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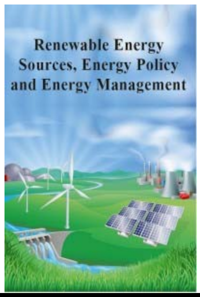

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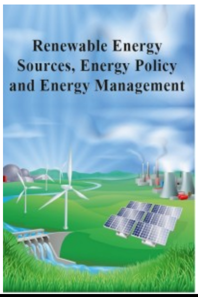

Original Research Article

Capacity Calculation and Subsidization Proposals for Rooftop PV Energy for a Residential Building in İstanbul

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ABSTRACT

Urban transformation works ongoing in metropolitan cities pose an opportunity for application of PV energy for multi-story residential buildings. In this study, PV energy production capacity of a 6-floor (14 flats) residential building located in İstanbul is modeled using PVsyst software, with its cost payback period to household owners calculated as 23 years without any energy feed-back scheme. When excess energy is sold back to the grid at 0.133 USD/kWh, the payback period reduces to 6.6 years. An alternative incentive scheme providing 60% of the initial cost by the state reduces owner's payback to 9.4 years while the state's share is paid back in 18.3 years with a price of 0.04 USD/kWh, which is lower than 0.06 USD/kWh production cost of conventional power plants, suggesting a policy to replace investment on new power plants with PV incentives to building owners. For 121 MWh production, saved carbon emissions is calculated as 44.692 t CO_2/year.

Keywords: Rooftop PV system design, renewable energy, solar energy feasibility, energy production for self consumption, urban transformation, energy subsidization policy

1.Introduction

Residential buildings constitute an average of 20% -in developed countries- to 35% -in developing countries- with expected increase in demand in the future [1]. In Turkey, residential buildings consume 24% of the total electricity production [2]. Focusing on the supply of electricity for residential buildings from renewable sources can contribute considerably to sustainable development, since it will have positive impacts from the environmental, economic and social points of view, in reference to the sustainability triangle [3]. That is, environmental benefits of reducing the use of non-renewable natural sources for energy can be achieved along with the social benefit of providing robustness for occupants in terms of independence from the energy grid along with the long-term economic benefits for occupants and national economy, especially for energy-dependent countries.

As of February 2021, the distribution of Turkey's installed power according to resources is; 32.2 percent hydraulic energy, 26.6 percent natural gas, 21.0 percent coal, 9.5 percent wind, 7.1 percent solar, 1.7 percent geothermal and 1.9 percent based on other sources [4]. Although Turkey has great solar energy potential, solar energy installations are lagging behind most of the European countries, such as that of Germany, which is capturing 60 percent less solar rays, [5].

1.1. Analysis Objectives

The analysis presented in this study aims to investigate feasibility of roof-top photovoltaic (PV) power for multi-storey residential buildings to supply electricity load of the whole building. Although there are studies on feasibility of PV power for various types of buildings, the study presented here aims to include the efficiency losses of shading in a dense community, to reflect efficiency losses, as well as sufficiency of roof area to supply energy load of the whole residential building having a typical size that may be found in İstanbul. The analysis further tries to assess financial feasibility of roof-top PV for owners and tries to relate alternative subsidization policies for building owners to savings that may be achieved from de-investments on power plants at the country scale.

The paper is organized in three sections. Section 1 introduces the motivation for this study as well as literature review relevant to the objectives of this study. Section 2 describes the methodology and analysis. Section 3 provides discussions and policy proposals base d on the findings. Finally, Section 4 presents conclusion and recommendations of the analysis.

1.2. Literature Review

There have been some applications and studies on feasibility of photovoltaic (PV) power plants in Turkey for rural areas, showing a payback period of 6.7 years, [6]. Comparison of feasibility of an 8,865 kWp installed capacity PV-powerplant for three major cities of Turkey; namely Istanbul, Ankara and Izmir shows a payback period of 13.6, 6.7 and 7.0 years to support 6,518, 7,257 and 7,802 households annually, for an ideal four-season inclination of PV modules at 32.60º, 32.70º and 32.80º, respectively, [7].

There are also studies on feasibility of PV-energy for own-use. It is shown that initial investment on the PV systems for residential buildings dominate their feasibility and on-grid systems may produce a saving of 0.27 USD/kWh/year [8]. Another study for the application of PV systems for university campus buildings in Isparta, Turkey has shown a payback period of 14 years for grid-connected 25 kW PV-capacity on building roofs, providing 15% of the energy requirement, [9]. A study for residential use in Adıyaman, Turkey, where solar radiation potential is given as 1,600-1,750 kWh/m2-year shows that for a house with annual consumption of 3,647 kWh and daily demand of 10 kWh, designing the system for extra 50% increase in demand, the initial cost was calculated as approximately 5800 USD based on the rates of the study date, payback period was calculated as 10 years and the required area for the PV system was 24 m2 for this demand, [10]. An application for a smart home, which is consuming as low as 149.925 kWh/year energy is also studied and it was calculated that a 2.5 kW off-grid system cost would be approximately 4,300 USD and on-grid system cost would be approximately 3,100 USD based on the rates of the study date, the difference being due to the cost of battery system needed and the payback period was calculated as 8 years for both systems, [11].

Provision of off-grid PV energy for rural areas where on-grid supply is not available or feasible or for providing self-sustainability of these modes of living has also been an area of interest because the renewable energy becomes a necessity rather than a preference. A study by Ahsan et al. includes design and cost analysis and field testing of a 1.0 kW off-grid roof-top PV energy system for a small house in New Delhi rural area, consisting of 5 PV modules and 2 batteries, supporting a small home designed by using the PVsyst software and found that the solar energy generated was 3,102.2 kWh/year supplying 2,933.4 kWh/year, due to insufficient demand at times or insufficient storage capacity; and stated that with 50% incentive for the initial cost the system needed no additional payment by the user, [12]. A study of similar context was carried out for off-grid energy supply of plateau houses having a weekly demand of 25,207.5 kWh (daily demand of 3.6 kWh) and a system with 5.54 kWh supply is designed with 8 PV modules having an installed power of 3 kW and costs were calculated as approximately 5,300 USD and 6,900 USD based on the rates of the study date for a stationary system and a moving system, respectively. It is also shown that the costs would be factored with 3.2 and 3.5, respectively if the installed power was increased to 10 kW [13].

Regarding feasibility of grid connected PV-energy; Mounouni et al. studied usage of a 5 kW residential grid-connected photovoltaic system and calculated that the electricity bills were reduced to 8.03% to 12.20% of the utility bill from May to July in Nevada, [14]. Bukar et al. studied 4.4 kWp peak power capacity photovoltaic grid-connected system in Nigeria, having lithium-ion battery storage to study the economic contribution of the battery as compared with the case without the battery and found that the energy consumption from the grid is reduced by 45.7%, [15]. Ellabban and Alassi analyzed the economic parameters of an existing PV-connected residential region with an average of 2.45 kWp PV system size on a case study in Australia, and based on 54 customers' data, various tariff schemes were proposed which yielded a payback period of 7.61 to 10.75 years with an internal rate of return (IRR) of 18% to 14%, [16]. In another study by Davi et al., for on grid-connected residential buildings in Brazil with capacities of 3.68 and 4.14 kWp, a payback period of 13 to 31 years were calculated, [17]. A study for Honduras shows that the payback period is 10 years, for 5.12 kWp system for an annual production of 6.3 MWh/year [18]. Another study involves a house with PV system in France to have 25 years of the payback period for a certain range of price and it was concluded that incentive-based policies were necessary, [19]. A study for Romania involving 5.5 kW rooftop solar system with battery capacities of 3.3, 6.5 and 9.8 kW concludes that due to high investment costs, the system could only be profitable with subsidies, which already exist as 90% of investment costs and supported by a feed-back price of 0.0587 USD compared to the tariff rate of 0.1567 USD per kWh, as calculated for an investment cost of 1,500 USD/kW and operational cost of 1% of total investment [20].

2. Methodology

In this study, an on-grid roof-mounted PV system was designed for a multi-story residential building by using PVsyst software. It is aimed to determine the energy that can be supplied given the roof space constraint, taking into account the shading from neighboring buildings. Later, economic analysis of the system was studied based on the payback period for the building owners. Finally, alternative subsidization policy schemes are analyzed to reduce the economic burden to the building owners. Economic burden of the subsidization to the state is also compared with the payback from the savings on the operational costs of the conventional power plants. It is investigated whether the subsidization costs to the state can be paid back with de-investment from conventional power plants. Thus, it is aimed to understand the applicability of PV energy for mass housing projects in cities to create a large impact in state economy by diverting high investment costs on conventional power plants as subsidies to building owners.

2.1. Design Parameters for Photovoltaic (PV) Systems

Determining meteorological data is the first step of the PV system design. The coordinates of the building are taken from Google Earth and it is fed on the PVsyst software. PVsyst provides access to several meteorological databases. In this project, monthly meteorological data were imported from Meteonorm 7.2. in PVsyst software, and generated hourly data is used for improvement of the models, [21].

The location of the building was selected as Istanbul, Turkey since there has been major residential building constructions under the urban transformation law. In this study, simulation of a typical single building with 6 floors having 18 meters building height and a basement floor plan area of 803.25 m^2 was conducted. Coordinates of the location, time zone, altitude, dimensions, number of floors, and height of the building are given in Table 1.

