Evolving Power Dynamics: A Study of India's Electricity Generation Trends (2013-2023)

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***Abstract*—Sun-kissed ambition collides with carbon shadows in India's electricity sector amid the 'Green Gigawatt Race' and the persistent 'Coal Conundrum'. The decade from 2013 to 2023 marked transformative changes, witnessing a surge in renewables and a gradual decline in coal dominance. To dissect this evolving energy mix, we leverage daily power generation data from sources like POSOCO reports and state statistics. Employing exploratory data analysis (EDA), visualizations, and statistical/machine learning, we critically examine India's power dynamics. This analysis unveils key trends in the energy landscape, regional disparities, and insights into driving factors. Our investigation aims to illuminate the path to a secure, sustainable energy future for India, where clean energy fuels ambitions and equitable access powers growth. Findings from this study are vital for steering the nation toward a balanced and resilient energy paradigm.[1][2]**

***Index Terms*—Electricity generation in India,Renewable energy,Energy mix,EDA,Policy recommendations,Sustainable development,Visualization,Climate change .**

I. Introduction

India's electricity landscape presents a paradox, ranking third globally in production with 1,844 TWh generated in 2022-23, yet relying heavily on coal for three-quarters of its power. Despite this, renewable energy claims 40.7 percent of installed capacity, driven by government initiatives. The 2023-2027 National Electricity Plan[3] aims to halt new fossil fuel plants and target nearly half of electricity from clean sources by 2030. Challenges include low per-capita consumption and uneven distribution, especially in vital sectors like agriculture. This exploration aims to unravel these complexities, illuminating a path toward a sustainable and equitable energy future.[4]

II. Methodology

A. Data extraction

In our quest to delve deep into India's electricity generation landscape, we undertook a digital excavation mission. We meticulously sifted through over 3,600 daily reports, sourced from POSOCO's website , extracting valuable data. Leveraging the BeautifulSoup and PyPDF2 libraries, alongside Camelot for PDF parsing, we transformed these seemingly static documents into dynamic datasets, as depicted in Fig. 1 and Fig. 2, primed for thorough analysis.

Daily_Power_Gen_Source_march_23

source	NR	WR	SR	ER	NER	All India	date
Hydro	139.0	43.0	72.0	30.0	7.0	292	2013-03-31
Total	675.0	820.0	697.0	306.0	28.0	2526	2013-03-31
Wind Gen(MU)	2.0	19.0	13.0	0.0	0.0	34	2013-03-31
Hydro	137.0	43.0	83.0	32.0	5.0	300	2013-04-01
Total	683.0	841.0	706.0	316.0	29.0	2575	2013-04-01
Wind Gen(MU)	7.0	21.0	19.0	0.0	0.0	48	2013-04-01
Wind Gen(MU)	8.0	25.0	15.0	0.0	0.0	48	2013-04-02
Total	675.0	836.0	709.0	311.0	28.0	2558	2013-04-02

Fig. 1. Dataset 01- "Daily-Power-Gen-States"

Daily_Power_Gen_States_march_23

	Region	States	Max.Demand Met during the day(MW)	Shortage during maximum Demand(MW)	Energy Met (MU)	date
1	Region	States	Max.Demand Met during the day(MW)	Shortage during maximum Demand(MW)	Energy Met (MU)	date
2	NER	Mizoram	77	1.0	1.2	2015-01-01
3	WR	DD	214	0.0	4.8	2015-01-01
4	WR	Goa	383	0.0	7.3	2015-01-01
5	WR	Maharashtra	14837	57.0	315.0	2015-01-01
6	WR	MP	5740	0.0	109.8	2015-01-01
7	WR	Gujarat	11383	0.0	246.4	2015-01-01
8	WR	Chhattisgarh	3052	18.0	64.6	2015-01-01
9	WR	DNH	581	0.0	14.0	2015-01-01
10	NR	Chandigarh	224	0.0	3.8	2015-01-01
11	NR	HP	1367	0.0	25.1	2015-01-01
12	NR	Uttarakhand	1768	0.0	33.9	2015-01-01
13	NR	UP	9998	3645.0	244.0	2015-01-01
14	NR	Delhi	4009	0.0	67.6	2015-01-01
15	NR	Rajasthan	9810	0.0	204.9	2015-01-01
16	NR	Haryana	6025	0.0	116.8	2015-01-01
17	NR	J&K	1959	346.0	37.3	2015-01-01
18	NR	Punjab	5045	0.0	93.3	2015-01-01
19	WR	Essar steel	258	0.0	5.4	2015-01-01

Fig. 2. Dataset 02- "Daily-Power-Gen-Source

B. Exploratory Data Analysis

Datasets underwent meticulous cleaning using Python libraries like pandas and numpy, followed by visualization using matplotlib and seaborn. Statistical methods such as correlation, linear regression, and time series analyses were employed with sklearn for deeper insights.The whole flowchart of the process is depicted in Fig. 3. The link to the Github repository.[5]

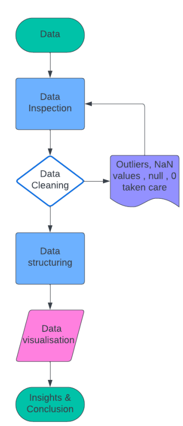

Fig. 3. EDA flowchart for the dataset.

