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Analysis of a Hybrid Nuclear Renewable Energy Resource in a Distributed Energy System for a Rural Area in Nigeria

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Abstract: Climate change is one of the global issues being combatted in recent times. One of the measures is a worldwide cutdown on carbon emissions. This has brought about the rapid development of technologies that can best actualise this goal. The decentralised energy system is designed to harness the strengths of small power-generating sources such as renewable energy sources in a noncentralised manner to help meet the global need for clean energy. Renewable energy sources are faced with the challenge of intermittency, which brings about instability in the grid. Another source of clean energy is nuclear energy, which is traditionally large and not flexible; however, the recent development of technology has resulted in a scaled-down version of the large nuclear plants that are more flexible yet provide clean and stable electricity. This paper explores the possibility of deploying nuclear microreactors in the decentralised energy system and describes the features and the challenges of a decentralised energy system. The features of the small modular reactor that make it a viable candidate for the generating source in the decentralised energy system are explored. A case study for a DES system with a microreactor was conducted for a rural area in Nigeria. The HOMER software was used in simulating the optimum system, while TOPSIS was used in ranking the systems. The result showed that the PV/nuclear/battery system ranked first, followed by the PV/nuclear/wind and battery system.

Keywords: climate change; decentralised energy system; renewable energy sources; small modular reactors



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1. Introduction

Energy production (electricity, heat, and transport) produces about 73.2% of the global greenhouse gas emissions [1]. The need to address the issue of climate change has given rise to the need to reduce carbon emissions, resulting in the worldwide interest vested in adopting technologies that best proffer these solutions. The decentralised energy system has gained so much attention recently because of its ability to provide electricity using technology with minimal-to-zero carbon emissions in a sustainable manner. This is also very useful at this time because of the global rising energy need for the burgeoning population, with about 13% without access to electricity [2].

Conventional nuclear plants are designed to produce vast amounts of energy, mainly as a baseload. These giant plants are used in centralised energy systems; they are not usually flexible and cannot be integrated into a decentralised energy system. The problem of climate change has resulted in the need for more sources of green energy, which is seen in the influx of renewable energy sources [3]. Due to the intermittent nature of renewable energy sources, they are mainly best deployed in a hybrid energy system. Nuclear energy is a huge source of clean energy. To remain relevant, there is a need for flexibility and the ability to be integrated into the distributed energy system. Small modular reactors are small-sized nuclear reactors that can fit a decentralised energy system.

This work aims to analyse a hybrid system that comprises a nuclear reactor diesel plant and renewable energy resources. This is achieved in a case study of a rural community

in Nigeria, using an optimisation software, HOMER, to simulate the hybrid systems, and further, using a ranking tool, TOPSIS, to obtain the optimal system based on multicriteria. This paper is organised into seven sections: the remaining parts after this introduction include Section 2, which describes a distributed energy system; Section 3, describes the nuclear energy system of interest, Section 4, which comprises a study of the distributed energy systems and includes using the HOMER software to simulate the energy systems; Section 5, which comprises the ranking process using TOPSIS; Section 6, which is the discussion; and the final section is the conclusion.

2. Decentralised Energy Systems

A decentralised energy system, also known as a distributed energy system, involves using an energy system that generates energy close to the consumer [3]. The energy is not generated centrally like the conventional centralised energy system, but is developed from different sources and distributed through smaller grid systems called microgrids. In a decentralised system, the energy sources are close to the consumers reducing the electricity losses accrued to energy transmission. There is also flexibility in energy use, which is most needed for renewable energy sources because of their intermittent nature. The DES is an advancement in power systems that introduces better energy resource optimisation, smart metering, demand response, and renewable energy sources [4]. The DES was designed mainly as an improvement on the centralised energy system and accommodates the influx of renewable energy in the energy systems. The DES has several unique features that differentiate it from the centralised system; these features are further expounded.

The energy sources are close to the consumers, unlike the centralised system, in which energy sources are far from the point of consumption. This has helped reduce the problem associated with transporting electricity over long distances. In addition, rural areas without access to the centralised grid can harness the advantages of DES, thereby improving rural electrification. In DES, consumers can also be involved in the energy production process through demand response and other generation sources, leading to prosumers. Prosumers are energy consumers that are also able to produce energy.

DES also allows for an optimised harnessing of the available local energy resources, allowing for energy independence. With DES, a consumer will use an energy source with abundant raw material. For example, a community with a river will use hydropower, another community with a lot of wind will use a wind turbine, and a community with plenty of sunshine will use solar power. Different energy sources can be combined depending on the available natural resource. This helps consumers to maximise the available natural resource and gives the consumer energy independence. The grid system used in DES is often called a microgrid [5]. A microgrid is a local electrical system that is smaller than the conventional centralised grid. It is a cluster of micro-energy sources and loads that operates as a controllable unit and serves its locality electricity and/or heat [6]. The microgrid can be connected to the centralised grid and islanded (i.e., it can work alone). DES allows for the incorporation of more than one energy source. There are different approaches to combining this energy resource. Some terminologies used in describing these approaches are multienergy, polyenergy, and hybrid energy. The multienergy system uses various energy resources in a microgrid, such as solar energy, wind vanes, storage systems, electric vehicles [7], and possibly more energy resources. A polyenergy system refers to a source of energy producing more than one energy form, for example, using a small modular reactor for electricity, water desalination, and heating. A polyenergy system can also involve using a multienergy system to produce more than one energy form. The standard polyenergy system produces electricity, heating, and cooling, which are called the combined heat and power (CHP) system and the combined cooling, heat, and power (CCHP) system [4]. Hybrid energy refers to an energy source powered by different energy sources, such as an energy storage system powered by solar, wind, and other energy sources. The combinations can be used in many ways and interwoven depending on the method employed in a particular microgrid. When there is more than one energy resource, the

