance. To accomplish this, MDT has two loops. The first loop iterates through potential designs. The second loop simulates each design for thousands to hundreds of thousands of years to properly characterize the effects low-frequency DBT events or combinations of reliability failures can have on the system.

Table 1 EnergyPlus Run Cases

Case	Description	Peak Load	Annual Load
1. Baseline (BL)	Multi-unit DOE residential proto-type climate Zone 4B IECC 2018 on-slab, with 1) electric heat and conventional air-conditioning 2) heat pump, 3) natural gas and conventional air-conditioning.	148-249 kW [505-850 kBTU/hr]	560-942 MWh [1912-3216 MMBTU]
2. Maximum Insulation (MI)	BL with 1) 100 R (17.6 RSI) insulation added to all opaque surfaces 2) All window's changed U-factor from 0.32 to 0.053 $Btu/hr \cdot ft^2 \cdot {}^oF$ (1.82 to 0.3 $W/m^2/K$) 3) Infiltration reduced by 75%	134-177 kW [457-604 kBTU/hr];	608-883 MWh [2075-3013 MMBTU]
3. Limited HVAC and Maximum Insulation (ML)	MI with a thermo-stat range widened to -40°F (-40°C) to 104°F (40°C) to keep HVAC off most of the time. Investigation showing HVAC still operating at a couple of times for non-thermostat related control issues.	108-159 kW [369-543 kBTU/hr]	481-768 MWh [1641-2621 MMBTU]

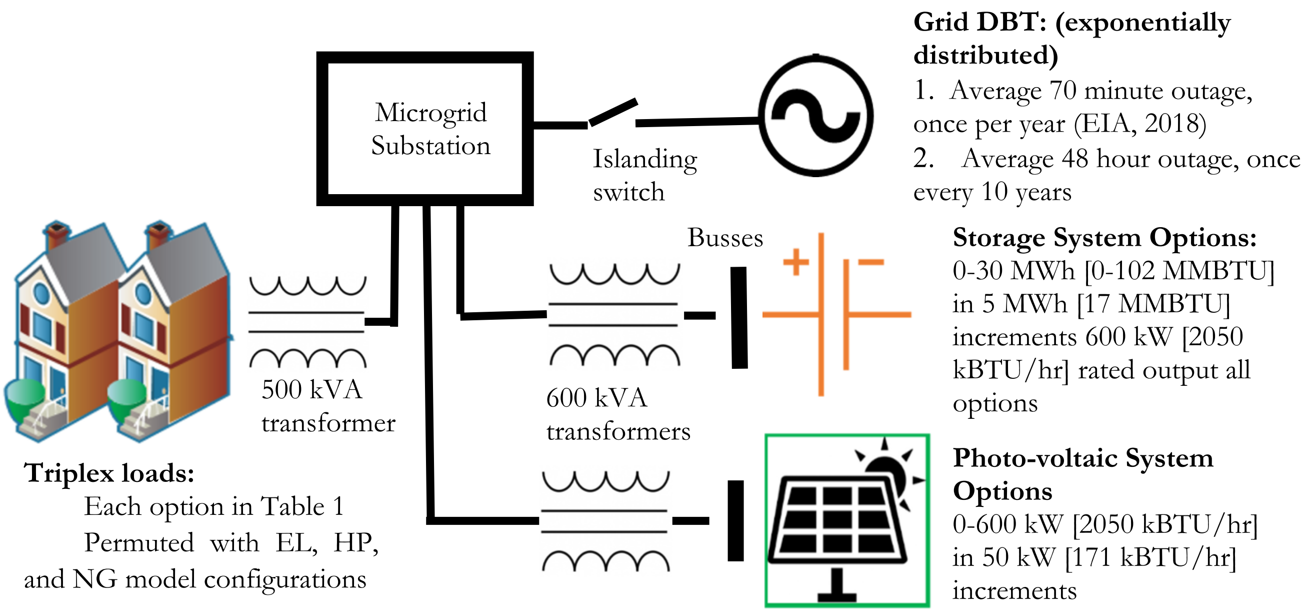

Figure 1 Microgrid analysis specifications and layout

The comprehensive treatment of normal operating conditions (bluesky) and DBT conditions (blacksky) coupled to weather, reliability, and maintenance inputs makes MDT have the potential to fully optimize resilience metrics versus cost.

