

Research Article

Integrating Small-Scale Geothermal into a Mini-Grid to Improve Electricity Access in Nigeria

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Abstract

Increasing local energy access in developing countries, particularly in off-grid regions where mini-grids are often overloaded, remains a critically underexplored area in energy transition. These regions often face significant technical and economic challenges, such as low generation capacity, high energy costs, limited energy access, and heavy reliance on diesel fuels. This study explores capacity expansion by integrating small-scale geothermal energy into such a mini-grid system to enhance the local energy supply. Unlike commonly studied solar-wind hybrid systems, this study evaluates the largely untapped potential of decentralized small-scale geothermal energy in providing a clean, reliable baseload complement to the variable solar PV system at Eka Awoke, Ikwo, Ebonyi State, Nigeria, at a minimal cost. The linear programming (LP) model presents the first in-depth analysis of the integration of small-scale geothermal energy into an existing mini-grid in sub-Saharan Africa. It evaluates the energy system under four realistic demand scenarios: Baseline, suppressed demand, increased connection demand, and increased connections with eCooking demand scenarios. The results obtained show that the geothermal capacity increased by 21.21% and 77.71% for the increased connection and increased connection with eCooking, respectively, while it decreased by 37.7% for the suppressed demand scenario. These findings provide valuable insights for energy providers and policymakers seeking to decarbonize and design more capacity and cost-effective strategies for increasing local energy access in mini-grids.



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Keywords

Mini-grids; small-scale geothermal energy; electricity access; Nigeria

1. Introduction

In 2022, for the first time in decades, the number of people worldwide without access to electricity increased, reaching 760 million [1]. Additionally, the recent crises stemming from the impacts of the Russian invasion of Ukraine and the post-COVID-19 pandemic, reported by the International Energy Agency (IEA), disclosed that the number of people without access to electricity has returned to the number it was in 2019. This increase is particularly evident in Sub-Saharan Africa, where it is reported that 80% of the population still lacks access to electricity. Currently, fewer than one in five African countries has established targets to achieve universal electricity access by 2030 [2]. Although approximately 45% of the continent has established electricity access targets, these targets are less ambitious compared to those outlined under Sustainable Development Goal 7 (SDG7). Despite this, increasing the capacity of existing mini-grids to ensure reliable access to electricity is a key challenge impeding the socio-economic development of rural and remote communities, particularly in sub-Saharan regions. Moreover, critical data for effective off-grid energy access planning, such as the population distribution and resource availability, remains absent for many of the remote regions and small island communities. A consequence of this is the need to utilize renewable energy as a mini-grid supply to address the growing energy demand and to align with the global climate change mitigation objectives.

In Nigeria, the recent report by the World Bank collection of development indicators shows that over 76% of people living in rural communities in Nigeria, as of 2020, have no access to electricity [3]. This could be the reason why many households in remote regions rely on kerosene lanterns, candles for lighting, traditional firewood cookstoves for cooking, and diesel power generation to carry out their daily activities. These sources are generally not feasible for rural electrification and are not sustainable as their activities could cause illness, pneumonia, stroke, ischemic heart disease, etc. [4]. Addressing these significant energy access deficits requires decarbonizing and designing more efficient capacity expansion and cost-effective strategies for increasing local energy access.

Mini-grids driven by renewable energy sources present a practical solution to energy poverty, fossil fuel dependence, and encourage low-carbon energy generation in rural off-grid regions. Solar and wind energy sources have been widely discussed in the literature and have shown success in improving local energy access in communities where central grid connection is not possible [5, 6]. The capacity limits of these energy sources encouraged the continued dependence on diesel generators to augment the energy sources, affecting the effectiveness and sustainability of the renewable energy sources [7-9]. Hence, encouraging a hybrid mini-grid configurations that integrate sources like biomass, solar, and wind energy options to increase local energy access and reduce fossil fuel dependence [10, 11]. Additionally, [9, 12] investigated an integrated mini-grid capacity expansion planning for rural electrification, and were faced with key issues like capacity sizing, demand variability, and cost uncertainties to optimize mini-grid investments and economic viability. Hence, this study explores the potential of small-scale geothermal energy technologies alongside

solar PV, wind energy, and storage technologies in providing new pathways to a reliable, cost-effective, and low-carbon solution for rural electrification.

A consensus has long existed within the energy utility sector that renewable energy generators like solar and wind energy are unreliable and intermittent to the point that they will never be able to provide a reliable electricity supply [13]. The introduction of a geothermal energy system as a dispatchable resource operating on available local renewable resources to meet local energy demands could provide a more sustainable option for remote regions to address the problems of other renewable energy sources. Several past studies consistently highlight small-scale geothermal energy as a modular set that is reliable, cost-effective, weather-independent energy source, that is suitable for rural and off-grid applications even without connection to a central grid [14-17]. Unlike solar and wind energy sources, geothermal energy offers high-capacity factors and stable output, making it an ideal complement to issues like lack of inertia, efficiency, and intermittent renewables [18]. The study also indicated that integrating geothermal energy with storage devices can increase the stability and flexibility of the energy system. Athari, Kiasatmanesh [19] suggested an auxiliary generation option to meet local energy demand through an innovative small-scale geothermal-driven system. It stated that uncertainties in energy demand could be addressed using local energy sources like geothermal, which could be designed as a small-scale, multigenerational system to effectively address the uncertainties.

A variety of optimization models are proposed in the literature to analyse future energy planning to increase local energy access. For example, Arnette and Zobel [20] were able to identify the optimal blend of renewable energy sources and existing fossil fuel facilities on a regional scale using a Multi-Objective Linear Programming (MOLP) model. Their model enabled decision-makers to balance annual generation costs with associated greenhouse gas emissions, facilitating a more comprehensive approach to energy planning. The study also revealed that the model's flexibility allows modifications to existing energy sources within the region without compromising its mathematical integrity. Additionally, it emphasized the need for an adaptable framework that can be altered to reflect new realities. Falke, Krengel [21] employed multi-objective optimization to assess the impact of various technologies and efficiency measures on costs and emissions in energy supply. They concluded that future research should focus on developing local incentive measures, particularly for smaller cities, to enhance the effectiveness of these technologies and measures. Riva, Gardumi [22] adopted a bottom-up model, a stochastic load profile generator, and an energy optimization model to find the economic optimum model and revealed that the costs and demand vary, respectively. The study noted that enhanced demand forecasting and planning methodologies could enhance the developed optimization model to be able to address the uncertainties surrounding the model. Among the optimization types, the Mixed-Integer Linear Programming (MILP) has emerged as an effective option in handling complex decision-making scenarios involving mini-grid capacity sizing, investment planning, storage, and resource scheduling [23-28]. Also, the MILP models have recently been applied in rural and off-grid contexts to ascertain the optimal renewable energy generation mix and storage technologies that would minimize the total costs generated while satisfying demand and technical constraints [29, 30]. Recent studies in Sub-Saharan Africa and Asia show the effectiveness of MILP in microgrid planning, incorporating technical issues such as voltage drop, load profiles, and renewable energy variability [31]. [32] adopted the linear programming (LP) model to optimize rural household energy using secondary data to find the cost-effective option in the electrification of remote regions. [33] explored the potential of a linear

programming model in analyzing different solutions for the decarbonization of energy systems on small islands. Given flexibility and scalability, the study adopts the LP-based optimization model to explore the cost-effective capacity expansion option for the solar PV-diesel mini-grid in the remote region, aiming to integrate small-scale geothermal and wind energy under varying demand, capital costs, and capacity uncertainties.

