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IMPACT ANALYSIS OF EXTREME WEATHER ON THE ENERGY PERFORMANCE OF PHOTOVOLTAIC (PV) USING MULTISTEP REGRESSION MODEL DEVELOPED FROM NEURAL NETWORK TECHNIQUE

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Abstract: Balancing energy between generation and consumption is crucial in minimizing waste and supporting responsible utilization as promoted by UN SDG 12. To reliably depend on energy supply of a solar photovoltaic (PV), forecasting its output is necessary for effective energy production, utilization, and security. Climate change makes weather events becoming more extreme and adverse, and therefore; has potential influence on the energy performance of a PV. This paper investigates main climate-inducing weather events that extremely affect energy performance of PV in the subregions of Northern Nigeria. The weather dataset is collected from Nigerian Meteorological Agency (NiMet), and main technical specifications of PV are adopted from existing applications. Analysing the influence of the extreme weather is carried out using a machine learning (ML) based neural network (NN) technique. The analysis provides multistep energy performance prediction of varying-rated PV. Evaluation metrics utilised in the analysis show reliable prediction as indicated by mean-square-error (MSE) and r-square (R^2) which are having range of values between 0.0511 to 0.2833 and 0.6371 to 0.9632 respectively. This paper provides climate-inducing weather-based guides on the implementation and/or maintenance of PV systems in the Northern region of Nigeria, and beyond. It also supports responsible PV energy utilisation and security.

***IndexTerms** - energy performance, photovoltaic, climate change, extreme weather, Northern-Nigeria.*

INTRODUCTION

The sustainable development goals (SDGs) initiative of the United Nations (UN) that promote fast progressive agenda toward global sustenance. The SDGs support strategies that promote efficient utilisation of resources like SDG 7, 9, 11,12,13,17 that are promoting clean energy supply, sustainable innovation and infrastructure, smart communities, responsible production and consumption, any climate action, and collaboration to achieve all the goals, respectively. The 2021 Climate Change Conference (COP26) held in Glasgow recommends initiatives by agreement among representatives of participating countries which promote moving towards reducing the usage of fossil fuels [5]. The Conference highlights opportunities for governments to prioritize health and equity in the international climate movement and sustainable development agenda, which is necessary to create systems that address related climate-inducing challenges. Several countries have committed to achieving net-zero targets by 2050. The targets imply mass-scale deployment of zero-carbon energy technologies such as solar and wind power, likely in combination with negative emission technologies [9]. The SDGs provide a framework for nations' long-term development and progress by focusing on economic growth, inclusiveness, and environmental conservation [8]. Solar energy is environmentally friendly technology as well as most significant renewable and green energy sources that plays substantial role in achieving sustainable solutions regarding energy production and utilization [3]. Solar energy provides attractive electrical resource. Solar technologies and applications are continuously developed to fulfil demanding energy specifications and requirements.

Renewable energy sources such as solar; draw significant attention worldwide. As up 2022, the solar energy provides about 3.6% of global electricity production [6]. Intermittent of solar energy production makes commercialization of large-scale solar power generation difficult to achieve, and limit the development of solar technologies [10]. Operational duration of a photovoltaic is crucial in order to assess its energy performance. Inherent intermittency and variability of solar radiation influenced by climate-inducing extreme weather events pose operational challenges to energy generation and utilization. Proper estimation and approximation of photovoltaic energy optimizes energy usage and reliance, and support efficient design, installation, operation, and management of photovoltaic system.