In this analysis, a minimalistic microgrid was used that provides islanding capability. The basic design is shown in Figure 1 which shows the DBTs and design alternatives provided. Only Battery Energy Storage (BES) and amount of Photo-Voltaic (PV) power were explored over each triplex load case (Table 1). The cost and reliability of the system were characterized by Mean Time Between Failures (MTBF) and Mean Time To Repair (MTTR). These failure rates were assumed to have an exponential distribution. The inputs are shown in Table 2.

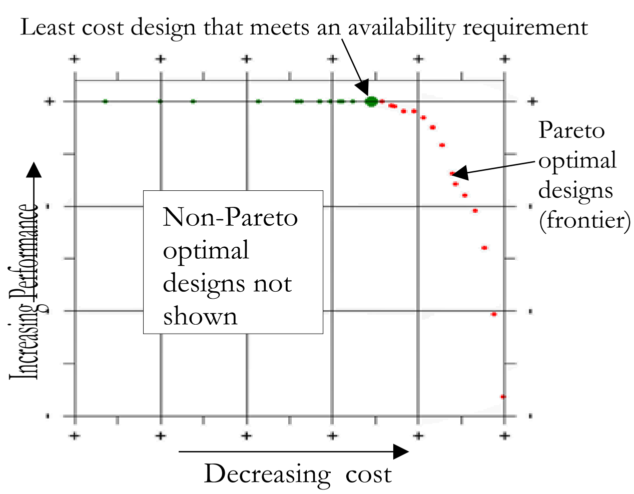

Figure 2 MDT Pareto front least cost design that meets availability constraint (large green circle)

The best designs form a Pareto frontier (Cui et. al., 2017) which represents the best case trade-offs between cost and availability. Figure 2 shows one of the resulting Pareto frontiers used in this analysis and the corresponding large green dot marks the least cost design that has greater than 80% availability. Many of the designs evaluated by MDT are not Pareto optimal and are not shown in Figure 2.

The PV generation profile was approximated using the National Renewable Energy Laboratory (NREL) PVWatts calculator (PVWatts, 2020). For this load profile, the DC system size was set to 300 kW (1024 kBTU/hr) with 15% nominal efficiency, 30° fixed-tilt south facing (180° azimuth angle), with a 1:1 DC-to-AC size ratio. The 1:1 DC-to-AC size ratio simplification is appropriate here because all designs would share the same kinds of inefficiencies making relative comparisons between costs unaltered in this study. More detailed analyses of microgrids would need to consider the details of the electric design though. PVWatts uses different weather data than TMY3 leading to possible asynchronization of weather boundary conditions. However, the overall seasonal and daily variations are captured. This is not a concern for the stochastic nature of this analysis though. It is assumed that geographic smoothing between system sizes is negligible so the same normalized PV profile can be scaled to each size of PV farm being evaluated by MDT. The total simulation length on each MDT design alternative was confined to 1000 1 year simulations to produce the lowest cost cases. This number captures the 1 in 10 year 48 hr outage event 100 times on average which should provide reasonable statistics on the low frequency events for each microgrid design.

Table 2 Cost and Reliability Inputs

Case	MTBF(hr)	MTTR (hr)	Cost	Source
PV	8468	55	1130 $/kW [331.2 $/(kBTU/hr)]	Failure: Oozeki, 2007; Cost: NREL, 2018
BES	8468	55	380 $/kWh [111.3 $/kBTU]	Failure: Oozeki, 2007*; Cost: Cole, 2019

*Feasible failure rates for BESS were not found for the systems of interest in this study, so the same failure rates for PV were used. While this is less than ideal, the significance of this assumption was tested and found to have a maximum change in availability of 7% for ±50% variation in the MTBF. This sensitivity was less than that for random variation in the results caused by MDT's statistical sampling algorithms. The influence of this assumption is therefore deemed to be acceptably small.