Several studies considered the integration of other renewable sources into mini-grid systems to increase the local energy supply. However, to the best of our knowledge, there has been a lack of sufficient studies for the consideration of small-scale geothermal energy as the supply source of mini-grid systems. Small-scale geothermal-driven mini-grid systems will be explored to contribute to the ongoing debate on the need for a more sustainable option of rural electrification, which would also operate at lower running costs and maintenance.

To address the identified gap, an optimization model is developed in this study to minimize the cost of the integration of a small-scale geothermal energy into an existing solar PV mini-grid. The most important innovation is the consideration and integration of small-scale geothermal energy into an existing Solar PV mini-grid to increase local energy access at minimized costs. The study marks the first in which small-scale geothermal energy is reviewed and integrated into the existing mini-grid system to provide sufficient energy for the various demand regions in the study. A general framework for the energy system design is established, which can improve the renewable energy supply and optimization. Different scenarios on demand and sensitivity analysis about cost are conducted to reveal the uncertainties. This paper applies the developed approach at Eka Awoke Community, Ikwo Local Government Area of Ebonyi State, Nigeria, as a case study.

The remaining part of the article is organized as follows: Section three outlines the Methodology and case study used, Section four presents the specific findings, and Section five discusses the results and draws conclusions.

2. Methodology

2.1 Model Development

2.1.1 LP Problem Formulation

This study develops a comprehensive LP mini-grid planning tool designed to enable decision-makers to accurately assess three renewable energy options and determine the optimal capacity for generating units and storage devices. Consider the community depicted in Figure 1, which features a centralized solar PV mini-grid system. In this setting, the decision-maker is responsible for allocating reliable electricity from the central facility to various villages within a specified time horizon. The goal is to minimize system costs through optimized capacity expansion planning. The proposed renewable energy system includes several technologies for energy generation and utilization. For instance, there are two additional power generation technologies available alongside the existing solar PV mini-grid, as well as diesel generators that can serve as backup power sources.

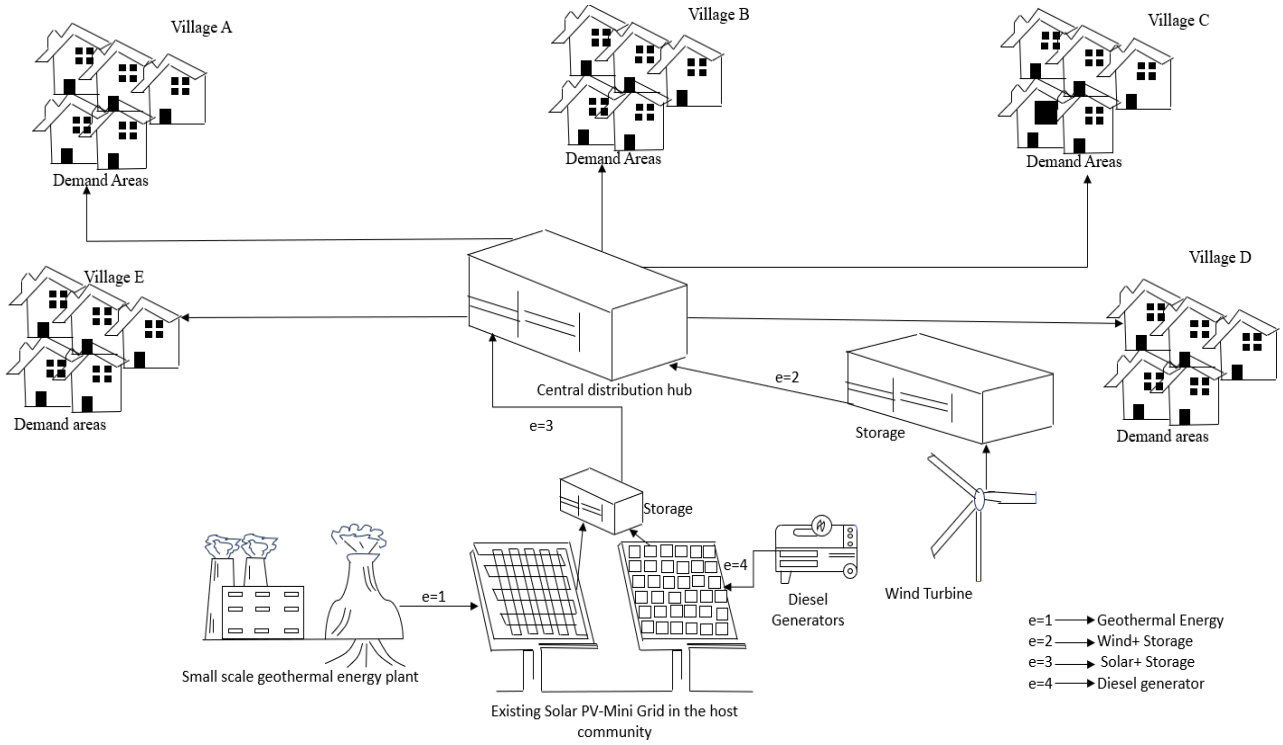


Figure 1 A sketch of the proposed energy capacity expansion system for households in five villages of the selected community.

2.1.2 Objective Function

The objective function seeks to minimize the total cost of meeting the electricity demand using the existing PV mini-grid, along with the new generation and electricity storage technologies throughout the planning period.

Thus, the total cost in Equation (1) can be minimized as:

$$\text{Minimize Total Cost} = C_{TOT}^{CAP} + C_{TOT}^{VOM} + C_{TOT}^{FOM} + C_{TOT}^{Emission} \quad (1)$$

Capital Costs.

Capital expansion costs in Equation (2) are calculated by multiplying the capital cost of each newly added system by its corresponding capacity.

$$C_{TOT}^{CAP} = \sum_{e=1}^4 CRF \cdot C_{(e)}^{CAP} \cdot X_{(e)} \quad (2)$$

Variable Operational and Maintenance Costs.