Table 2 shows the horizontal global irradiation, horizontal diffuse irradiation, temperature, wind velocity, linke turbidity, and relative humidity values for the selected location, as calculated from PVsyst database. PV system is designed and simulated according to the worst-case scenario, when the lowest irradiation is obtained. Although this approach produces more expensive PV system, it was aimed that the apartment would provide the 100 percent of energy demand in the month having lowest irradiation and sell excess electricity to finance this cost, while making the building independent of the grid, except for failure of the system. In Istanbul, the lowest irradiation is in December. On annual basis, 1,350.7 kWh/m^2 of horizontal global irradiation and 680.3 kWh/m^2 of horizontal diffuse irradiation is gained. A more elaborate study can be carried out to take into account the winter and summer seasons. For instance, from April to September, the average horizontal global irradiation and horizontal diffuse irradiation are 162.8 kWh/m^2.month and 77.9 kWh/m^2.month, respectively. In the worst-case scenario, from October to March, the average horizontal global irradiation and horizontal diffuse irradiation values are calculated as 62.3 kWh/m^2.month, and 35.5 kWh/m^2.month, respectively. In the case of yearly irradiation yield, PVsyst software showed the loss with respect to optimum as -5.1% and computed the global irradiation on collector plane as 1,457 kWh/m^2. In contrast, for the summer season including April to September, the loss with respect to optimum, and global irradiation on the collector plane are found as -0.9% and 1,008 kWh/m^2, respectively. In winter season that corresponds to the period from October to March, these values are found as -20.1% and 449 kWh/m^2.

Table 1 - Information on the building and location

Coordinates of the building	40.97 ˚ N 29.05 ˚ E
Time Zone	UT +3
Altitude	10 m
Dimensions of the building in the basement floor plan	25.5x31.5 m^2
Number of floors	6
Number of flats	14
Height of the building	18m (6 floors)

Table 2 - Geographic site parameters obtained from PVsyst Database

Months	Horizontal Global Irradiation kWh/m^2.month	Horizontal Diffuse Irradiation kWh/m^2.month	Temperature ˚C	Average Wind Velocity m/s	Linke Turbidity [-]	Relative Humidity %
January	43.5	26.3	6.2	4.79	2.700	75.6
February	55.6	31.6	6.3	4.89	2.933	75.7
March	95.0	59.3	9.1	4.50	3.152	71.4
April	132.1	69.9	12.4	4.10	3.422	67.3
May	173.7	76.9	17.9	4.00	3.222	65.2
June	186.2	91.6	22.5	4.19	3.290	59.9
July	191.2	88.2	25.7	4.70	3.290	58.5
August	167.0	81.0	25.5	4.80	3.422	63.4
September	126.8	59.8	20.9	4.30	3.222	68.1
October	85.3	44.0	17.1	4.20	2.933	72.7
November	54.1	28.7	11.9	4.29	2.857	75.6
December	40.2	23.0	8.3	4.89	2.700	73.5
Year	1350.7	680.3	15.3	4.5	3.095	68.9

2.2. Photovoltaic (PV) System Components

Photovoltaic (PV) Systems use solar energy and consists of solar cells that are composed of semiconductor materials basically characterized by two behaviors; while exhibiting insulator effects at lower temperatures, if energy is available, they can act as conductors [22]. According to the study of Almosni et al., there are three generations of PV cells, namely mono and poly crystalline silicon cells, thin film cells, and the third-generation cells, among which selection of the base material is dominated by various factors such as production cost, lifetime, and efficiency [23]. There are major energy losses in producing electricity from solar energy, related to transmission and thermalization losses and several approaches are proposed, including hot-carrier solar cells, intermediate band solar cells and multi-junctions to decrease the loss levels [23]. However, from the practical point of view, still mono crystalline and poly crystalline PV cells are common in the industry.

Basically, PV systems an be implemented as on-grid systems or off-grid systems. In on-grid systems, excess production of electricity can be fed into the utility grid and in case of inadequate solar electricity production which occurs generally at nights, electricity can be received from the utility grid. Unlike on-grid systems, off-grid systems contain battery or hydrogen technologies in order to store excess electricity production for later use, when there is insufficient PV energy production. In this study, an on-grid system design is proposed for reliability.

Main components of an on-grid system are PV arrays, solar inverters, fuse box, utility meter, solar cables and grid lines. The basic layout of the system is shown in Figure 1. PV modules produce DC from solar energy, and a solar inverter converts DC to AC that is the commonly used current. PVsyst database allows selection of the PV system components from a vast number of manufacturers.

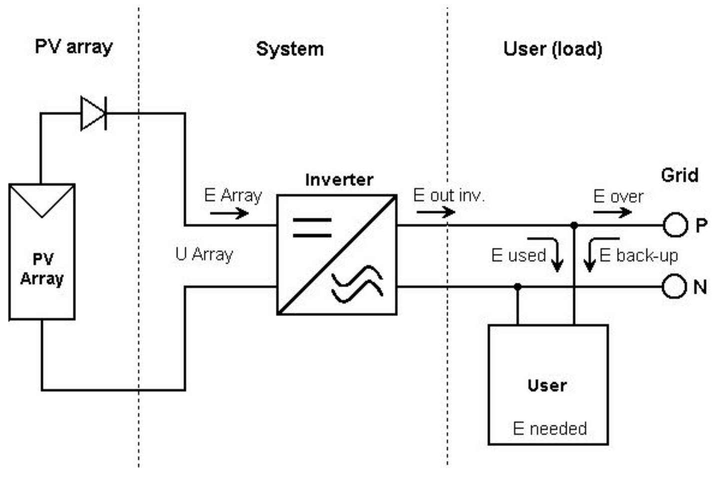

Figure 1 - Basic layout of the system modeled by the software

Mechanical and electrical data of the modules selected are given in Table 3 and Table 4. In this system, 305 Wp of Si-mono PV modules were used and each module has 1.919 m^2 area and 23 kg weight. The efficiency of the cells is given as 17.7 % by the manufacturer.

Table 3 - Mechanical Data of the PV modules

Module		Cells	
Length	1,954 mm	In series	72
Width	982 mm	In parallel	1
Thickness	40 mm	Cell area	238.9 cm^2
Weight	23 kg	Total no of cells	72
Module Area	1.919 m^2	Cells area	1.72 m^2

Table 4: Electrical Data of the PV modules

Technology	Si-mono
Nominal Power at STC	305 Wp
G_{ref}	1,000 W/m^2
I_{sc}	8.840 A
I_{mpp}	8.330 A
Temperature coefficient	5.3 mA/˚C
T_{ref}	25 ˚C
Open circuit, V_{oc}	45.20 V
V_{mpp}	36.60 V

2.3. Orientations of the PV Modules

In this study, a gable roof was used for simulation. Since the gable roof has a slope, the optimum angle was not considered in simulation because the erection of the modules may be a problem and may lead to high labor costs. If a flat roof is used to design, the optimum tilt angle should be investigated with respect to location and azimuth angle of the installation. Hence, two sub-arrays were placed on both sides of the gable roof of the building, based on their azimuth angles; the first sub-array was planned to be placed on the roof with -44˚ and the other one was planned to be placed with 136˚, with tilt angle as 20˚ as shown in Figure 2. To be able to obtain accurate results from the simulation, azimuth angles should be correctly defined. Azimuth angles were taken from the location of the building by using Google Earth tool. Once the azimuth angles and tilt angles were determined according to dimensions of the roof of the building, these parameters were defined to the orientation section of the PVsyst software.

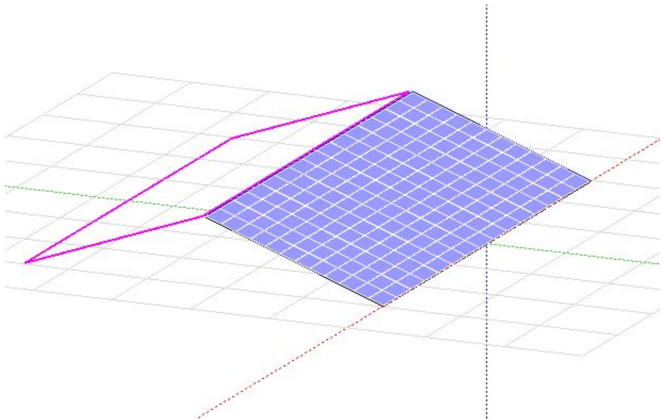

Figure 2: Landscape positioning of the PV modules on the roof

2.4. Calculation of the Nominal Power of the Array

Each sub-array consists of 180 PV modules laid out in 10 strings and 18 modules in series, and with two inverters, with total PV array covering the roof area of 690 m^2.

Nominal (STC) Array Global Power was determined by multiplying the total number of modules with the nominal power of the PV module (305 Wp) given in Table 4. As a result, Nominal Array Global Power was determined as

54.9 kWp. (*Table 5*). 25 kW inverters were used in sub-arrays. The total power of the arrays and total power of the inverters were determined as 110 kWp and 100 kWac, respectively.

Table 5: Sub-array #1 and sub-array#2 data

Number of PV modules in series	18 modules
Number of PV modules in parallel	10 strings
Total number of PV modules	180
Nominal (STC) Array Global Power	54.9 kWp
Array Global Power at operating condition (50˚)	48.7 kWp
Array Operating Characteristics (50˚) for U_{mpp}	582 V
Array Operating Characteristics (50˚) for I_{mpp}	84 A
Unit Nominal Power of the Inverter	25.0 kWac
Operating Voltage of the Inverter	280-950 V
Number of Inverters	2
Total Arrays Global Power (Nominal STC)	110 kWp
Total Module Area	691 m^2
Total Cell Area	619 m^2
Total Power of Inverter	100 kWac

$P_{nom}\,ratio$ can be defined as the ratio of the array power to the inverter power. In Turkey, array power is recommended to be approximately 10 percent greater than the inverter power, [24]. The ratio was calculated as 1.10 by Equation (1). Hence, it is possible to say that the designed system is acceptable.

$$P_{nom}\,ratio = \frac{54.9\,kWp}{2 \times 25\,kWac} = 1.10 \tag{1}$$

2.5. Performance of On-grid PV Systems

The study of Sharma, Chandel, and the study of Marion et al., shows the parameters for the performance of on-grid PV systems based on International Energy Agency (IEA) [25, 26]. According to the study of Marion et al., among the IEC standard 6174 performance parameters, final PV system yield, performance ratio, and reference yield parameters can predict the overall response of the PV system, where final PV system yield is defined as the ratio of the net energy output to the power of the installed PV array, reference yield as the ratio of the total in-plane irradiance to the reference irradiance of the PV [26]. Performance ratio (PR), one of the key parameters in order to evaluate the performance of the designed PV system, can be determined using Equation (2), [27].

$$PR = Y_f / Y_r \tag{2}$$

where, Y_f and Y_r are mean final PV system yield and reference yield, respectively. In PVsyst, the performance ratio is defined by Equation (3). Based on performance evaluation of the PV system, design can be rectified or modified, considering the aforementioned parameters.

$$PR = \frac{E_{grid}}{Glob_{inc} \times P_{nom}} \tag{3}$$

Based on performance evaluation of the PV system, design can be rectified or modified, considering the aforementioned parameters.