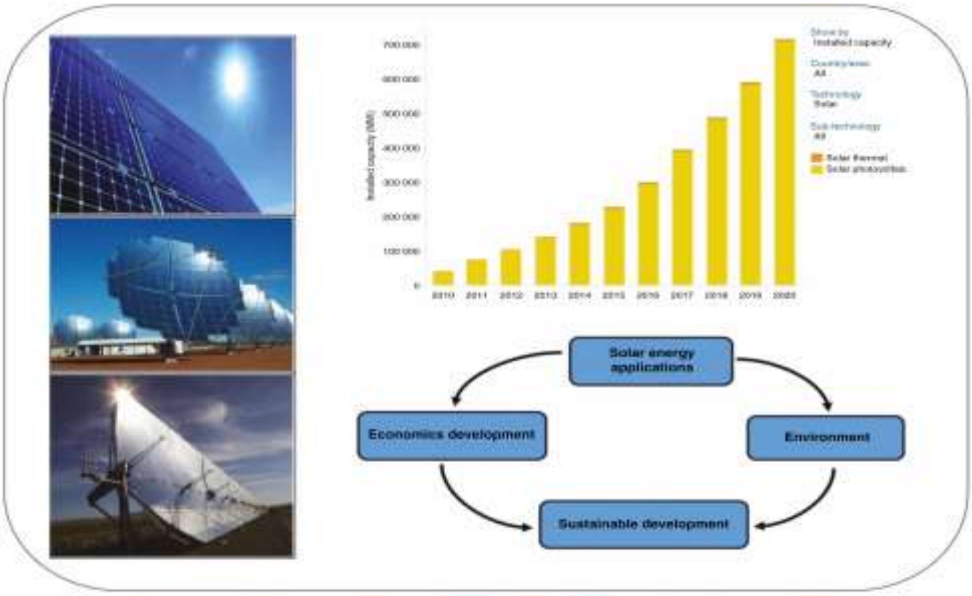

Figure 1: Solar energy technology and its roles in sustainable development [3]

Predicting of PV energy generation helps strategize better energy balancing thereby improving energy security. Energy prediction leverage data-driven techniques such as statistical and ML to analyse influence of complex relationships among meteorological features (such as temperature, humidity, sunshine, etc.) on the energy performance of photovoltaic. Models of machine learning can learn patterns of extreme weather events to offer accurate prediction of energy performance.

This paper investigates significant climate-inducing extreme weather events, and analyse their present and future influence on energy performance of varying-rated photovoltaic system in Northern region of Nigeria. Extreme weather events (temperature, humidity, rainrate, sunshine, air pressure, etc.) are collected from NiMet.

2. FUNDAMENTALS

This section reviews some existing works that examine or analyse energy performance of photovoltaic systems. It also discusses basic mathematical process of designing and analysing energy performance (output) of photovoltaic system. The fundamentals explained the need for this paper.

2.1 Existing Works

Forecasting solar energy represents a key element in increasing competitiveness in energy market, and reducing the dependence on fossil fuels in economic and social development [11]. Conventional machine learning models such as neural network, reinforcement learning, federated learning, regression, etc., are important predicting solar energy performance. Several existing models are evaluated for real-time photovoltaic energy forecasting to ensure enhanced management by integrating solution based on appropriate predictive model. The accuracy of forecasting solar energy can be obtained using several tests reported in several geographic regions (North America, Europe, Asia, Australia) [37]. Various forecasting models exist which include persistence, statistical, machine learning, cloud-motion tracking, weather prediction, hybrid, etc. ML models have performance in forecasting energy output for under all climates. Forecasting output of renewable energy has a considerable impact on decisions about the operation and management of power systems [31]. Accurate forecast of energy output assures dependability and sustainability of energy production. ML forecasting-based models like long short-term memory (LSTM) have attracted researchers toward estimating solar energy production for responsible consumption aligning closely with SDG 12. For many years, solar energy has taken an increasingly important part, which will continue to rise, driven by carbon peaking and carbon neutrality strategic goals [19]. Intermittence and volatility of sunshine, photovoltaic power generation is more erratic than conventional power which results in some challenges such as frequency instability, dispatch difficulty, voltage and current surges, etc. Energy forecasting is a significant issue of photovoltaic system's utilization for achieving reliable and sustainable supply. Power generation using photovoltaic support the realization of low carbon consumption, low cost of installation, operation, and maintenance, ease of deployment to various systems and applications [17]. For effective forecast of energy production from a photovoltaic, a forecasting method should consider both technical requirements and external parameters such as weather. Machine learning based energy forecasting techniques are important in stabilizing electricity for reliable utilisation. The techniques like clustering techniques, convolutional neural network (CNN), long short-term memory (LSTM), deep learning, etc. can be deployed to achieve more accurate energy generation forecasting results for the photovoltaic systems. Deep Learning model achieves great results in short-term time-series forecasting on photovoltaic energy generation [38]. The ML-based forecasting techniques are suitable in forecasting energy production and consumption; most notably are convolutional neural network and long short-term memory deploy for accurate and reliable forecasting. The stochastic and intermittent nature of energy generation of solar systems, climate change, and inefficiency of modern power systems due to zero inertia have created many challenges for on-grid operations [39]. ML-based solar forecasting techniques can potentially provide sustainable solutions toward solar energy production and consumption. The ability to offer accurate prediction is hampered by sporadic nature of solar radiation. ML-based technique of multiple linear regression can be integrated into Pearson correlation coefficient to test solar energy generation. Testing of solar energy generation depends on features that significantly improve the reliability of forecasting system. Techniques such as extreme gradient boosting (XGBoost) and principal component analysis (PCA) can be integrated in order to tract photovoltaic performance.

