Renewable energy optimization for sustainable power generation

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ABSTRACT

To improve sustainability in power generation, this study presents a thorough data-driven method for maximizing renewable energy sources. It employs measures like capacity utilization factor (CUF) and efficiency to evaluate the performance of solar and wind energy using historical weather and energy-generating data. The study offers practical suggestions for improving renewable energy systems, such as weather-energy correlation analysis and machine learning-based forecasting models. In addition, a comparative analysis is carried out to ascertain which energy source is better, and useful real-world data is provided, including a summary of all India's total renewable energy generation (excluding large hydro) for June 2023 and a performance comparison year over year. A useful, data-driven approach for enhancing renewable energy is provided by this work, which advances the topic of sustainable energy.

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1. INTRODUCTION

India is positioned to take the lead globally in the switch to renewable energy sources (RESs), having set high goals and made significant strides in this area. With particular attention on the states of Rajasthan and Gujarat, the future of renewable energy in India is bright. Rajasthan [1], a state well known for its lofty goals, hopes to have an astounding 90 GW of renewable energy capacity by 2030. The state would have to surpass the record-breaking 2022 installations by adding 8.6 GW of RESs capacity annually for the next eight years to fulfill this goal [2]. Rajasthan demonstrated its commitment to sustainable power generation by exceeding its 2022 target and reaching 21 GW of RESs capacity by the end of 2022. Another Indian state, Gujarat, has set a lofty goal to attain 61 GW of RESs capacity by 2030, which is roughly two-thirds of Rajasthan's plan. Gujarat would need to add 5.4 GW of RESs capacity yearly to do this [3]. Gujarat has a good chance of achieving its 2030 target if it takes inspiration from Rajasthan's achievements in solar acceleration. Gujarat's RESs capacity exceeded its 2022 target, reaching 18.6 GW by the end of 2022 [4]. These accomplishments demonstrate India's unwavering commitment to RESs and its capacity to spearhead worldwide efforts towards the production of sustainable electricity.

This study explores data-driven optimization techniques within the framework of India's transition to renewable energy. By utilizing data analytics and machine learning [5], the research investigates how solar and wind energy affect India's energy environment. The operational efficiency of solar and wind energy sources is examined, and the capacity utilization factor (CUF) for each is examined in detail [6]. The objective is to maximize energy output by using data-driven forecasting algorithms to estimate the generation of solar and wind energy. Furthermore, the research assesses how weather patterns affect energy production and develops methods for producing energy with greater efficiency. The country's dedication to attaining a greener and more sustainable energy landscape is demonstrated by India's impressive advancements in renewable energy, as demonstrated by the states of Rajasthan and Gujarat.

2. LITERATURE REVIEW

The increased awareness of environmental issues and the pressing need to cut greenhouse gas emissions is driving up demand for sustainable energy solutions worldwide. To achieve their renewable energy targets, countries all over the world are setting out on ambitious journeys that will firmly establish the dominance of renewable sources in sustainable electricity generation [7]. The global transition to renewable energy is being propelled by environmental consciousness, technological breakthroughs, and shifting economic environments [8]. By 2026, it is predicted that the capacity of renewable energy sources will have increased by 80% globally, with solar and wind power leading the way. By 2024, 30% of the world's electricity will come from renewable sources, according to the international energy agency (IEA). India is generating a lot of renewable energy, and many regions are contributing significantly to this achievement. To combat climate change and provide a more environmentally friendly future for all, this move towards renewable energy is essential [9].

2.1. Global perspectives on renewable energy growth

The world's demand for sustainable energy solutions is gathering speed as a result of growing environmental awareness and the urgent need to reduce greenhouse gas emissions. To reach their renewable energy targets, nations all over the world have set out on audacious adventures that have solidified the dominance of renewable sources in the landscape of sustainable power generation [10]. Growing environmental consciousness, technological improvements, and shifting economic landscapes are just a few of the elements driving the global shift toward renewable energy [11]. These changes have the potential to significantly alter how energy is produced and consumed worldwide in the future, in addition to demonstrating a commitment on the part of nations to combat climate change [12].

2.2. Renewable energy generation across India's regions

Except for major hydro projects, India's overall renewable energy generation reached 36,936.82 million units (MU) in June 2023. With RESs like wind and solar contributing significantly generating 11,557.77 MU and 9,607.58 MU, respectively the data shows tremendous growth compared to June 2022. The year-over-year rise in these sources is 116.32% and 119.05%, respectively. Though in smaller amounts, biomass and tiny hydro-energy sources were also crucial. Remarkably, in June 2023, the large hydro category demonstrated consistent generation at 13,946.11 MU.