2.6. 3-D Model of the System Considering Shading Effects

In order to carry out a realistic analysis, shading must be taken into account for PV systems because it reduces electricity production, due to the decreasing receival of irradiation from the sun. Generally, it is impossible to get rid of shading in the PV system completely because of many reasons such as dust, obstacles, wrong mounting process. Several studies claim that even small amount of shadows may lead to power reduction of the entire PV systems. For the problem of hot-spots leading to high temperatures that result in reduced currents [28], it is proposed to use bypass diode in order to avoid hot-spot [29, 30, 31, 32]. Tripathi, Aruna and Murthy carried out an experimental study for the impact of shading on the monocrystalline and poly crystalline PV systems' response in terms of open circuit voltage (V_{OC}) and short circuit current (I_{SC}). They state that 25% of shading as measured by the ratio of the shaded area to the total area of the PV system leads to 47.72% of short circuit reduction in mono crystalline PV module and 60.86% of reduction in poly crystalline one. Besides, they found that the decrement of the maximum power output of mono crystalline PV module is less than that of poly crystalline PV module [28]. As a consequence, it is possible to say that under the same shading level, mono crystalline modules are less affected than poly crystalline ones. In this study, this result from Tripathi, Aruna and Murthy was also taken into account and mono crystalline PV modules were selected for the simulation in order to obtain more electricity production.

Since this study was performed as a rooftop PV system for residential buildings in Istanbul, Turkey, where majority of the buildings are constructed very close to each other, two higher buildings were placed as obstacles on two sides of the building under consideration. Once the system components such as PV modules, and inverters are defined, 3-D model of the buildings are prepared as shown in Figure 3. Two buildings of 24 m height are located on both sides of the designed building at approximately 10 m distance from the building on which the PV system is installed. PV modules are defined on the roof, and shading analysis is performed according to the module layout. The software also allows animations for the desired day.

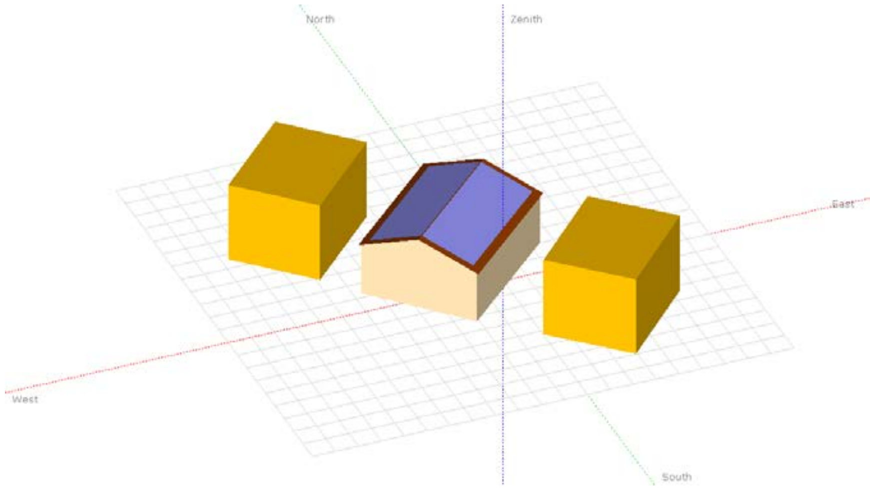

Figure 3: 3-D view of the system

2.7. Economic Analysis Based on Payback Period

A comprehensive feasibility analysis on a real case would require calculation of the net present value and internal rate of return (IRR) besides the payback period, to substantiate the benefits of investing on solar energy. However, for the sake of understanding the order of magnitude of the investment in response to the benefits, payback period is calculated from equation (4), for the household owners, given various subsidization models from the state, as well as the payback period on the state's side based on the production costs of the conventional energy alternatives.

$$Payback\ Period = \frac{Initial\ Investment}{\sum(Earning\ From\ Selling\ to\ Grid +\ Annual\ Savings\ from\ Electricity\ Bills)} \quad (4)$$

3. Results

3.1. Results of the PVsyst Analysis of the System

Simulation results reported by PVsyst show that system production is 121 MWh/year, specific production is 1,102 kWh/kWp/year, and normalized production is 3.02 kWh/kWp/day. Figure 4 shows the normalized production distribution within a year and the useful energy after losses.

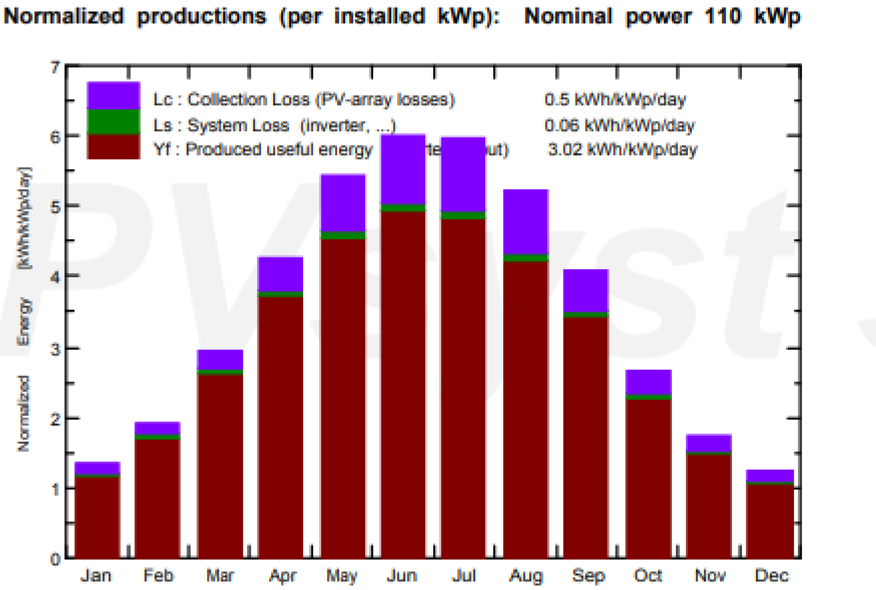

Figure 4: Normalized Production Distribution Within a Year

Performance ratio (PR) was determined by PVsyst as 0.843.

Figure 5 shows the performance value variation in months. It is possible to say that the largest values of the PR were obtained in February and March, due to the fact that there is less shading and lower ambient temperature, resulting in lower loss hence higher PR.

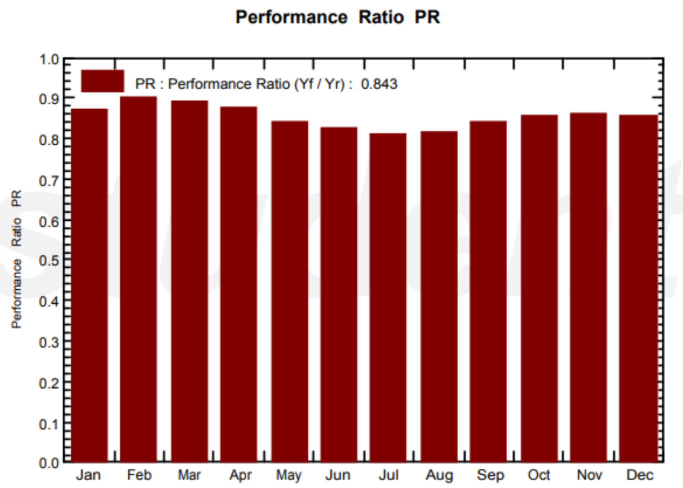

Figure 5: Performance Ratio

Table 6 shows the results of the analysis in terms of several parameters with respect to the months. According to the results, the average ambient temperature was 15.37 ˚C. The system generates 123.57 MWh with 121.03 MWh of energy fed back to the grid in a year. According to the loss diagram of the system, where although horizontal global irradiation amount is 1,351 kWh/m^2, the collector can receive 96.8 % of this amount which corresponds to 1,307.8 kWh/m^2. Effective irradiation on the collector was determined by Equation (5), after other losses. Due to 15.89 % of efficiency at the standard test condition, 136.3 MWh was calculated as the array's nominal energy. Additionally, the system was exposed to several losses such as shading, temperature, ohmic wiring, etc. According to the diagram, the major loss of the system is related to the temperature which is 6.79 %.

Table 6: Results of the simulation

	GlobHor (kWh/m^2)	DiffHor (kWh/m^2)	T_Amb (°C)	GlobInc (kWh/m^2)	GlobEff (kWh/m^2)	Earray (MWh)	E_Grid (MWh)	PR
January	43.5	26.30	6.22	42.6	39.4	4.19	4.08	0.873
February	55.6	31.58	6.27	53.8	50.6	5.44	5.31	0.899
March	95.0	59.26	9.05	91.8	86.9	8.97	8.97	0.891
April	132.1	69.87	12.42	127.4	121.6	12.23	12.23	0.874
May	173.7	76.94	17.88	167.8	160.5	15.48	15.48	0.840
June	186.2	91.57	22.47	179.9	171.7	16.29	16.29	0.825
July	191.2	88.20	25.68	184.9	176.7	16.42	16.42	0.809
August	167.0	80.95	25.54	161.4	154.2	14.44	14.44	0.814
September	126.8	59.75	20.93	123.0	117.1	11.33	11.33	0.839
October	85.3	43.98	17.05	82.8	78.1	7.79	7.79	0.857
November	54.1	28.70	11.93	52.8	49.1	4.98	4.98	0.859
December	40.2	22.96	8.26	39.4	36.2	3.71	3.71	0.858
Year	1,350.7	680.05	15.37	1,307.5	1,242.1	123.57	121.03	0.843

$$Effective\ irradiation\ on\ collectors = 1242\ \frac{kWh}{m^2} \times 691\ m^2 = 858.2\ MWh \tag{5}$$

3.2. Energy Demand of the Building

According to Energy Market Regulatory Authority (EPDK) of Turkey, the minimum monthly electricity consumption of a family of four-people is 230 kWh. However, the system is designed for 253 kWh consumption excluding heating demand for each flat. Given the constant building roof area, the percentage of the demand that can be supplied with PV energy at each month are given in Table 7, with respect to the grid energy capacities (E_Grid) given in Table 6. It can be observed that the PV system can provide all of the demand throughout the year, providing the ability for survival in case of power cut in addition to eliminating the energy cost of the users. In December where the energy supply is minimum, the system provides 104.7% of the energy demand.

