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Microgrids as an Affordable Resilience Source for Rural Communities

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SUMMARY

This paper explores the use of microgrid technology to improve the resilience and reliability of power systems in rural communities. Rural areas are often subject to extreme weather conditions and have limited access to resources, making it harder to respond to contingencies. The Energy Improvements in Rural or Remote Areas (ERA) program is intended to enhance the resilience, reliability, and affordability of energy systems in rural communities. Microgrids have been increasingly deployed as a technology to improve system resilience. This paper reports the results of a study on a microgrid to be implemented in a rural community. The study evaluates the resilience enhancement of the microgrid through a simulation of a catastrophic event and discusses a framework for conducting cost-benefit and affordability analysis of the microgrid. The paper concludes that microgrid technology has the potential to offer economic advantages and enhance reliability and resilience for rural communities.

KEYWORDS

Microgrid affordability, Resilience, Rural communities

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I. Introduction

Electric power systems in rural areas often have lower reliability due to their simpler configuration and limited access to resources, which can make it harder to respond to contingencies. Additionally, rural areas are vulnerable to extreme weather conditions that can damage the transmission and distribution infrastructure and lengthen outage times [1].

The Energy Improvements in Rural or Remote Areas (ERA) program, operating under the Office of Clean Energy Demonstrations (OCED), has been established to enhance the resilience, reliability, and affordability of energy systems in rural communities. The program aims to promote the development of clean energy demonstrations and energy solutions that can be easily replicated and scaled up [2].

Microgrids have been increasingly deployed as a technology to improve the resilience of power systems [3]. This is especially relevant during severe weather events that can cause significant economic losses and result in catastrophic power outages. By serving critical loads and sustaining essential societal functions [4], microgrids can help mitigate the impacts of extreme events.

According to the Department of Energy (DOE), a microgrid is a collection of interconnected loads and distributed energy resources within clearly defined electrical boundaries that functions as a single controllable entity with respect to the power grid. A microgrid is capable of both connecting and disconnecting from the grid, allowing it to operate in both grid-connected and islanded modes [5]. The design of a microgrid aims to improve system resilience by providing the capability to withstand and recover from disruptions and operate independently [6].

Microgrid technology has the potential to offer economic advantages and enhance reliability for various stakeholders. However, incorporating this technology necessitates additional investments in components and their integration. The costs associated with microgrid technology are hard to generalize since each installation has its unique design and architectural features that impact the total cost of the required microgrid components. In the United States, the National Renewable Energy Laboratory (NREL) has identified the costs of microgrid components and integrated systems for installations, as reported in [7].

This study presents a proposal for a microgrid to be developed in a rural community, which considers the necessary parameters and data. Resilience enhancement of the microgrid is evaluated through a simulation of a catastrophic incident. Additionally, the paper discusses a framework for conducting cost-benefit and affordability analyses of microgrids [8].

This paper is organized as follows. Section II introduces the Rappahannock Electric Cooperative. Section III discusses the need for microgrids in REC system. Section IV describes the REC microgrid modeling. Section V presents the simulation results of REC microgrid. Section VI evaluates the framework for microgrid affordability. Section VIII concludes this work.

II. Rappahannock Electric Cooperative

Rappahannock Electric Cooperative (REC) is a not for profit electric distribution cooperative incorporated under the laws of the Commonwealth of Virginia. Its main objective is to distribute electric power to its member-owners at an affordable cost. REC covers a vast area of approximately 22 counties, serving around 170,000 meters from the Blue Ridge Mountains to the tidal waters of Chesapeake Bay, stretching between Richmond, Virginia, and Washington, D.C. The electricity provided to REC's members is supplied by First Energy, Dominion Energy, Old Dominion Electric Cooperative (ODEC), and the Southeastern Power Administration (SEPA) [9].

Due to the increasing frequency of extreme weather events caused by climate change, power grids are susceptible to damage, leading to economic losses. To enhance the resilience of the system, a microgrid is proposed to be developed in Spotsylvania County, which is the largest customer base for REC, serving 15% of the total customers in its territory.

III. Need for Microgrids in REC System

Reference [10] highlights that, in rural communities, the power grids may face limitations in accessing necessary resources during extreme events, leading to a prolonged restoration process.