RESULTS AND DISCUSSION

The 9 EnergyPlus model results load profiles for the TMY3 weather are shown in Figure 3. These profiles were used in MDT whose solutions were tracked at 80%, 90% and 99% availability on the Pareto optimal set of designs. Of the thousands of microgrid designs analyzed, this leads to 27 optimal designs (9 load cases x 3 availability levels) from the MDT analysis. These designs are shown in Table 3. The first column contains the case identifier. Each case includes a combination of the EnergyPlus model configuration (Table 1: BL, MI, ML), the HVAC technology (EL, HP, NG), and the target level of availability (80%, 90%, 99%). The closest design on the Pareto front to the target availability was selected because MDT did not solve for the target availability exactly. The second and third columns of Table 3 contain the annual peak load and total power predicted by EnergyPlus. The 4th and 5th columns contain the availability and cost data. Finally, the last three columns contain the specifications for the microgrid sizing.

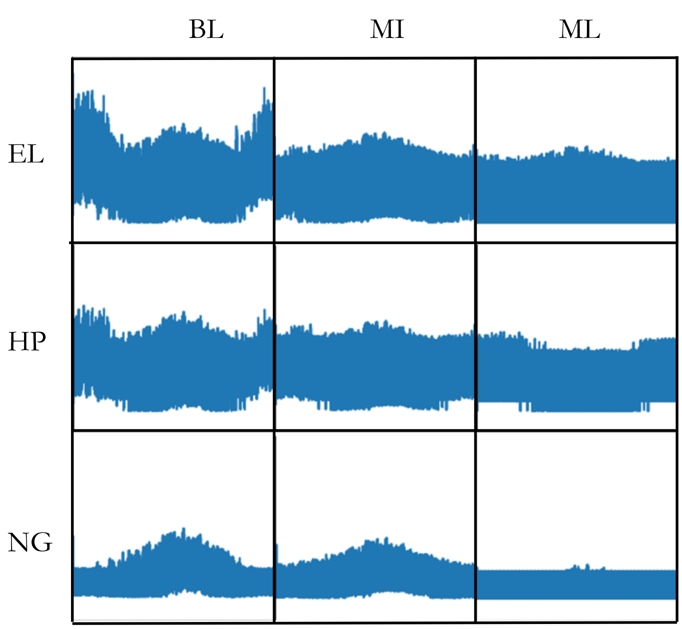

Figure 3 EnergyPlus hourly total energy for the 9 profiles. X axis ranges from hour 1 to hour 8760 of the year and the y axis ranges from 0 to 300 kWh/hr (1023 BTU/hr)

Interpolation of the splines fit to the results show that reducing availability has the strongest affect on price compared to increasing insulation or limiting HVAC. For example, the BL EL case has 50% cost savings from 90% availability to 99% availability and 64% cost savings for 80% availability. Including insulation further increased the cost savings to 63% and 70%. Finally, reducing HVAC increased the cost savings to 67% and 74%. This shows that decreasing availability is the best option in this study for reducing costs. The other cases can be computed using points picked from Figure 4.

The availability versus cost is plotted in Figure 4 where pairs of three points with common model configuration and HVAC technology are connected by spline fits. The relationship between cost and availability is clearly nonlinear with much more significant increases in cost from 90% to

99% in comparison to 80% to 90%. This nonlinear effect is much less pronounced for the NG cases though because an alternate source of energy is available for heating making the probability of not meeting the load much smaller. The colors and line style of each case are designed to make it easier to compare different cases. Looking at all three cases of a single color shows a comparison between the effectiveness of different HVAC technologies for constant model configuration. Doing this clearly illustrates that, for the BL case, HP is slightly better than EL but that adding maximum insulation (MI) reverses this effectively making investment in a heat pump less desirable.