Table 7: Energy Demand of the 14-flats building and energy supply of the system

Months	Energy Demand (kWh)	Surplus Energy (kWh)	Percent of the Supplied Energy for Demand
January	3,542	538	115.2%
February	3,542	1,768	149.9%
March	3,542	5,428	253.2%
April	3,542	8,688	345.3%
May	3,542	11,938	437.0%
June	3,542	12,748	459.9%
July	3,542	12,878	463.6%
August	3,542	10,898	407.7%
September	3,542	7,788	319.9%
October	3,542	4,248	219.9%
November	3,542	1,438	140.6%
December	3,542	168	104.7%

3.3. Economic Analysis of the System

Considering the initial cost of the PV system, shown in Table 8 which is quite high since PV-units are imported, it is calculated that for a 6-floor residential building, the payback of the system is calculated as 23.4 years, based on the parameters listed in Table 9 and based on the rates of the study date, [33]. However, if the surplus energy is fed back to the grid at 0.133 USD/kWh price that was implemented previously by the state, then the payback period becomes 6.6 years, as shown in

Table 11. When the generated electricity is sold at 0.08 USD/kWh, which is approximately the unit price of electricity for residential consumers, then the payback is calculated as 9 years. Calculations for other variations of feed-back price are shown in Table 11. According to a study [34], energy production cost of the powerplant investors per kWh is in the range of 0.066-0.151 USD/kWh for coal-based power plants and 0.061-0.087 USD/kWh for natural gas-based power plants as of 2014, in Turkey. So, even a feed-back price of 0.04 USD/kWh, which is lower than the cost of production of energy to the energy producer, the payback period for the consumer is reduced to 13.3 years, while this price becomes a saving that is transferred from the production cost to the consumer, creating also a future saving from new plant investment. Alternatively, a more encouraging scheme for the consumers would be a feed-back scheme with 0.133 USD/kWh price for the first 5 years, 0.08 USD/kWh for the second 5 years, and 0.04 USD/kWh for the remaining years, which imply an incentive by the state for the first five years, the payback period is calculated as 8.2 years.

Table 8: Initial Investment Cost

Investments	Quantity	Unit Price	Total Price
PV modules	360	200 USD	72,000 USD
Inverter	4	2,500 USD	10,000 USD
Supports for modules	110 kWp	0.08 USD/Watt	8,800 USD
Installation and other expenses (bi-directional meters, cables, etc.)	Lump-sum	Lump-sum	5,000 USD
Total			95,800 USD

Table 9: Payback Period of the System without Feeding Back to Grid

Unit price of the electricity per kWh (USD/kWh)	0.1171
Energy consumption of each flat per month (kWh)	253
Monthly electricity bill cost of each flat (USD/month)	24,33
Total electricity cost of each flat per year (USD/year)	291.93
Initial investment cost of the system (USD) - for 14 flats	95,800
Payback period of the system (year)	23.4

Table 10: Payback Period of the System with Feeding Back to Grid

Unit selling price to the grid (USD/kWh)	0.133
Earning from the surplus energy per year (USD/year)	10,443.96
Total saving from electricity cost of the building per year (USD/year)	4,086.98
Total earning from the system (USD/year)	14,530.94
Payback period (year)	6.59

Table 11: Payback Period of the System with Feeding Back to Grid in Different Prices

Description	%60 of 0.133 USD	%50 of 0.133 USD	%40 of 0.133 USD	%30 of 0.133 USD
Unit selling price to the grid (USD/kWh)	0.08	0.07	0.05	0.04
Earning from the surplus energy per year (USD/year)	6,266.37	5,221.98	4,177.58	3,133.19
Total earning from electricity cost of the building per year (USD/year)	10,353.35	9,308.96	8,264.56	7,220.17
Payback period (year)	9.25	10.29	11.59	13.27

3.4. Alternative Subsidization Schemes for Initial Cost of the System

Alternative subsidization schemes are also possible to decrease the initial investment burden on the households, which may increase the willingness to adopt the rooftop PV electricity generation.

It is proposed that 60% of state incentives on the initial investment cost, which corresponds to 57,480 USD can be exchanged for the excess energy that is produced throughout the year until this incentive is paid back, where this pay-back duration for the state is calculated as 18.3 years based on the 0.04 USD/kWh saving that can be achieved from the conventional energy production cost. By doing so, the payback period for households can reduce to 9.38 years, as shown in Table 12, among other alternative subsidization shares. One should also consider the additional saving on the state's side by refraining from new power plant investments in this proposed scheme while the auto-producers are provided with part of the capital that is hardly available for an average income family.

Table 12: Payback Period of the System in case of Incentive

Percent that compensates the initial investment cost of the system (%)	0%	10%	20%	30%	40%	50%	60%
Initial Investment cost (USD)	95,800	86,220	76,640	67,060	57,480	47,900	38,320
Payback period (years)	23.44	21.10	18.75	16.41	14.06	11.72	9.38

This subsidization scheme can be further developed. For example, the state can subsidize the system 100% and receive free energy from the system (producers) until this investment is paid back to the state. This system completely discharges the financial burden on the auto producers while gradually shifting the residential buildings to be part of an inter-active power plant system serving the self- and also the higher energy demanding buildings, replacing the polluting power plants alternatives.

3.5. Carbon Balance Calculations of the System

According to a study by Shahsavari and Akbari, 80% of carbon dioxide emissions and more than half of the greenhouse gas emissions is due to energy production [35]. They state that 4,600 GW of installed PV capacity can save more than 4 gigatons of carbon dioxide emissions annually, because PV systems do not lead to greenhouse gases in its operation and do not cause other pollutants [36]. PV systems generate electricity with low carbon emissions compared to non-renewable ones. The amount of saved CO_2 emissions were evaluated in this study, by using Carbon Balance Tool in PVsyst software for the on-grid PV system design with a capacity of 110 kWp. The calculation based on Life Cycle Emissions (LCE) takes into account the total life cycle of components used in design or the energy amount. The Carbon Balance Tool executes this calculation by comparing the electricity produced by the designed PV system and the electricity supplied by the existing grid by calculating the difference between the produced and saved amount of CO_2 emissions [37]. In PVsyst, carbon balance is calculated from four key factors which are the designed PV system production obtained by simulation for one year, system lifetime, life cycle emissions (LCE) of the grid, and life cycle emissions of the designed PV system [37]. LCE of the grid is given in $\frac{gCO_2}{kWh}$, and means the average CO_2 emissions for the electricity supplied by the grid. In contrast, LCE of the designed PV system is given in tCO_2 and includes the total CO_2 emissions due to the process of the installation and the construction [37]. In this study, annual degradation was taken as 1% for the simulation. Saved CO_2 emissions were determined as 1,340.761 tons for 30 years of system lifetime, by using Equation (6) that is taken from PVsyst and yearly carbon savings are calculated as shown in Table 13.

$$E_{grid} \times System\ Lifetime \times LCE\ Grid - LCE\ System = Carbon\ Balance \qquad (6)$$

Table 13: Carbon Balance Values with respect to kWp and years

E_{grid}	121 MWh
System Lifetime	30 years
LCE Grid	489 g CO_2/ kWh
LCE System	199.8 t CO_2
Carbon Balance	1,340.761 t CO_2
Carbon Balance	44.692 t CO_2 / year
Carbon Balance	12.211 t CO_2 / kWp
Carbon Balance	0.407 t CO_2 / kWp / year

Variation of CO_2 balance with time is plotted by PVsyst software as shown in Figure 6.

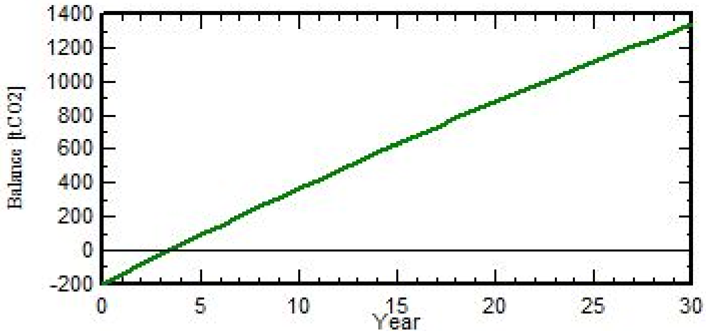

Figure 6: CO_2 Balance with respect to Years

4. Conclusions and Policy Implications

An on-grid PV rooftop system is designed to supply 100 percent of the electricity need in each month for a 6-floor, 14 flats residential building in Istanbul. A PV array with a capacity of 110 kWp, providing a monthly demand of 3,542 kWh/month was housed on the roof area of 691 m^2. System produces an annual 175 kWh/m^2 of installed array, which is less than 228 kWh/m^2 for a much smaller house demand of 3,647 kWh/year with 50% extra capacity in Adıyaman [10]. Cost of the 110 kW capacity system designed can be calculated as 871 USD/kW, which is very small compared to a 5.5 kW capacity system with battery in Romania [20], having a cost of 1,500 USD/kW and to the 2.5 kW on-grid system studied in Turkey [11], having a cost of 1,240 USD/kW, suggesting a smaller cost for multi-storey systems. For an off-grid system with a small capacity of 3 kW in Turkey, cost was calculated as 1,767 USD/kW [13].