The variable operational and maintenance costs in Equation (3) are determined by the sum of the product of the variable operational and maintenance costs and the electricity generated by the system.

$$C_{TOT}^{VOM} = \sum_{e=1}^4 C_{(e)}^{VOM} \cdot EG_{(e)} \quad (3)$$

The electricity generated $EG_{(e)}$ in Equation (4) is given by:

$$EG_{(e)} \leq CF_{(e)} \cdot (X_{(e)} + E_{(e)}) \cdot T_{(e)} \quad (4)$$

Fixed Operational and Maintenance Costs.

The fixed operational and maintenance costs in Equation (5) are determined by the sum of the fixed cost per unit capacity, multiplied by the installed capacity of the system.

$$C_{TOT}^{FOM} = \sum_{e=1}^4 C_{(e)}^{FOM} \cdot (X_{(e)} + E_{(e)}) \quad (5)$$

Carbon Emission Costs.

The carbon emission costs in Equation (6) are calculated by multiplying the emission factor for each energy source by the electricity generated, and then by the CO₂ emission cost coefficient.

$$C_{TOT}^{Emission} = \sum_{e=1}^4 EF_{(e)} \cdot \beta \cdot EG_{(e)} \quad (6)$$

2.1.3 Constraints

Total Local Electricity Production.

The balance between supply and demand is crucial for power system expansion planning. Initially, the electricity supply was primarily from conventional sources like diesel, and the presence of a solar energy PV mini-grid source meets some aspects of the community's energy demand. The expansion of the existing solar PV is explored to address the issue of increasing demand. To meet the community's demand, the total energy from existing and new sources must be able to meet the demand and distribution losses as given in Equation (7)

$$\sum_{e=1}^4 EG_{(e)} \geq (D + L) \quad (7)$$

$L = 10\%$ is assumed as the total distribution lossess [34].

Environmental Impact Constraints.

The costs for the total emissions in Equations (8) and (9) in a year must not exceed the maximum allowable costs for the total emissions for that year:

$$Emit^{Year} = \sum_{e=1}^4 EF_{(e)} \cdot EG_{(e)} \quad (8)$$

$$Emit^{Year} \leq \sum_{e=1}^4 Emit_{(e)}^{Max} \quad (9)$$

Technical Constraints.

Each energy source's capacity in Equation (10) must be non-negative:

$$X_{(e)} \geq 0 \quad (10)$$

Additionally, the electricity generation of each energy source must be non-negative:

$$EG_{(e)} \geq 0$$

Capacity Constraints.

The installed capacity of each energy source in Equation (11) should not exceed the maximum allowable capacity.

$$X_{(e)} \leq MAC_e^{max} \quad (11)$$

The model makes use of annualized CAPEX to ensure consistency and comparable cost assessment across technologies with different lifetimes and O&M profiles. Using capital recovery factors shown in the equation below:

$$CRF = \frac{r(1+r)^n}{(1+r)^n - 1} \quad (12)$$

Levelized cost of electricity (LCOE) and Net Present Costs (NPC) are also computed for each of the technologies considered in this study, to enable a realistic comparison of the cost effectiveness of the energy sources.

2.2 Case Study: The Mini-Grid at Eka Awoke, Ikwo

The developed mathematical model was applied to the Solar PV mini-grid in Appendices A and B at Eka Awoke Community in the Ikwo Local Government Area of Ebonyi State, Nigeria. Ikwo, the largest local government area in Ebonyi State, is in the eastern part of the state, covering an area of 690.9 km². It shares borders with the Abakaliki and Ezza Local Government Areas within Ebonyi State, as well as Cross River State. Ikwo is inhabited by a subgroup of the Igbo race, who are native to southeastern Nigeria.

Eka Awoke, a community in Ikwo, is very rich in both human and mineral resources. The community is also rich in Agriculture as its soil is overly fertile for rice and yam plantation. To this end, only farming activities have been recorded in this region of Ebonyi State despite the countless efforts of companies in negotiating the exploration of the vast mineral deposits in the region. Eka Awoke is blessed with five villages, which include Aguiyima, AcharaUkwu, Ezeke, Ndigu Umoka, and Ndiufu Umuota, and these villages are to be electrified. Currently, there is no access to the national grid in the community, and this is not expected to change in the future for several reasons, such as topography, distance, etc.

The community was selected due to its significant capacity shortage, unavailability of operational data, mining activities, the fact that it is in a hot semi-arid tropical climate, geological subsurface activities, and housing the first mini-grid in the region. Eka Awoke lies between 6°3.3' N latitude and 8°3.8' E longitude (See Appendix A and Appendix B) with an elevation of 10 to 282 m above sea level, with a mean annual temperature of 29°C. The location of mini-grid spots in Ebonyi State is presented by SE4ALL in Figure 2.

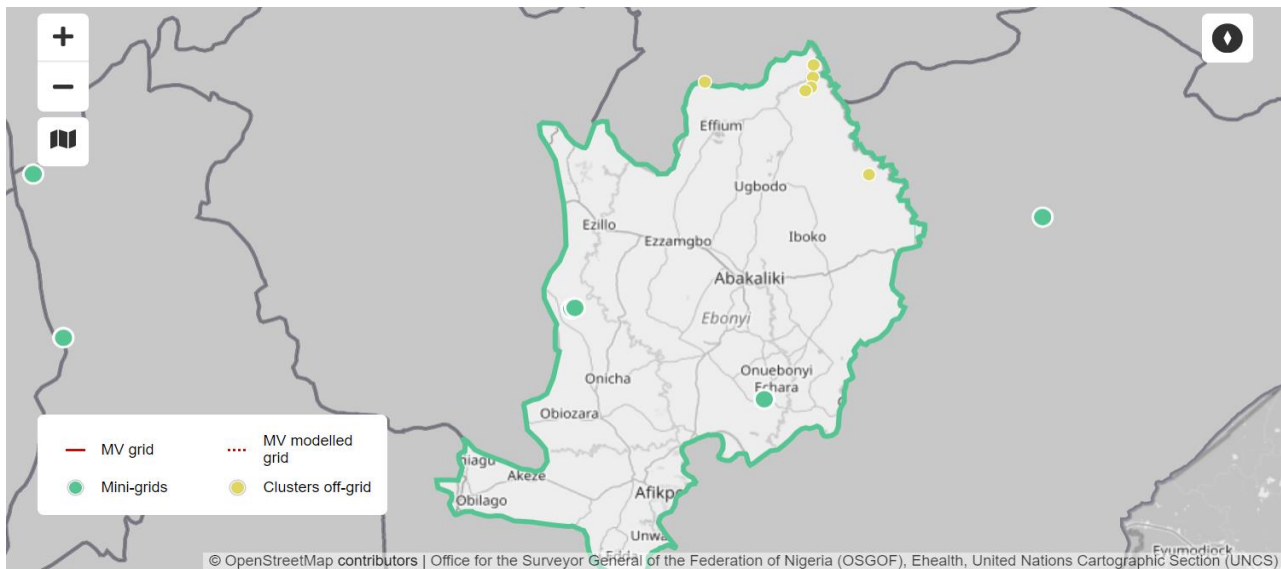


Figure 2 Mini-grid at Ebonyi State (SE4ALL).