The Northwest and Central Regions of Virginia experienced heavy snowfall and 40 mph wind gusts during winter storm “FRIDA,” while the Eastern Region received wind speeds of 50 mph and rainfall. From January 3 to January 12, 2022, the storm affected electric services in Virginia, with REC's first outage recorded on January 3 at 4:04 AM. Out of the 170,989 customers in REC's service territory, around 61.5%, or 105,162 customers, were impacted by the storm. REC reported a total of 141,500 outages, resulting in 6,483,071 customer-hours of outage and 2,933 work orders.

The Blue Ridge, Bowling Green, and Culpeper regions recorded 503, 71,488, and 69,509 outages, respectively. REC identified 779 broken poles, 412 broken cross-arms, and 218,547 ft of conductor that required restrung. Of the total outage events, 93.8% were caused by trees outside the right-of-way. REC's restoration efforts involved 132 company line employees, 244 support employees, and additional personnel from contractors and mutual aid, totaling 725. The restoration for all members was completed in approximately 9.5 days.

Due to the winter storm, the bulk grid required a 9.5-day restoration. However, if a microgrid had been in place, critical loads in the affected area could have been served by distributed energy resources (DERs) and sustained essential functions such as shelters for residential areas. The energy provided via DERs could also enhance the resilience of the system.

IV. REC Microgrid Modeling

In Spotsylvania County, an elementary school and a middle school are chosen as the critical loads served by microgrid under an islanded mode. While natural disasters occur, the schools can operate as temporary shelters.

Currently, a 2MW emergency diesel generator (SG) is installed in the school area. To enhance the system resilience using microgrid capacity, a 1MW/4MWh battery energy storage system (BESS) and a 2MW solar energy system (PV) are proposed for the microgrid. The system configuration of the proposed REC microgrid is given in Figure 1.

The REC microgrid is proposed to develop on a feeder branch, with a normally closed switch designated as the point of interconnect (POI) connecting the distribution system and the microgrid. Inside the microgrid, a loop configuration is employed with a normally open switch to supply power to the critical loads. The existing SG is connected to the loop, while the proposed BESS and PV system are located at the POI and elementary school, respectively.

The system described in this section has been modeled in DIgSILENT PowerFactory using real feeder parameters and historical load data.

