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Microgrid Tiered Circuits Effects for a Planned Housing Community in Puerto Rico

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ABSTRACT

Puerto Rico faced a double strike from hurricanes Irma and Maria in 2017. The resulting damage required a comprehensive rebuild of electric infrastructure. There are plans and pilot projects to rebuild with microgrids to increase resilience. This paper provides a techno-economic analysis technique and case study of a potential future community in Puerto Rico that combines probabilistic microgrid design analysis with tiered circuits in building energy modeling. Tiered circuits in buildings allow electric load reduction via remote disconnection of non-critical circuits during an emergency. When coupled to a microgrid, tiered circuitry can reduce the chances of a microgrid's storage and generation resources being depleted. The analysis technique is applied to show 1) Approximate cost savings due to a tiered circuit structure and 2) Approximate cost savings gained by simultaneously considering resilience and sustainability constraints in the microgrid optimization. The analysis technique uses a resistive capacitive thermal model with load profiles for four tiers (tier 1-3 and non-critical loads). Three analyses were conducted using: 1) open-source software called Tiered Energy in Buildings and 2) the Microgrid Design Toolkit. For a fossil fuel based microgrid 30% of the total microgrid costs of 1.18 million USD were calculated where the non-tiered case keeps all loads 99.9% available and the tiered case keeps tier 1 at 99.9%, tier 2 at 95%, tier 3 at 80% availability, with no requirement on non-critical loads. The same comparison for a sustainable microgrid showed 8% cost savings on a 5.10 million USD microgrid due to tiered circuits. The results also showed 6-7% cost savings when our analysis technique optimizes sustainability and resilience simultaneously in comparison to doing microgrid resilience analysis and renewables net present value analysis independently. Though highly specific to our case study, similar assessments using our analysis technique can elucidate value of tiered circuits and simultaneous consideration of sustainability and resilience in other locations.

INTRODUCTION

The current climate crises (UN, 2022; IPCC, 2021; Willis et. al., 2022; ASHRAE, 2021) is increasing the urgency to adapt infrastructure systems to Earth's changing climate. This is not only based on hypothetical future events. Puerto Rico faced a double strike from historically record-breaking hurricanes Irma and Maria in 2017 resulting in the longest disaster response recovery in the history of the United States (Sayers et. al., 2022). As a result, significant efforts are being made to assure that Puerto Rico's infrastructure will be more resilient in the future. Creating distributed, renewable, electric microgrids

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that can function on their own if a power outage happens (Petrelli et. al., 2021; Mathiesen et. al., 2021; Broderick et. al., 2021; Dagar et. al., 2021; Kwasinski et. al., 2012) can be a way to increase the probability that Puerto Rico's electric infrastructure will retain critical functions during future disasters. Even so, such microgrids are expensive additions relative to the cost of current electrical systems. This makes methods for reducing costs of microgrids worth investigating.

As a result, this study investigates whether tiered circuits in buildings can reduce microgrid costs. This paper provides an overview of a techno-economic analysis technique that combines probabilistic modeling of microgrids with tiered demand loads from buildings (i.e. tiered energy in buildings (TEB)). The analysis produces pareto-optimal designs based on a Monte Carlo study of a microgrid design space where the microgrid can turn tiered demand loads on or off to increase the availability of higher tiers. We define a tiered circuit as a grouping of electricity load types in a building. We define availability as the percentage of the load energy served by the microgrid during power outages, not including the startup period. A case study of our technique is conducted on a potential future community in Puerto Rico to seek to answer the research question, "Can tiered circuits and co-optimization of normal (blue-sky) and resilience (black sky) conditions save money for the proposed future community? The case study is on a proposed future community that will potentially be added to an existing neighborhood that has many problems. Sections of the existing neighborhood are at sea-level making them prone to flooding. Many residents in this community have not been able to fully reconstruct damages since Maria and Irma and have used tarps on roofs for years. Furthermore, many parts of the community have never had sanitary sewer services. The biggest resilience problem for the community is the fact that a body of water adjacent to the community floods and mixes with sewage during hurricanes and rainstorms. Housing redevelopment projects, therefore, must be built to solve these problems. Strong advantages for new developments are improved social and health conditions, comfort, convenience, and energy resilience (Jeffers et. al., 2020). Though the problems faced by the community are many, this paper only focuses on energy resilience through application of tiered circuits to decrease microgrid costs for the community.

