Research Article

A Technoeconomic Feasibility Analysis for Affordable Energy System in the East African Community Countries

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Access to energy is among the key pillars to socioeconomic and improved life style. The East African Community (EAC) countries, also members of sub-Saharan Africa, are among countries with enough energy resources but still struggling with low electricity access, and the lower proportion of citizens with electricity access challenges such as expensive tariff, frequent blackouts, and unreliable service still persists. Diesel technology is among the easy and fast installation technologies for a location with an urgent need of electricity while solar is a clean technology with free fuel. Considering the diversity of electricity tariffs, cost of diesel fuel, and suitability to solar energy exploitation in EAC, this paper intends to provide a technoeconomic analysis for reliable, affordable, and sustainable energy system in the region. A daily load of 94.44 kWh recorded from averaging electricity bills of a luxury house in Kigali, Rwanda, is used as research object, and HOMER simulations are carried on considering the level of such daily load being supplied by either (a) diesel generator, (b) solar + diesel technology, (c) PV + battery storage, or (d) PV + battery storage + grid system in each member country of the EAC. The results show that (a) solar energy is a feasible and applicable technology for energy generation for the whole six EAC countries; (b) for South Sudan, if it is a standalone system, the diesel technology is less costly than solar technology; however, solar energy can still be recommended to be adopted as it has no gas emissions; (c) except South Sudan, PV + battery storage technology is found to be more affordable and cleaner than any technology including diesel; and (d) the option of connecting PV + battery storage to the grid is found more economical for locations where grid interaction is possible because their levelized electricity costs (LCOE) are lower than the real electricity tariffs currently in use within each of the six EAC countries. The solar energy system with battery storage (both off-grid and grid connected) proposed in this research can lead to an efficient increase of national energy resource exploitation in the EAC countries, resulting in reliable, affordable, and sustainable energy access to all the citizenry of the EAC.

1. Introduction

Access to energy is among the key pillars to socioeconomic and improved life style [1]. Key indicators from different research perspectives show that electrification has acquired steady progress worldwide within the past decade. However, there is a huge population around the globe who has not yet acquired access to electricity (estimation of 770 million population globally with energy poverty where around 577.5 million (75%) are located in sub-Saharan Africa) [2, 3]. Living without access to electricity is a major challenge and ultimate economic obstacle as it prevents people from fully participating in the modern economy. The East African Community (EAC) countries, which are also members of sub-Saharan Africa, are among countries with enough energy resources but still struggling with low electricity access, and to the lower proportion of citizens with electricity access, challenges such as expensive tariffs, frequent blackouts, and unreliable service still persist [4, 5]. Figure 1 indicates the actual location of the East African Community countries as both an economic and a linguistic block on the map of Africa [6].

In modern era, different technologies (renewables and nonrenewable) are adopted, and others are being developed all for the purpose of taking off energy crisis and shortage worldwide in different countries. Diesel technology is a fast and rapid energy solution for a location with urgent need of electrification due to its straightforward and swift installation; diesel generators are highly useful devices that apply diesel fuel to generate electricity [1, 3, 5]. To produce electricity, these devices combine an electric generator with a diesel engine. However, with the current mitigation policies and regulations, their adoptions must be carefully analysed before their recommended usage to a certain area [3]. Solar energy technologies transform sunlight radiations into usable electrical energy either through PV modules or mirrors that concentrate sunlight radiation. This energy can be utilized to produce electric power or can be kept in energy-storing devices (batteries) or thermal storage battery devices. Africa is considered the “sun mainland” or the landmass with the highest sun’s effect. Also, the “World Sunshine Map” indicates that Africa receives abundant sunlight all year than other continents on the Earth. Despite the enormous solar capacity, the penetration of solar power in Africa is presently very low [7–11]. Photovoltaic solar energy is a viable and promising alternative and prospect because it authorizes the rapid deployment of carbon-free, economically accessible energy on a large scale. But, only a limited number of solar technologies have been installed in Africa to date.

Except diesel technology and solar energy, there are other energy technologies like hydropower, coal-fired, biomass, wind, tidal, geothermal, and bioenergy. Hybrid energy technology and systems tie together two or more technologies in order to build more effective systems. They integrate multiple power generation and storage units to meet the needs of the environment [12]. There is some existing research exploring and analysing technoeconomic concepts of applicability and adoption of different renewable energies in some African regions such as sub-Saharan Africa and each country as well; however, (a) there is no existing research analysing solution

FIGURE 1: Location of EAC countries on the map of Africa.

to affordable energy option for the whole EAC country members; (b) some EAC members such as Burundi and South Sudan still have not enough scientific research works published investigating technoeconomic situation related to renewable energy exploration. Thus, the research in this paper is intended to provide cost comparison of technology approaches which can lead to affordable and reliable energy systems and services in the East African Community countries. Different alternative technologies: (a) diesel technology, (b) solar PV + diesel technology, (c) PV + battery storage, and (d) PV + storage battery + grid, are analysed to find the least cost and affordable technology with respect to different climatic weather conditions and diesel fuel price levels in the six EAC countries. It is hypothesised that high solar energy exploitation in EAC countries can contribute a lot to ameliorate the energy crisis and shortage in EAC with citizens without electricity access and solve the affordability and unreliability issues for grid-connected users in the region. Table 1 describes the analogy of different state-of-the-art analyses with the proposed solution.