2.3. The dominance of solar and wind energy in India

India has started a revolutionary path toward the adoption of RESs in response to its rapidly expanding economy and rising energy demands. India's pursuit of sustainable energy solutions stems from the necessity to address its growing energy needs while also reducing the environmental damage caused by conventional energy sources [13]. This section provides a thorough summary of how India's renewable energy environment is changing, outlining the goals and regulations that have sparked a rapid increase in the use of renewable energy.

India's wind energy industry is in a unique position to take advantage of its enormous export potential and solve internal issues at this crucial juncture. With the potential to surpass 26 GW in an accelerated growth scenario, the nation has set lofty goals, hoping to build about 22 GW of wind energy capacity over the next five years. The federal and state markets' rising demand as well as the commercial and industrial consumers' growing desire for clean energy are the main drivers of this increase [14]. India is a highly desirable location for the development of a global supply chain center due to its important geopolitical position and size, provided that the industry's competitiveness is increased [15]. Although the Indian government wants to attain 140 GW of cumulative installed wind energy capacity by 2030, it would be more realistic, according to analysts, to reach about 100 GW by the end of the decade. Proactive policy assistance and strategic industry actions will be essential to closing this gap.

The Indian wind energy industry is dynamic and ever-changing, as seen by the combination of growing domestic demand, increasing tender awards, and investigation of new wind energy pathways. According to the India Wind Energy Market Outlook 2023–2027, one of the main goals is to match the market's demand trajectory with predetermined goals. This entails making sure that renewable purchase obligations (RPOs) are met and providing strong support for the commercial and industrial (C&I) segment. Free trade agreements (FTAs) and other international trade agreements are also essential for gaining competitive access to vital raw materials and state-of-the-art wind technologies [16], which will boost India's competitiveness internationally and draw capital into the wind energy industry.

As leaders in India's renewable energy revolution, the states of Gujarat and Rajasthan have set high goals that greatly advance the country's overall renewable energy objectives. Rajasthan plans to beat current installation records by adding 8.6 GW of capacity yearly for the following eight years, in line with its ambitious goal of reaching 90 GW of renewable energy capacity by 2030. Rajasthan surpassed its 2022 objective in 2022, having already reached a renewable energy capacity of 21 GW. Gujarat also wants to install 5.4 GW of renewable power per year, with a target of 61 GW by 2030. Gujarat accomplished a spectacular feat by exceeding its 2022 objective and reaching a total renewable energy capacity of 18.6 GW by the end of 2022, building on Rajasthan's success with solar acceleration [17]. These outstanding accomplishments in Gujarat and Rajasthan show how India can lead the world in utilizing clean energy and provide a blueprint for realizing the full potential of wind and solar energy. India is positioned to lead the globe in advancing clean and sustainable power generation through the unleashing of solar and wind energy, especially with its position as the G20 chair in 2023.

3. METHOD

Renewable energy is essential for addressing environmental concerns and achieving long-term energy generation. The work presented here presents a detailed methodology for assessing and optimizing two significant renewable energy sources, solar and wind [18]. Using historical data and machine learning techniques, this methodology includes a systematic approach to analyzing the performance and efficiency of these energy sources. The study begins by loading historical energy and meteorological data, simulating the collection of essential data for analysis [18]. It goes through a series of analytical procedures, starting with computing the CUF for both energy sources, which measures the efficiency of energy generation concerning installed capacity.

After that, the methodology compares the CUF values of these sources over time to determine how effective they are and to identify any trends in their performance [19]. The impact of meteorological conditions is then taken into account when training machine learning models to forecast energy generation. Based on the relationship found between weather characteristics and energy generation, recommendations are given, and additional optimization measures that are specifically designed to increase energy efficiency are also advised. Which energy source performs better is determined by comparative analysis, and the outcomes are clearly illustrated through graphic aids. In addition to measuring energy source efficiency [20], this all-inclusive method offers stakeholders in the renewable energy sector insightful information that can be used to improve sustainability and generation.