Table 3 Baseline Study Results

Case	Annual Peak Demand (kW) [kBTU/hr]	Total Annual Power (MWh) [MMBTU]	Availability (%)	Purchase Cost (Million USD)	PV Generation (kW) [kBTU/hr]	Battery Storage (kWh) [kBTU]	Total Generation Capacity (kW) [kBTU/hr]
BL EL 80%	248.6 [848.3]	942.2 [3214.9]	81.11%	1.02	400 [1364.9]	1500 [5118.2]	1000 [3412.1]
BL HP 80%	201.5 [687.5]	892.7 [3046.0]	81.22%	1.02	400 [1364.9]	1500 [5118.2]	1000 [3412.1]
BL NG 80%	147.7 [504.0]	559.8 [1910.1]	83.37%	0.66	250 [853.0]	1000 [3412.1]	850 [2900.3]
MI EL 80%	177 [603.9]	835.6 [2851.2]	80.65%	0.83	400 [1364.9]	1000 [3412.1]	1000 [3412.1]
MI HP 80%	177.3 [605.0]	883.3 [3013.9]	80.35%	0.95	500 [1706.1]	1000 [3412.1]	1100 [3753.4]
MI NG 80%	134.3 [458.3]	608 [2074.6]	84.76%	0.72	300 [1023.6]	1000 [3412.1]	900 [3070.9]
ML EL 80%	154.6 [527.5]	712.1 [2429.8]	82.70%	0.78	350 [1194.2]	1000 [3412.1]	950 [3241.5]
ML HP 80%	158.9 [542.2]	768 [2620.5]	80.29%	0.83	400 [1364.9]	1000 [3412.1]	1000 [3412.1]
ML NG 80%	107.4 [366.5]	481 [1641.2]	82.65%	0.61	200 [682.4]	1000 [3412.1]	800 [2729.7]
BL EL 90%	248.6 [848.3]	942.2 [3214.9]	92.84%	1.63	600 [2047.3]	2500 [8530.4]	1200 [4094.6]
BL HP 90%	201.5 [687.5]	892.7 [3046.0]	90.62%	1.33	500 [1706.1]	2000 [6824.3]	1100 [3753.4]
BL NG 90%	147.7 [504.0]	559.8 [1910.1]	90.15%	0.89	450 [1535.5]	1000 [3412.1]	1050 [3582.7]
MI EL 90%	177 [603.9]	835.6 [2851.2]	90.58%	1.08	450 [1535.5]	1500 [5118.2]	1050 [3582.7]
MI HP 90%	177.3 [605.0]	883.3 [3013.9]	91.27%	1.27	450 [1535.5]	2000 [6824.3]	1050 [3582.7]
MI NG 90%	134.3 [458.3]	608 [2074.6]	93.34%	0.97	350 [1194.2]	1500 [5118.2]	950 [3241.5]
ML EL 90%	154.6 [527.5]	712.1 [2429.8]	93.04%	1.02	400 [1364.9]	1500 [5118.2]	1000 [3412.1]
ML HP 90%	158.9 [542.2]	768 [2620.5]	91.80%	1.08	450 [1535.5]	1500 [5118.2]	1050 [3582.7]
ML NG 90%	107.4 [366.5]	481 [1641.2]	90.64%	0.66	250 [853.0]	1000 [3412.1]	850 [2900.3]
BL EL 99%	248.6 [848.3]	942.2 [3214.9]	98.06%	2.58	600 [2047.3]	5000 [17060.7]	1200 [4094.6]
BL HP 99%	201.5 [687.5]	892.7 [3046.0]	98.62%	2.58	600 [2047.3]	5000 [17060.7]	1200 [4094.6]
BL NG 99%	147.7 [504.0]	559.8 [1910.1]	99.24%	1.44	600 [2047.3]	2000 [6824.3]	1200 [4094.6]
MI EL 99%	177 [603.9]	835.6 [2851.2]	99.25%	2.01	600 [2047.3]	3500 [11942.5]	1200 [4094.6]
MI HP 99%	177.3 [605.0]	883.3 [3013.9]	99.18%	2.58	600 [2047.3]	5000 [17060.7]	1200 [4094.6]
MI NG 99%	134.3 [458.3]	608 [2074.6]	99.09%	1.44	600 [2047.3]	2000 [6824.3]	1200 [4094.6]
ML EL 99%	154.6 [527.5]	712.1 [2429.8]	99.16%	1.44	600 [2047.3]	2000 [6824.3]	1200 [4094.6]
ML HP 99%	158.9 [542.2]	768 [2620.5]	99.40%	2.14	550 [1876.7]	4000 [13648.6]	1150 [3924.0]
ML NG 99%	107.4 [366.5]	481 [1641.2]	99.43%	1.16	350 [1194.2]	2000 [6824.3]	950 [3241.5]

Key: BL = baseline, MI = max insulation, ML = max insulation + limited HVAC, EL=electric heating with conventional air conditioning, HP = air-source heat pump, NG = natural gas with conventional air-conditioning