2.2 Mathematics

Forecasting energy performance of a PV is obtained from basic mathematical equation which integrates the linear and nonlinear relationships existing among the relevant parameters such as sunshine, capacity, performance-ratio, etc., as describes in equation 1.

$$\text{Energy}_{\text{performance}} = \text{Sunshine}_{\text{Duration}} \times \text{PV}_{\text{Capacity}} \times \text{Performance}_{\text{ratio}} \quad (1)$$

Where;

- Energy performance: Refers to energy output of PV, expressed in 'Wh' or 'KWh' per month.
- Sunshine: Refers to duration of sunshine, usually expressed in hours (hr).
- PV Capacity: Refers to electrical ratings of a PV including power, voltage, current, etc.
- Performance Ratio (PR): Ranges $70 - 90\%$. It compares actual energy output to the theoretical maximum output under ideal conditions. PR accounts for losses, poor design, shading effect, etc. Real-world average is set at 80%.

The energy performance describes the amount of energy output expected from PV system after considering losses and tolerance occasioned as a result of environment (weather) and technical requirements. In this paper, performance ratio of 80% (0.80) is considered to account for shading, design, and losses, as it is adopted as real-world average ratio.

2.3 Location of Interest

This paper considers Northern region of Nigeria which comprises of three subregions; Northwest, Northeast, and Northcentral.

- Northeastern Nigeria experiences arid (desert) climate; characterised by extremely high temperature, wind, air, etc., and low rainfall and humidity.
- Northwestern Nigeria has semi-arid climate which is characterised by high temperature, air, wind, etc.
- Northcentral Nigeria experiences the tropical savannah climate which has moderate weather conditions.

Varying climate features affect operation of PV system, and therefore, regional prediction of energy performance is essential to assess energy output of solar photovoltaic.