strength of the different energy sources is harnessed and maximised, and the weaknesses of the energy sources are minimised. For example, a community with lots of sunshine in the daytime and lots of wind at night will combine solar energy and wind energy. The energy solar provides electricity during the day; and at night, wind energy provides electricity. A lot of interest has been vested in the DES technology because it can deliver power for ancillary services, reduce demand on the central grid, maximise local energy resources, and minimise transmission complexities [5].

Some of the notable work conducted in the literature on DES include: a study of the impact of DES on energy transition in European urban cities, in which the role of renewable energy sources in the future microgrid was predicted to increase to 52% in 2050 [8]; and a review of different optimisation methods for distributed energy systems for rural electrification in India, which assessed the feasibility of rural microgrids in India [9]. In their work, Basit et al. (2020) explained the limitations and challenges of renewable energy systems [10]. The challenges faced by DES are mainly due to the problems associated with the use of renewable energy sources (RES). RES, due to its intermittent nature, causes instability in the grid. It also reduces grid reliability. There is a need for an energy source with a high capacity factor to bring stability to the grid and make the microgrid more reliable. The conventional fossil fuel-based generators are stable, but they can only add to the carbon emission; for cleaner energy, they need to consider other clean energy sources such as nuclear reactors.

The DES comprises different technologies, including bioenergy, geothermal, solar photovoltaic (PV), wind, hydro, fuel cells, microturbines, heat storage, and internal combustion engines [6]. Different designs have been developed to optimise the other energy resources in the microgrid. Aly et al. designed a microgrid that works with flywheels for energy storage [11]. In their study, two systems were developed, one with flywheel storage and another without flywheel storage. The two microgrids were analysed using the HOMER software; the microgrid with the flywheel storage system gave optimal results. Sanjay et al. [12] used the HOMER software in deriving the optimal system for an agriculture farm through the analysis of capital and operating cost of the hybrid renewable energy system that consists of solar PV with gasifier and solar PV with biogas. Ekren et al. [13] analysed the optimal solution for a hybrid renewable system for charging electric vehicles using the HOMER software. Babatunde et al. used HOMER for the feasibility study of a hybrid renewable energy system, which included batteries for a university in Nigeria.

Many researchers have used the HOMER software to analyse and obtain optimal results for microgrid systems with different energy source [12–14]. In this work, the HOMER software will be used to analyse the hybrid system that comprises a solar PV, a wind turbine, and a nuclear microreactor.

3. Nuclear Reactors

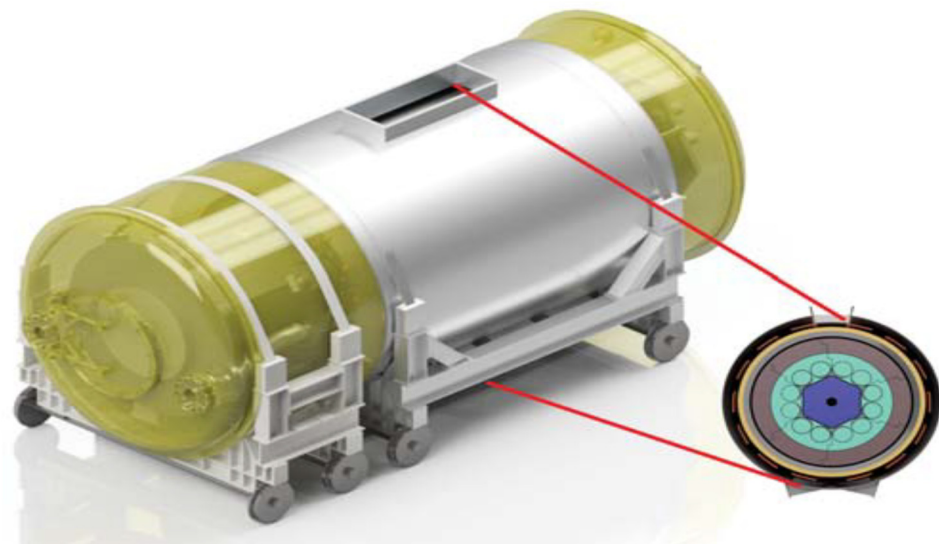
Nuclear reactors are systems that generate electricity using the heat energy produced from the fission process, which happens in the reactor's core. Nuclear reactors can be classified based on size, into large reactors, which generate power greater than 700 MW(e); and small modular reactors (SMR), which are nuclear reactors that generate power of about or lower than 300 MW(e). They are smaller than conventional nuclear power plants. The IAEA defines small and medium reactors as reactors producing up to 300 MW(e) (small-sized or small modular) and reactors producing 300–700 MW(e) (medium-sized), respectively [14,15]. Small modular reactors are designed to be inherently safe using passive safety systems. SMRs are capable of operating in the load-following mode. Small modular reactors are also designed to offer non-electrical applications such as district heating, desalination of seawater, and hydrogen production.