Economic analysis of the system showed that, when all of the initial cost of the system was compensated by households, the payback period was determined as 23.4 years. Payback periods for various on-grid systems having much smaller capacities ranging from 2.5 kW to 5.5 kW reported to range between 8 to 11 years, [10, 11, 16, 18], whereas for a 25 kW residential system is Turkey payback is calculated as 14 years [9], suggesting a less feasible system with increased capacity for roof-top PV systems. Although PV powerplants with larger capacities show a payback of 7 to 14 years [6, 7], this cannot be compared to roof-top PV, because of different efficiencies in production and distribution.

Alternative subsidization schemes are investigated under two headings. The first subsidization scheme involved feeding-back the excess energy to the city grid. It is proposed that, if energy is sold back to the grid at 0.133 USD/kWh, the pay-back time is 6.6 years which may be tolerable by the household owners. However, this scheme may not be preferred on the state’s side, since after 6.6 years household owners start to profit from this scheme. Hence, an alternative incentive scheme of 0.133 USD/kWh for first 5 years and later, a price set approximately at the cost of production of energy of conventional power plants is proposed as 0.08 USD/kWh for the second 5 years, and reduced by half to 0.04 USD/kWh for the remaining years with a 8.2 years payback period.

The second group of subsidization scheme considers partial subsidization of the initial investment by the state. A subsidy of 60% of the initial investment yields 9.4 years of payback period for the households. The state then may receive the excess energy free of charge from these households until the subsidized amount is paid back in 18.3 years to the state, with the saving from the production cost of 0.06 to 0.15 USD/kWh that the state would pay otherwise. It is proposed in other countries that subsidization of the initial investment is necessary, given the very long payback time [19] and the rate of subsidization proposed were as much as 50% to 90% [12, 20].

It is shown that an optimum subsidization scheme that would encourage investment of the household owners while saving the state from capital intensive and polluting power plant investments is possible, and may help faster adoption of the PV energy while leading to a substantial saving on carbon emissions of the buildings.

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Original Research Article

Assessment of Renewable Energy Potentials of The Northeast Geopolitical Region of Nigeria

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ABSTRACT

Energy is key to socioeconomic and sustainable development of any society. Northeast geopolitical region of Nigeria is the region with the least access to grid electricity and the region with the least per capita electricity consumption in Nigeria. A desk research was undertaken to assess the renewable energy resources available in the region and their viability for the generation of electricity to meet the needs of the region and those of other regions in the country. Five renewable energy resources were appraised: solar; wind power; hydroelectric power; municipal solid waste and biomass. It was found that 367,702.10 MW of electricity can be generated with the use of photovoltaic solar technology. It was also found that wind power technology is feasible in two of the states in the region. The study also revealed that up to 5,125 MW of electricity can be recovered from two states in the region when hydroelectric power technology is used. All six states in the region were found to be viable for the generation of electricity from municipal solid waste and biomass with each having a potential of generating up to 1,249 MW and 4,752 MW of electricity respectively. According to the study, since each of the states has at least two different renewable energy resources, friendly policies are needed to attract investors to exploit these resources for the benefit of the region and the country as a whole.
Keywords: Biomass; Hydroelectric Power; Municipal solid waste; National; Nigeria; Renewable Energy; Solar Energy; Sustainable Development; Wind Power Energy.

1.Introduction

Energy is the lifeline of modern economies, and it is also equally an important factor in determining a society's quality of life. The need for energy in the 21st century can never be over-emphasised; it is the key to the fulfilment of basic individual and communal needs in the modern society. It is no surprise that the need for all to have access to affordable, reliable, sustainable, and modern energy is identified as the 7th agenda of the 17 listed sustainable development goals (SDGs) of the United Nation.

Electricity, as the easiest and most consumable form of secondary energy is critical to an economy's sustainable development while its absence can have negative effects that are harmful to the society as a whole [1]. Thus, the availability and accessibility of electricity is used as an index for assessing a country's or a society's quality of life [2].

Nigeria has a population of about 200 million people [3], however, only about 48% of this population has access to grid electricity [1]. In addition, most of the people who have access to electricity do not enjoy 24 hours supply as such they have to run personal generators to meet their electricity needs.

The northeast geopolitical region (NE) of Nigeria is one of the six geopolitical regions in the country, the others being: northwest; northcentral; southeast; southwest and south-south. North-eastern Nigeria which is made up of six states (Adamawa, Bauchi, Borno, Gombe, Taraba and Yobe) and has a population of about 27 million people [3] lies within longitude 9.9992 and 13.1520 and latitude 11.8846 and 7.9867 [4]. Of the six geopolitical regions in the country, it is the region with the least access to grid electricity – just about 16% of its populace have access to grid electricity. This is in sharp contrast to the south-south and south-west regions of the country where about 82% and 75% of their populace respectively have access to grid electricity [5]. The double jeopardy scenario facing the region is that in addition to the abysmal low access to grid electricity, the few who are connected to the grid have an average daily electricity supply of just about 5 hours – the least in the country [6].

The electricity woes of the region which is a miniature representation of the situation in the country persist in spite of the abundant renewable and non-renewable energy sources available in the region and the country at large. The sustainable development of any country is hinged on its ability to exploit its available primary energy sources for secondary energy production like electricity which is required for use by businesses and households. The need to fully exploit the region's existing primary energy resources becomes crucial in order for the region to grow sustainably and, as a result, to alleviate the sufferings of the people caused by inadequate electricity supply, this paper intends to appraise the renewable energy potentials of the northeast geopolitical region of Nigeria, with the aim of identifying the potentials and demerits of each source.

2. Background and Energy Scenario in Nigeria And the NE Region

The first instance of electricity generation in Nigeria dates back to 1896 when the first generating power plant was installed by English colonists in Lagos. The capacity of the electricity plant was 60 kW [7]. Since then, there have been numerous independent power plants dotted all-over the country. In 1951, an act of parliament birthed the Electricity Corporation of Nigeria (ECN) which was established to take over and coordinate all matters relating to the generation, transmission and distribution of electricity in the country [8]. In 1962, another Act of Parliament established the Niger Dams Authority (NDA) for the development of hydroelectric power. Ten years later, ECN and NDA were merged to form the National Electric Power Authority (NEPA) which was to be responsible for all power related matters [9]. Despite numerous efforts and interventions in the years following NEPA's establishment, it was clear that the organization, which held monopoly in the power sector, was unable to meet the country's needs. This reality led to the introduction of the National Electric Power Policy (NEPP) which was meant to be the beginning of the complete overhaul of the power sector so as to make it market driven and have it meet the electricity needs of the country. The policy led to the signing into law and creation of the Electric Power Sector Reform (EPSR) Act in 2005 which was expected to level the playing ground for potential investors and improve the wellbeing of its citizens [1]. The EPSR Act transformed and led to the unbundling of NEPA into the newly incorporated Power Holding Company of Nigeria (PHCN) comprising 18 separate successor companies that took over the assets, liabilities and employees of NEPA. The entities created by the unbundling of NEPA were 6 power generation companies (GENCOs), the Transmission Company of Nigeria (TCN) and 11 distribution companies (DISCOs) [9]. These companies were responsible for the generation, transmission, distribution, trading, bulk supply and resale of electricity in the country. As part of the process of overhauling the sector, Nigerian Electricity Regulatory Commission (NERC) was created to regulate the activities of the companies created. The functions of NERC were to regulate tariffs, ensure that companies provide quality service, and effectively oversee the electricity industry [10].

The unbundling of NEPA has not yielded the desired result as electricity generation and supply capacities have not improved since then. Aminu and Peterside [11] adequately captured the failures of the whole scheme in this sentence: "power sector privatization in Nigeria has only succeeded in entrusting the collective wealth of the people in the hands of few elites, retrenchment of workers, high electricity bills without commensurate services among other negative impacts". Adedeji [12] further buttressed this by stating in his finding that the NERC which oversees the players in the sector has fined these players for poor performance and inefficiency. Clearly, the current setting of the power sector is not living to the desired expectations had of it when it was unbundled. Researchers have stated that the best way of making the sector as efficient as it should be is by fully deregulating the industry which will encourage competition and eliminate government interference which is largely seen as the reason for the progress of the industry, they also alluded that fully deregulating the industry will spur the growth of RE resources in the energy mix of the country [1, 13-16].

Nigeria has 25 on-grid power generating plants whose installed capacity is approximately 12,500 MW. However, due to a myriad of factors such as poor maintenance and vandalism, only about 4,000 MW is currently in operation [17]. The energy mix supplying the national grid comprises power from hydroelectric dams which are all situated in the northern part of the country and natural gas power plants which are all based in the southern part of the country – close to the source of the required natural gas. The gas-powered plants are responsible for 80% of the power supplied to the grid while the hydroelectric dams are responsible for the remaining 20% [17]. Table 1 shows the name, location, installed and average operational capacities of the on-grid power plants in the country while Figure 1 shows the location of the plants on the map of the country [17].