Except for major hydro projects, India's overall generation of renewable energy reached an astounding 36,936.82 MU in June 2023. With renewable energy sources like wind and solar contributing significantly—generating 11,557.77 MU and 9,607.58 MU, respectively—the data shows tremendous growth compared to June 2022. The year-over-year rise in these sources is 116.32% and 119.05%, respectively. Though in smaller amounts, biomass and tiny hydro energy sources were also crucial. Remarkably, in June 2023, the large hydro category demonstrated consistent generation at 13,946.11 MU. India's progress towards sustainable energy targets is demonstrated by the cumulative generation of renewable energy, which showed an impressive 100.70% achievement between April 2023 and June 2023 compared to the same months the previous year [21]. The block diagram of the proposed code regions is depicted in Figure 1.

3.1. Load historical and weather data

This initial step involves loading historical energy generation and installed capacity data from available sources into a data frame. The data includes information for different years. In this step, historical weather data is gathered, including average solar irradiance and wind speed, and organized into a data frame. This data is essential for understanding the weather conditions that affect energy generation. The next step involves calculating the CUF for both solar and wind energy sources. It assesses the efficiency of energy generation based on changes in CUF over time.

3.2. Train solar model and generate forecasts and train wind model and generate forecasts

This initially merges historical energy data with historical weather data using the 'Year' column. Prepare input features (average solar irradiance and wind speed) and the target variable (solar generation). Split the data into training and testing sets. Train a machine learning model for solar energy forecasts using the training data. Generate solar energy generation forecasts for future weather data. Merge historical energy data with historical weather data using the 'Year' column. Prepare input features (average solar irradiance and wind speed) and the target variable (wind generation). Split the data into training and testing sets. Train a machine learning model for wind energy forecasts using the training data. Generate wind energy generation forecasts for future weather data.

3.3. Visualizing data and analysis

Merge historical energy data with historical weather data using the 'Year' column. Calculate the correlation between solar energy generation and average solar irradiance. Calculate the correlation between wind energy generation and average wind speed. Create an empty list to store recommendations. If the correlation between solar energy and solar irradiance is greater than 0.7, add a recommendation for solar energy. If the correlation between wind energy and wind speed is greater than 0.7, add a recommendation for wind energy. India visualizes data, comparative analysis, and main function. In this final step, various visualizations are created, including plots for CUF and efficiency change over time. The data frame with energy and weather data is displayed, and recommendations are printed. The main program orchestrates the entire workflow by calling each step-in sequence. It loads historical data and weather data, calculates CUF and efficiency, trains models, generates forecasts, calculates factors, provides recommendations, and visualizes the results.

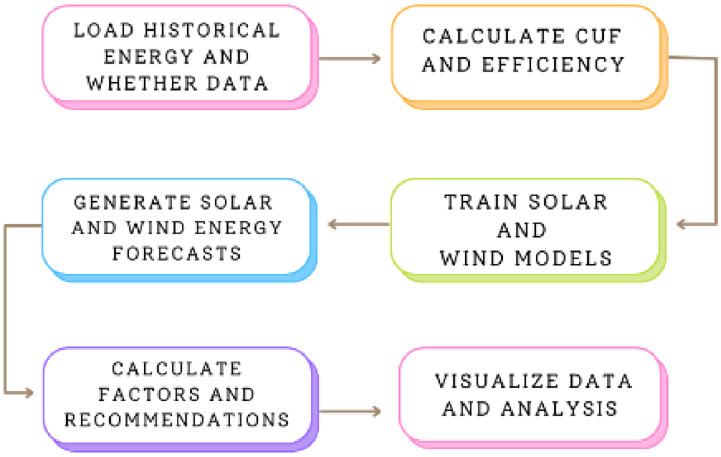


Figure 1. Sequential flow of functions

4. RESULTS AND DISCUSSION

In India, the quest for ecologically friendly and sustainable electricity generation is heavily reliant on renewable energy. Solar and wind energy have become two of the most significant contributions to India's clean energy transition among the numerous renewable sources [14]. The performance analysis and optimal use of these two plentiful resources are the main goals of the Python code that is provided here. It is organized into seven main processes, the first of which is gathering and analyzing historical data on solar and wind energy. The objective of this data-driven approach is to increase the efficiency of these energy sources by comprehending and optimizing their CUF [14]. Additionally, the code makes use of machine learning models to estimate energy generation and generate projections for upcoming years [6]. With the help of these projections, interested parties can decide how best to utilize solar and wind energy's potential for India's transition to a more sustainable energy source. Ultimately, the code presented in Figure 1 facilitates India's transition to a cleaner and more sustainable energy landscape.