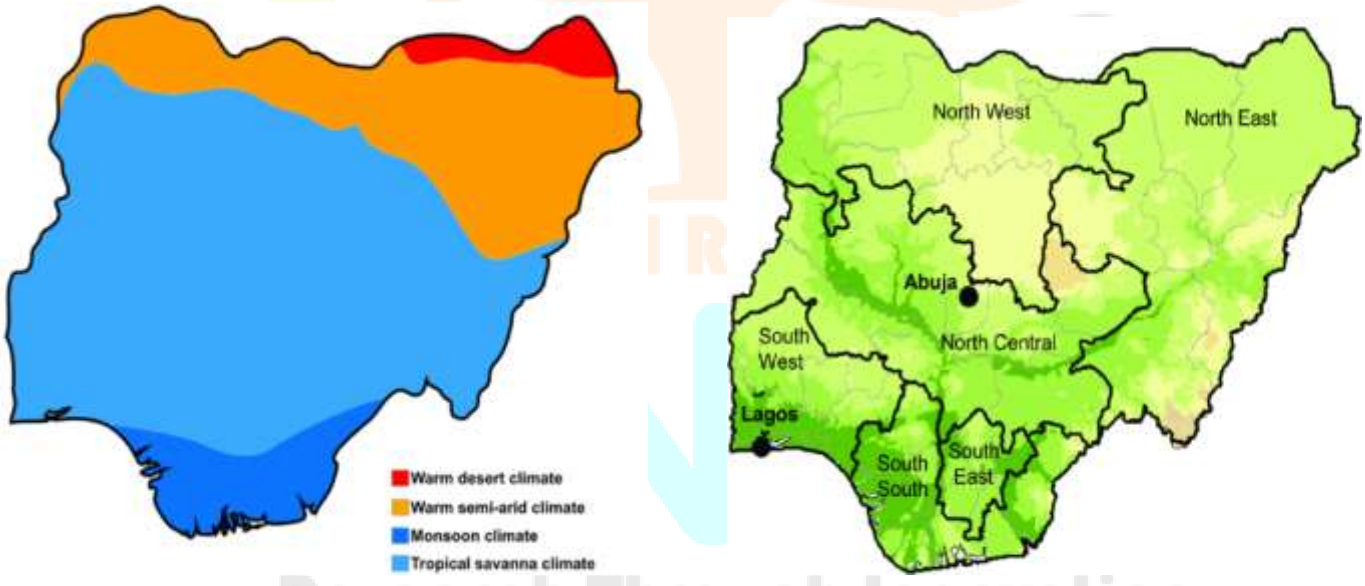

Figure 2: Climate classifications, and geographical regions in Nigeria [22, 41]

3. METHODOLOGY

Regional extreme weather events (such as ran, humidity, temperature, air, wind, sunshine duration, etc.) that can potentially affect energy performance of solar PV are investigated and collected from relevant agency in Nigeria; the NiMet. The technical specifications of PV (performance ratio, capacity, etc.) are also investigated and adopted from existing applications.

The weather and technical parameters are combined to form the dataset, which later undergoes preprocessing to handle outliers, duplications, missing values, and so on. The parameters are process using ML-based NN approach to analyse to assess their degradable influence on energy performance of PV in the North, Nigeria.

In figure 3 below, extreme weather events collected are sunshine, temperature, humidity, rain, and air pressure. Adopted technical specifications of PV include capacity, performance ratio, and reference (previous) energy output.