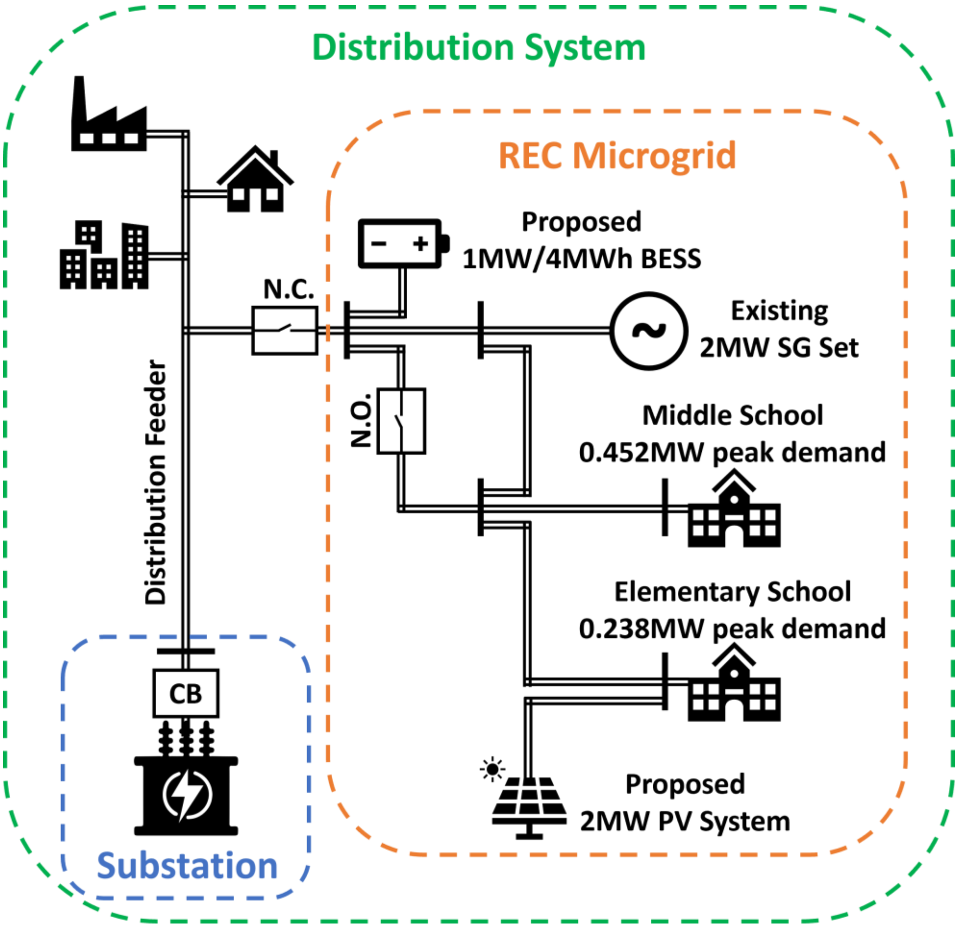

Figure 1 Proposed REC Microgrid

V. Resilience Enhancement by REC Microgrid

In order to evaluate the proposed REC microgrid discussed in section IV, a quasi-dynamic simulation is conducted using DIgSILENT PowerFactory, simulating the contingency outlined in section III. The simulation is carried out in 15-minute time intervals over a period of 10 days, starting from Jan-3-2022 12:00 a.m. and ending on Jan-13-2022 12:00 a.m., covering the entirety of the contingency.

The Bundesverband er Energie- und Wasserwirtschaft (BDEW) load profile on winter days, derived from the German Association of Energy and Water Industries, is used for the two critical loads based on their peak demands. The PV power outputs are based on the historic Global Horizontal Irradiance (GHI) with the 60-minute period of time in Spotsylvania County [11].

The combined load profile of the two critical loads is shown in Figure 2, while Figure 3 illustrates the active power of DERs during the contingency. During this period, the SG maintains a constant active power output of 0.2 MW, which is equivalent to 10% of its capacity. The BESS is employed to maintain the power balance between generation and demand. During early mornings when PV output is low, the BESS discharges. Conversely, during noon when PV output is high, the BESS is charged. Figure 4 presents the state of charge (SOC) of BESS. It can be observed that the lowest SOC during the contingency is approximately 30%. This observation suggests that the BESS performs its function to maintain the SOC effectively.