There are presently over 70 SMRs being designed across the world. There are presently 5 SMRs being operated, 4 under construction, 17 designs near the deployment stage, about 21 at the early design stage, and 11 tiny reactors (≥ 25 MW(e)) being designed. Small modular reactors can also be classified based on their coolants [16] which are five types:

integrated pressurised water, gas-cooled, molten-salt-cooled, liquid-metal-cooled, and sodium heat pipe. Classification according to size includes medium-sized (300–700 MW(e)), small-sized (≥ 300 MW(e)), and very small-sized (≥ 25 MW(e)) [16]. Classification based on the technology stage includes innovative, advanced, modified, and conventional SMRs [17]. They are also classified as land-based, floating, and immersed reactors [18]. For a microgrid, the reactor of interest is the very small-sized reactors, which are also called microreactors. For the simulation in this work, the eVinci reactor was used. The eVinci reactor was chosen because it can easily fit into a microgrid due to their size and capacity.

The eVinci Microreactor

The eVinci microreactor is being developed by Westinghouse with the capability of producing between 200 kWe to 5 MW(e) of combined heat and power [19]. The reactor has a unique design that removes decay heat using the heat pipe technology. The innovation in this reactor is combining the heat pipe technology, liquid metal, and commercial nuclear technology concepts in a simple, safe, and sustainable manner. The design is aimed to be deployed commercially by 2025. It is presently in the licensing stage. The eVinci reactors are small in size and are enclosed in canisters that allow for ease of transportation on rail, road, and sea. They are designed to be built in the factory and transported to the site of operation. The reactor is designed with passive safety systems that will shut down safely without requiring the operator's action in the event of an accident [20]. The reactor can also be easily refuelled and decommissioned by returning it to the manufacturer [21]. The eVinci reactor is designed to have up to 10 years' operational lifetime. The reactor core is designed to operate for more than 10 years, therefore removing the need for frequent refuelling [22]. This reactor was chosen for this research because of its design, which is proliferation-resistant due to the encapsulated core, which also enhances its safety [22]. The reactor can also be easily transported due to the size and containment. The reactor core can operate for 10 years without refuelling, and waste management is being handled by the manufacturer. It can also be easily integrated into a renewable-energy microgrid. Figure 1a,b show the eVinci reactor.



(a)

Figure 1. *Cont.*

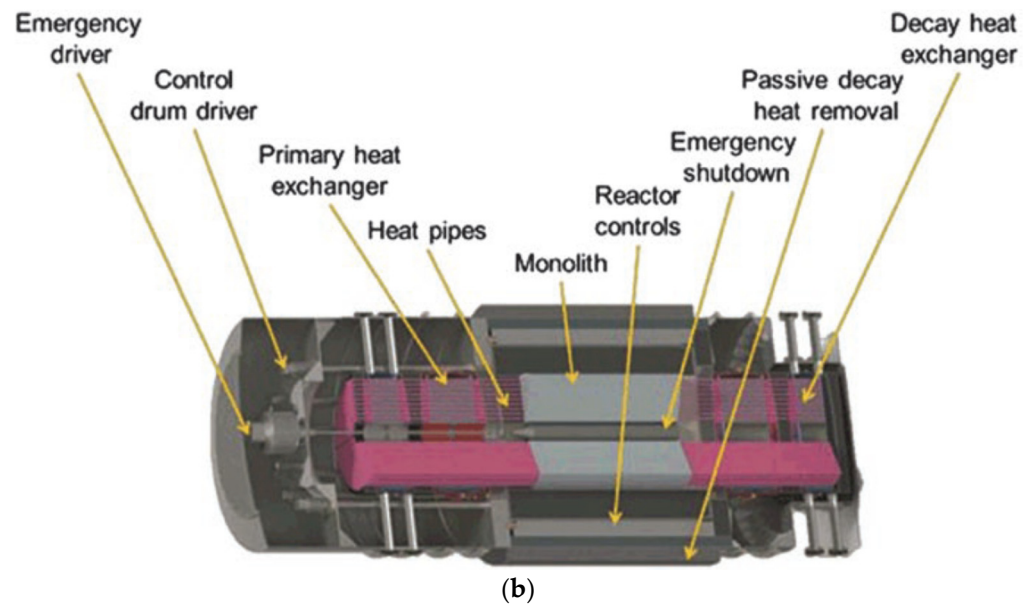


Figure 1. (a) eVinci reactor encapsulated in protective canisters [19]. (b) A crosssection showing the components of the eVinci reactor [22].