The energy demand of the people of Eka Awoke has been mainly satisfied by household diesel generators, with no prospect of grid electricity for decades. Replacing this type of resource with new technologies that utilize renewable energy sources would significantly enhance the regularity and reliability of the electricity supply while also reducing carbon emissions.

Although the PV mini-grid in the community has no form of backup diesel mini-grid generator, as reported in other studies [35-37], that is used to generate power, several households opted to use conventional diesel to augment the generated power. There is no record of wind energy in the region in the literature. Therefore, solar energy is the only resource considered for power generation in the community. All the system components for the Solar PV systems include PV modules, battery, converter, AC bus, distribution loads, and loads.

Recently, solar energy was extracted, transformed, and transported via a mini-grid to supply electricity to some of the houses in the community by the Rural Electrification Agency of Nigeria. It is the first successful project by the Rural Electrification Agency (REA) in Eka Awoke, connecting five villages at a close distance and managed by the host community. According to information on the REA website, the installed solar hybrid mini-grid power plant has a total capacity of 100 kW. It features 330 high-grade solar panels and a 12 km distribution cable.

The availability of sunlight and the region's hilly terrain have made this technology well-suited for generating electricity for lighting and other productive uses in the clustered remote villages of the community. However, reports from the Rural Electrification Agency of Nigeria indicate that the electricity generated is insufficient to meet the needs of all the households in the community [38], prompting the need to increase the penetration of renewable energy generation technologies, such as the addition of geothermal energy. Ebonyi state has often been listed in the Benue Trough and Lower Niger Basin, where moderate-temperature hydrothermal systems (60–110°C) occurring at depths of 2-3 km, provided the geothermal assumptions [39]. Although the community does not have any direct drilling data, but that they belong to the same tectonic band as the Benue Trough and Lower Niger Basin further suggests that the community has low-enthalpy resources that might be used for small-scale geothermal development. There is no subsurface characterization or comprehensive local geothermal resource data available in the study region. The community is part

of the southern end of the lower Benue trough of Nigeria and is associated with the occurrence of dolerite, monzonite, and syenite igneous intrusions, among other volcanic with sedimentary rocks. The 3,000-meter-thick Asu River Group was the first sediment to be deposited in the Lower Benue Trough. The Odukpani Formation was deposited during the transgressive Cenomanian period. The Eze-Aku Group and the maritime Agwu shale were deposited because of the Turonian incursion. The Turonian–Coniacian sequence ranges in thickness from 1,300 to 2,000 meters [40]. In the absence of site-specific geothermal energy data, this study considered a hypothetical integration of small-scale geothermal systems with characteristics (cost, capacity factor) in Table 1 under realistic Sub-Saharan conditions.

Table 1 Parameters for the energy system calculation.

Energy source	Parameter	Value	References
Geothermal	Capital cost (\$/kW)	2000	[41]
	Maximum allowable capacity (kW)	1000000	[42]
	Variable O&M (\$/kWh)	0.015	[43]
	Fixed O&M (\$/kW/year)	110	[41]
	Capacity factor (%)	82	[41]
	Annual operational lifespan (Years)	25	[41]
	Emission factor (gCO ₂ /kWh)	0	[44]
	Emission cost coefficient index (\$/tCO ₂)	0	[44]
	Existing capacity (kW)	0	
Solar PV energy calculations+Battery	Capital cost (\$/kW)	1500	[45]
	Existing capacity (kW)	100	[46]
	Maximum allowable capacity (kW)	1000000	[47]
	Variable O&M (\$/kWh)	0.002	[48]
	Fixed O&M (\$/kW/year)	13	[49]
	Capacity factor (%)	20	[50]
	Sum annual operational lifespan (Years)	30	[50]
	Emission factor (g/kWh)	0	
	Emission cost coefficient index (\$/tCO ₂)	0	
Wind energy calculation+Battery	Capital cost (\$/kW)	1800	[51]
	Existing capacity (kW)	0	
	Maximum allowable capacity (kW)	1000000	[52]
	Variable O&M (\$/kWh)	0.006	[53]
	Fixed O&M (\$/kW/year)	35	[54]
	Capacity factor (%)	25	[55]
	Sum annual operational period (Years)	20	
	Emission factor (g/kWh)	0	
	Emission cost coefficient index (\$/tCO ₂)	0	
Diesel generator	Variable O&M (\$/kWh)	0.30	[56]
	Fixed O&M (\$/kW/year)	20	[57]
	Capacity factor (%)	69	[58]
	Sum annual operational period (Years)	30	

Emission factor (g/kWh)	232.5	[59]
Emission cost coefficient index (\$/tCO ₂)	50	[60]
Existing capacity (kW)	100	[46]
Maximum allowable capacity (kW)	1000000	

To provide sufficient and reliable electricity to the unelectrified areas in the community, the addition of small-scale geothermal energy and a wind turbine to increase the generation capacity of the existing central solar PV mini-grid energy system is explored.

2.3 Data and Scenario

2.3.1 Data

The parameters used in the model are derived from various academic reports. When there is significant variation in the reported values, the most frequently cited sources are used as estimates for the model. The cost, efficiency, and emission-related parameters for different technologies are shown in Table 1. The existing capacity data was obtained from [46]. The reported costs are in actual USD for 2024. According to REA [3], measurements from functioning solar mini-grids in southeast Nigeria are used to calculate the expected 10% distribution loss, 1,000,000 kW as the maximum allowable capacity was used as a non-binding upper bound placeholder in the manuscript to prevent solver infeasibility.

The PV+storage setup was modeled as a combined system, with the capacity factor standing for the battery discharge and the current solar mini-grid's effective utilization rate rather than the PV array alone. Therefore, the value of 20% [61] represents the total energy output over the course of a year from combined solar generation and battery operation.

This aggregated CF was chosen to maintain model tractability within an annual energy-balance framework, even if it simplifies the solar–storage interaction. Future temporal or hourly simulations will incorporate an improved PV-only CF with independent storage modeling, acknowledging the restriction. For diesel, the fixed O&M costs are set at 20\$/kW/yr [57]. While the carbon price is set at 50\$/tCO₂ [60] and modeled with variable O&M costs (\$0.30/kWh), which explicitly includes fuel and routine maintenance costs [56]. These assumptions provide a more realistic representation of the diesel energy source costs and emissions, allowing the model to completely assess and decarbonize the demand scenario, reduce bias, and demonstrate the economic transition to renewable energy. The model is in line with HOMER-style mini-grid analysis frameworks since it only takes direct operational emissions into account. Therefore, diesel emissions are computed using an emission factor of 50\$/tCO₂, whereas renewable technologies (solar, wind, and geothermal) are assigned zero operating emissions. Since operational decarbonization of current mini-grids, rather than embedded manufacturing emissions, is the focus of the study, lifetime emissions were not included.