The technique presented in this paper is a step forward in probabilistic microgrid analysis. Most probabilistic microgrid analyses have unchanging load profiles for electricity demand. For normal design conditions this works because over-design is used to assure microgrid functionality. Resilience analysis of extreme events has more demanding requirements to characterize failure rates of microgrid operation leading to the need for electricity demand models that have weather, building dynamics, and occupant behaviors included. It would therefore be ideal to fully integrate building energy modeling (BEM) and occupant behavior models into microgrid analysis. This is complex to implement and very expensive computationally.

As an intermediate step to full integration between buildings and electric grid simulations, our TEB approach allows combinations of electric loads on different tiers. This requires no new capabilities in BEM tools but does require extensive classification of all loads into different tiers and additional simulations of thermal and electrical performance for every tier combination. For example, the input for load break down between tiers is seen in Table 1 for residential buildings in this analysis. A large parameter study of all building types and tiers can therefore provide many load profiles for a microgrid analysis where the microgrid can shed load according to the tier structure. The microgrid analysis can then include performance on different tiers at different times to assure delivery of power to different priority loads during power outage/disaster conditions. The TEB approach therefore avoids direct coupling of the microgrid and BEM analyses.

METHOD

Our analysis technique involves calculating load profiles for tiered circuits using BEM. These TEB load profiles are then derived for the community in Puerto Rico. The TEB load profiles are then used as input within the Microgrid Design Tool (MDT) where tiered loads are also modeled separately so that they can be switched on and off. Three analyses are then applied to provide an answer to our research question.

Tiered Energy in Buildings

The building demand loads are calculated using an open-source tool called Tiered Energy in Buildings (TEB) (Villa, 2021). TEB is used to produce community-wide electric load profiles for the highest importance loads (Tier 1), and consecutively less important loads (Tier 2, Tier 3, and non-critical loads). These load profiles are then used by the Microgrid Design Toolkit (MDT) (Eddy and Giletly, 2021) to analyze renewable and non-renewable microgrid options.

The development of TEB was driven by the need for a fast, low order building energy model that could be used alongside

MDT. TEB uses a resistive capacitive (RC) model obtained from another open-source tool called the RC Building Simulator (Jayathissa et. al, 2017; Jayathissa, 2022) with 5 resistive and 1 capacitive element in conformance with the International Organization for Standardization (ISO) standard 13790 (ISO, 2008). The models from the RC Building Simulator were adjusted to the needs of TEB. The final model includes dynamics for solar gains, sun angle, windows, infiltration, heat flow to ground, occupant sensible thermal loads, internal dehumidification via wall A/C units, heat gains from electric loads, 8760 weather boundary conditions, and heat capacitance of cinder block/prefab concrete panel construction. For thermodynamic relationships used in psychrometric calculations, the National Institute of Standards and Technology (NIST) REFPROP database (Lemmon et al., 2018) is used alongside an equation for vapor pressure in the literature (Buck, 1981).

The level of detail in TEB is intended to provide physically parameterized (gray-box) hourly temporal thermal feedback without detailed spatial dynamics. It can stack simulation of many different types of buildings with multiplying factors for total demand loads of a community. The input to TEB is extensive for the community described in the next section and is only described partially. Please make a request to the corresponding author if input decks and analysis scripts are desired.

Table 1 Tiered circuit break-down of appliance for residential units.

Non-critical	Tier 3	Tier 2	Tier 1
1) Dryer/washing machine 2) Wall AC units 3) 5 interior light fixtures 4) Central AC 5) All other plug loads 6) Ceiling fans	1) Electric Vehicle (EV) 2) TV 3) Microwave 4) 5 Interior light fixtures	1) Home Mobility Scooter (select units) 2) Laptop Charging 3) Stove range 4) 8 interior light fixtures	1) Cell phone charging, Internet Wi-Fi 2) Medical Equipment (select units) 3) Refrigerator 4) Wall AC for Home Medical (select units) 5) 1 plug in fan per bedroom 6) 3 interior and 1 exterior light fixture