Table 1. On-Grid Power Plants in The Country and Their Capacities

S/N	Name	Type	Location (State)	Installed Capacity (MW)	Average Operational Capacity (MW)
1	AES	Gas	Lagos	180	0
2	Afam IV-V	Gas	Rivers	724	2
3	Afam VI	Gas	Rivers	685	455
4	Alaoji NIPP	Steam	Abia	720	67
5	ASCO	Gas	Rivers	294	0
6	Egbin	Steam	Lagos	1,320	539
7	Geregu	Gas	Kogi	414	131
8	Geregu NIPP	Gas	Kogi	450	179
9	Ibom	Gas	Akwa Ibom	190	76
10	Ihovbor NIPP	Gas	Edo	434	182
11	Jebba	Hydro	Kwara/Niger	570	262
12	Kainji	Hydro	Niger	720	173
13	Odukpani NIPP	Gas	Cross River	561	64
14	Okpai	Gas	Delta	900	375
15	Olorunsogo	Gas	Ogun	335	189
16	Olorunsogo NIPP	Gas	Ogun	760	171
17	Omoku	Gas	Rivers	110	0
18	Omotosho	Gas	Ondo	335	163
19	Omotosho NIPP	Steam	Ondo	500	169
20	Rivers IPP	Gas	Rivers	136	0
21	Sapele	Steam	Delta	504	69
22	Sapele NIPP	Gas	Delta	450	111
23	Shiroro	Hydro	Niger	600	153
24	Trans Amadi	Gas	Rivers	150	0
25	Transcorp Ughelli	Gas	Delta	480	374
	TOTAL			**12,522**	**3,904**

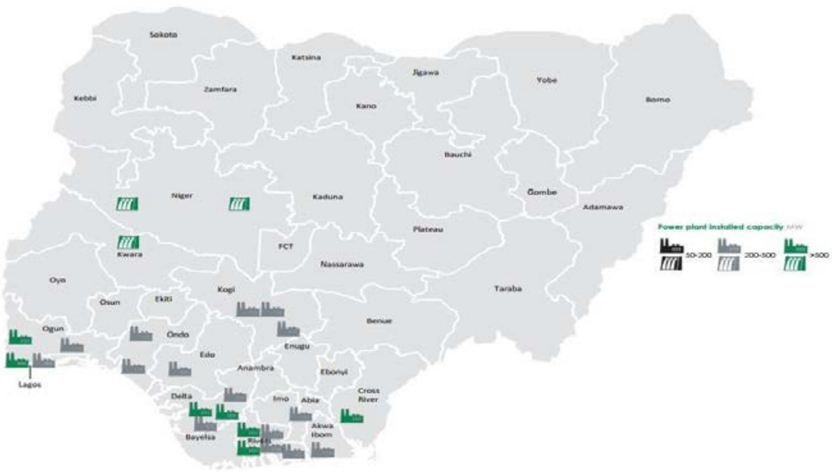

Figure 1. Locations of On-Grid Power Plants on the Map of Nigeria [17]

Nigeria has one of the least per capita electricity consumptions in the world. With a paltry 156.73 kWh per capita, it is dwarfed by other countries even in the same West African subregion. For example, Ghana's per capita grid electricity consumption is about twice that of Nigeria (305 kWh) [18]. When the per capita electricity consumption of the 10 African countries with the highest nominal GDPs are juxtaposed, it is found that despite Nigeria having the highest nominal GDP, it has the 3rd least per capita grid electricity supply. As compared to Egypt and South Africa, the continent's second and third largest nominal GDP countries, Nigeria's desperate situation is more evident, as these two countries have per capita grid electricity supplies that are 32 and 13 times greater than Nigeria's. Figure 2 shows the countries with the largest 10 largest nominal GDPs in Africa (in descending order) and their corresponding per capita electricity consumption [19].

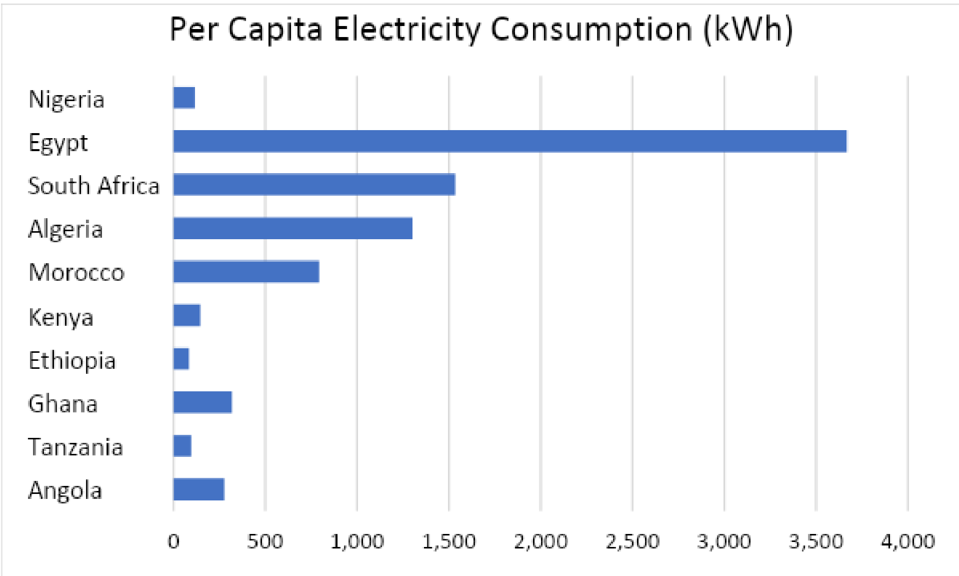

Figure 2. Per Capita Grid Electricity Consumption of the 10 Largest GDPs in Africa

Looking at the per capita electricity supply within Nigeria on region-by-region basis, the northeast geopolitical region has the least supply of electricity. According to Olaniyan et al., [5], per capita electricity consumption in North-Eastern Nigeria is just about 1 kWh, this far lower than what is obtainable in other geopolitical regions – for instance, the Southeast geopolitical region boasts of 36 kWh of electricity per capita. Even though the lack of electricity supply is prevalent across Nigeria, the Northern part of the country suffers more. Ohiare [20] pointed out in his research that Taraba state which is in the northeast geopolitical region in the year 2009 had the highest number of households (81.3%) without access to any form of electricity supply, whereas, Lagos state (Southwest Nigeria) recorded the least percentage of households without access to electricity at (6.1%). Monyei et al., [21] further exposed the energy poverty in the northeast by pointing out that the region's yearly per capita electricity consumption was just about 35.39 kWh while that of Lagos is 15 times higher (543.49 kWh). From Figure 3 which is a map of Nigeria showing electrified communities graphically and the energy poverty bedevilling NE Nigeria, it can be seen the northeast region has the least electrified communities.

Figure 3. Electrified Communities in Nigeria [22]

The low access and supply of grid electricity to the northeast geopolitical zone has greatly lowered the quality of life of the residents of the region and hampered its economic development by restricting the growth of small and medium scale industries which are the backbone of most economies [23].

3. Energy and Renewable Energy Policies in Nigeria

The National Energy Policy of 2003 was the first comprehensive energy policy approved in the country. The policy which was developed by the Energy Commission of Nigeria (ECN) was aimed at outlining government's policy on the production, supply and consumption of energy. The main goal of the policy is to create energy security through a robust energy supply mix by diversifying the energy supply and energy carriers based on the principle of *"an energy economy in which modern renewable energy increases its share of energy consumed and provides affordable access to energy throughout Nigeria, thus contributing to sustainable development and environmental conservation"* [24].

Renewable Electricity Policy Guidelines (REPG) was developed in 2006 by the federal ministry of Power and Steel. Its mandate was to oversee the expansion of the energy mix of the country to include more renewables (at least 5%) [25]. REPG outlines the plans, policies, strategies and objectives of the government of Nigeria for the promotion of renewables in the power sector.

In 2007, Nigerian Biofuel Policy and Incentives (NBPI) was enacted, it was aimed at developing and promoting the domestic ethanol industry by inculcating its usage in everyday activities. In line with this, the state oil company was mandated to create an environment that promotes the blending of ethanol with fossil fuel for use in internal combustion engines so as to reduce the nation's dependence on imported gasoline, and also reduce environmental pollution, while at the same time creating a commercially viable industry that can precipitate sustainable domestic jobs [24]. The benefits of the policy as stated in the policy document was "to create additional tax revenue, provision of jobs to reduce poverty, boost economic development and empower those in the rural areas, improve agricultural activities, energy and environmental benefits through the reduction of fossil fuel related GHGs in the transport sector [26].

The National Renewable Energy and Energy Efficiency Policy (NREEEP) is now the ultimate policy guiding generation and use of electricity from RE sources in the country, it also advances energy efficiency. NREEEP majorly exists to meet electric power supply targets in a sustainable manner [27]. The policy marks the initial steps of aligning the country's renewable energy and energy efficiency policies with those of the West African subregional group. The main renewable energy sources focused on in the policy are; hydropower, wind and, solar (photovoltaic and thermal) [27].

Objectives of the policy as reported in the policy document are thus [28]:

i. Set out a framework for action to address Nigerians' challenge of inclusive access to modern and clean energy resources, improved energy security and climate objectives;
ii. Recognise the national significance of renewable electricity generation activities by providing for the development, operation and maintenance, and upgrading of new and existing renewable electricity generation activities;
iii. Declare that the proportion of Nigeria's electricity generated from renewable energy sources shall increase to a level that meets or exceeds the ECOWAS regional policy targets for renewable electricity generation and energy efficiency for 2020 and beyond;
iv. Declare Energy Efficiency as a large, low cost, and under-utilized Nigerian energy resource offering savings on energy bills, opportunities for more jobs, improved industrial competitiveness, and lower air pollution;
v. Recognise that poverty mitigation and environmental protection are hindered by the continued predominance and inefficient use of oil and natural gas in meeting our energy needs;
vi. Take a step in the right direction and broadens the definition of energy security to include renewable energy and energy efficiency as equally important indigenous sources of energy, in addition to oil and gas;
vii. Incorporate provisions for renewable energy and energy efficiency generation activities into state policy statements and plans, and recognizes the importance of enabling framework conditions for private investment in renewable energy and energy efficiency;
viii. Set national targets for achievements in electricity from renewable energy and energy efficiency capacity addition by 2020 and beyond;
ix. Require the preparation of national action plan for renewable energy and for energy efficiency and sets a time frame within which implementation is required;
x. Recommend that signatory parties to this policy should collaborate in preparation of the action plans and work together in achievement of the final mandatory targets;
xi. Make it mandatory for the Ministry of power to facilitate the development of an integrated resource plan (IRP) and ensure the continuous monitoring and review of the implementation and effectiveness of the action plans prescribed under the national policy statement and;
xii. Facilitate the establishment of framework for sustainable financing of renewable energy and energy efficiency projects and programmes in Nigeria.