2.3.2 Demand Scenarios

This study explored annual aggregated demand values due to the lack of hourly, seasonal load, and generation data for the study area. While the approach is appropriate for capacity expansion studies for off-grid regions with data scarcity conditions [62], the study did not capture the seasonal

variability of solar PV output and therefore did not model the state of change dynamics of the storage system. However, geothermal energy, which is the primary expansion option, remained the cost-effective option and therefore less affected by temporal resolution.

Base Case Scenario-PV Minigrid-Eka Awoke. The baseline represents the current condition with an estimated 3,200 households and 128 SMEs connected. The annual electricity consumption in this scenario is estimated at 1,383,120 kWh/year, shown in Table 2. This study adopts average monthly electricity consumption values of 30 kWh/month per household and 150 kWh/month for Small and Medium Enterprises (SMEs) based on figures reported by [63] for application in a rural community context.

Table 2 Summary of the scenarios.

Scenario	Households (kWh/year)	SMEs (kWh/year)	Total (kWh/year)
Baseline	1,152,720	230,400	1,383,120
Suppressed Demand	768,480	153,600	922,080
Increased Connections	1,368,720	273,600	1,642,320
eCooking Integration+increased connections	2,053,320	273,600	2,326,920

Scenario 1 - Increased Connection Demand. The increased connection demand scenario is used to show what happens when there is an increase in the number of connected households and SMEs. This scenario assumes that there are an additional 600 households and 24 SMEs added from a neighbouring village, thereby increasing the total demand consumption to 1,642,320 kWh/year shown in Table 2.

Scenario 2 - Suppressed Demand. This suppressed electricity demand scenario illustrates the gap between the need for energy and the actual ability to consume it, driven primarily by economic challenges and a lack of affordable infrastructure. The total demand for this scenario is restricted to 922,080 kWh/year shown in Table 2.

Scenario 3 - eCooking Integration+Increased Connections. Electric cooking (eCooking) is introduced as a potential appliance type that could significantly impact the community's electricity demand profile. The adoption of eCooking technologies such as electric stoves, rice cookers, or induction cooktops would drastically increase household electricity consumption. The eCooking scenario highlights the opportunity to reduce the over-reliance on traditional cooking fuels such as wood and charcoal. It is assumed that 30% of the households adopt eCooking appliances (e.g., induction stoves, electric pressure cookers) and the eCooking consumption per HH is 50 kWh/month [64]. The total energy consumption for the eCooking with increased connection scenario, shown in Table 2, is estimated at 2,326,920 kWh/year.

The study lacks high temporal resolution data for hourly or seasonal load and generation to support multi-period in the community. However, the focus of this study is to compare capacity expansion outcomes under different demand scenarios rather than focus on detailed dispatch power. The annual aggregated demand data used in this study is therefore sufficient to assess the

impacts of the demand scenario on the obtained generational capacity and system costs while maintaining model simplicity and trackability(See Appendix C).

2.4 Sensitivity Analysis

The sensitivity analysis is based on the uncertainties in capital cost and maximum capacity shortage to understand the technical and economic behavior of the energy system in increasing local energy access in the community.

3. Results and Discussion

3.1 Category 1: With Diesel

This section presents the results under the assumption that the existing diesel generator will still be in use.

3.1.1 Optimal Capacity Additions and Electricity Generation

The existing solar PV with diesel capacity remains unchanged in the four demand scenarios. The addition of geothermal energy increased the capacity of the energy supplied by the solar PV and diesel generator. Geothermal energy dominates as the cost-effective option due to its higher capacity factor and lower capital costs, as shown in Table 3. Additionally, the percentage increase from the baseline scenario shows that the geothermal energy capacity additions would need to be expanded by 21.21% and 77.71% for the increased connection and increased connection with eCooking demand scenarios, respectively, while the baseline would be reduced by 37.7% for the suppressed demand scenario.

Table 3 Optimal capacity additions by component type for each scenario.

Energy sources	Baseline (kW)	Suppressed Demand (kW)	Increased Connection (kW)	eCooking+Increased Connections (kW)
Geothermal	187.41	116.81	227.11	331.94
Wind+storage	0.00	0.00	0.00	0.00
Solar PV+storage	0.00	0.00	0.00	0.00
Diesel	0.00	0.00	0.00	0.00

Additionally, in terms of generation shown in Table 4, solar+storage and diesel utilization remain unchanged, and they generate the same amount of electricity with their existing capacity across the demand scenarios. Geothermal energy generates electricity based on the built capacities to meet the total demand.

Table 4 Electricity generation by different energy sources.

Scenario	Geothermal kWh	Wind+storage kWh	Solar+storage kWh	Diesel	Total kWh
Baseline	1,346,232	0	175,200	0	1,521,432
Suppressed demand	839,088	0	175,200	0	1,014,288
Increased connection	1,631,352	0	175,200	0	1,806,552
eCooking+increased connection	2,384,412	0	175,200	0	2,559,612

3.1.2 Total Costs

Table 5 shows the variation of the total annualized costs of the energy sources across the different demand scenarios for the entire planning period in the community. As expected, the total annualized energy costs of the community increase as demand increases. In terms of the demand and generation capacity in the baseline scenario, the total costs increase by 20.3% and 73.5% for the increased connection and increased connection with eCooking, respectively, while there is a 35.9% reduction of the total costs in the suppressed demand scenario. Increases in the capital and fixed O&M costs vary across the demand scenarios in this study and are in line with [65]. The objective function values from the baseline represent the total costs for the energy sources for the electrification of 3202 households and 128 SMEs in the community. The annual costs distribution demonstrates that geothermal dominates the energy system costs, with annual capex and O&M accounting for the majority of the total annual costs. For instance, in the baseline scenario results, geothermal contributes \$75,922.44 (95.41%) out of \$79,572.84 per year, highlighting its importance in the community, while wind+storage contributes 0%, solar PV+storage contributes 2.07%, and diesel contributes 2.51% (see Table 5). Thus, the model finds geothermal energy expansion more cost-effective to develop in the local community. For other scenarios, the results obtained show that geothermal energy contribute 92.85%, 96.20% and 97.36%, wind+storage contributes 0%, solar PV+storage contributes 3.24%, 1.73% and 1.19%, diesel contributes 3.92%, 2.09% and 1.45% of the total annualized costs of the energy system, respectively, for the suppressed increased connections, and increased connections+eCooking demand scenarios. The discounted cash flow in Appendix D-G accounts for uncertainty in capital budgeting decisions.

Table 5 Total annualized cost distribution of energy sources.