Community Concept Description

The site layout in Figure 1 depicts basic features of the new community. The new site is on higher ground than the rest of the surrounding communities making it a good candidate for new development. It is planned to contain features that residents of the neighborhood do not have good access to presently. Envisioned are institutional spaces consisting of a community center to the southmost tip and a grocery store on the northmost tip. The large buildings that surround the community next to a major road are commercial space on the bottom floor with apartments above them. Special apartments for elderly occupants are envisioned for the lower residential mix. The buildings enclosed by the commercial/apartment perimeter are single unit walk-in homes (center and southeast perimeter) and townhomes (to the north) for larger families. To the east of the community a park is desired. Many design specifications for the community were not available but were estimated. The total area of the community was set to 23,745 m^2 (255,590 ft^2) of space with 5,415 m^2 (58,290 ft^2) of commercial, 5,914 m^2 (63,660 ft^2) of institutional, and 12,416 m^2 (133,640 ft^2) of residential space. The actual use cases of the new community were not well defined and were therefore constructed using reasonable values for energy demand in comparison to the Residential Energy Consumption Survey (RECS) and the Commercial Building Energy Consumption Survey (CBECS) (EIA, 2018). Adjustments were intuitively made based on significantly lower A/C consumption in Puerto Rico.

Typical construction plans including 2-bedroom and 3-bedroom townhomes were provided by Puerto Rican authorities. Also provided were plans for a 3-bedroom unconnected house. Fenestration ratios for each direction and envelope thermal mass and insulation were derived from the engineering drawings of these plans. These drawings were also used to set magnitudes for plug, water use, and lighting loads based on socket counts and appliance designations in the plans. Due to lack of further information, a reasonable combination of loads was sought based on combinations of load profiles from similar communities elsewhere in Puerto Rico. Twenty-four-hour energy use load profiles for home medical devices were applied to 12% of the residential units, home mobility devices for 4%, electric vehicles on 1.4%, A/C for 25%, and elevated flood protection in 80%. Loads were then divided into tiers for residential, commercial, and institutional spaces. A single typical day was applied for all hourly schedules which were obtained from studies on end use demand loads (Sheppy et. al., 2014; Wilson et. al., 2014)

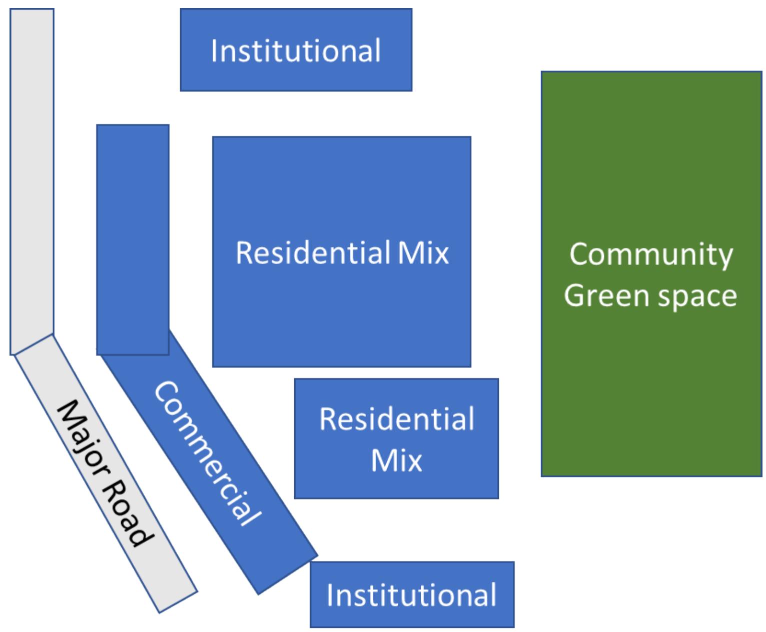

Figure 1 Proposed community basic layout.

Microgrid Design Tool Analysis

The MDT software performs a technoeconomic analysis on microgrids (Cuisinier et. al., 2020; Suk and Hall, 2020). MDT's inputs include 1) Generation Assets, 2) Electric loads, 3) Optimization parameters, 4) Reliability definitions and 5) Design Basis Threat(s) (e.g., probability of power outage events). In MDT, complex networks of electric grid elements are linked to demand loads. Each grid element can be static or can be a design variable. An example of a design variable is for a Photo-Voltaic (PV) solar array to be able to be three different size arrays (100kW, 200kW, 300kW). An analysis can include several design variables. These are evaluated by a double loop structure in MDT. The first loop selects a design vector by randomly sampling each design variable. The second loop runs many simulations of the selected design subject to Design Basis Threats (DBT's). At each time step the possibility of failures and beginning of DBT events are analyzed. The combination of weather, failures, and DBT's produce resilience metrics within a Monte-Carlo study. In this study energy availability was used as a performance metric, defined as the percentage of the load energy served by the microgrid during power outages, not including the startup period. Availability is useful because it gives a measure of what percentage of time a microgrid can function under DBT's. An optimization routine in MDT tracks the designs that have the pareto optimal cost and availability. Our previous work on a New Mexico neighborhood gives a good example of another application of MDT (Villa et. al., 2022).