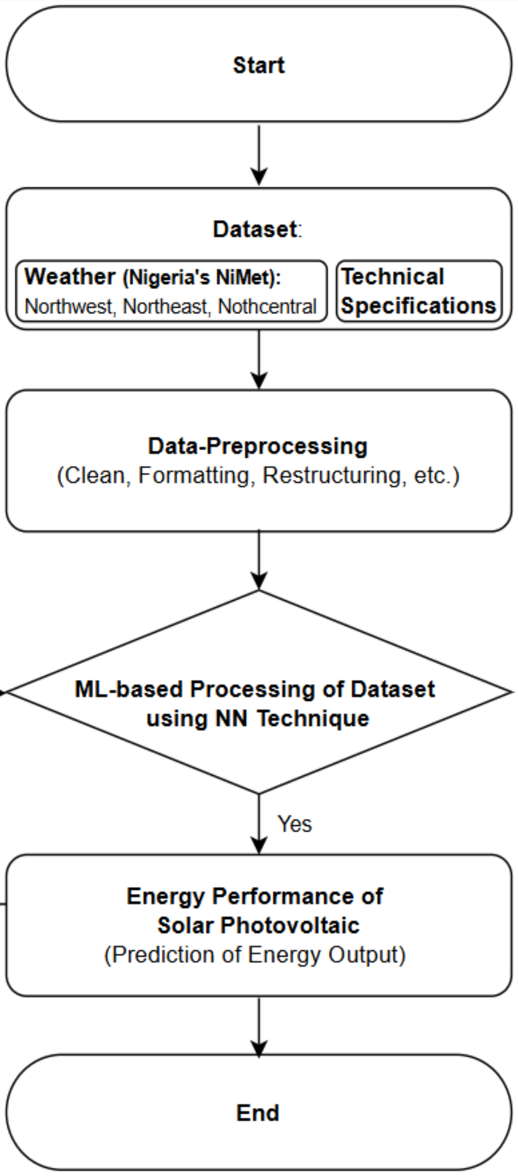

Figure 3: Development process of assessing energy performance of solar PV

3.1 Parameters

Figure 3 above shows the development process of the work in this paper. Two set of parameters are utilised in the paper; weather events and PV technical specifications. Table 1 below describes the designed parameters utilised in this analysis.

Table 1: Design parameters.

Parameter	Range	Unit
Temperature	29.8 – 37.9	^{0}C
Rainrate	0.0 – 0.36	mm
Relative-Humidity	23 – 87	%
Air-Pressure	970.4 – 974	hPa
Sunshine-Duration	2.1 – 11.2	hours
PV Capacity	100, and 1000	W
PV Performance Ratio	75 – 90%	%

Sources: Weather (NiMet, 2024, [42,47]), PV Technical Specifications [44, 45, 46]

3.2 ML-based NN Structure

To efficiently assess energy performance of PV, the data is process using NN technique of ML because of its simplicity and suitability to produce powerful weather-based predictions. Figure 4 below, shows the structure of the neural network technique utilised in the analysis.

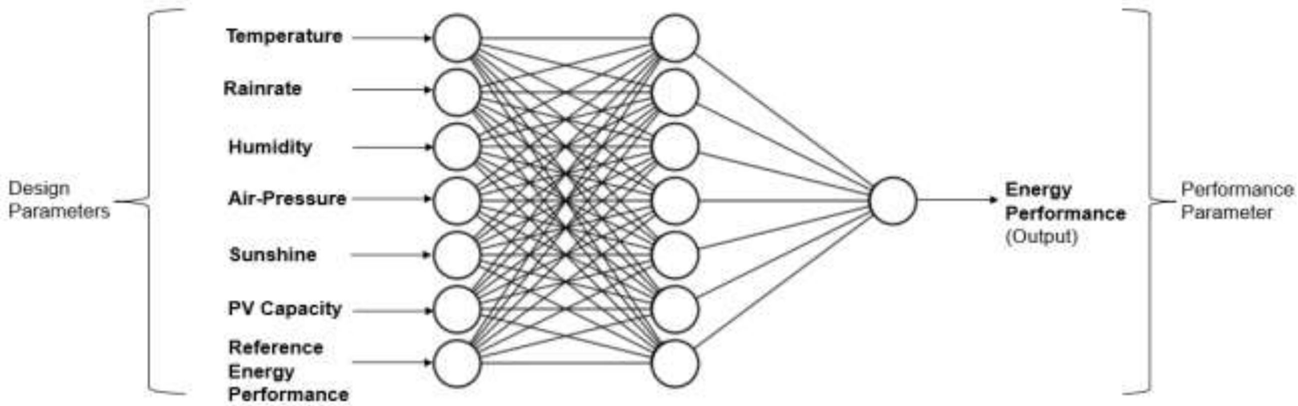

Figure 4: Two-layer structure of the NN technique utilised in the analysis.

The first layer collects input parameters, and the second (hidden) layer enables the ML to learns and process the parameters, so to produce output(s). The design (input) parameters consist of historical weather events and some technical specifications of PV. The output of the process provides a prediction on energy performance of a PV at different subregions of Northern Nigeria. The Python script is adopted and restructured to serve the purpose of this analysis. It is developed inside the Google Colab environment.