4. Case Study of SMR in a Distributed Energy System in a Rural Area in Nigeria Using HOMER Software and TOPSIS

In this section, the possibility of having a distributed energy system (DES) with an SMR is demonstrated using HOMER software. The location for this case study is Irele, a local government area in Ondo state in the western part of Nigeria. The local government has a population of about 141,000 people. For this case study, we designed an off-grid distributed energy system for an area in the local government. The community comprises 200 households, 3 schools, 1 hospital, 2 clinics, 3 bakeries, 4 block industries, 5 borehole water pumps, 1 bank, and 1 police station. A hypothetical load profile was developed based on a typical load pattern of a rural community. Two scenarios were created, which are scenario 1—DES comprised of renewable sources and a nuclear micro reactor; and scenario 2—DES comprised of renewable energy sources and a diesel generator. Load was classified as residential and nonresidential load. The energy resources used included a microreactor, a diesel generator, a solar photovoltaic cell, a wind farm, a converter, and a battery. Different combinations of resources were analysed and a ranking was made using a multicriteria approach.

4.1. The HOMER Software

The HOMER (Hybrid Optimization Model for Electric Renewable) software was used to analyse the microreactor and renewable distributed energy systems. HOMER is a tool that was originally developed at the National Renewable Energy Laboratory. HOMER combines the technical and the economical aspects of energy and is able to conduct optimisation analysis, sensitivity analysis, and a simulation of hybrid systems. In this case study, the HOMER was used to model the nuclear-renewable system and also optimise the cost of electricity. The output of the HOMER software, alongside other criteria, are used in ranking the different DES.

4.2. Input Parameters

This section contains the input to the HOMER software, which includes the load profile, the energy sources, and the environmental resources for the location of interest (Irele).

4.2.1. Load Profile

A hypothetical load profile was developed for a community Irele consisting of about 1800 people in 200 households. The load profile includes the residential load profile and the nonresidential load profile. The residential load profile was calculated based on household items, which include televisions (100 W each), refrigerators (100 W each), lighting bulbs (15 W each), and fans (70 W each). For the 200 households, the average daily load is 1084.4 kW/day and a peak load of 176.36 kW. The nonresidential load comprises all the other loads not included in the residential load: it covers for the 3 schools, 1 hospital, 2 clinics, 3 bakeries, 4 block industries, and 5 borehole water pumps. The average nonresidential load is 1002 kW/day and a peak load of 171.23 kW. The load profile for the community is given in Figure 2.

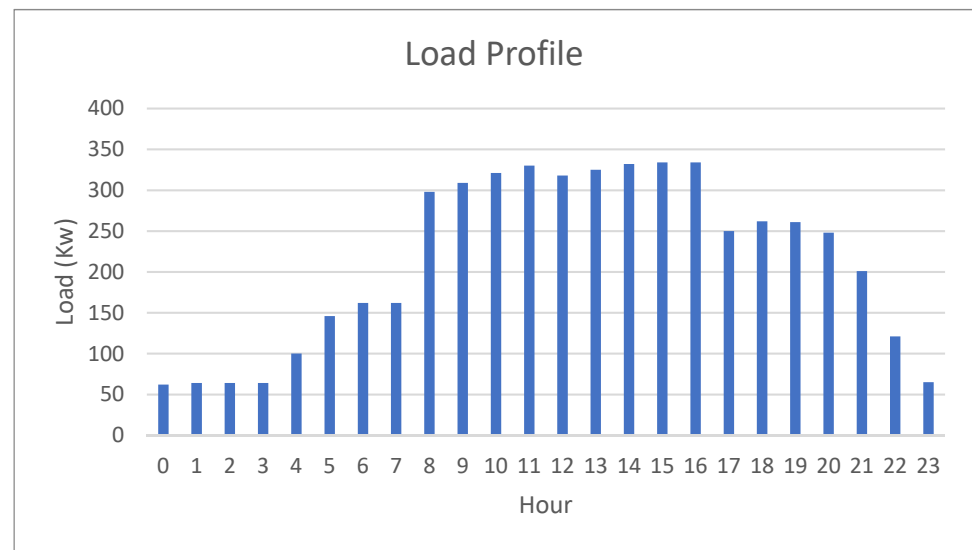


Figure 2. Load profile for Irele community.

4.2.2. Energy Resources

In this study, the first simulation contained renewable energy sources, and the small modular reactors as shown in Figure 3.

The second simulation contained renewable energy sources and a diesel generator. The renewable energy components are solar photovoltaic cells and wind turbine. It also contains a converter and a battery. The parameters for the energy resources are in Table 1. The cost for the energy systems was based on the present cost of the systems in Nigeria, except for nuclear plant, which was adapted from the National Renewable Energy Laboratory (NREL), which gave a present average cost of the nuclear plant. The number of operating years of the eVinci reactor, which is 10 years, was used for the life span of the nuclear reactor.