A microgrid study using MDT was conducted on the community with load demand profiles from the TEB tool. For the MDT analysis, the tier structure of loads was used so that the microgrid controller could prioritize load shedding with reintegration into the microgrid as generation capacity permits. The generation assets considered in the design included PV, battery storage, propane, natural gas, and diesel generation. Figure 2 illustrates a general overview of the microgrid model with most of the electric elements (transformers, switches, controllers, etc..) neglected for simplicity. Generation design variables in MDT are shown on the right-hand side of Figure 2.

The main inputs of the simulation were the PV output profile, the DBT settings, the generation design variables, and the desired performance metrics for the optimization process. The PV output was obtained using the PVWatts tool (Dobos, 2014), which utilized a measurement from the San Juan, Puerto Rico area within one mile of the proposed community site. Five DBT's were added as seen in Table 2. The five DBTs consist of grid outages ranging from as short as 2-days occurring annually to year-long outages. These were all cycled in the simulations to occur many times for a robust design accounting for virtually all anomalies of time of year and equipment

failures. All generation options were assigned failure rates consisting of a Mean Time Between Failures (MTBF) and Mean Time To Repair (MTTR) as seen in

Table 3. The metrics in Table 2 and

Table 3 reflect parameters for probability distributions. The DBT's are characterized by bi-linear distributions whose peak is the average of the duration range. The equipment failure rates are characterized by exponential distributions with an assigned probability function to vary the occurrences of each setting. For performance, each of the three tiers were assigned energy availability thresholds of 99.9% (Tier 1), 95% (Tier 2), and 80% (Tier 3). Non-critical loads were not given a threshold making 0% availability during DBT's acceptable. The upfront purchase cost limit was set to $5M with a $3M target.

Three analyses were conducted to answer our research question. The first did not use MDT and used Net Present Value (NPV) to assess the economic return on PV. The purpose of this analysis was to assess the normal (blue sky) value of 2,300 kW of solar to the community without considering black-sky conditions. The solar array size was chosen because it balances the generation price structure to zero cost for energy purchases. It also had to assure that less than 25% of generation annually came from fossil sources when the PV was non-operational. Cost for electricity was set to $0.2242/kWh without demand charges or time of use structures. This was an average for the time of the study, although as of July 2022 residential rates were around $0.35/kWh. Net metering was used monthly throughout the year, with any end of year surpluses awarded $0.07/kWh (as per Puerto Rico rules). A discount rate of 6.5% was used in the analysis and a time horizon of 20 years was used for the NPV. The second analysis was an MDT black-sky analysis with no prioritization of renewables (i.e., no encouragement of sustainability). The third analysis was a combined MDT blue-sky/black-sky analysis with 2,300 kW of PV and no diesel generation (i.e., encourage both renewables and resilience simultaneously)