The results also illustrate that there is a complex tradeoff between availability, EE, and microgrid cost. Looking at the same linestyle on Figure 4 provides a comparison of how MI and ML affect a constant HVAC technology in comparison to BL. Such comparisons show that, depending on the technologies being used, investment in EE measures could be of greater value than investment in more renewables. For example, the EL 99% cases indicate that MI can reduce microgrid costs by 27.5% (0.75 Million USD) through reduction in the amount of BES that have to be installed. For EE by MI to be more competitive in these conditions, costs for additional insulation beyond IECC 2018 must be less than 2.5 USD/ft^2 (27 USD/m^2) floor space which is a competitive possibility in current cost markets per the National Residential Efficiency Measures Database (NREMD, 2021) where adding R15 (2.6 RSI) to walls costs on average 2.2 USD/ft^2 (24 USD/m^2) per square foot of exterior wall. Assuming a 60 ft (18.3 m) by 50 ft (15.2 m) triplex with 12 ft (3.7 m) walls, this means that the walls require a total of 2640 ft^2 per triplex producing and equivalent cost of 1.94 USD/ft^2 (20.88 USD/m^2) floor space. Adding roof insulation and a radiant barrier cost on average 0.43 USD/ft^2 of roof and 2.7 USD/ft^2 for an additional R19 (3.4 RSI) of fiberglass fill-in insulation. This totals to an approximated 5.07 USD/ft^2 to insulate the triplexes. If only first costs are considered, this would leave increasing insulation as a poor choice. The lifetime of the insulation technologies is often on the order of the lifetime of the building though (NREMD, 2021) whereas the life-time of battery technologies are 2500-5000 cycles equivalent to about 7-14 years depending on how the batteries are cycled (Lin et. al., 2019; Jiménez et. al., 2018). Both insulation and batteries have performance degradation that have to be considered as well. Regardless, this discussion has shown the intricacies of the tradeoffs between EE measures and microgrid capacity. For the lower availability cases, the benefits of insulation shrink to 0.6 Million USD and 0.3 Million USD for 90% and 80% availability respectively. These benefits make it much less feasible that EE would outweigh the benefits of having more batteries available for storage. We therefore conclude that EE is most likely to outcompete microgrid capacity sizing when high availability is needed. Finally, it is noteworthy that the NG cases have the least cost but have the undesirable side-effect of burning fossil fuels. Though not accounted for, carbon taxes in the future could add costs not included in this study (Baratsas et. al., 2022; Roth et. al., 2020).

The results are clearly too granular for several of the cases including for HP vs. EL where the microgrid design was the same even though peak load and total annual power were significantly different. Future work will need to refine the MDT analysis to include more designs than those specified in Figure 1 as a result. It would also enhance the study if many more availabilities were evaluated so that the spline fits could be replaced with more accurate regressions. Regardless, the results clearly demonstrate the main hypothesis of this work—that reducing availability can drastically reduce the cost of microgrids.

CONCLUSION

The results of this study show an example of how reducing availability for a community residential microgrid can reduce costs significantly. A strong nonlinear relationship between availability and cost is seen in Figure 4 for a range of EnergyPlus model configurations and HVAC technologies (Figure 4). From these results, an 80% availability over 48 hours is suggested as an approach that is a good compromise between cost and resilience. Such low-cost residential microgrids can complement increasing willingness of residents to pay for resilience services (Hotaling et. al., 2021; Baik et. al., 2020). Adopting such an approach may provide a basis for increased deployment of microgrid technology for residential communities such that grid services from non-utility installations can be a significant part of the future smart grid. Such an approach will diversify the methods used to meet clean energy acts such as the New Mexico Clean Energy Act (Senate Bill 489, 2019). Correspondingly, low-availability, low-cost microgrids can provide a way for residential connected communities that have increased potential for load sharing and community EE measures through higher resolution control of the community. Finally, the 80% availability over 48 hours approach makes it much more feasible to implement microgrids that are fully renewable.