2. Experimental Methodology

2.1. Site Location and Visit. Site visits were made to an electricity user with luxury house located in Rwanda, Kigali city (Kimisagara National Road, Kigali, Rwanda) ($1^{\circ} 57.2' \text{ S}$, $30^{\circ} 2.8' \text{ E}$), and its average electric load was calculated based on the electricity bill for the past eight months and the electricity tariff. The average load was estimated at 23.85 kW daily peak load, 182 kWh per day, and 66430 kWh annual load. This load structure was used as a research object in the other five EAC countries with different locations (as shown in Figure 2) such as at 2 Mulago III 2662, Kampala, Uganda ($0^{\circ} 20.8' \text{ N}$, $32^{\circ} 34.9' \text{ E}$), for Uganda; at Unnamed Road, Dodoma, Tanzania ($6^{\circ} 10.3' \text{ S}$, $35^{\circ} 45.6' \text{ E}$), for Tanzania; at Times Tower, Nairobi, Kenya ($1^{\circ} 17.5' \text{ S}$, $36^{\circ} 49.4' \text{ E}$), for Kenya; at Bentiu, South Sudan ($9^{\circ} 13.9' \text{ N}$, $29^{\circ} 48.0' \text{ E}$), for

TABLE 1: Analogy of different state-of-the-art analyses with the proposed solution.

Reference	Country of application	Resource parameters	Power ratings of model architecture	Expression of initial capital cost	Operating cost (\$/year)	NPC(US\$)	LCOE (US\$/ kWh)	Other metric parameters
[27]	Mbuguni, Arumeru district, Tanzania	Global horizontal irradiation for the entire country varies between 5.2 and 6.4 kWh/m ² Annual average solar irradiation: 5.6 kWh/m ² /day Annual average wind speed: 5.17 m/s	SPV-W-GEN					
			Solar PV: 0.764 kW					
			1 wind turbine: 1 kW					
			5 batteries: 12 V, 83.4 Ah		239.86	6259.86	0.21467	52.42 L of diesel
			Converter system: 0.824 kW					
			Generator: 1.40 kW					
			SPV					
			Solar PV: 3.36 kW					
			16 batteries: 12 V, 83.4 Ah	Capital cost	359.30	10638.52	0.32599	Pure renewable
			Converter system: 1.37 kW	Solar PV: 1000\$/kW				
			SPV-wind	Wind turbine: 780\$/kW				
			Solar PV: 1.30 kW	Battery: 150\$				
			1 wind turbine: 1 kW	Replacement cost				
			10 batteries: 12 V, 83.4 Ah	Solar PV: 900\$/kW	218.95	7110.53	0.24394	Pure renewable
			Converter system: 1.15 kW	Wind turbine: 780\$/kW				
			SPV-Gen	Battery: \$150				
			Solar PV: 2.25 kW					
			9 batteries: 12 V, 83.4 Ah		388.90	9505.97	0.32599	69.92 L of diesel
			Converter system: 1.1 kW					
			Generator: 1.40 kW					
			Wind-Gen					
			10 batteries: 12 V, 83.4 Ah		413.81	8031.25	0.27541	183.32 L of diesel
			Converter system: 0.75 kW					

TABLE 1: Continued.

Reference	Country of application	Resource parameters	Power ratings of model architecture	Expression of initial capital cost	Operating cost (\$/year)	NPC(US\$)	LCOE (US\$/kWh)	Other metric parameters
[28]	Djounde, Mora, Cameroon 11° 30' 00" north 14° 18' 00" east	Average annual wind speed at the site was 4.95 m/s at 50 m anemometer 6.67 kWh/m ² /day maximum solar irradiation and minimum: 4.77 kWh/m ² /day	Generator: 1.40 kW	Generator: 1.40 kW	2409.94	31,854.57	1.09238	1654.39 L of diesel
			Gen					
			Generator: 1.40 kW PV: 81.8 kW Biogas generator: 15 kW Wind turbine: 15 kW Pumped hydrostorage converter: 40 kW	323,750\$	4031	451165.19	0.316	Power production (kWh/year) PV array: 141,046 Wind turbine: 0 Biogas generator: 17,794 Total: 158,840 Consumption (kWh/year) 125,056
[29]	Batocha, Cameroon	5.93 kWh/m ² /day Annual average horizontal irradiation 9 L/s annual average flow rate	Solar PV: 5 kW	Solar PV: 21,000\$	PV: 703			Power production (kWh/year) PV array: 9831.0 (39.0%)
			Hydro turbine: 2.12 kW	Hydro turbine: 6000\$	Hydro turbine: 1562			Diesel: 191.0 (1.0%)
			Diesel: 1 kW 125 batteries Inverter: 6 kW Rectifier: 6 kW	Diesel: 1000\$ Batteries: 3000\$ Converter: 5143\$ Total system replacement: 28,897\$	Diesel: 1765 Battery: 976 Converter: 1339 Other: 101	70,042	0.278	Hydro turbine: 15,493.0 (61.0%) Unmet load: 172.0 (1.0%) Capacity shortage: 309.0 (2.0%) Excess electricity: 9110.0 (33.0%)
[30]	Rwanda	—	Hydro: 10 kW	Capital cost	1895.49	126,324.10	0.1715	Production (kWh/year) Hydro: 122,716 (82.6%) Solar PV: 1620 (1.09%) Wind turbine: 24,203 (16.3%)
			Wind turbine: 100 kW	Wind turbine: 80,000\$				
			Solar PV: 1.09 kW Converter: 0.05 kW Hydro (1 turbine): 10 kW PV: 1.09 kW Converter: 10 kW	Hydro: 20,000\$ Solar PV: 16,000\$ Batteries (1 kWh each): 2400\$ Converter: 30,000\$	1495.49	41,210.80	0.05601	Production (kWh/year) Hydro: 122,716 (98.7%) Solar PV: 1620 (1.3%)
[26]	Golbo II village, Aadaa district,	Solar radiation: 3.74 kWh/m ² /day	Hydro: 10 kW	Wind turbine: 100 kW	1873.48	124,175.90	0.1688	Production (kWh/year) Hydro: 122,716 (83.5%) Wind turbine: 24,401.3 (16.5%)
			Scenario 1 Solar PV: 20 kW 3 wind turbines:	Wind turbine: initial cost 2000\$/kW	Wind turbine 50\$/year/turbine Diesel generator:	82,734	0.207	Power production PV array: 41,957 (80%) Wind turbines: 7306 (14%)

TABLE 1: Continued.