III. An Overview of the Decade 2013-23.

Electricity Generation by Source distribution

The pie chart in Fig. 4, based on Python libraries, closely matches data from the Government of India's Ministry of Power report "Power Sector at a Glance ALL INDIA" . It highlights the dominance of non-renewable sources, such as coal, thermal, and lignite, as the main drivers of India's GDP growth from 2013 to 2023. India's ability to shift half of its energy dependency to non-renewables is noteworthy, especially compared to global standards for low to middle-income countries [6].

India's electricity generation has surged, rising from 179 TW-hr in 1985 to 1,057 TW-hr in 2012, primarily due to coal-fired facilities and unconventional renewable energy sources. Between 2012 and 2017, coal-fired and RES facilities drove the main growth, while contributions from natural gas, oil, and hydro plants declined [7].

In the fiscal year 2021–22, gross utility electricity generation reached 1,484 billion kWh, with renewables contributing approximately 21.7 percent. Notably, in 2019–20, all new electricity generation came from renewables, leading to a decline in fossil fuel-based power. By 2022–23, renewables constituted 22.47 percent of utility power generation, marking a significant increase [8].

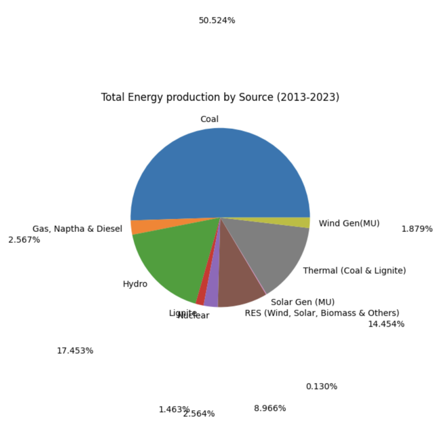

Fig. 4. Pie chart of India's energy mix

IV. Source-wise insights.

A. Coal

Human development, marked by progress and convenience, has led to a surge in greenhouse gas (GHG) emissions, exacerbating global warming and its adverse effects like glacier melting, heat waves, irregular precipitation, water depletion in rivers, and rising sea levels. India, heavily reliant on monsoon-based agriculture, faces heightened vulnerability to these impacts. Despite its per capita CO2 emissions being lower than Russia and the United States, India aims for net-zero emissions by 2070, targeting a 45 percent reduction in emission intensity of GDP and 500 GW of renewable energy capacity by 2030.

India's recent increase in coal-based electricity generation and imports as seen clearly in Fig. 5 (with variations due to the ever changing nature of monsoons in India), seemingly contradictory to sustainability goals, is driven by energy security concerns, especially with over 85 percent of petroleum needs reliant on imports. Immediate cessation of coal-based generation isn't feasible, necessitating continued reliance for the next two decades unless groundbreaking discoveries or technological innovations provide viable alternatives. This transitional phase is vital before achieving a diversified energy portfolio.[9]

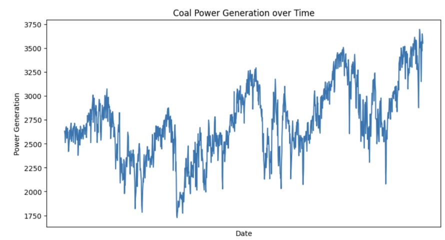

Fig. 5. Coal power

B. Nuclear

India's burgeoning energy needs have ignited a bold vision: becoming a major nuclear power player. With plans to tenfold its nuclear output by 2031, nearly quadrupling its share in the national electricity mix, India aims for 22,480 MWe by the decade's end, showcasing its unwavering commitment to a nuclear future. Although India has been unable to convert this vision into reality clearly shown in Fig. 6, which depicts a marginal increase in Nuclear Power generation.

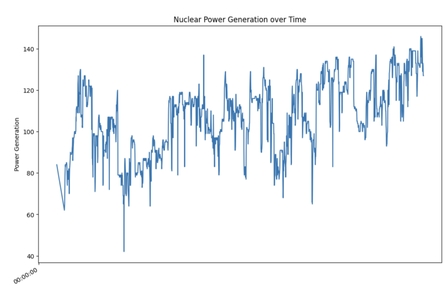

Fig. 6. Nuclear power

Indigenous Approach: India's nuclear program heavily relies on indigenous technology and resources, straining access to crucial materials and expertise, potentially impeding expansion. Remaining outside the Nuclear Non-Proliferation Treaty (NPT) has consequences, limiting international nuclear cooperation and fuel supplies for non-signatories, adding complexity to India's ambitions.