4. RESULT

Simulated results have shown varying influence of extreme weather events on monthly solar PV energy performance. The energy performance prediction is carried out considering different PV capacities (100 W, and1000 W) at each subregion of the Northern Nigeria. 0.8 is adopted as the usual practical performance ratio which accounts for losses, shading, design issues, and tolerance. Dataset of historical weather events is validated using appropriate tool for each event, and verified on real-time weather monitoring platforms on the internet. The ML-based analysis (prediction) is evaluated using metrics such as the mean squared error (MSE) and r-square (R^2) score. MSE measures the amount of error between reference and predicted values. Smaller MSE means lower error and indicates good prediction. The R^2 ranges between 0 to 1, and it describes suitability and fitness of dataset into ML process. Higher R^2 shows better suitability and fitness of data in the process, and makes prediction becomes more reliable. Table 2 below provides multistep prediction of subregional PV energy performance for future months in Northern Nigeria.

Table 2: Weather-based monthly prediction of energy performance of PV in Northern Nigeria.

Month	**Reference-Energy** (W)	**Predicted-Energy** (W)	**MSE**	**R^2**
Northwestern-Nigeria				
100 W Photovoltaic				
January	617.00	626.87	0.2833	0.9606
February	162.00	187.12	0.2833	0.9606
March	701.00	671.10	0.2833	0.9606
April	802.00	831.88	0.2833	0.9606
June	388.00	381.28	0.2833	0.9606
July	638.00	612.60	0.2833	0.9606
August	818.00	809.44	0.2833	0.9606
September	838.00	857.26	0.2833	0.9606
October	810.00	819.04	0.2833	0.9606
November	603.00	513.79	0.2833	0.9606
December	618.00	592.83	0.2833	0.9606
1000 W Photovoltaic				
January	6163.00	6569.52	0.1535	0.8197
February	1608.00	2549.31	0.1535	0.8197
March	7039.00	6060.97	0.1535	0.8197
April	8078.00	8173.87	0.1535	0.8197
June	3921.00	4486.53	0.1535	0.8197
July	6403.00	5913.41	0.1535	0.8197
August	8166.00	9275.63	0.1535	0.8197
September	8319.00	8432.29	0.1535	0.8197

October	8001.00	8259.71	0.1535	0.8197
November	6077.00	4835.94	0.1535	0.8197
December	6041.00	5831.92	0.1535	0.8197
Northeastern Nigeria				
100 W Photovoltaic				
January	618.00	593.37	0.0511	0.9632
February	789.00	809.28	0.0511	0.9632
March	761.00	768.74	0.0511	0.9632
April	807.00	804.56	0.0511	0.9632
June	754.00	756.51	0.0511	0.9632
July	767.00	753.14	0.0511	0.9632
August	818.00	866.92	0.0511	0.9632
September	823.00	862.78	0.0511	0.9632
October	802.00	817.93	0.0511	0.9632
November	609.00	497.66	0.0511	0.9632
December	621.00	505.29	0.0511	0.9632
1000 W Photovoltaic				
January	6163.00	6081.83	0.2270	0.8556
February	7921.00	8171.19	0.2270	0.8556
March	7605.00	7574.90	0.2270	0.8556
April	8087.00	7584.61	0.2270	0.8556
June	7524.00	7543.77	0.2270	0.8556
July	7686.00	7451.22	0.2270	0.8556
August	8161.00	9289.09	0.2270	0.8556
September	8248.00	8775.78	0.2270	0.8556
October	8002.00	7870.42	0.2270	0.8556
November	6085.00	5144.59	0.2270	0.8556
December	7003.00	7271.49	0.2270	0.8556
Northcentral Nigeria				
100 W Photovoltaic				
January	617.00	602.09	0.0765	0.9084
February	183.00	261.38	0.0765	0.9084
March	706.00	655.30	0.0765	0.9084
April	809.00	943.72	0.0765	0.9084
June	391.00	437.83	0.0765	0.9084
July	665.00	654.17	0.0765	0.9084
August	819.00	793.81	0.0765	0.9084
September	835.00	827.13	0.0765	0.9084
October	808.00	775.32	0.0765	0.9084
November	606.00	614.79	0.0765	0.9084
December	658.00	683.98	0.0765	0.9084
1000 W Photovoltaic				
January	6164.00	6557.69	0.0865	0.6371
February	1841.00	3714.41	0.0865	0.6371
March	7043.00	6651.68	0.0865	0.6371
April	8087.00	7843.49	0.0865	0.6371
June	3923.00	5574.19	0.0865	0.6371
July	6648.00	6540.17	0.0865	0.6371
August	8165.00	9569.79	0.0865	0.6371
September	8321.00	7121.46	0.0865	0.6371
October	8001.00	8313.63	0.0865	0.6371
November	6082.00	4154.06	0.0865	0.6371
December	6009.00	5007.08	0.0865	0.6371