Reference	Country of application	Resource parameters	Power ratings of model architecture	Expression of initial capital cost	Operating cost (\$/year)	NPC(US\$)	LCOE (US\$/ kWh)	Other metric parameters
[31]	Oromia Region, Ethiopia	Solar radiation: 3.74 kWh/m ² /day Diesel consumption: 2233 L	3 kW Diesel generator: 5 kW 24 batteries: 2 V, 3000 Ah Converter	Replacement 1600\$/kW Diesel generators: Capital outlay: USD 250/kW Restoration: USD 200/kWh Converter; capital cost: 1300.0 USD/kW	USD 0.3/hour Converter: 5 USD/year Battery: 20 USD/ year	85,754	0.214	Generator: 3073 (6%) Total production: 52336 kWh AC primary load served: 37,780 kWh Excess electricity: 5779 kWh (11%) Unmet load: 1676 kWh (4%) Capacity shortage: 2295 kWh (6%) Power production: PV array: 41,957 (87%) Generator: 6014 (13%) Total production: 47,970 kWh AC primary load served: 37,838 kWh Excess electricity: 1686 kWh (4%) Unmet load: 1619 kWh (4%) Capacity shortage: 2303 kWh (6%)
			Scenario 2 Solar PV array: 20 kW Diesel generator: 7 kW 24 batteries: 2 V, 3000 Ah	Replacement: 1000 USD/kW Batteries: Capital cost: 400 USD/kWh Replacement: 300 USD/kWh				
			Scenario 3 3 water turbine: 3 kW each Diesel generator: 7 kW 24 batteries: 2 V, 3000 Ah					
			Diesel consumption: 12,973 L			141,126	0.352	
	Ethiopia 2 3 sites Site 1: Serwat	Diesel consumption: 17,507 L/ year Diesel consumption: 16,898 L/ year	Scenario 4 Diesel generator: 7 kW 20 batteries: 2 V, 3000 Ah 5 wind turbines: Diesel generator: 110 kW 240 batteries Converter: 100 kW Solar PV: 5 kW 5 wind turbines: Diesel generator: 110 kW 240 batteries Converter: 100 kW	USD 501,031	—	153,249	0.384	Renewable fraction: 0.86 Renewable fraction: 0.87
						1,248,119	0.574	

TABLE 1: Continued.

Reference	Country of application	Resource parameters	Power ratings of model architecture	Expression of initial capital cost	Operating cost (\$/year)	NPC(US\$)	LCOE (US\$/kWh)	Other metric parameters
Site 2: Feleg Daero		Diesel consumption: 5767 L/year	Solar PV: 180 kW	USD 1,170,839	—	1,526,634	0.702	Renewable fraction: 0.94
			Diesel generator: 70 kW 400 batteries Converter: 150 kW					
		Diesel consumption: 0 L/year	Solar PV: 180 kW	USD 1,404,230	—	1,733,954	0.797	Renewable fraction: 1.00
			3 wind turbines 560 batteries Converter: 130 kW					
		Diesel consumption 137,797 L/year	Diesel generator: 150 kW	USD 27,083	—	6,161,842	2.831	Renewable fraction: 0
			Solar PV: 30 kW 2 wind turbines:					
		Diesel consumption: 11,299 L/year	Diesel generator: 50 kW	USD 353,875	—	754,408	0.605	Renewable fraction: 0.85
			120 batteries Converter: 50 kW					
		Diesel consumption: 13,092 L/year	3 wind turbines:	USD 323,445	—	766,324	0.614	Renewable fraction: 0.85
			Diesel generator: 50 kW 160 batteries Converter: 70 kW					
		Diesel consumption: 5991 L/year	Solar PV: 100 kW	USD 624,249	—	\$886,466	0.711	Renewable fraction: 0.91
			Diesel generator: 30 kW 200 batteries Converter: 70 kW					
			Solar PV: 100 kW					
			2 wind turbines, 320 batteries					

TABLE 1: Continued.

Reference	Country of application	Resource parameters	Power ratings of model architecture	Expression of initial capital cost	Operating cost (\$/year)	NPC(US\$)	LCOE (US\$/ kWh)	Other metric parameters
[32]	Khartoum, Sudan	—	Converter: 90 kW	USD 24,505	—	3,758,776	3.012	Renewable fraction: 0.00
			Diesel generator: 85 kW					
			Solar PV: 5 kW	USD 101,081	—	191,580	0.410	Renewable fraction: 0.90
			1 wind turbine					
			Diesel generator: 10 kW					
			32 batteries					
			Converter: 10 kW	USD 81,081	—	\$198,261	0.425	Renewable fraction: 0.84
			1 wind turbine					
			Diesel generator: 10 kW					
			32 batteries					
[32]	Khartoum, Sudan	—	Converter: 10 kW	USD 179,390	—	241,049	0.517	Renewable fraction: 1.00
			Solar PV: 15 kW					
			1 wind turbine	USD 7762	—	781,317	1.673	Renewable fraction: 0.00
			80 batteries					
			Converter: 15 kW					
			Diesel generator: 15 kW					
			Solar PV: 0.15 kW	150.98707\$	—	224.1269	0.12	—
			2 batteries: 6 V, 225 Ah					
			Solar PV: 1 kW					
			1 wind generator: 3 turbines, 0.5 kW					
[32]	Khartoum, Sudan	—	16 batteries: 6 V, 225 Ah	1902.8909\$	—	2052.8777	0.06	—
			Solar PV: 2 kW					
			1 wind generator: 3 turbines, 0.5 kW	2388.1036\$	—	3569.872	0.05	—
			24 batteries: 6 V, 225 Ah					
			Solar PV: 2 kW					
			1 wind generator: 3 turbines, 0.5 kW					
			24 batteries: 6 V, 225 Ah					
			Solar PV: 2 kW	2388.1036\$	—	3569.872	0.05	—
			1 wind generator: 3 turbines, 0.5 kW					
			24 batteries: 6 V, 225 Ah					