		Scenario		Baseline	
Source	Annual CAPEX	Variable O&M	Fixed O&M	Emission	Total
1	35,113.42	20,193.48	20,615.54	0.00	75,922.44
2	0.00	0.00	0.00	0.00	0.00
3	0.00	350.40	1,300.00	0.00	1,650.40
4	0.00	0.00	2,000.00	0.00	2,000.00
Total					79,572.84

		Scenario		Suppressed demand	
Source	Annual CAPEX	Variable O&M	Fixed O&M	Emission	Total
1	21,885.72	12,586.32	12,849.38	0.00	47,321.42
2	0.00	0.00	0.00	0.00	0.00
3	0.00	350.40	1,300.00	0.00	1,650.40
4	0.00	0.00	2000.00	0.00	2,000.00
Total					50,971.82

		Scenario		Increased connections	
Source	Annual CAPEX	Variable O&M	Fixed O&M	Emission	Total
1	42,550.13	24,470.28	24,981.72	0.00	92,002.14
2	0.00	0.00	0.00	0.00	0.00
3	0.00	350.40	1,300.00	0.00	1,650.40
4	0.00	0.00	2000.00	0.00	2,000.00
Total					95,652.54

		Scenario		Increased connections+eCooking	
Source	Annual CAPEX	Variable O&M	Fixed O&M	Emission	Total
1	62,192.00	0.00	36,513.72	0.00	134,471.90
2	0.00	0.00	0.00	0.00	0.00
3	0.00	350.40	1,300.00	0.00	1,650.40
4	0.00	0.00	2000.00	0.00	2,000.00
Total					138,122.30

The Levelized Cost of Electricity (LCOE) is presented for both at the system level in Table 6 and individual energy sources (Table 7) to provide a clear measure of the average costs to produce one kilowatt-hour of electricity over the lifetime of each energy source. The results are presented below:

Table 6 System-level analysis.

Scenario	Annualized costs (\$)	NPC (\$)	LCOE (\$/kWh)
Baseline	79,572.84	781,257.87	0.0523
Suppressed demand	50,971.82	500,448.83	0.0503
Increased connections	95,652.54	939,130.72	0.0529
Increased connections+eCooking	138,122.30	1,356,105.10	0.0540

Table 7 LCOE by source per scenario.

Scenario	Source 1 (\$/kWh)	Source 2 (\$/kWh)	Source 3 (\$/kWh)	Source 4 (\$/kWh)
Baseline	0.0564	N/A	0.0094	N/A
Suppressed demand	0.0564	N/A	0.0094	N/A
Increased connections	0.0564	N/A	0.0094	N/A
Increased connections+eCooking	0.0564	N/A	0.0094	N/A

Evaluating the technical and financial viability of integrating geothermal energy into an existing solar mini-grid framework was the aim of the study. The model also incorporates capacity-limit sensitivity studies in Table 7 to examine outcomes under constrained geothermal availability, even though the geothermal resource potential in the study region (Eka Awoke, Ebonyi State) has not been directly validated. This recognizes the unpredictability of resources and how it may affect system configuration. However, these assumptions are still preliminary and need more geophysical confirmation.

3.1.3 Uncertainty in Capital Costs and Capacity Limit

In this study, capital costs and capacity limits were identified as the key sensitive parameters affecting the optimization results. Sensitivity analysis is conducted to explore the tipping point of each parameter to ascertain the uncertainties in the capital costs of the wind+storage. A similar pattern was reported by [63] in mini-grid capacity expansion to capture plausible uncertainties in capital costs due to fluctuations in market, supply, and technology. Table 8 shows that with an increase of 115% in capital costs of geothermal energy, the model selects solar+storage as the cost-effective solution, with a 60% reduction of the capital costs of wind+storage, the model selects wind+storage as the cost-effective option. With a 40% decrease in the capital costs of solar+storage, the model selects solar+storage as the cost-effective option, as shown in Table 8.

Table 8 Sensitivity cost analysis results of geothermal energy, solar+storage, and wind+storage.

Capital costs	Energy sources	Baseline (kW)	Suppressed Demand (kW)	Increase Connection (kW)	eCooking+Increased Connections (kW)
Geothermal +115%	Geothermal	0.0	0.0	0.0	0.0
	Wind+Storage	0.0	0.0	0.0	0.0
	Solar+Storage	768.40	478.93	931.14	1360.97
	Diesel	0.0	0.0	0.0	0.0
Wind+storage energy -60%	Geothermal	0.0	0.0	0.0	0.0
	Wind+Storage	614.72	383.15	744.91	1088.77
	Solar+Storage	0.0	0.0	0.0	0.0
	Diesel	0.0	0.0	0.0	0.0
Solar+storage energy -40%	Geothermal	0.0	0.0	0.0	0.0
	Wind+Storage	0.0	0.0	0.0	0.0
	Solar+Storage	768.40	478.93	931.14	1360.97
	Diesel	0.0	0.0	0.0	0.0

With the predicted cost and capacity factor, geothermal energy will be the first option for the system. In this section, different maximum capacities of geothermal are added as a constraint to explore the optimal pathway when there is a limit to developing geothermal energy. As shown in Table 9, solar energy with storage will be selected under the increased connection scenario and eCooking scenarios when the maximum capacity of geothermal is 100 kW. When geothermal energy is capped at 200 kW, the optimal solution will be a mix of geothermal and solar+storage only under the eCooking scenario. If geothermal energy capacity is expanded to 300 kW, no other energy sources will be selected in the studied area except geothermal energy as the cost-effective option. The capacity-limit sensitivity studies in Table 9, which show situations in which the availability of geothermal resources is limited to 100–300 kW, are used to address this uncertainty. They demonstrate how the ideal mix changes in favor of solar+storage.

Table 9 Energy capacity expansions under 4 scenarios with different geothermal capacity limits.

Geothermal Capacity Limits (kW)	Energy sources	Baseline (kW)	Suppressed Demand (kW)	Increase Connection (kW)	eCooking+Increased Connections (kW)
100	Geothermal	100.00	100.00	100.00	100.00
	Wind+Storage	0.0	0.0	0.0	0.0
	Solar+Storage	358.40	68.93	521.14	950.97
	Diesel	0.0	0.0	0.0	0.0
200	Geothermal	187.41	116.81	200.00	200.0
	Wind+Storage	0.0	0.0	0.0	0.0
	Solar+Storage	0.0	0.0	111.14	540.97
	Diesel	0.0	0.0	0.0	0.0
300	Geothermal	187.41	116.81	227.11	300.00
	Wind+Storage	0.0	0.0	0.0	0.0
	Solar+Storage	0.0	0.0	0.0	1300.97
	Diesel	0.0	0.0	0.0	0.0

3.2 Category 2: Decarbonization (Phasing Out Diesel)

This section presents the results under the assumption that the existing diesel generator will not be in use.