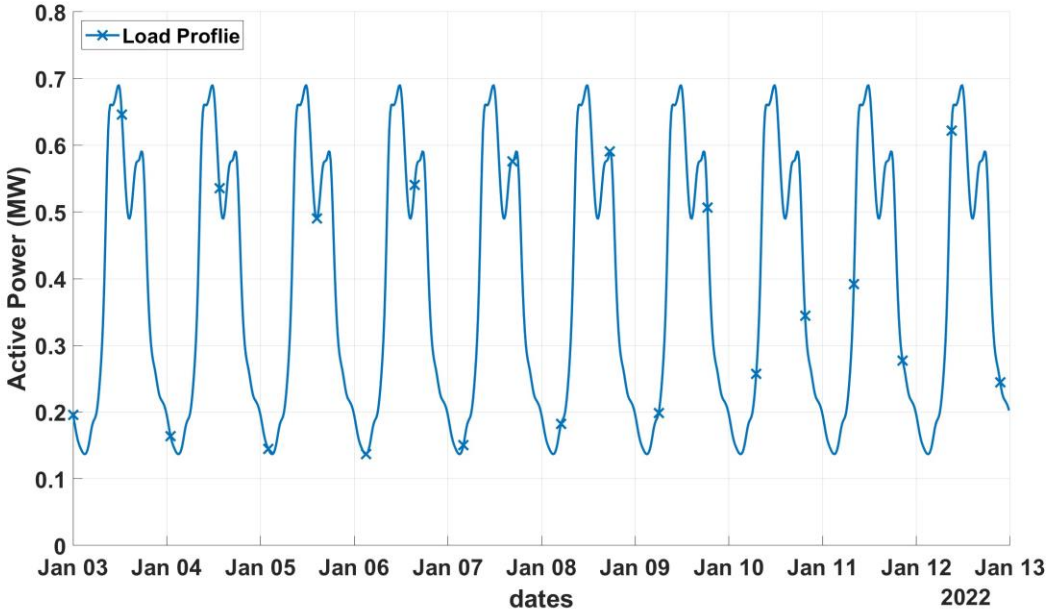

Figure 2 Load Profile during the Contingency

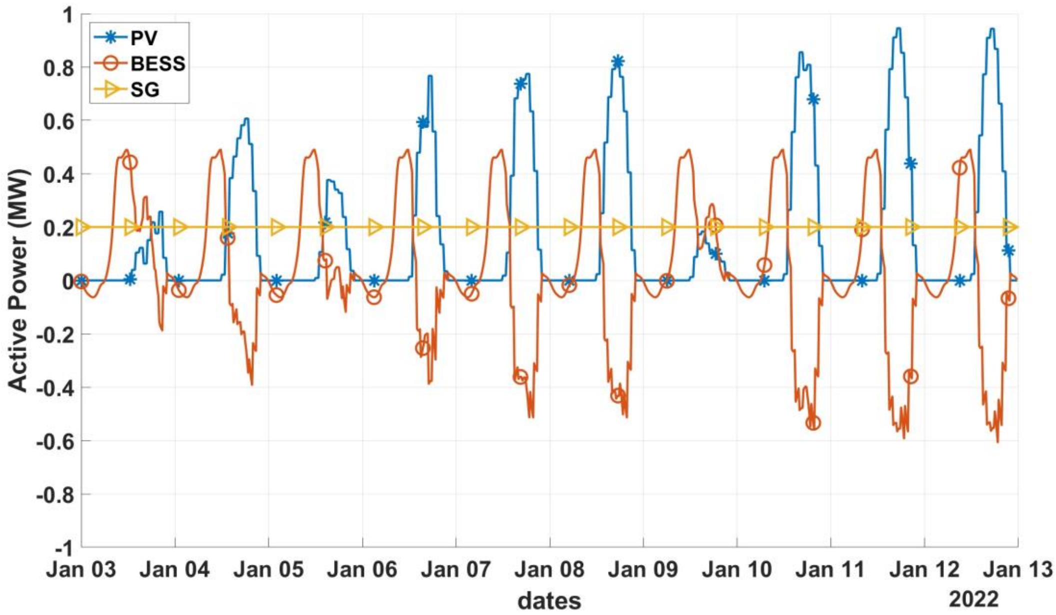

Figure 3 Active Power of DERs during the Contingency

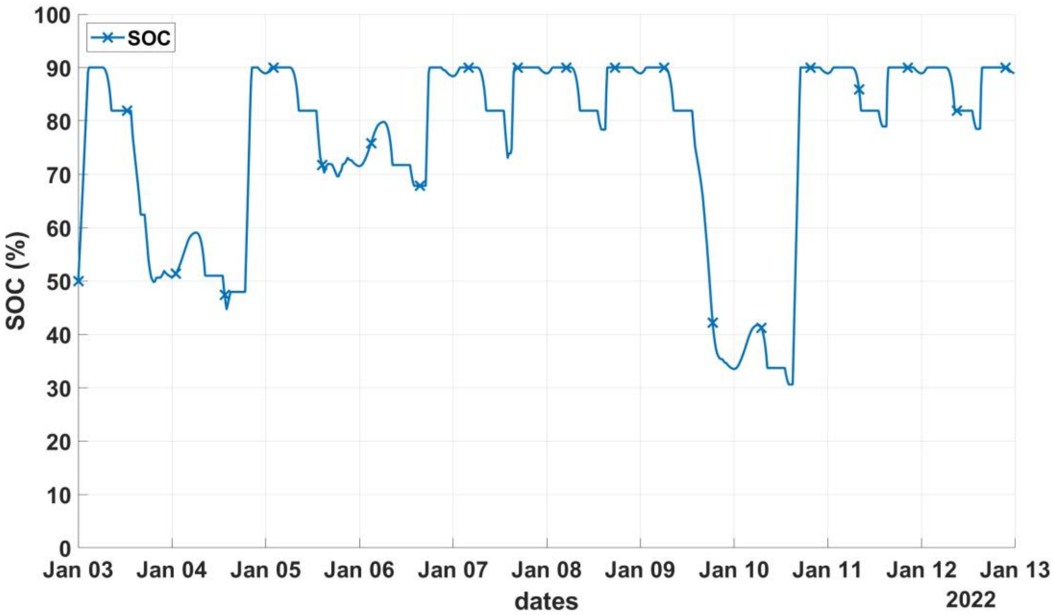

Figure 4 SOC of BESS during the Contingency

A metric was proposed in [12] to quantify the level of system resilience. Figure 5 depicts the idea of resilience using the system performance curve, and the improvement in resilience can be calculated by the amount of energy supplied during the outage.