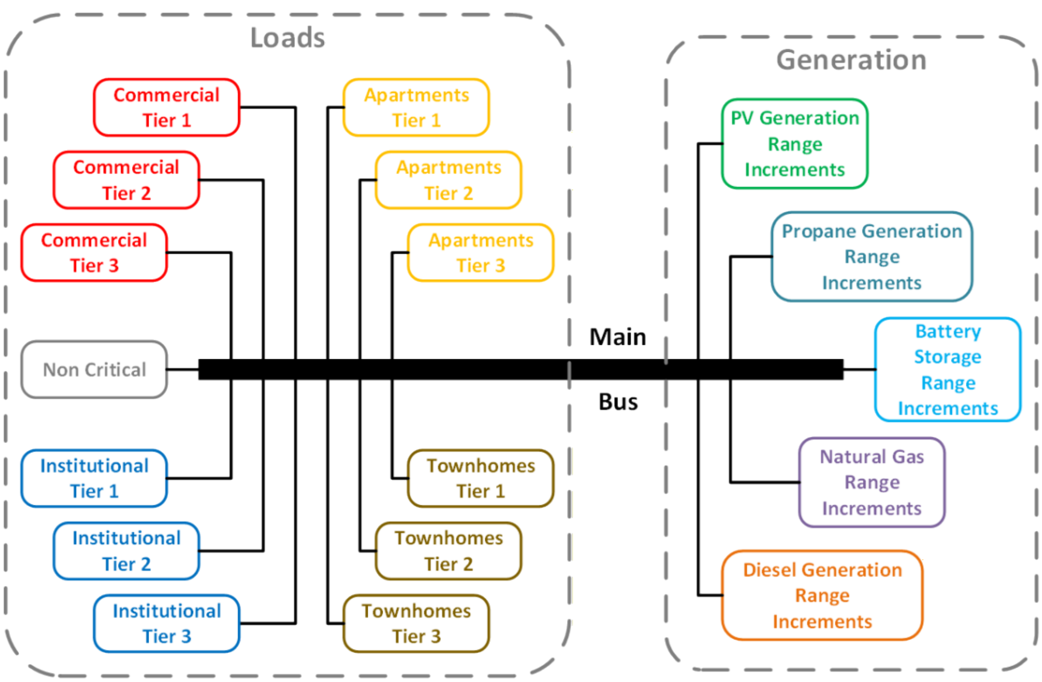

Figure 2 MDT model general layout

Table 2 Design Basis Threats (DBT) specifying probability of power outage

DBT Frequency (yrs)	Duration (days)	Duration Range	1000 Year Simulation Occurrences	Outage Duration (days)	Percent Simulation Time
1	2	1-2 days	1000	2000	0.55%
10	14	7-14 days	100	1400	0.38%
50	40	30-60 days	20	800	0.22%
100	180	4-8 months	10	1800	0.49%

500	365	8-16 months	2	730	0.20%
		Totals:	1132	6730	1.84%

Table 3 Costs and generation asset failure rates

Asset Types:	Range:	Increments:	MTBF (h):	MTTR (h):	Capital Cost:
PV	50kW-1MW	50/100/500kW and 1MW	8468	55	$1800/kW
Lithium-Ion Batteries	50-500kW	50/100/500kW (4-Hour batteries)	8000	168	$2604/kW
Diesel Generators	50kW-1MW	50/100/500kW and 1MW	10500	37	$850/kW
Natural Gas Generators	1MW	1MW	30000	6	$1000/kW
Propane Generators	50kW-1MW	50/100/500kW and 1MW	30000	6	$2750/kW

RESULT

The community total Energy Use Intensity (EUI) was adjusted via alteration of several BEM variables to a value of 45.0 kBTU/ft^2/yr (14.3 kWh/m^2/yr). This was deliberately placed below the typical value expected for the mixture of grocery, commercial, community center, and residential with similar climate for CBECS and RECS EUI's which came out to 67.1 kBTU/ft^2/yr (21.3 kWh/m^2/yr). This approach is founded on the hypothesis that Puerto Rican's consume less power per area than the CBECS and RECS data partly because of higher prices and partly because of less economic capacity to pay for services. This was confirmed by comparing yearly kWh consumption of the whole island. A better analysis would require surveys in Puerto Rico or access to commercial billing from the local utility. Figure 3 shows the TEB community wide load profiles for minimum and maximum days selected from the 1-year hourly results.