TABLE 1: Continued.

Reference	Country of application	Resource parameters	Power ratings of model architecture	Expression of initial capital cost	Operating cost (\$/year)	NPC(US\$)	LCOE (US\$/kWh)	Other metric parameters
[33]	Sokoto, Nigeria Latitude 10.0° N and longitude 8.0° E	Wind speed: between 4.5 m/s and 5.2 m/s at ≥10 m	Solar PV: 2.5 kW					
			2 wind generators	5338.6579\$	—	4878.2071	0.06\$/kWh	—
			24 batteries: 6 V, 225 Ah					
			Solar PV: 3.5 kW					
			2 wind generators					
			3 turbines, 0.5 kW	3823.3956\$	—	4735.2341	0.04	—
			8 batteries 6 V, 225 Ah					
			Solar/wind system					
			Solar PV: 35.21 kW	Capital cost Solar PV: 105,604.91 USD	Operation & replacement cost for solar PV: 4501.66			
			Wind turbine: 250 kW and 4.75 kW mean output	Wind turbine: 58,333.33 USD Battery: 80,700 USD	Wind turbine: 33,102.53 Battery: 96,930.33			Total production/year: 93,300 kWh PV: 57.5% Wind: 42.5%
[34]	NyongYapalsi, Karaga district, Ghana 9° 46.601' N, 0° 36.944' W	Solar resource: average annual solar irradiance of 5.57 kWh/m ² /day	24 batteries : 12 V, 83400 Ah	Converter: 5232 USD	Converter: 2183	—	—	
			Converter: inverter: 17.44 kW	Total system cost: 249910.24 USD	Total system replacement cost: 82914.85			
			Rectifier: 15.66 kW		Maintenance cost: 53802.80			
			Solar PV minigrid with storage batteries					
			Solar PV: 24.4 kW	Capital cost: \$72,324.00	Operating cost: \$4233/yr.	119,479.00	\$0.480	Total electricity production: 53,211 kWh Surplus: 46.5%
			Converter: 11.4 kW					
			156 batteries: 12 V, 200 Ah					
			Solar PV minigrid with storage batteries					
			Solar PV: 24.4 kW	—	—	82,166.00	\$0.330	—

TABLE 1: Continued.

Reference	Country of application	Resource parameters	Power ratings of model architecture	Expression of initial capital cost	Operating cost (\$/year)	NPC(US\$)	LCOE (US\$/kWh)	Other metric parameters
[35]	Gweru, Zimbabwe	Wind potential: 15.0 W/m ² in Kariba to 115.0 W/m ² at 50.0 m hub height in Gweru Monthly wind speed: 4.215 m/s Solar potential: 5.81 kWh/m ² /day annual average	Converter: 11.4 kW	—	—	4350.0	0.175	(400 – 245)/400 = 38.75% Energy storage reduced by 38.75%
			156 batteries: 12 V, 200 Ah					
			This arrangement has free solar PV panels					
			Solar PV-wind hybrid:					
			Battery capacity: 245.0 Ah/24.0 V					
			Power source: 300.0 W Wind turbine and					
			2 × 125.0 W PV modules					
			LED streetlights 80 W/24 V					
			Charge controller 20 A/24 V Solar-Wind Hybrid (PMW)					
			PV stand-alone					
			Battery capacity 400 Ah/24 V	—	—	—	—	—
			Power source: 2 × 210.0 W PV modules					
			LED streetlights: 80.0 W/24 V					
			Charge controller 20.0 A/24 V Solar charger					
			Controller (PWM)	—	—	—	—	—

TABLE 1: Continued.

Reference	Country of application	Resource parameters	Power ratings of model architecture	Expression of initial capital cost	Operating cost (\$/year)	NPC(US\$)	LCOE (US\$/ kWh)	Other metric parameters
[36]	South Africa		Solar PV: 5 kW 30 batteries 2 V, 720 Ah: Generator: 5.5 kW, 50 Hz, rpm 3000 Converter: 6 kW	Capital cost: Solar PV: \$4250 Battery: \$269 Generator: \$313 Converter: \$3731 Fuel: \$0.7/L: \$32,990 Fuel: \$0.9/L: \$15,398	—	\$62,402.0 at 0.7\$/L \$65,833.0 at 0.9\$/L	—	Least case diesel use (Upington) 1267.0 L/year at \$0.7/L and 1275 L/year at \$0.9/L 3.336 tons/year CO ₂ emissions for diesel priced at 0.7\$/L and 3.359 tons/year CO ₂ emissions for diesel priced at 0.7\$/L

Conversion rate: 1 euro equals 1.2179631\$, 1\$ equal to 409.903 Sudan Pound; date of conversion: 23rd May 2021; conversion source: <https://www.xe.com/>. Table 1 indicates the analogy of different state-of-the-art analyses (studies using different energy technologies including renewable and conventional energy resources) and the proposed solution. It can be seen that different parameters such as net present value cost (NPC), levelized electricity expense (LCOE), renewable energy percentage, and electricity production from the system have played a key role in deciding and concluding the energy system which is optimal, reliable, sustainable, and affordable for the study cases.