The study also shows how EE can reduce the cost of a microgrid showing that investments should always consider the cost of DER's vs. EE. The resulting complexity is made apparent by the results of this study. It is important that analyses like this one be conducted as smart grid initiatives develop so that a well-balanced approach between EE and other DER's is taken. Also, analyses of this type that combine microgrid and building energy modeling need to become standard practice as the nexus between EE and resilience becomes increasingly important because of the present climate crisis. Finally, the limited HVAC case shows how microgrid cost could be reduced by load shedding if cooling and heating were placed on tiered circuits similar to the work of Wang et. al. (2021).

Continuation of this research should include running MDT with a finer resolution to provide a more continuous Pareto front and detailed EnergyPlus modeling of the actual triplex design in place of the DOE multi-unit proto-type. The EE work needs to be expanded to look at costs of EE, and engineering economic analysis needs to be conducted to account for the net present value of reoccurring costs for both EE and microgrid issues.

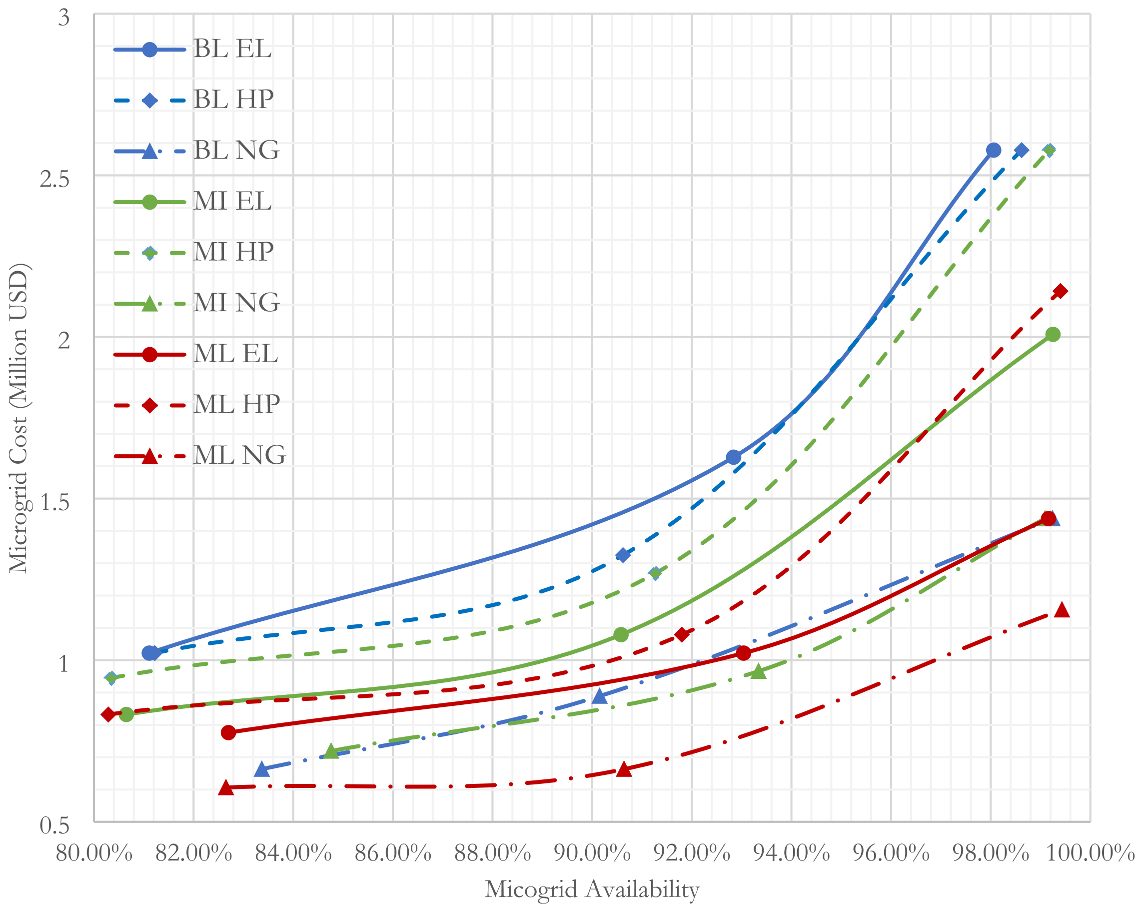

Figure 4 Microgrid cost vs. availability for HVAC and EE measure configurations

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