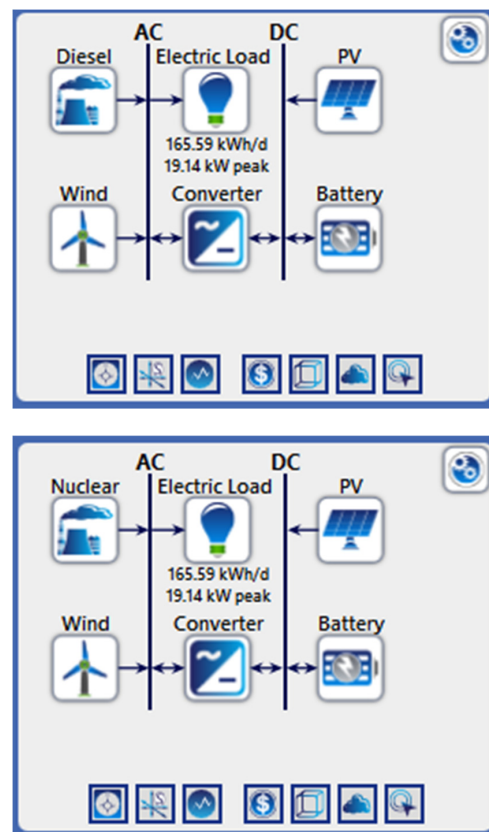


Figure 3. Distributed energy system showing the energy resource scenario 1 and 2.

Table 1. Energy resource parameters.

Generator	Capital Cost (USD)/KW	Replacement (USD)	O and M (USD)/Year	Lifespan (Year)	Source
Solar PV	3250	3200	3	20	Jumia [23]
Converter	621.8	569	3	15	Babatunde et al. [24]
Wind	12,000	11,000	100	15	Babatunde et al. [24]
Nuclear	7388	7000	145	10	NREL [25]
Diesel	7227	9885	43,848	2	Naijatechguide [26]

4.2.3. Renewable Energy Resource

The renewable resource for the wind turbine was imported on the HOMER software from the NASA Prediction of Worldwide Energy Resources (POWER) for the location of interest (Irele). Figure 4 shows the monthly average wind speed for this location.

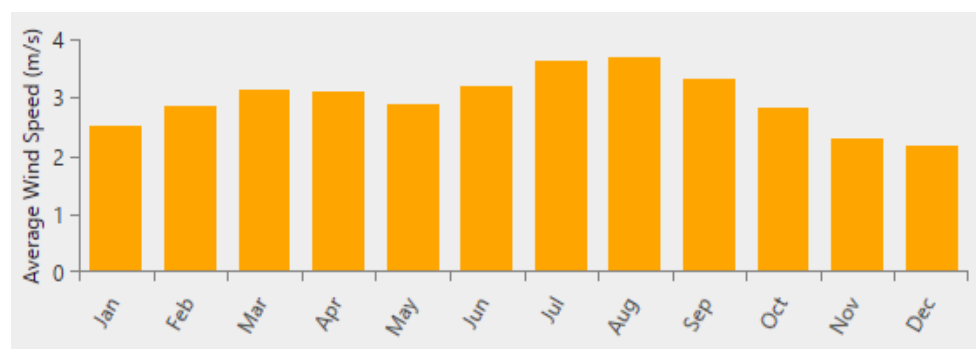


Figure 4. Irele monthly average wind speed.

The daily solar radiation was also retrieved from the NASA Prediction of Worldwide Energy Resources for Irele, shown in Figure 5.

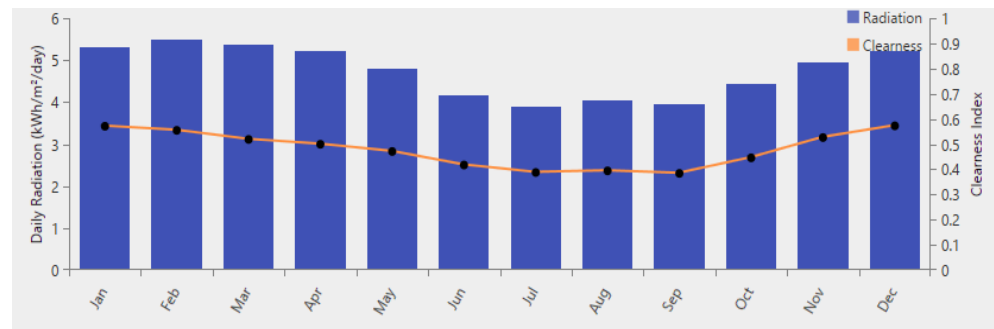


Figure 5. Irele solar radiation.