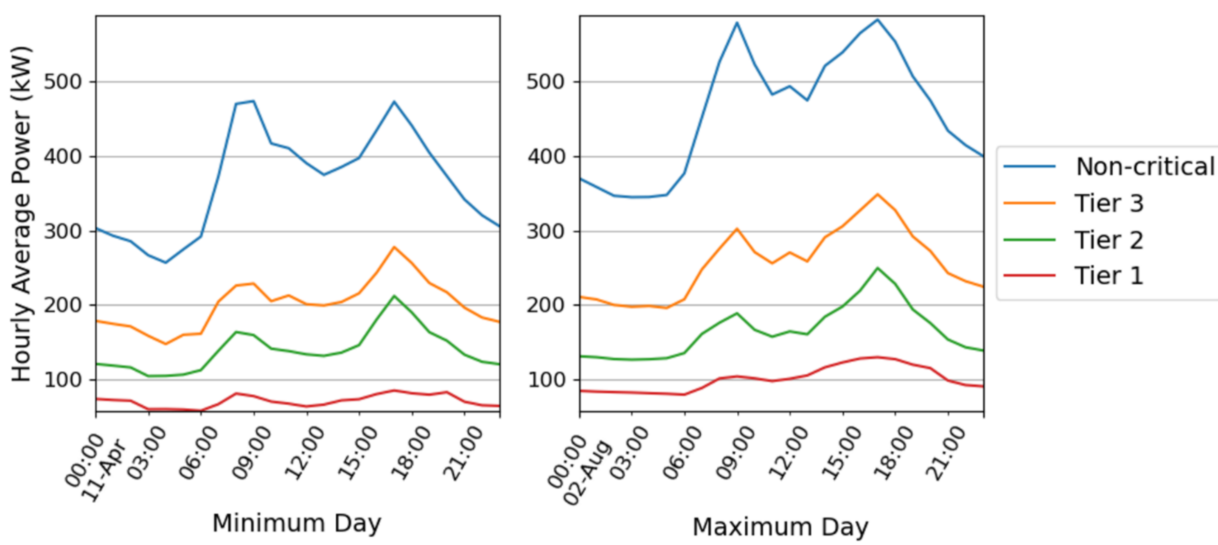

Figure 3 Community load profile calculated by TEB

The first analysis (Table 4) yielded a NPV of 4.46 million USD for a 20-year time horizon. It also reduced CO_2 emissions by 2530 tonne/yr (2790 ton/yr). Unfortunately, such a system has little resilience value as configured.

The second analysis (Table 5) shows that adding resilience from non-sustainable sources is much less expensive up front. An islandable microgrid with high reliability for tier 1 and 2 loads costs 0.825-1.18 million USD with availability of non-critical load ranging from 4.66-99.98% and tier 3 loads ranging from 96.87-99.98%. This demonstrates reduction of capital expenditure of 0.355 million USD due to the presence of tiered circuits in the community. Since MDT only considered upfront costs, none of the solutions have significant renewables or battery storage though. This shows that low-cost diesel, natural gas, and propane generators are the best way to meet the need for resilience when immediate cost is the only concern. These solutions rely on fossil power sources though with 0.80 million USD of energy purchases per year.

The third MDT analysis that included both blue-sky and black-sky considerations with 2,300 kW PV and no diesel generators shows combined optimization upfront costs of 4.69-5.10 million USD with non-critical loads ranging from 47.36%-59.20% and tier 3 loads ranging from 83.72-99.94% availability. Here the availability is higher because the large amount of solar tends to meet daytime loads when an outage occurs whereas the second analysis cases fail to meet load when fuel runs out regardless of whether the sun is shining. With no fuel noncritical loads must be shed immediately. The tiered structure saves 0.405 million USD for this third analysis.

Table 4 Analysis 1 results

Description	PV	Utility	NPV of PV Investment	
Fuel Cost	$ -	$ -	NPV of Baseline Cash Flows	$8,837,387
O&M Cost	$43,150	$ -	NPV of Investment Cash Flows	$475,090
CO2/Demand Charges	$ -	$ -	NPV Annual Cash Flow v. Base	$8,365,297
Energy Purchases	$435,830	$802,049	Capital Expenditure of Investment	$4,132,800
Energy Sales (at 2.24)	$435,830	$ -	NPV of EOL Salvage Investment	$234,575
Energy Sales (at 0.07)	$33	$ -	Total Capital Expenditure	$3,898,225
Net Annual Cash Flow	$43,117	$802,049	Net Benefit v. Baseline	$4,464,072
Local CO2 (tonne/yr)	0	0	CO2 Emissions v Baseline(tonne/yr)	-2530
Utility CO2 (tonne/yr)	1374.6	2529.7		
Offset CO2 Emissions (tonne/yr)	-1374.6	0		
Net CO2 Emissions (tonne/yr)	-0.3	2529.7		

Table 5 MDT results (each row is a pareto optimal solution)