FIGURE 2: A map that depicts different selected sites in the East African Community countries: (a) is the Kimisagara National Road, Kigali, Rwanda ($1^{\circ} 57.2' S$, $30^{\circ} 2.8' E$); (b) is the Chaussee de L'Agriculture, Bujumbura, Burundi ($3^{\circ} 21.7' S$, $29^{\circ} 21.5' E$); (c) is the 2 Mulago III 2662, Kampala, Uganda ($0^{\circ} 20.8' N$, $32^{\circ} 34.9' E$); (d) is the Unnamed Road, Dodoma, Tanzania ($6^{\circ} 10.3' S$, $35^{\circ} 45.6' E$); (e) is the Times Tower, Nairobi, Kenya ($1^{\circ} 17.5' S$, $36^{\circ} 49.4' E$); while the Bentiu, South Sudan ($9^{\circ} 13.9' N$, $29^{\circ} 48.0' E$) is shown in (f).

South Sudan; and at Chaussee de L'Agriculture, Bujumbura, Burundi ($3^{\circ} 21.7' S$, $29^{\circ} 21.5' E$), for Burundi. The luxury house electric load data was used in the paper to prove that solar energy can still be an affordable and reliable option regardless of the energy consumption size range.

2.2. Load Profile. Figure 3 depicts the daily load variation of the luxury house used in the research.

The load pattern indicates a fluctuation from 4.00 kW (0.00 hr) to 2.50 kW (04.075 hrs), 5.00 kW (05.00 hrs), 10.00 kW (08.15 hrs), 9.25 kW (9.15 hrs), 12.00 kW (13.225 hrs), 9.00 (15.00 hrs), 10.00 kW (16.375 hrs), 15.00 kW (18.45 hrs), 16.50 kW peak (19.30 hrs), 15.00 kW (20.00 hrs), and 7.00 kW (23.45 hrs).

2.3. HOMER Simulation and Scenario Analysis. The scenarios to be carefully analysed as shown in Figure 4, include (a) use the diesel system to supply the loads during day and night times; (b) solar PV system without battery storage system to supply the loads at daytime and diesel generator as alternative to supply the load during daytime if the irradiance is not enough to generate the level of electricity which can satisfy the load and also at night; because there is no sunshine, the diesel generator will be the supply; (c) use the PV system with storage systems during daytime and night time; (d) use the PV with storage the whole day to supply the loads and inject extra electricity to the grid or draw electricity from the grid in case the electricity generation capacity from the hybrid system is lower than the load capacity.

2.4. Estimation of LCOE, NPC, and OPEX. The LCOE is also the income estimation needed to develop and run an ener-

gy/electricity generation plant during the cost recovery period. The LCOE can be expressed by Equations (1) and (2) [13–15].

$$\text{LCOE} = \frac{\text{Cycle life of the total life}}{\text{Total lifetime power generated}}, \quad (1)$$

$$\text{LCOE} = \frac{\sum_{t=1}^n ((I_t + M_t + F_t)/(1+t)^t)}{\sum_{t=1}^n (E_t/(1+t)^t)}, \quad (2)$$

where I_t stands for the spending on investments for the year t ; M_t , expenditures on operations and maintenance during the fiscal year t ; F_t , fuel expenses for the year t ; E_t , amount of electrical energy produced in a given year t ; r is the discount rate; and n is the anticipated system or power station lifespan.

Homer software uses the concept shown in Equation (3) to calculate and compute the levelized cost of energy depending on different parameters.

$$\text{LCOE} = \frac{C_{\text{ann},t}}{E_{\text{prim}} + E_{\text{def}} + E_{\text{grid,sales}}}, \quad (3)$$

where $C_{\text{ann},t}$ stands for the total cost for the whole year and E_{prim} and E_{def} stand for the yearly total primary and deferrable load.

$$\text{LCOE}_{\text{PV}} = \frac{\sum_{t=0}^n ((C_{\text{PVextra}} + C_{\text{PVdirect}})_t/(1+r)^t)}{\sum_{t=0}^n ((E_{\text{PVextra}} + E_{\text{PVdirect}})_t/(1+r)^t)}, \quad (4)$$

$$\text{LCOE}(E_{\text{out}}) = \frac{C_{\text{PVextra}}}{\eta E_{\text{PVdirect}}} + \frac{C_{\text{EES}}}{E_{\text{EES}}}. \quad (5)$$

Then, the overall levelized cost of electricity for the whole hybrid system (stand-alone PV and storage) $\text{LCOE}_{(\text{system})}$ can be expressed in the following equation.

$$\text{LCOE}_{(\text{system})} = \frac{\sum_{t=0}^n (C_{\text{system}}/(1+r)^t)}{\sum_{t=0}^n (E_{\text{system}}/(1+r)^t)} = \frac{C_{\text{PVextra}} + C_{\text{EES}} + C_{\text{PVdirect}}}{E_{\text{EES}} + E_{\text{PVdirect}}}, \quad (6)$$

where r stands for the discount rate factor; n stands for the lifespan; E_{PVdirect} and C_{PVdirect} stand for the direct energy from the PV to the load and its cost, respectively; E_{system} and C_{system} stand for the system's energy and its cost; and E_{EES} and C_{EES} stand for the energy in the energy storage device and its cost.