4.1. Observation table

The information given shows how India's renewable energy generation and infrastructure have changed over nine years, from the fiscal year 2014–2015 to 2022–2023. The installed solar power capacity and associated energy generation are shown in Table 1. It illustrates the solar energy industry's phenomenal rise in India, whose installed capacity increased from 3,744 MW in 2014–2015 to an astounding 66,781 MW in 2022–2023. This growth is reflected in the energy generation, which increased from 4.60 TWh to a remarkable 102.01 TWh, underscoring the significant role that solar power plays in India's energy balance.

A comparable overview of the wind power industry is given in Table 1, which also shows the rise in installed wind power capacity and energy production. Indicating the country's dedication to using wind energy, India's wind power capacity increased from 23,447 MW to 42,633 MW over that time. With a notable increase in energy generation from 28,214 GWh to 71,814 GWh, wind energy's significance in India's renewable energy landscape is highlighted. Table 2 provides historical meteorological data for solar and wind for the years 2020, 2021, and 2022 to help you better understand the trends in energy generation. It sheds light on the average solar irradiance and wind speeds throughout this time, two critical variables affecting the production of energy [22] shows in Table 3. These numbers support a comprehensive understanding of India's RESs, facilitating more effective use and long-term planning for sustainable energy. The analysis sheds light on India's advancements in wind and solar energy optimization is shown in Table 4. Figure 2 depicts the CUF over time in Figure 2(a) and efficiency change over time in Figure 2(b).

Table 1. Installed solar and wind power capacity and generation in India

S. No.	Financial year	Solar installed capacity (MW)	Solar generation (TWh)	Wind installed capacity (MW)	Wind generation (GWh)
1	2014-2015	23,447	28,214	23,447	28,214
2	2015-2016	26,777	28,604	26,777	28,604
3	2016-2017	32,280	46,011	32,280	46,011
4	2017-2018	34,046	52,666	34,046	52,666
5	2018-2019	35,626	62,036	35,626	62,036
6	2019-2020	37,669	64,485	37,669	64,485
7	2020-2021	38,785	59,824	38,785	59,824
8	2021-2022	40,355	68,640	40,355	68,640
9	2022-2023	42,633	71,814	42,633	71,814

Table 2. Historical weather data for solar and wind

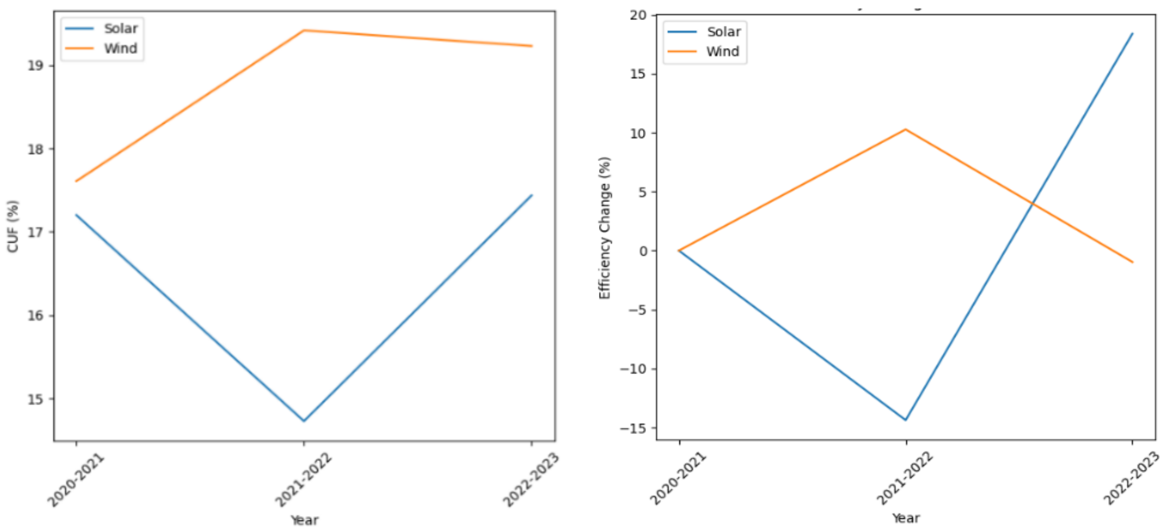
S. No.	Financial year	Average solar irradiance (W/m²)	Average wind speed (m/s)
1	2020-2022	1,200-2,300	4-9