	Availability (%)				Generation (kW)					Total Install Capacity (kW)	Cost (million USD)
Analysis	Tier 1	Tier 2	Tier 3	NC	PV	Natural Gas	Diesel	Li-Ion Battery	Propane		
1	-	-	-	-	2300	0	0	0	0	2300	4.133
2	99.95%	98.95%	96.87%	4.66%	0	0	0	0	300	300	0.825
2	99.96%	98.95%	97.89%	10.06%	0	0	50	0	300	350	0.871
2	99.95%	99.94%	99.69%	6.63%	0	0	0	50	300	350	0.955
2	99.98%	99.96%	99.90%	12.66%	50	0	50	50	300	450	1.091
2	99.98%	99.97%	99.98%	99.98%	100	1000	0	0	0	1100	1.180
3	99.99%	99.88%	83.72%	47.36%	2300	-	-	0	200	2500	4.690
3	99.55%	91.41%	87.50%	47.59%	2300	-	-	50	200	2550	4.820
3	99.77%	99.63%	95.85%	47.41%	2300	-	-	100	200	2600	4.950
3	99.96%	99.94%	99.57%	55.90%	2300	-	-	0	200	2600	4.965
3	99.98%	99.96%	99.94%	59.20%	2300	-	-	50	300	2650	5.095

DISCUSSION

The results show that tiered circuits are a good mechanism for adding the flexibility needed to directly offset their own costs when resilience is needed on critical loads. The modest monetary savings through tiered circuits could be increased by allowing tier 2 loads to have a lower availability. The 3rd MDT analyses did not provide perfect control over the tiered load thresholds (i.e., 99.9% for tier 1, 95% for tier 2, and 80% for tier 3 making the savings due to tiered loads non-exact for the first analysis. The 2nd MDT analysis provides a near perfect assessment of savings due to the tiered loads thresholds since the fifth case with natural gas generation provided 99.9% availability for all loads. Regardless, cost savings of 30% (i.e., 0.355 million USD/1.18 million USD) for analysis 2 easily justifies the additional circuits, switches and wiring needed to introduce tiered circuits. Some environmental benefit is also expected since less fossil fuel generation is needed. The cost savings are similar for the 3rd analysis but a much less small factor since the cost of the project is five times larger leading to 8% savings due to tiered circuits. Benefits once again are found through need for less propane generation and no need for Li-Ion batteries.

The combination of normal (blue-sky) and resilience (black sky) considerations with tiered circuits in a single analysis shows promise for cross benefits between technologies. The increase in availability of non-critical loads is significant due to the presence of solar power. The combined NPV of analyses 1 and 2 ranges from 3.28-3.64 million USD. Combining these represents a naïve approach where resilience and sustainability are considered separately. On the other hand, analysis 3 considers resilience and sustainability simultaneously. Its results yield NPV's of 3.50-3.91 million USD showing increased NPV of 0.21-0.27 million USD in comparison to the naïve approach. The combined value added by using tiered circuits and considering black-sky and blue-sky simultaneously is therefore 0.58-0.68 million USD reaching over 10% of the total project benefit.

The results clearly show alongside other studies (Newlun et. al., 2020) how both renewables and resilience through microgrids are economical for Puerto Rico where costs are high, risk is high due to hurricanes and earthquakes, and reliability of the electric grid is low. Under such conditions, these investments pay for themselves and can be mostly sustainable. This win-win situation is not present in many other locations globally where prices keep NPV of resilient, sustainable solutions too high.

Finally, the accuracy of our analysis type for actual sites is greatly hindered due to lack of end-use demand in the CBECS and RECS databases. Given Puerto Rico's win-win status for renewable microgrids, generation of equivalent energy end-use surveys for Puerto Rico is important (Villa and Jefffers, 2021).

CONCLUSION

The analyses conducted have demonstrated cases where: 1) Tiered circuits can pay for themselves in both a fossil fuels and renewable energy context. In paying for themselves, they can reduce the maintenance costs associated with more generation and storage and can reduce carbon emissions for fossil fuel. 2) Combined consideration of resilience and sustainability also has been shown to provide cost savings in comparison to implementation of renewables and resilience independently.

Future work for microgrid and building energy modeling analysis in Puerto Rico should look at how inefficient configurations of wall A/C units might waste enough energy to justify community level implementation of central A/C. Also, energy consumption surveys like RECS and CBECS would greatly enhance future community studies like the one conducted here for calibration of our modeling technique to current conditions. An alternative data source would be actual billing data (as aggregates for privacy) from the local utility. Finally, research is needed to understand how energy consumption is affected by extreme event conditions. Answering the basic research question, "How much power do consumers use during emergency conditions," is needed because the present resilience analysis assumes consumption from a microgrid does not change during a power outage. Although there have been focus groups and small-scale data collection efforts on this, a comprehensive study does not exist. (O'Neill-Carrillo, 2019)

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DISCLAIMER

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