The term “net present cost” (NPC) refers to the present value of all expenses during the term of interest, including residual values such as negative costs, all added together; it is the present value of all expenses associated with installing and running the Component during the project's lifespan, subtracting the present value of all revenues earned over the project's duration [4, 16, 17]. The operating expenses or expenditure (OPEX) refer to the expenses incurred by a firm in carrying out its day-to-day activities [18].

FIGURE 3: Daily load variation for the luxury house used as a research object.

FIGURE 4: Various configurations of energy technologies: (a) diesel technology, (b) diesel + PV technology, (c) PV + battery storage technology, and (d) PV + battery storage + grid.

The NPC (C_{NPC}) and OPEX can be expressed through the following equation [13]:

$$C_{NPC} = \frac{C_{ann,tot}}{CRF(i, N)},$$

$$CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1}, \quad (7)$$

$$C_{OPEX} = C_{ann,tot} - C_{ann,cap},$$

where $C_{ann,tot}$ stands for the annualized total cost, i stands for the interest rate (discount rate), N represents the project lifetime, $C_{ann,cap}$ stands for the annualized capital cost, and CRF stands for the capital recovery factor.

From Figure 5 [13], it can be seen that the climatic weather conditions and geographical location of different African countries are attractive to the exploitation of different renewable energy resources. Figure 6 [19–22] depicts the cost of diesel fuels as used in this research.

FIGURE 5: Climatic weather parameters (annual) for the six EAC countries.

3. Results and Discussion

3.1. Levelized Cost of Electricity (LCOE) for Various Scenarios

3.1.1. Scenario 1: Diesel. Figure 7 indicates that the LCOE of diesel generator microgrid technology for each of the six EAC countries was US\$ 0.719/kWh for Uganda, US\$ 0.813/kWh for Burundi, US\$ 0.667/kWh for Kenya, US\$ 0.411/kWh for South Sudan, US\$ 0.617/kWh for Tanzania, and US\$ 0.701/kWh for Rwanda, respectively. The most expensive LCOE for diesel technology was for Burundi (US\$ 0.813/kWh). The most optimal and least cost LCOE US\$ 0.411/kWh was for South Sudan. The LCOE for South Sudan with diesel microgrid technology is the lowest among the other cases analysed in this study as the price for diesel fuel is lower than in the other EAC member countries. The lowest LCOE US\$ 0.411/kWh for South Sudan was twice cheaper and more affordable than the LCOE US\$ 0.945/kWh in Tanzania [23]. Also, the US\$ 0.617/kWh

(LCOE) obtained in this study for Tanzania is lower than that in [23].

3.1.2. Scenario 2: Diesel + PV. The diesel + PV hybrid technology LCOE in Figure 7 indicates that each of the LCOE for the six EAC countries was US\$ 0.661/kWh for Uganda, US\$ 0.728/kWh for Burundi, US\$ 0.626/kWh for Kenya, US\$ 0.411/kWh for South Sudan, US\$ 0.560/kWh for Tanzania, and US\$ 0.625/kWh for Rwanda. Simulation analysis shows that combining PV and diesel is not optimal. Also, HOMER optimization results showed that energy from diesel generator microgrid is more affordable than combining diesel and PV system. This conclusion is due to the low price of diesel in South Sudan. Apart from South Sudan, the US\$ 0.560/kWh LCOE for Tanzania was the lowest among the EAC countries analysed. It is also higher than both the calculated LCOE (US\$ 0.433/kWh) of the hybrid diesel-generator and storage energy systems for Tanzania in [23]

FIGURE 6: Diesel prices (USD/L) and electricity tariff (USD/kWh) for the six EAC countries.

FIGURE 7: Levelized cost of electricity for all EAC countries with all the analysed energy technologies.

and the LCOE \$0.260/kWh for a PV-diesel-battery micro-grid system designed for Algeria [24].

3.1.3. Scenario 3: PV + Battery Storage Technology. The LCOE for the PV + battery storage technology is plotted in Figure 7 where each of the six EAC countries' LCOE for the technology was US\$ 0.302/kWh (Uganda), US\$

0.331/kWh (Burundi), US\$ 0.333/kWh (Kenya), US\$ 0.306/kWh (South Sudan), US\$ 0.296/kWh (Tanzania), and US\$0.329/kWh (Rwanda), respectively. The least LCOE for the system was US\$ 0.296/kWh (Tanzania) which was also lower than US\$ 1.820/kWh LCOE obtained from the "Comparative Analysis of Reliable, Feasible, and Low-Cost Photovoltaic Microgrid for a Residential Load in Rwanda"

FIGURE 8: NPC and OPEX with diesel technology.

[16]. The US\$ 0.360/kWh LCOE for the “Photovoltaic Solar Technologies: Solution to Affordable, Sustainable, and Reliable Energy Access for All in Rwanda” [4] was more expensive than US\$ 0.333/kWh (Kenya); more expensive than 0.2\$/kWh for a hybrid made of a microhydropower technology, diesel, and storage [25]; and more expensive than US\$0.207/kWh for “Optimization and Cost-Benefit Assessment of Hybrid Power Systems for Off-Grid Rural Electrification in Ethiopia” [26].