3.2.1 Optimal Capacity Addition and Electricity Generation

Geothermal energy dominates as the cost-effective option; the results obtained are shown in Table 10. Wind and solar with their storage were not selected for lower capital, operation, and maintenance costs.

Table 10 Optimal capacity additions by component type for each scenario.

Energy sources	Baseline (kW)	Suppressed Demand (kW)	Increased Connection (kW)	eCooking+Increased Connections (kW)
Geothermal	187.41	116.81	227.11	331.94
Wind+storage	0.00	0.00	0.00	0.00
Solar PV+storage	0.00	0.00	0.00	0.00

Decarbonizing the system has little impact on the model, as diesel was not cost-effective.

The generation result obtained is shown in Table 11. Geothermal energy also dominates electricity generation and is increasingly used to meet rising demand under the capacity factor, costs, and technical assumptions of electricity generated. Solar+storage remains constant under the demand scenarios based on the existing capacity. Wind+storage is not selected; it is neither built nor generated under the demand scenarios.

Table 11 Electricity generation by different energy sources.

Scenario	Geothermal kWh	Wind+storage kWh	Solar+storage kWh	Total kWh
Baseline	1,346,232	0	175,200	1,521,432
Suppressed demand	839,088	0	175,200	1,014,288
Increased connection	1,631,352	0	175,200	1,806,552
eCooking+increased connection	2,384,412	0	175,200	2,559,612

3.2.2 Total Costs

Table 12 shows the variation of the total annualized costs of the energy sources across the different demand scenarios for the entire planning period in the community. As expected, the total annualized energy costs of the community increase as demand increases. Compared to the baseline scenario, the total costs increase by 20.7% and 75.5% for the increased connection and increased connection with eCooking, respectively, while there is a 36.9% reduction of the total costs in the suppressed demand scenario. The annual costs distribution demonstrates that geothermal dominates the energy system costs, with annual capex and O&M accounting for the majority of the total annual costs. For instance, in the baseline scenario results, geothermal contributes \$75,922.44 (97.90%) out of \$77,572.84 per year, highlighting its importance in the community, while wind+storage contributes 0%, and solar PV+storage contributes 2.13%. Thus, the model finds geothermal energy expansion more cost-effective to develop in the local community. For other scenarios, the results obtained show that geothermal energy contributes 96.64%, 98.26% and 98.75%, wind+storage contributes 0%, solar PV+storage contributes 3.37%, 1.76% and 1.21%, of the total annualized costs of the energy system, respectively, for the suppressed increased connections, and increased connections+eCooking demand scenarios.

Table 12 Cost distribution of energy sources.

		Scenario	Baseline		
Source	Annual CAPEX	Variable O&M	Fixed O&M	Emission	Total
1	35,113.42	20,193.48	20,615.54	0.00	75,922.44
2	0.00	0.00	0.00	0.00	0.00
3	0.00	350.40	1,300.00	0.00	1,650.40
Total					77,572.84
		Scenario	Suppressed demand		
Source	Annual CAPEX	Variable O&M	Fixed O&M	Emission	Total
1	21,885.72	12,586.32	12,849.38	0.00	47,321.42
2	0.00	0.00	0.00	0.00	0.00
3	0.00	350.40	1,300.00	0.00	1,650.40
Total					48,971.82
		Scenario	Increased connections		
Source	Annual CAPEX	Variable O&M	Fixed O&M	Emission	Total
1	42,550.13	24,470.28	24,981.72	0.00	92,002.14
2	0.00	0.00	0.00	0.00	0.00
3	0.00	350.40	1,300.00	0.00	1,650.40
Total					93,652.54
		Scenario	Increased connections+eCooking		
Source	Annual CAPEX	Variable O&M	Fixed O&M	Emission	Total
1	62,192.00	0.00	36,513.72	0.00	134,471.90
2	0.00	0.00	0.00	0.00	0.00
3	0.00	350.40	1,300.00	0.00	1,650.40
Total					136,122.30

The Levelized Cost of Electricity (LCOE) is presented for both at the system level in Table 13 and individual energy sources (Table 14) to provide a clear measure of the average costs to produce one kilowatt-hour of electricity over the lifetime of each energy source. The results are presented below:

Table 13 System-level analysis.

Scenario	Annualized costs (\$)	NPC (\$)	LCOE (\$/kWh)
Baseline	77,572.84	761,621.57	0.0510
Suppressed demand	48,971.82	480,812.53	0.0483
Increased connections	93,652.54	919,494.43	0.0518
Increased connections+eCooking	136,122.30	1,336,468.81	0.0532

Table 14 LCOE by source per scenario.

Scenario	Source 1 (\$/kWh)	Source 2 (\$/kWh)	Source 3 (\$/kWh)
Baseline	0.0564	N/A	0.0094
Suppressed demand	0.0564	N/A	0.0094
Increased connections	0.0564	N/A	0.0094
Increased connections+eCooking	0.0564	N/A	0.0094

3.2.3 Uncertainty in Capital Costs and Capacity Limits

The capital cost and capacity constraints are both adjusted to ascertain their influence on optimal decarbonized investment strategies of the energy sources. To assess the impact of the variability of the capital costs of geothermal, wind+storage, and solar+storage energy sources in the absence of diesel, a sensitivity analysis was also carried out in the literature to identify the range of uncertainty in the capital cost values [63] whose analysis stated that the mini-grid needs to be expanded by 30%, 157% and 236% in the scenarios considered in their study. Our study considered a relatively moderate percent change in the capital costs, for example; a 115% increase of the capital costs for geothermal energy, a 60% reduction of the capital costs for wind+storage, and a 40% reduction of the capital costs for solar+storage energy, with the fixed and variable O&M costs remaining constant, to examine the potential fluctuations in capacity additions and the tipping points. Table 15 shows that with an increase of 115% in capital costs of geothermal energy, the model selects solar+storage as the cost-effective solution. The maximum capacity values for the wind resource potential are set to a high value to ensure they do not restrict the optimization solver. The optimal solution consistently selected zero wind capacity under the demand scenarios, thereby reflecting low wind potential in the region. Under sensitivity scenarios, with a 60% reduction in capital costs of wind+storage, the model selects wind+storage as the cost-effective option, demonstrating that wind is economically noncompetitive at relative costs and resource levels., while with a 40% reduction in the capital costs of solar+storage, the model selects solar+storage as the cost-effective option as shown in Table 15.

Table 15 Sensitivity costs analysis results of geothermal energy, wind+storage, and solar+storage.