4.2.4. HOMER Software Output

This section is comprised of the results obtained from the HOMER software, which are comprised of both the economic and technical optimisation of the DES. The output from HOMER can be classified into economic, technical, and environmental output.

i. Economic output

The economic output obtained includes the net present cost (NPC), levelised cost of energy (LCOE), and the operating cost. In HOMER, the NPC represents the present value of all costs, which includes the cost of operations, maintenance, and fuel cost that is generated by the system over their lifetime minus the revenue earned over the lifetime of the system [27]. The NPC can be used to evaluate how feasible a project can be. The lower the NPC, the higher the feasibility of the system. The levelised cost of energy (LCOE) represents the price for 1 Kwh of electricity produced by the system [27]. The systems with microreactors had lower LCOEs compared with the system, which had a fully renewable operating cost. The operating cost is the annualised value of all cost minus the initial capital cost [27]. In this case study, the operating costs for 100% renewables are higher than the system with SMRs.

ii. Technical Output

The technical output from HOMER is comprised of excess electricity, unmet electric load, capacity shortage, and renewable fraction. Excess electricity is obtained when the minimum output from the energy source is greater than the load, then the surplus electricity needs to be dumped [27]. The unmet electric load is comprised of the loads that are unable to receive electricity supply from the system. Capacity shortage occurs when the capacity of a system is below that required by the microgrid. Renewable fraction represents the fraction of power supplied from a renewable energy source.

iii. Environmental Output

The HOMER software also estimates the emissions of greenhouse gases to the environment. The diesel generator has the highest greenhouse gas emission, while the renewable and nuclear sources do not have these emissions during electricity production.

The outputs from the HOMER software are shown in Tables 2 and 3.

Table 2. HOMER output for scenario 1 with nuclear energy and renewable sources.

	PV/N/B	PV/W/N/B	N/B	W/N/B	N	PV/N	W/N	PV/W/N
Operating Cost USD/year	15,132	15,049	60,558	60,378	145,185	145,188	145,559	145,591
COE USD/kWh	0.581	0.604	1.13	1.15	2.45	2.45	2.48	2.49
Tot. Electrical Production kWh/year	89,853	90,619	76,369	76,270	219,000	219,309	219,655	223,637
Ren. Fraction	86	87	0	0	0	0	0	0
Cap. Shortage kWh/year	0	0	0	0	0	0	0	0
Unmet Load kWh/year	0	0	0	0	0	0	0	0
Excess Electricity kWh/year	19,910	20,773	418	364	158,558	158,867	159,213	163,195
CO ₂ Emissions kg/year	0	0	0	0	0	0	0	0
ROI %	55.6	50.7	142.8	106.2	0	−4.6	−6	−5.6

Table 3. HOMER output for scenario 2 with diesel generator and renewable sources.

	PV/D/B	PV/W/D/B	PV/B	PV/W	D/B	W/D/B	D	PV/D
Operating Cost USD/year	16,084	16,281	13,016	16,387	52,336	52,343	119,606	119,609
COE USD/kWh	0.564	0.588	0.904	0.929	0.992	1.01	2.03	2.03
Tot. Electrical Production kWh/year	86,376	86,880	225,944	184,233	76,358	76,268	219,000	219,306
Ren. Fraction	79.7	79.9	100	100	0	0	0	0
Cap. Shortage kWh/year	0	0	58.4	57.8	0	0	0	0
Unmet Load kWh/year	0	0	48.3	44.8	0	0	0	0
Excess Electricity kWh/year	16,396	17,004	156,855	115,072	348	367	158,558	158,864
CO ₂ Emissions kg/year	11,719	11,576	0	0	66,846	66,602	209,077	209,077
ROI %	49.6	45.3	17.3	17.7	110.5	83.7	0	−4.6

5. Ranking of DES Using TOPSIS

To obtain the optimal DES, it is best to use more than one criterion, which is the reason for the choice of a multicriteria decision tool for ranking the system. The technique for order of preference by similarity to ideal solution (TOPSIS) is a technique that can be used in ranking using different criteria. A review of different of multicriteria decision-making (MCDM) tools was performed by Indre et al. [28]. The TOPSIS approach is used amongst many other MCDM tools in this work because of the computational efficiency and because it can be easily comprehended. The following six steps are included in TOPSIS: (i) forming a decision matrix; (ii) obtaining weights for the criteria; (iii) obtaining the weighted matrix; (iv) obtaining the positive ideal solution and the negative ideal solution; and (vi) estimating the closeness coefficient, which is used for ranking the systems. Eleven criteria were used as the basis of the ranking, which include the economic, technical, and environmental output from the HOMER simulator, as well as the social criteria, which were obtained based on expert judgment.

(i) Step 1: The decision matrix.

The first step in TOPSIS is to build a decision matrix. The output from the HOMER software is shown in Table 4. The energy sources in the table are represented as follows: solar PV as PV, wind as W, nuclear as N, diesel as D, and battery as B.

Table 4. Output from HOMER software used to form decision matrix.