The renewable energy policies in the country can be said to have failed in achieving their objectives. This is so when the timelines for attaining major RE sufficiency milestones as outlined by the NREEEP policy document are examined. It would be noted that none of the targets for achieving RE sufficiency (as seen in Table 2) in the country as outlined in the NREEEP policy document has been attained and from the looks of things, none will be achieved.

Table 2. NREEEP Targets [29]

Milestone	Targets
2015	300 MW of Solar PV by 2015
	100 MW of Small Hydropower (SHP)
2020	40 MW of Wind Power
	30 MW of Biomass-fired capacity
2025	4,000 MW of Solar PV
	760 MW of SHP
	18% of electricity from RE sources
2030	20% of Solar PV by 2030

4. Renewable Energy Potentials of Northeast Nigeria

The potential for renewable energy (RE) in Nigeria is mostly unexploited in spite of the prevailing pervasive energy poverty in the country. The main barriers to the exploitation of RE resources in the country is the large oil and gas production activities in the south of the country together with government fuel subsidies, the lack of clarity/market information on private sector opportunities, and a general knowledge gap concerning financial support mechanisms available within and outside the country [30]. The huge RE energy potentials of Nigeria is such that when fully exploited, it will lead to the reduction of poverty in the country and also fast track its sustainable development [31]. If exploited, RE resources of the northeast geopolitical region will not only meet the needs of the region but those of other regions. These RE sources and their potentials will be explored methodically examined in the succeeding subsections.

4.1 Solar Energy

Solar energy is one of the most thriving RE sources in the world, owing to the simplicity and relative cheapness that comes with its installation and operation. Nigeria lies within a high sunshine belt which makes it possible for it to enjoy between 6 – 12 hours of sunshine on a daily basis. As reported by Uzoma et al., [32], Nigeria has an average solar radiation of about 5.8 kWh/m^2 per day and if solar collectors with conversion efficiency of 20% are used to cover 1% of Nigeria's land area, it is possible to generate 1,850×103 GWh of solar electricity per year; this is over one hundred times the current grid electricity consumption level in the country (5.8 kWh/m^2 x 0.2 x 365 days x 923768x106 m^2 x 0.01 = 3,911,233,712,000 kWh or 3,911,233.712 GWh or 3,911x103 GWh).
The NE region of the country is one of the regions with the highest solar irradiation [33], this makes the use of solar technology a viable RE resource in the region. Figure 4 is the solar irradiation map of Nigeria, it can be seen from it that the NE which falls within Zone I, on average is the most irradiated geopolitical region in the country.
To estimate the amount of electricity that can be generated by the use of photovoltaic (PV) solar technology in NE Nigeria, equation 1 was used thus [35]:

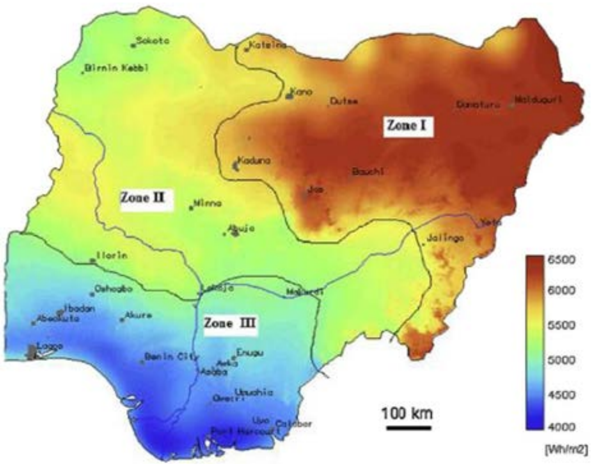

Figure 4. Nigeria's Solar Radiation Map [34]

$$E = 365 G_{hi} \text{Pr} \qquad \text{(Eqn.1)}$$

Where
E = Power obtainable/m^2
Ghi = Solar irradiation for the given location
Pr = Performance ratio of the PV panel = 20%.
For this study, it was assumed that horizontally stationed PV panels with rated power of 1 kW per module and 0.75 performance ratio for the entire system. Using solar irradiation data found in literature for each of the states [35-37], Table 3 presents the potential amount of electricity that can be generated if 1% of the landmass of each state in the region is used for solar PV technology with the aforementioned specification. The following equations were used for this estimation.

$$P_{1\%} = E \times 1\% \; of \; Land \; mass \text{ (Eqn. 2)}$$

Where
P1% = Power obtainable from 1% of the land mass of each state (kWh)
E = From Equation 1 (kWh/m^2)

Table 3. Electricity Generation Potentials from Solar Energy in the North East

State	Annual Average Irradiation per Day (kWh/m^2)	Power Obtainable Per Square Metre per Year considering performance factor (kWh/m^2)	1% of Land Mass ($m^2 \times 10^3$)	Power Obtainable when 1% of landmass is used (MW)
Adamawa	5.92	432.16	369,170	43,829.81
Bauchi	6.11	446.03	708,980	86,875.37
Borno	6.22	454.06	708,980	88,439.41
Gombe	6.0	438.00	187,680	22,583.47
Taraba	6.06	442.38	544,730	66,202.65
Yobe	6.55	478.15	455,020	59,771.38
Total			**2,756.77**	**367,702.10**

As can be seen from Table 3, generation of electricity through solar PV technology is viable in all states of the region. That notwithstanding, Borno state is the most viable state in the region, it has the double advantage of having the highest solar irradiation and the largest landmass. Even though, Gombe state has the least solar irradiation level and the smallest landmass thus making it the state with the least solar energy potential. Nevertheless, it still has the potential of generating 22,583 MW of power, this is about 4 times the current grid capacity of Nigeria and about the exact amount of the forecasted residential, commercial and industrial electricity demands of the country by the year 2030 [38]. The siting of solar projects in the NE will be a feasible renewable and sustainable energy project. Even if financial constraints will hinder the siting of large solar farms, mini off-grid systems that will serve communities that are currently without can be considered.

4.2 Wind Energy

Wind energy is one of the most economical and reliable RE source, its versatile nature and suitability for use as an off-grid source makes it one of the most desirable RE resources especially in far flung locations where extending grids to reach those places will not be cost effective [39]. Wind power projects are not without their disadvantages, one of the major disadvantages especially in developing countries is the high technical expertise they require. Another general drawback to wind power is the intermittent nature with which electricity is generated making it unsuitable for use as sole energy source [40], [41].

Research has shown that Nigeria as a country has high potentials for generation of electricity using wind power technology, this potential however, is largely untapped. In instances where attempts were made, the projects were largely abandoned due to inappropriate evaluation of its potentials, poor management and maintenance operations and management [31].

To determine the wind power potentials of NE Nigeria, this research utilised secondary data which originated from Nigeria Meteorological Agency (NIMET) in conjunction with data from literature. Data used include the mean monthly wind speed for the different locations within the NE geopolitical region at the standard height of 10 m and the effective wind area of each of the states in the region. Air density (ρ), wind speed (v) and the area swept by wind turbine rotor are the crucial parameters for determining wind power potentials of a wind turbine, but in instances where available data is limited, the capacity factor approach is used [35]. Capacity factor (CF) of a wind turbine is the ratio of the actual power produced over a given period of time to the hypothetical maximum capacity of the wind turbine or any generating facility running full time at rated power [42]. The CF is estimated using equation 3 [42]:

$$CF = 0.087V - \frac{P_R}{D^2} \quad \text{(Eqn. 3)}$$

Where PR is the rated power, V the wind speed and D turbine blade diameter.

Using the details for a commercially available wind turbine (NEG Micron), which has a rated power of 1000 kW, speed of 16m/s, cut in speed of 3m/s and rotor diameter of 60 m [35], the potential wind power energy of the region on an annual basis is then estimated using equation 4 [42]:

$$WPE = 8760 \times P_R \times CF \text{ (Eqn. 4)}$$

Given that the optimal radius between one wind turbine to another is 5 rotor diameters [43], and assuming 1% of the effective wind areas in each of the states is used for the wind power project [44], the annual potential amount of energy that can be recovered in each state of the region is presented in Table 4 along with the wind velocity at 10m, the corresponding capacity factor, and the effective wind area.

Table 4. Wind Energy Potential for the Six States in the Region

State	Wind speed (m/s)	Capacity Factor ($\frac{m}{s} - \frac{kW}{m^2}$)	Annual Recoverable Energy (MWh/Wind Turbine)	Effective Wind Area (km^2)	Annual Recoverable Energy from 1% of Effective Wind Area (MW)
Adamawa	4.16 [35]	0.08412	736,891	17,081	159,650
Bauchi	3.2 [45]	0.0006	5,256	24,098	1,607
Borno	6.88 [45]	0.32076	2,809,857	72,767	2,593,415
Gombe	3.40 [46]	0.018	157,680	17,428	34,856
Taraba	3.60 [47]	0.0354	310,104	23,672	93,110
Yobe	5.24 [35]	0.17808	1,559,980	44,880	888,025
	Total		**5,579,768**	**199,926**	**3,770,663**

It can be seen from Table 4 that Borno state has the highest wind speed and effective wind area making it the most viable state for the siting of a wind power project in the region. Yobe state which has a similar climate with Borno equally has a high wind velocity making it suitable for wind power projects. It can also be seen from the table that if 1% of the effective wind areas of the two most viable states (Borno and Yobe) are used for generation of electricity using wind power, 2,681,440 MW of electricity can be generated. This is more than sufficient to meet the energy needs of the region and the whole country. The categories of wind available in the remaining 4 states make them suitable for off-grid hybrid power generation [48].

4.3 Hydroelectric Power

Hydroelectric Power (HEP) is one of the oldest forms of energy generation techniques in the world, it is also one of the cleanest energy generating technologies. Power is generated by building a dam across flowing water to drive turbines which in turn drive huge electrical motors that convert mechanical energy into electrical energy. HEP has assumed great significance because of its renewable nature, low operational cost and its high conversion efficiency (about 90%) [49]. HEP dams are responsible for producing about 25% of the world's electricity, supplying more than one billion people with power [50]. HEP is the most common RE source globally, this makes it pivotal in the supply of clean energy [51]. Though HEP dams are void of greenhouse emissions which happen to be the main concern of environmentalist at the moment, they are not devoid of other environmental effects, these effects include the disruption of ecosystem and risk of floods faced by communities that are situated at the river's downstream [52].