3.1.4. Scenario 4: PV + Battery Storage + Grid Hybrid Technology. Figure 7 plots the LCOE for the PV + battery storage + grid hybrid technology of the six EAC countries. The LCOE for each of the six EAC countries was US\$ -0.0155/kWh (Uganda), US\$ -0.567/kWh (Burundi), US\$ 0.000584/kWh (Kenya), US\$ -0.123/kWh (South Sudan), US\$ 0.0167/kWh (Tanzania), and US\$ -0.0373/kWh (Rwanda), respectively. Also, the LCOEs of the grid tied PV systems with storage in the study were lower than both the US\$ 0.125/kWh and US\$ 0.0645/kWh LCOEs obtained by other researchers in [4, 16]. The implementation of the proposed system indicates that Uganda gains US\$ 0.0155 for every kWh generated, Burundi gains US\$ 0.0567 per kWh generated, Kenya spends US\$ 0.000584 per kWh generated, South Sudan gains US\$ 0.123 for every kWh generated, Tanzania spends US\$ 0.0167 for every kWh generated, and Rwanda gains US\$ 0.0373 for every kWh generated, respectively.

3.2. Analysis of Net Present Cost (NPC) and Operating Expenditure (OPEX). Figure 8 depicts the net present cost and OPEX of using the diesel technology for each of the six EAC countries as focused in this study. The NPC for Uganda was US\$ 369,723.00, US\$ 417,712.10 for Burundi, US\$ 342,955.30 for Kenya, US\$ 211,528.00 for South Sudan, US\$ 316,911.00 for Tanzania, and US\$ 360,559.30 for Rwanda, respectively. The most expensive NPC was Burundi (US\$ 417,712.10), and the lowest NPC was South Sudan

(US\$ 211,528.00). The NPCs hover between US\$ 417,712.00 (Burundi) and US\$ 211,528.00 (South Sudan), respectively.

The OPEX for each of the six EAC countries was US\$ 46,034.00 for Uganda, US\$ 52,236.00 for Burundi, US\$ 42,575.00 for Kenya, US\$ 25,591.00 for South Sudan, US\$ 39,210.00 for Tanzania, and US\$ 44,850.00 for Rwanda, respectively. The OPEX varied between US\$ 25,591.00 (South Sudan) and US\$ 52,236.00 (Burundi). The OPEXs lie between US\$ 52,236.00 (Burundi) and US\$ 25,591.00 (South Sudan), respectively.

Figure 9 shows the NPC and OPEX for the diesel + PV hybrid technology for the EAC cases simulated in this paper. Each NPC of the six EAC countries was US\$ 339,718.50 for Uganda, US\$ 374,418.10 for Burundi, US\$ 321,602.80 for Kenya, US\$ 211,528.00 for South Sudan, US\$ 287,930.00 for Tanzania, and US\$ 321,290.40 for Rwanda. Moreover, the least cost was US\$ 211,528.00 (South Sudan), but there was no PV penetration, and US\$ 374,418.10 for Burundi was the most expensive for the hybrid technology. The NPCs lie between US\$ 374,418.10 (Burundi) and US\$ 211,528.00 (South Sudan).

Each of the OPEX values for the six EAC countries was US\$ 34,682.00 for Uganda, US\$ 39,176.00 for Burundi, US\$ 33,128.00 for Kenya, US\$ 25,591.00 for South Sudan, US\$ 29,108.00 for Tanzania, and US\$ 32,644.00 for Rwanda. However, the OPEX for the diesel + PV hybrid varied between US\$ 39,176.00 (Burundi) and US\$ 25,591.00 (South Sudan). The OPEXs ranged between US\$ 39,176.00 (Burundi) and US\$ 25,591.00 (South Sudan), respectively.

Figure 10 shows the NPC and OPEX for the PV + storage battery technology for the simulated case studies. Each NPC of the six EAC countries was US\$ 155,191.40 (Uganda), US\$ 170,139.40 (Burundi), US\$ 171,266.50 (Kenya), US\$ 157,082.60 (South Sudan), US\$ 157,107.30 (Tanzania), and US\$ 169,290.10 (Rwanda). Moreover, US\$ 171,266.50 was the highest NPC (Kenya) and the lowest (US\$ 152,107.30) was for Tanzania. The NPCs hover around

FIGURE 9: NPC and OPEX with the diesel + PV technology.

FIGURE 10: NPC and OPEX with the PV + storage technology.

FIGURE 11: NPC and OPEX with the PV + storage + grid technology.

TABLE 2: Summary.

Diesel technology					
	NPC (\$)	LCOE (\$/kWh)		FGC (\$/hr)	MGC (\$/kWh)
Burundi	417712.1	0.813		3.53	0.285
Kenya	342955.3	0.667		3.07	0.212
Rwanda	360559.3	0.701		3.18	0.229
Tanzania	316911.0	0.617		2.90	0.187
South Sudan	21528.0	0.411		2.24	0.0835
Uganda	369723.0	0.719		3.23	0.238
PV + diesel technology					
	NPC (\$)	LCOE (\$/kWh)	DFGC(\$/hr)	MGC (\$/kWh)	PV LC(\$/kWh)
Burundi	374418.1	0.728	3.53	0.285	0.00326
Kenya	321602.8	0.626	3.07	0.212	0.0327
Rwanda	321290.4	0.625	3.18	0.229	0.0322
Tanzania	287930.3	0.560	2.90	0.187	0.0281
South Sudan	211528.0	0.411	2.24	0.0835	—
Uganda	339718.5	0.661	3.23	0.238	0.00327
PV + storage technology					
	NPC (\$)		LCOE (\$/kWh)		PV LC(\$/kWh)
Burundi	170139.4		0.331		0.0326
Kenya	169290.1		0.329		0.0327
Rwanda	169290.1		0.329		0.323
Tanzania	152107.3		0.296		0.0281
South Sudan	157082.6		0.306		0.0285
Uganda	155191.4		0.302		0.0307
PV + battery + grid technology					
	NPC (\$)		LCOE (\$/kWh)		PV LC(\$/kWh)
Burundi	121395.40		-0.0567		0.0326
Kenya	1243.24		0.000584		0.00327
Rwanda	80580.55		-0.0373		0.0322
Tanzania	35080.86		0.0167		0.0322
South Sudan	291931.30		-0.123		0.285
Uganda	34840.53		-0.0155		0.0307

NPC: net present cost; LCOE: levelized cost of electricity; DFGC: diesel fixed generation cost; MGC: marginal generation cost; hr: hour; PVLC: levelized cost for photovoltaic system.