	PV/N/B	PV/W/N/B	PV/D/B	W/N/B	PV/W/D/B	PV/W	W/D/B
Operating Cost USD/year	15,132	15,049	16,084	60,378	16,281	16,387	52,343
COE USD/kWh	0.581	0.604	0.564	1.15	0.588	0.929	1.01
Tot. Electrical Production kWh/year	89,853	90,619	86,376	76,270	86,880	184,233	76,268
Ren. Fraction	86	87	79.7	0	79.9	100	0
Cap. Shortage kWh/year	0	0	0	0	0	57.8	0
Unmet Load kWh/year	0	0	0	0	0	44.8	0
Excess Electricity kWh/year	19,910	20,773	16,396	364	17,004	115,072	367
CO ₂ Emissions kg/year	0	0	11,719	0	11,576	0	66,602
ROI %	55.6	50.7	49.6	106.2	45.3	17.7	83.7

The decision matrix formed is shown in Table 5. For this work, the decision matrix for the seven selected systems from the HOMER software was built based on 11 criteria, which are: operating cost USD/year; cost of energy (COE) USD/kWh; total electricity production (Tot. Electrical Production) kWh/year; renewable fraction (Ren. Fraction); capacity shortage (Cap. Shortage) kWh/year; unmet load kWh/year; excess electricity kWh/year; CO₂ emissions kg/year; ROI (return on interest) %; availability; and public acceptance. These criteria are classified under economic, technical, environmental, and social criteria. Output for the systems from the HOMER software was used in forming the decision matrix using fuzzy linguistic variables.

Table 5. Decision matrix using output from HOMER software.

	PV/N/B	PV/W/N/B	PV/D/B	W/N/B	PV/W/D/B	PV/W	W/D/B
Operating Cost USD/year	G	G	G	Vp	G	G	Vp
COE USD/kWh	F	F	F	p	F	P	Vp
Tot. Electrical Production kWh/year	F	G	F	G	F	Vg	G
Ren. Fraction	Vg	Vg	G	F	G	Vg	F
Cap. Shortage kWh/year	Vg	Vp	Vp	Vp	Vp	Vp	Vg
Unmet Load kWh/year	Vg	Vg	Vg	Vg	Vg	Vp	Vg
Excess Electricity kWh/year	G	G	G	G	G	P	G
CO ₂ Emissions kg/year	Vg	Vg	P	vg	P	vg	P
ROI %	F	F	F	Vg	F	P	G
Availability	Mg	Mg	Vg	mg	Vg	g	Vg
Public Acceptance	Mg	Mg	Vg	mg	Vg	Vg	G

The fuzzy scale is used in the decision matrix. The linguistic variables can be expressed using fuzzy numbers. The triangular fuzzy number is used in obtaining the fuzzy scale in Table 6. Fuzzy scales are chosen because of their robustness, as they are able to analyse vague inputs [29].

Table 6. Linguistic variables using fuzzy numbers.

Linguistic Variables Using Fuzzy Numbers.	
Very poor (vp)	0,0,1
Poor (p)	0,1,3
Medium poor (mp)	1,3,5
Fair (f)	3,5,7
Medium good (mg)	5,7,9
Good (g)	7,9,10
Very good (vg)	9,10,10

(ii) Step 2: Normalised Decision matrix

This involves normalising the decision matrix. The decision matrix is normalised and given in Table 7.

Table 7. Normalised decision matrix.

	PV/N/B	PV/W/N/B	PV/D/B	W/N/B	PV/W/D/B	PV/W	W/D/B
Operating Cost USD/year	0.92	0.92	0.92	0.35	0.92	0.35	0.92
COE USD/kWh	0.92	0.92	0.92	0.24	0.92	0.24	0.06
Tot. Electrical Production kWh/year	0.35	0.6	0.35	0.6	0.35	0.67	0.6
Ren. Fraction	0.58	0.58	0.52	0.3	0.52	0.58	0.3
Cap. Shortage kWh/year	0.75	0.026	0.026	0.026	0.026	0.026	0.75
Unmet Load kWh/year	0.67	0.67	0.67	0.67	0.67	0.023	0.67
Excess Electricity kWh/year	0.5	0.5	0.5	0.5	0.5	0.08	0.5
CO ₂ Emissions kg/year	0.92	0.92	0.13	0.92	0.13	0.92	0.13
ROI %	0.41	0.41	0.41	0.8	0.41	0.11	0.72
Availability	0.58	0.58	0.8	0.58	0.8	0.72	0.8
Public Acceptance	0.54	0.54	0.75	0.54	0.75	0.75	0.67

iii. Step 3: Criteria weight

The Criteria weight W_j s obtained based on expert opinion. The eleven criteria used in ranking assigned weight were based on expert judgement. These assigned weights are shown in Table 8. The experts' opinion was obtained from 10 nuclear experts who met the criteria for selection for this study. The criteria for selection are: (i) that they should be involved in SMR research; (ii) that they should be working in a nuclear agency; and (iii) that they should be involved in nuclear power project planning. The experts that gave their opinion are nuclear experts with the Nigeria Atomic Energy Commission; Nigeria Nuclear Regulatory Commission; Harbin Engineering University, China; Oakridge national laboratory (ORNL), USA; and Stellenbosch University, South Africa. The experts chosen for this study met one or more of these selection criteria. Slottje et al. [30] in their study recommended that the minimum number for expert judgment was 6. In this study, 10 experts' opinions were obtained, and the average ranking for each of the criteria was obtained and shown in Table 8. The criteria were ranked on a scale of 0 to 100%. It is an estimate of the importance of each criterion for SMRs in a distributed energy system.