System states at corresponding timestamps of the metric are defined in Table 1. Resilience enhancement, R_{en}, can be calculated by system performance (MWh) in ΔT_4 and ΔT_5 where the islanded microgrid serves critical loads without the main grid.

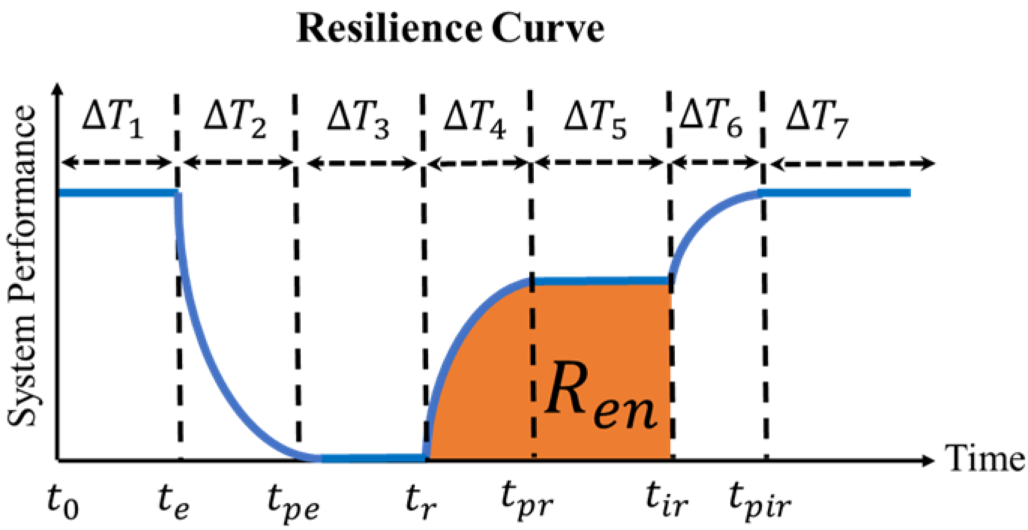

Figure 5 Conceptual Resilience Curve

Table 1 System States of Resicilience Metric

System States	
ΔT_1	Pre-Event State at t_0
ΔT_2	Event Progress at t_e
ΔT_3	Post-Event Damage Assessment State at t_{pe}
ΔT_4	Restoration State at t_r
ΔT_5	Post-Restoration State at t_{pr}
ΔT_6	Infrastructure Recovery at t_{ir}
ΔT_7	Post-Event State at t_{pir}

Based on the load profile, the daily energy demand amounts to 9.2MWh, and the SG can supply 4.8MWh a day in the simulation scenario. Consequently, the proposed PV and BESS system is expected to furnish an additional 4.4MWh a day without relying on fuel. This would enable the microgrid to operate continuously even when access is restricted in rural areas under extreme weather conditions. Additionally, throughout the entire contingency, a 10-day simulation is performed with 9.2MWh power consumption per day. In total, the microgrid has the potential to enhance system resilience by 92MWh without being connected to the main power grid.

VI. Microgrid Affordability

Microgrid affordability depends on the comparative relationship between stakeholders' willingness to pay (WTP) and the costs associated with microgrid functions. Due to the lack of data and tools for accurately valuating the stakeholders' WTP for a microgrid, it is assumed that benefits of the stakeholders represent their WTP in this paper.

Due to confidentiality of business data, the analysis presented in this paper is approximate using the publicly available information. For simplicity, it is assumed in this study that there are three stakeholders. For the proposed REC microgrid, the Microgrid Customers (MCs), Microgrid Operator (MOs), and Distribution Network Operator (DNO) are Spotsylvania County Schools, RE Communications LLC, and Rappahannock Electric Cooperative, respectively. RE Communications LLC is a subsidiary company of REC who is responsible for newly installed PV and BESS systems and their operation and maintenance (O&M).

For the proposed microgrid, the assumed investment cost for utility-scale PV installation is \$1.14 million/MW, with an Operations and Maintenance (O&M) cost of \$13/kW-year, based on the average cost of a small-project PV in 2021 [13]. The installed PV's mean capacity factor is assumed to be 26.8% [14]. The BESS is estimated to be installed at a cost of \$345/kWh, which reflects the average cost of a 4-hour duration utility-scale battery in 2021 [15]. Additionally, the installation of the microgrid controller and associated communication system incurs an additional cost of \$129,000 [8]. The annual O&M of the microgrid system and BESS will take 2% of the investment cost [8,15]. In this study, the synchronous machine and the distribution feeder already exist. Based on the aforementioned data, the equivalent annual cost (EAC) of the proposed microgrid project is calculated considering a 20-year lifetime and a 5% discount rate applied annually.