US\$ 171,266.50 (Kenya) and US\$ 152,107.30 (Tanzania), respectively.

Each of the OPEX values was US\$ 5,729.00 (Uganda), US\$ 6,239.00 (Burundi), US\$ 5,729.00 (Kenya), US\$ 5,697.00 (South Sudan), US\$ 5,662.00 (Tanzania), and US\$ 6,231.00 (Rwanda), respectively. The PV + storage technology ranged between US\$ 6,239.00 (Burundi) and US\$ 5,662.00 (Tanzania). The OPEXs lie between US\$ 6,239.00 (Burundi) and US\$ 5,697.00 (South Sudan), respectively.

Figure 11 indicates the NPC and OPEX for the PV + storage + grid hybrid technology as simulated in the cases study. Each of the six EAC countries' NPC was 34,840.53 (Uganda), US\$ 121,395.40 (Burundi), US\$ 1243.24 (Kenya), US\$ 192,931.30 (South Sudan), US\$ 35,080.86 (Tanzania), and US\$ 80,580.55 (Rwanda), respectively. However, the NPC varied between US\$ 1243.24 (Kenya) and US\$ 291,931.30 (South Sudan). The NPCs ranged between US\$ 291,931.30 (South Sudan) and US\$ 12,432.40 (Kenya).

Each of the OPEX prices was US\$ -17,180.00 (Uganda), US\$ -281,365.00 (Burundi), US\$ -12,517.00 (Kenya), US\$ -50,403.00 (South Sudan), US\$ -7,717.00 (Tanzania), and US\$ -23,091.00 (Rwanda), respectively. These results indicate that all the six EAC countries will benefit immensely by implementing the PV + storage + grid hybrid technology for electricity generation. The OPEX of the PV + battery storage + grid hybrid technology ranged between US\$ -50,403.00 (South Sudan) and US\$ -7,717.00 (Tanzania). The OPEXs hover around US\$ -171,180.00 (Uganda) and US\$ -7,717.00 (Tanzania), respectively.

The implementation of this grid-connected system indicates that Uganda gains US\$ 0.0155 for every kWh generated, Burundi gains US\$ 0.0567 per kWh generated, Kenya spends US\$ 0.000584 per kWh generated, South Sudan gains US\$ 0.123 for every kWh generated, Tanzania spends US\$ 0.0167 for every kWh generated, and Rwanda gains US\$ 0.0373 for every kWh generated, respectively.

4. Discussion and Summary

Table 2 summarizes the details of important parameters from each technology covered in the research of this manuscript. We note that the results were based on the simulation of different energy technologies through HOMER software and with different parameter assumptions such as prices of diesel and electricity tariffs, respectively: (0.899\$/L and 0.201\$/kWh for Kenya, 0.7911\$/L and 0.115\$/kWh for Tanzania, 1.209\$/L and 0.310\$/kWh for Burundi, 0.972\$/L and 0.259\$/kWh for Rwanda, 1.010\$/L and 0.185\$/kWh for Uganda, and 0.354\$/L and 0.43\$/kWh for South Sudan).

5. Conclusion

The research used a daily load of one luxury house as a research object and carried out modelling and optimization of least cost, efficient, and reliable electricity generation technology among four technologies: (a) diesel energy technology, (b) PV + diesel technology, (c) PV + storage battery, and (d) PV + battery storage + grid, for all the EAC countries. The following conclusions were drawn from the study:

- (1) For off-grid users, the PV + storage battery technology was found to be the least costly and recommendable than any other technology including diesel technology
- (2) However, for South Sudan, the combination of PV + diesel technology, the sensitivity, and optimization analysis showed that the diesel technology would still dominate and be least costly technology than solar energy. This is so because South Sudan has the lowest price for diesel than any other countries in the EAC, but due to greenhouse gas emissions, solar energy would still need to be highly recommended
- (3) The proposed technology for the study is PV + battery storage + grid hybrid because the LCOE was each US\$ -0.0155/kWh (Uganda), US\$ -0.0373/kWh (Rwanda), US\$ 0.0167/kWh (Tanzania), US\$ 0.000584/kWh (Kenya), US\$ -0.123/kWh (South Sudan), and US\$ -0.0567/kWh (Burundi), respectively. Furthermore, each of the NPCs of the proposed PV + battery storage + grid hybrid technology was US\$ 34840.53 (Uganda), US\$ 80580.55 (Rwanda), US\$ 35080.86 (Tanzania), US\$ 1243.24 (Kenya), US\$ 291931.30 (South Sudan), and US\$ 121395.40 (Burundi), respectively
- (4) The proposed PV + battery storage + grid hybrid technology is recommended for possible adoption in each of the six EAC countries because both the LCOEs and NPCs are lower than the real electricity tariffs currently in use within these six EAC countries. Also, the connection of PV + battery storage to the grid (for locations wherever possible) would lower and provide affordable, reliable, and sustainable electricity prices in these countries. The findings in this paper are limited to a technoeconomic feasi-

bility analysis of affordable energy systems that focuses only on the EAC region

Data Availability

The data used in this research are available upon the request from the corresponding author.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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