Table 8. Criteria weight (W_j).

Criteria	Weight
Operating Cost USD/year	0.92
COE USD/kWh	0.92
Tot. Electrical Production kWh/year	0.67
Ren. Fraction	0.58
Cap. Shortage kWh/year	0.75
Unmet Load kWh/year	0.67
Excess Electricity kWh/year	0.50
CO ₂ Emissions kg/year	0.92
ROI %	0.80
Availability	0.80
Public acceptance	0.75

(iv) Step 4: Estimating the weighted decision matrix

The weighted decision matrix (V_{ij}) is estimated using an equation. The decision matrix obtained is shown in Table 9.

$$V_{ij} = D_{ij} \cdot W_j \quad (1)$$

Table 9. Weighted decision matrix.

	PV/N/B	PV/W/N/B	PV/D/B	W/N/B	PV/W/D/B	PV/W	W/D/B
Operating Cost USD/year	0.92	0.92	0.92	0.03502	0.92	0.92	0.03502
COE USD/kWh	0.92	0.92	0.92	0.2447	0.92	0.2447	0.0607
Tot. Electrical Production kWh/year	0.3464	0.6007	0.3464	0.6007	0.3464	0.67	0.6007
Ren. Fraction	0.58	0.58	0.5200	0.2999	0.5200	0.58	0.2999
Cap. Shortage kWh/year	0.75	0.02556	0.02556	0.02556	0.02556	0.0256	0.75
Unmet Load kWh/year	0.67	0.67	0.67	0.67	0.67	0.02287	0.67
Excess Electricity kWh/year	0.5	0.5	0.5	0.5	0.5	0.0767	0.5
CO ₂ Emissions kg/year	0.92	0.92	0.1265	0.92	0.1265	0.92	0.1265
ROI %	0.4137	0.4137	0.4137	0.8	0.4137	0.1100	0.7173
Availability	0.5791	0.5791	0.8	0.5791	0.8	0.7173	0.8
Public Acceptance	0.5429	0.5429	0.75	0.5429	0.75	0.75	0.6724

(v) Step 5: Estimation of the positive and negative solution

The ideal positive (P^+) and negative (N^-) solutions are calculated using Equations (2) and (3). The result obtained is shown in Table 10.

$$P^+ = \sum_{j=1}^n d(v_{ij}, v_j^+) \tag{2}$$

$$N^- = \sum_{j=1}^n d(v_{ij}, v_j^-) \tag{3}$$

where $v_j^+ = (1,1,1)$, $v_j^- = (0,0,0)$, v_{ij} represents elements in the matrix of interest, and d represents the distance between two matrixes.

Table 10. The positive (P^+) and negative (N^-) solution.

Positive Solution P^+	Negative Solution N^-
1.258609	0.678116
1.484366	0.656246
1.769498	0.615881
1.92409	0.550041
1.769498	0.615881
2.122016	0.574783
1.943462	0.551013

vi. Step 6: Estimated closeness coefficient (CC)

In TOPSIS, the closeness coefficient is used in ranking and is estimated using Equation (4). The closeness coefficient (CC) is calculated, and rankings are shown in Table 11.

$$CC = N^- / (P^+ + N^-) \tag{4}$$

Table 11. Estimation of the coefficient of closeness and ranking.

DES	CC	Ranking
PV/N/B	0.350135	1
PV/W/N/B	0.306569	2
PV/D/B	0.25819	3
W/N/B	0.222317	5
PV/W/D/B	0.25819	4
PV/W	0.213135	7
W/D/B	0.220893	6

6. Discussion

The TOPSIS ranking using the eleven criteria returned the hybrid PV, nuclear, and battery system as the optimal system; followed by the PV, wind, nuclear, and battery system; and the third in the ranking was the PV, diesel, and battery system. This shows that the small nuclear reactor can be a good replacement for the diesel generator.

7. Conclusions

To meet the world energy demand without damaging our environment requires every available clean energy source to be harnessed economically and sustainably. This has increased renewable energy resources and interest in developing technologies that most efficiently harness them. Therefore, the development and continuing advancement in the design of the distributed energy system has been necessitated. The DES can easily accommodate RES better than the conventional centralised energy systems.

The influx of RES helps with green energy and the maximisation of local energy resources. This is also not without challenges, in particular the intermittent nature of the RES and instability to the grid. Hence, this paper has focused on introducing an energy source that is clean, flexible, and can bring stability to the DES. This work has explored the features of the nuclear microreactors that enable them to be suitable for DES.

A case study of electrification of a rural community in Nigeria was used to demonstrate the distributed energy system, which included the eVinci microreactor. Two scenarios were created: one with a hybrid nuclear and renewable energy source, and the other with a hybrid diesel and renewable energy source. The HOMER software was used in simulating the optimum system and TOPSIS was used in ranking the systems. The result shows that the PV/nuclear/battery system ranked first, followed by the PV/nuclear/wind and battery system.

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