With reference to extreme weather events in the subregions of Northern Nigeria, Table 1 provides range of prediction of future energy performance of a solar PV. In this analysis, 100W and 100W PV capacities are considered, but other capacities can deploy into the ML-based model for the same purpose.

Reference energy performance is calculated using the fundamental equation (equation 1) based on the previous record of weather. The reference provides the framework of predicting future performance, hence; the utilisation of ML in this paper to do so. The prediction is specifically for the three subregions of Northern Nigeria comprising Northwest, Northeast, and Northcentral which are having varying climate characteristics as follows arid, semi-arid, and tropical savannah respectively. In each subregion, climate-inducing extreme weather events show potential influence on the energy performance of a PV. The ML-based process shows low prediction error and good fitness of dataset in the work as indicated by both the MSE and R^2.

5. DISCUSSION

The paper utilises significant weathered events that are becoming more extreme as a result of change of patterns and shapes of climate. The solar energy is an important renewable source of electricity, and forecasting its energy availability helps to properly plan usage and promote energy reliability and security. This is why in this paper, the energy of solar photovoltaic is forecasted with reference to the potential influence of extreme and adverse weather events. Main weather events considered in the energy performance analysis are rain intensity, relative humidity, temperature, air pressure, and sunshine duration. Technical specifications adopted from existing applications include performance ratio of photovoltaic, capacity, and previous record of energy performance (as reference energy production). ML-based technique of NN is utilised to carried out the analysis that forecast monthly energy performance in the subregions of Northern Nigeria (Northwest, Northeast, and Northcentral), and two capacities of photovoltaic are considered (100W and 1000W). The analysis is not limited to the considered PV capacities; any capacity can be integrated to predict energy generation.

With the availability weather and technical information, the analysis carried out in this paper can be deployed to other regions in Nigeria and beyond. It can also be applied to forecast energy production of other energy systems upon the provision of relevant parameters. The analysis works with live data, and therefore requires continuous update on occurring weather events. Other weather events (such as occurrence of thunderstorms, precipitation, lightning strikes, solar radiation, wind, ice, snow, smoke, dust, fog, etc.) can also be explored and integrated into the analysis for further prediction.

6. CONCLUSION

The UN sustainable development goals (SDGs) support long lasting strategies that help to achieve set targets of the World's activities. Specific SDGs like SDG 7 and 12 are established to promote the use of clean energies (such as solar) and responsible consumption/production; respectively. For a responsible energy generation and utilisation, predicting PV energy performance is crucial in addressing electrical energy balancing and security. This paper investigates climate change-inducing weather events that are extreme and pose potential influence on the energy performance of a PV regarding energy generation in the subregions of Northwestern Nigeria. Historical climate-induced weather record is collected from NiMet, and main technical specifications of PV are adopted from existing applications. This paper provides weather-based prediction of energy performance in Northwest, Northeast, and Northcentral subregions of Northern Nigeria. The prediction will guide power stakeholders (industries, consumers, government, etc.) toward implementation and/or maintenance of solar PV system. It will also support effective utilisation of expected PV energy output; and energy security enhancement.

Conflict of Interest

The authors declared that there is no conflicting interest in this work.

Data and Script Availability

https://drive.google.com/drive/folders/10z8j-qic9Elee94KbE4fcYxb0qs1nqop?usp=sharing

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