Table 3. Projected future weather data

S. No.	Financial year	Average solar irradiance (W/m²)	Average wind speed (m/s)
1	2020-2022	1,300-2,400	4-8

Table 4. Solar and wind energy performance metrics

S. No.	Solar CUF	Solar efficiency	Solar energy generation forecast (TWH)	Wind CUF	Wind efficiency	Wind energy generation forecast (GWH)
1	17.2009	0	79.7566	17.6079	0	69338.3
2	14.7287	-14.3726	87.1744	19.4167	10.2728	70163.5
3	17.4376	18.3919	94.5922	19.2291	-0.966233	70988.8



(a) (b)

Figure 2. Capacity of (a) CUF over time and (b) efficiency change over time

India’s capacity to produce renewable energy has increased significantly in recent years. Remarkably, installed solar power capacity has increased to 66,781 MW in the fiscal year 2022–2023, translating to an astounding 102.01 TWh of energy generation [23], [24]. India’s clean energy aspirations will be greatly aided by this rise in solar capacity, which is complemented by greater electricity generation.

4.2. Discussion

Recommendation for wind energy is to optimize wind farm locations to capture high wind speed areas. The optimization strategy for solar energy is to invest in tracking solar panels to follow the sun’s path and maximize irradiance capture. The optimization strategy for wind energy is to conduct wind resource assessments to identify optimal wind farm sites with consistently high wind speeds. India’s wind energy industry has advanced significantly at the same time. With a significant energy generation of 71,814 GWh, the installed wind power capacity has increased gradually, reaching 42,633 MW in 2022–2023. It also means that wind energy is now more effectively harnessed, which will increase its share of India’s sustainable energy mix. The result of efforts to maximize the use of these RESs. The advice proposes purchasing tracking solar panels to maximize irradiance capture in order to further improve solar energy generation. The suggestion for wind energy highlights the necessity of optimizing wind farm locations [25], particularly in regions with consistently strong wind speeds. Improved solar and wind energy performance in India is contingent upon the use of these optimization technologies. Although each kind of energy has advantages of its own, the data shows that wind energy is outperforming solar energy in terms of CUF [26].

This emphasizes how crucial it is to carefully utilize wind resources in addition to steadily increasing solar capacity in order to establish a renewable energy landscape that is both optimal and sustainable in India. Adopting these tactics and making the most of India’s plentiful solar and wind resources will help the country move closer to a more environmentally friendly and energy-efficient future [27], [28]. With energy generation projections of 79.76 TWH and 87.17 TWH, and solar efficiency statistics of 0% and -14.37% from Table 4, the solar energy metrics for the years 2023 and 2024 show CUF values of 17.20% and 14.73%. In the meantime, wind energy showed wind CUF values of 17.61% and 19.42%, predicting energy output of 69.34 GWH and 70.16 GWH for the corresponding years [29], [30], as well as data on wind efficiency from Figure 2 of 0% and 10.27% from Table 4. These measurements are essential for emphasizing India’s changing energy landscape and optimizing policies involving renewable energy.

5. CONCLUSION

This study highlights India’s notable advancements in the field of renewable energy, primarily concentrating on wind and solar energy. The nation’s unwavering commitment to shifting to cleaner and more sustainable energy sources is demonstrated by the impressive growth in solar capacity, which increased from 3,744 MW in 2014–2015 to an astounding 66,781 MW in 2022–2023. Additionally, the significant growth in wind energy capacity, which increased from 23,447 MW to 42,633 MW in the same period, also shows this commitment. This study provides important insights for improving these renewable energy systems using a thorough data-driven methodology that includes CUF analysis and machine learning-based forecasts. Additionally, the comparison research shows that wind energy now performs better in terms of CUF than solar energy, highlighting the necessity of allocating resources strategically. India is establishing itself as a leader in the clean energy revolution as it keeps building out its infrastructure for renewable energy, which is essential to the world’s shift towards a cleaner and more sustainable energy landscape.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

Not applicable - this study did not involve human participants requiring informed consent.

ETHICAL APPROVAL

Not applicable - this study did not involve human participants or animals.

DATA AVAILABILITY

Data availability does not apply to this article as no new data were created or analyzed in this study.

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