Also, for simplicity, it is assumed that during normal times, MCs can purchase energy from DNO for 9.09 cents/kWh [16], representing the average price of commercial load in Virginia as of April 2023. After the microgrid installation, the MO will sell energy to MCs at a price that covers the EAC and provides a marginal profit of $5/MWh. Any excess power generated by the microgrid will be purchased by DNO at the load-weighted average Locational Marginal Price (LMP) of the PJM day-ahead energy market in 2022, which is $75.44/MWh [17].

VII. Preliminary Cost-Benefit Analysis

VII.1. Cost-Benefit Analysis of MO

1) **Cost:** *The cost incurred by the MO for the proposed microgrid includes the expenses of installation, operation, and maintenance.* RE Communications LLC, as the MO, is responsible for the installation and O&M of the microgrid. In the proposed case, its EAC amounts to $338,170.

2) **Benefit:** *The MO can generate revenues by selling electric energy and providing ancillary services.* In this proposed case, considering a 26.8% capacity factor, this microgrid can generate 4,380 MWh (The synchronous machine is not considered during normal operation). In order to cover the annual cost and make a $5/MWh profit margin, MO can sell the energy to MC at the price of 7.7 cents/kWh. This translates to an annual profit of $166,798. Additionally, by engaging in energy exchange with the DNO, the MO can generate an extra profit of $11,557 annually. Based on the simulation results presented in this paper, the microgrid has the capability to provide ancillary services such as load shifting, system reliability improvement, and resiliency enhancement. Therefore, the MO can benefit more by offering these ancillary services to the DNO.

VII.2. Cost-Benefit Analysis of MC

1) **Cost:** *The cost of the MC includes the payment for the energy generated by the microgrid compared to the energy generated directly by PV.* Compared to the average levelized cost of PV generation at $33/MWh [18], Spotsylvania County Schools may need to purchase the energy generated by the PV within microgrid at a price of $77/MWh. The price difference represents the cost of the microgrid from the MC's perspective.

2) **Benefit:** *The benefit for the MC may include the leasing income, energy cost reduction, reliability improvement, and resilience enhancement.* From their perspective, they can have income by leasing the land to MO and benefit from lease payments. Furthermore, despite the relatively higher price compared to the cost of a PV system, the MC in this case may still be able to reduce their energy cost. By accepting the price of energy generated by the microgrid, they can potentially reduce their energy cost by $46,698. Also, Spotsylvania County schools will have the benefits of enhanced reliability and resilience provided by the microgrid.

VII.3. Cost-Benefit Analysis of DNO

1) **Cost:** *The cost of the DNO can be income reduction due to microgrid competition.* As the DNO, Rappahannock Electric Cooperative may face a decrease in income if the MO offers a better price compared to the utility rate. In such a scenario, the MCs may choose to purchase the energy from microgrid to reduce the energy cost.

2) **Benefit:** *The DNO, in this case, can also expect to benefit from the ancillary services that can be provided by the installation of the microgrid.* From the system operation point of view, the load shift service provided by the microgrid will help the DNO to defer the system component update, which will save money for the DNO. Besides, the distribution system customers will also benefit from the microgrid with resilience enhancement during extreme events.

VIII. Conclusion

To summarize, microgrids offer a promising solution to improve the resilience of power systems in rural areas where access to energy resources is limited during extreme events. This study presents a proposal for a microgrid to be implemented in a rural community to enhance resilience, and it evaluates the framework for conducting cost-benefit and affordability analyses of microgrids.

A microgrid is proposed to be developed in Spotsylvania County, which is the largest customer base for Rappahannock Electric Cooperative system. The modeling and simulation of the REC microgrid show that critical loads can be served during natural disasters, enhancing the resilience of the system for residents.

A 10-day quasi-dynamic simulation is conducted using DIgSILENT PowerFactory. The simulation results indicate that the proposed PV and BESS system can provide additional resilience for rural communities under extreme weather conditions.

Overall, this study contributes to the deployment of microgrid technology and provides a plan for enhancing resilience of distribution systems in rural communities. Future research is needed to develop a systematic tool to evaluate the WTPs of different stakeholders.

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