Capital costs	Energy sources	Geothermal			
		Baseline (kW)	Suppressed Demand (kW)	Increase Connection (kW)	eCooking+Increased Connections (kW)
+115%	Geothermal	0.0	0.0	0.0	0.0
	Wind+Storage	0.0	0.0	0.0	0.0
	Solar+Storage	768.40	478.93	931.14	1360.97
Wind+storage					
-60%	Geothermal	0.0	0.0	0.0	0.0
	Wind+Storage	614.72	383.15	744.91	1088.77
	Solar+Storage	0.0	0.0	0.0	0.0
Solar+storage					
-40%	Geothermal	0.0	0.0	0.0	0.0
	Wind+Storage	0.0	0.0	0.0	0.0
	Solar+Storage	768.40	478.93	931.14	1360.97

The model also selects geothermal, solar+storage as the optimal solution for the increased connections and eCooking+increased connections demand pathways in Table 16 when the capacity limit of geothermal energy is 100 kW and 200 kW, selects only geothermal energy as the cost-effective solution for the eCooking+increased connection pathway only when the capacity limit is 300 kW.

Table 16 Capacity limits of geothermal energy for each scenario when the maximum limit of geothermal energy is reduced.

Capacity limits	Energy sources	Baseline (kW)	Suppressed Demand (kW)	Increase Connection (kW)	eCooking+Increased Connections (kW)
100	Geothermal	100.00	100.00	100.00	100.00
	Wind+Storage	0.00	0.0	0.00	0.00
	Solar+Storage	358.40	68.93	521.44	950.97
200	Geothermal	187.41	116.81	200.00	200.00
	Wind+Storage	0.0	0.0	0.0	0.0
	Solar+Storage	0.0	0.0	111.14	540.97
300	Geothermal	187.41	116.81	227.11	300.00
	Wind+Storage	0.00	0.00	0.00	0.00
	Solar+Storage	0.00	0.00	0.00	130.97

4. Conclusion

This study adopted the configuration of “geothermal”, “solar+storage”, and “wind+storage” to increase the existing Solar PV mini-grid capacity in the community. The result obtained presented

geothermal energy as a cost-effective solution in this study. Several important findings were extracted from the study.

The results revealed that small-scale geothermal energy is the most cost-effective option in the community to fully meet the load, and at a reduced cost, improving the reliability of the electricity supplied.

The study investigated the impact of the integration of small-scale geothermal energy into a burdened off mini-grid installed in a remote community in Nigeria. The capacity expansion aimed to determine the energy sources' capacity additions to meet the load and increase local energy access in the community, and reliability at the lowest cost possible under the different demand scenarios. The results obtained showed that small-scale geothermal energy emerged as the cost-effective option, and with a supplement of wind+storage and solar+storage, can satisfy the substantial increase in community electricity demand up to 68.23% more than the baseline.

The sensitivity analysis conducted showed that a thorough demand evolution in the community and in the face of uncertainties over time is critical for achieving a robust mini-grid capacity expansion. The investment decision across all the demand scenarios explored showed that geothermal energy selection as the optimal option is more sensitive to changes in capital costs and capacity limits considered. Even a modest reduction in the capacity limits from 100 kW, 200 kW, and 300 kW on its expansion can shift the optimal solution to geothermal and solar+storage, thereby demonstrating the importance of accurately estimating geothermal, solar+storage, wind, and storage parameters in the future.

Although the optimization approach for the expansion of the existing mini-grid with varying demand scenarios is used to determine the optimal mini-grid capacity expanded in each demand scenario, the capacity expansion is attained through an assumed demand rather than real-time electricity consumption data. The main reason behind this was the lack of available consumption data in the community.

Nomenclature

Symbol	Description	Unit	Type
e	Energy supply option index (1 = geothermal, 2 = wind+storage, 3 = solar+storage, 4 = diesel)	–	Set
C_{TOT}^{CAP}	Total capital expansion cost over the planning period	\$	Variable
C_{TOT}^{VOM}	Total variable operation and maintenance cost over the planning period	\$	Variable
C_{TOT}^{FOM}	Total fixed operation and maintenance cost over the planning period	\$	Variable
$C_{TOT}^{Emission}$	Total CO ₂ emission cost over the planning period	\$	Variable
$C_{(e)}^{CAP}$	Capital cost of new energy source e	\$/kW	Parameter
$X_{(e)}$	Capacity of the newly added energy source e	kW	Decision variable
$C_{(e)}^{VOM}$	Variable O&M cost of energy source e	\$/kWh	Parameter
$EG_{(e)}$	Electricity generated by an energy source e	kWh	Decision variable
$CF_{(e)}$	Capacity factor of energy source e	% or fraction	Parameter

$E_{(e)}$	Existing capacity of energy source e	kW	Parameter
$T_{(e)}$	Annual operational hours of energy source e	hours/year	Parameter
$C_{(e)}^{FOM}$	Fixed O&M cost of energy source e	\$/kW/year	Parameter
$EF_{(e)}$	Emission factor of energy source e	g CO ₂ /kWh	Parameter
β	CO ₂ emission cost coefficient	\$/g CO ₂	Parameter
D	Total electricity demand of the five villages	kWh	Parameter
L	Total distribution losses	% or kWh	Parameter
$Emit^{Year}$	Total annual CO ₂ emissions	g CO ₂ /year	Variable
$Emit_{(e)}^{Max}$	Maximum allowable CO ₂ emission from source e	g CO ₂	Parameter
MAC_e^{max}	Maximum allowable installed capacity of source e	kW	Parameter
D	Total electricity demand of the five villages	kWh/year	Parameter
r	Discount rate	%	Parameter
n	Sum annual operational period	Years	Parameter
LCOE	Levelized cost of electricity	\$/kWh	
NPC	Net present costs	\$	

Author Contributions

All authors contributed to the manuscript as section writers: Uchechukwu Nwaiwu, Matthew Leach, and Lirong Liu contributed to the conceptualization and writing, Uchechukwu Nwaiwu, Fan He, Matthew Leach, and Lirong Liu contributed to the methodology and visualization, and Matthew Leach and Lirong Liu led the organization and supervision of the study.

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Competing Interests

The authors affirm that they have no known financial or interpersonal conflicts that would have appeared to have an impact on the research presented in this study.

Data Availability Statement

The data supporting the reported results are available from the corresponding author on request.

Additional Materials

The following additional materials are uploaded at the page of this paper.

1. Appendix A: The solar PV mini-grid infrastructure at Eka Awoke, Ikwo, Ebonyi State, Nigeria.
2. Appendix B: Existing Solar PV mini-grid at Eka Awoke.
3. Appendix C: Codes for Capacity Expansion of the Community.
4. Appendix D: Discounted Cash Flow (DCF) for the Baseline Scenario.

5. Appendix E: Discounted Cash Flow (DCF) for the Suppressed Demand Scenario.
6. Appendix F: Discounted Cash Flow (DCF) for the Increased Connections Scenario.
7. Appendix G: Discounted Cash Flow (DCF) for the eCooking Integration+Increased Connections Scenario.

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