Researchers have stated that the total exploitable HEP in Nigeria from large scale HEP dams is about 14,120 MW and has the capacity to produce 50,832 GWh of electricity annually, however, only just about 13.50% of this potential is being exploited [31], [35]. As seen earlier in Table 1, there are only three HEP dams operational in the country. These dams have a combined power generating capacity of 1,890 MW.

Northeast Nigeria, despite having a number of rivers which can be exploited for the generation of electricity via small, medium and large-scale HEP dams, does not contribute a wattage of electricity to the national grid through this RE resource. Studies have shown that the rivers and waterfalls crisscrossing the region can be exploited using small and large dams to generate electricity that will sufficiently meet the energy needs of the region and those of other regions. Table 5 shows the rivers in the region and the potential amount of HEP energy that can be generated from each of them as obtained from literature [35].

Table 5: Hydro Power Energy Generation Potential in Northeast Nigeria [35]

River	Location	State	Potential (MW)
Benue	Yola	Adamawa	450
Niger	Donka	Adamawa	225
Gongola	Kiri	Adamawa	40
Danga	Mambila	Taraba	3,960
Taraba	Garin Dali	Taraba	135
Dongo	Gembu	Taraba	130
Kam	Karamti	Taraba	115
Suntai	Sarkin-Danko	Taraba	45
Gongola	Krumbo	Taraba	25
	Total		**5,125**

The NE region falls within the Sahel and Sudan Savanna climate belt which is largely dry [53], therefore, it is not surprising that only two states have the potential for HEP projects. As can be seen from Table 5, the region has a potential for the generation of up to 5,125 MW of electricity from the rivers that flow through Adamawa and Taraba states. This potential however is left unexploited. It can be seen from the table that the region has the potential for the siting of eight large and 1 small hydroelectric power projects.

4.4 Municipal Solid Waste

Recovery of energy from municipal solid waste (MSW) is not an entirely new phenomenon, humans have since been burning solid waste and recovering energy from it in the form of heat and electricity [54, 55]. There are two fundamental types of waste to energy (WtE) technologies: Thermochemical conversion methods (incineration, pyrolysis, and gasification); Biochemical conversion [56, 57]. Thermochemical conversion methods involve the use of heat to burn the waste and then recover the energy given off while biochemical methods involve the natural or aided biodegradation of waste and recovery of energy given off in the form of methane.

NE Nigeria like most other parts of the country generates huge quantities of MSW and yet has poor solid waste management services as such wastes can be seen littering the streets and clogging drainages and waterways [58]. Conversion of the waste generated in the region into energy is an ingenious solution to solve the waste management problem and energy poverty of the region. To estimate the potential amount of energy that can be recovered from the MSW generated in the region using thermochemical conversion method which has been found to be the most suitable for the region based on the profile of the waste disposed of at dumpsites [55, 57], equation 5 is used [58]:

$$E = H_n \times W \times \frac{1000}{859.4} \times \eta \quad \text{(Eqn. 5)}$$

Where Hn is the net calorific value; W=average daily weight MSW (tonnes); η = conversion efficiency (22%).

Table 6 shows the annual quantity of MSW generated in the state capitals of the region [57], their calorific values [59–62] and the estimated recoverable energy.

Table 6. Potential Recoverable Energy from MSW in Northeast Nigeria

State	Quantity of MSW (Tonnes)	Calorific Value (kcal/kg)	Recoverable Energy (MWh/day)	Recoverable Energy (MW)
Adamawa	49,447	593.05	7,506.86	114.16
Bauchi	71,700	1,307.92	24,006.43	365.09
Borno	61,317	1,212.85	19,037.74	289.53
Gombe	135,871	615.70	21,415.26	325.68
Taraba	19,750	1,200	6,067.02	92.27
Yobe	12,736	1,260.39	4,109.28	62.49
Total	**350,821**	**6189.91**	**82,142.59**	**1,249.22**

Bauchi state has the highest waste to energy potential in the region, this might not be unconnected to the fact that it has the highest population in the region as such generates a fairly large amount of MSW. Though a careful look at the data presented in Table 6 will reveal that the determining factor for its high energy recovery potential is the calorific value of the waste generated there. Collectively, the region has a potential for generating 1,249 MW of electricity from its waste, this is about a third of the current electricity generation capacity of the whole country, this makes the recovery of energy from MSW is a viable RE source in NE Nigeria. Note that this data reflects only the state capitals as data for other locations within the states are not available because there are hardly any formal waste management systems outside state capitals [57].

4.5 Biomass

Biomass is any material that is biological in origin, be it plants or animals that store sunlight in the form of chemical energy. Biomass can be classified into five groups, this classification is done based on origin of the material, these five categories are: wood and woody biomass; herbaceous biomass; aquatic biomass; animal and human waste biomass; and biomass mixtures [63]. The most common sources of biomass energy are virgin wood, energy crops and agricultural residues, industrial wastes, and sawmill residues. Biomass fuels are the most important energy sources for domestic rural households in developing countries, in these locations, biomass accounts for about 40% of rural energy needs and about 70% of their domestic fuel [44]. Technologies for generation of electricity from biomass can be classified into direct burning, physical conversion, biological conversion and liquefaction technology. Direct burning is the most used biomass energy conversion technology.

Nigeria has a huge potential for the successful deployment of biomass energy, the country has abundant fuelwood, animal wastes, energy crops, and agricultural residues. Nigeria has biomass potential of up to 1.2 million tonnes per day, this comprises of 11 million hectares of forest and woodland, 245 million assorted animals and 28.2 million hectares of arable land (30% of the country's total land mass) [64]. Another research found that the country has bio-energy reserves/potential comprised of 13 million hectares of fuelwood, 61 million tonnes per year of animal waste, and 83 million tonnes of crop residues making it total bioenergy reserves reaching an estimated of 1.2 Peta Joules [65]. These diverse biomass resources are scarcely being exploited, according Sambo [66], only fuelwood and agricultural residues are the biomass resources being exploited in the country with shares of 60% and 40% respectively.

Even though the northeast region of Nigeria falls within the Sahel Savanna and Sudan Savanna climate belt which has limited rainfall [53], the region is not without its own share of biomass energy resources, particularly fuelwood, agricultural residues and animal wastes [67]. Using data from literature [35, 67, 68], the annual energy that can be generated from the region's biomass resources are presented in Table 7.

Table 7. Potential Annual Biomass Energy Resources of Northeast Nigeria

Biomass Type	Energy		
	Joule ($\times10^{12}$)	MWh	MW
Fuelwood	2,250	625,000	71
Agricultural Residue	146,500	40,694,444	4,645.48
Animal Wastes	1,146.6	318,611.11	36.37
Total	**149,897**	**41,638,055**	**4,752.85**

Generation of energy from agricultural residues is the most viable biomass energy resource in the region. It can be seen that 99% of the energy that can be generated from biomass sources in the region is from agricultural residues. This energy source alone has the potential to generate more energy than is currently generated by the gas power plants and the hydroelectric power plants in the country. Though biomass energy source has its inherent disadvantages particularly fuelwood – which is the felling of trees at rates faster than they regenerate thus making them unsustainable, if generation of energy from this source is taken up then an aggressive afforestation programme can be initiated so that the rate of use becomes lower than the rate the trees regenerate thus making it sustainable.

5. Conclusion

The energy poverty in Nigeria is one of the highest in the world – even among developing countries. Within Nigeria, the NE geopolitical region is the region with the least per capita electricity consumption and access to grid electricity despite having abundant RE resources. This study appraised the potentials for the generation of electricity from these sources.

It was found that the region has vast untapped solar energy, wind energy, HEP energy, MSW and biomass energy sources. It was found that all the 6 states in the region are suitable for the generation of electricity with the use of solar PV technology. The region was estimated to be able to generate up to 367,702.10 MW of electricity using this technology. Though the potential for electricity generation via solar technology is enormous in NE Nigeria, one of the major hindrances to this is the investment cost involved. Solar power projects have been proposed and abandoned in a number of locations in NE Nigeria because the investment cost of PV panels and backup batteries have been prohibitive. This problem can be solved by introducing public private partnerships (PPPs) agreements that have investors make the initial investments and then gradually recoup their investments. Borno and Yobe states were found to be the states with the potential for generation of electricity using wind power technology. The two states were found to have the potential of generating up to 3,481 GW of electricity using this technology. The remaining states were noted to be suitable for small scale off-grid hybrid wind power technology. Adamawa and Taraba states were found to have the potential for generating 5,125 MW of electricity if the rivers that flow through the states are utilized for generation of power using HEP dam technology. This was found to be achievable via the deployment of 8 large scale dams and 1 small scale dam.

For MSW as a RE resource in the region, it was found that the wastes generated in the region are sufficient for the production of energy that can meet the current energy needs of the region. This resource was found to not only solve the electricity needs of the region, it also solves the solid waste management problems of the region since solid waste will become a sought-after primary energy resource.

The region was found to have biomass energy resources capable of meeting its energy needs, and the use of agricultural residue as a biomass energy resource has been identified as the most viable option. It was found that if 50% of the agricultural residues in the region and the available fuelwood and animal wastes are used for energy generation, 4,752 MW of energy could be generated from these biomass energy sources.

The electricity generation potential of hybrid systems was not considered in this study because the aim is to know how much energy can be generated from each of the RE resource analyzed.

Generation of energy from these RE sources is the key to the energy sufficiency, socioeconomic and sustainable development of the region. Though the initial investments required for the deployment of these technologies are high and might not be affordable to the governments in the region, it is advised that policies which will make the environment suitable for local and foreign investors be made so that the huge energy potentials of the region can be exploited.

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