Safety Concerns: Post-Fukushima, safety concerns linger over nuclear technology worldwide. India faces stricter regulations and project delays due to public apprehension.

Resource Crunch: Securing enough uranium for its ambitious plans is a constant battle for India. Limited domestic reserves and NPT-related restrictions on international sources drive exploration of innovative solutions like thorium-based reactor technologies.

Despite these hurdles, India's nuclear journey has not been in vain. Today, it boasts 22 operational reactors, 8 more under construction, and a 2022 record of 56.52 TWh of annual nuclear power generation. The government actively tackles challenges like uranium scarcity through domestic exploration and international collaborations.[10]

C. Gas,Naptha and Diesel

Once-prominent gas-powered plants in India now sit dormant due to high LNG prices and the nation's shift towards renewable energy along with the end of subsidies and freebies provided by Government of India on CNG and Diesel along with Kerosene which clearly reflects in Fig. 7. Expensive imported LNG renders these plants economically impractical, compounded by domestic gas production delays. However, despite challenges, these idle power plants offer agility to respond to peak demand fluctuations and stabilize the grid, presenting economic advantages over building new renewable capacity.

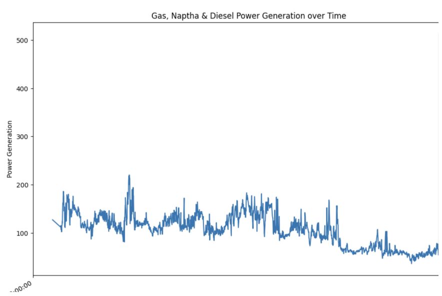

Fig. 7. Gas, Naptha and Diesel power

Reviving stranded assets entails navigating economic viability and environmental concerns. Solutions like gas-solar blending and maximizing domestic gas sources are crucial, balancing flexibility with environmental responsibility. Addressing the human impact requires thoughtful consideration to avoid social disruptions.

In conclusion, India's gas-powered narrative is at a crossroads, poised for transformation from liabilities to valuable contributors in the nation's journey towards a secure and sustainable energy future. Strategic utilization, economic solutions, and proactive consideration of environmental and social concerns are essential in shaping the role of these seemingly stranded assets [11].

D. Hydro-power

The cyclical pattern evident in Fig. 8 mirrors the unpredictable nature of the Indian monsoon, characterized by alternating dry and wet seasons or years. Despite India's economic prowess, the country grapples with the persistent challenge of energy poverty. Hydro-power emerges as a promising solution, yet controversies arise due to concerns about displacement and environmental impact. Sustainable hydro-power development

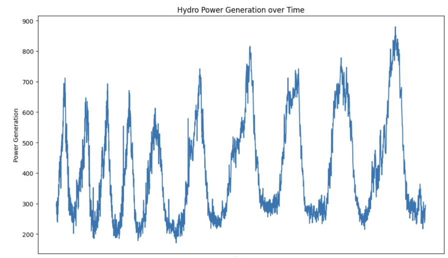

Fig. 8. Hydro power

requires careful planning, responsible execution, and active public involvement. Implementing short-term measures like transparent planning and long-term strategies such as the establishment of a dedicated sustainability institute is crucial for balancing development goals with ecological and social considerations in India's pursuit of a cleaner energy future.

Despite ranking as the fifth-largest economy globally, India's per capita electricity consumption is low at 1,208 kWh/year, compared to countries like Canada (14,612 kWh/year) and China (5,885 kWh/year). This gap poses a threat to India's economic aspirations, with hydropower emerging as a potential remedy. However, controversy surrounds dams, the linchpin of hydroelectricity, criticized for ecological disruption and social unrest in the Himalayas. Proponents highlight benefits like flood control, water security, and climate change mitigation. Discerning truth requires a nuanced perspective. While dams transform landscapes, a 2021 study in Science Advances found minimal regional climate impact from Himalayan reservoirs. Community resettlement can be managed through transparent dialogue and fair compensation. Achieving a balance between harnessing hydropower's potential and ensuring environmental and social sustainability demands rigorous scientific analysis, transparent planning, and dialogue with affected communities. Embracing a data-driven approach can unlock a promising future for hydropower, contributing to India's sustainable growth and environmental well-being [12].

E. Wind-energy

In 2015, wind energy became the top source of new power generation capacity globally, marking a turning point. China dominates, with its wind power capacity soaring from 300 MW in 2000 to 188,232 MW in 2017, representing 35percent of the world's total.

Asia leads in cumulative installed capacity, adding 24.5 GW in 2017, with Europe following, notably Germany with 6.5 GW. North America remains robust, driven by a stable 8.9 GW US market. Latin America, led by Brazil's 2.7 GW, and Africa and the Middle East show promise. Globally, wind power's trajectory is shaped by China's growth, top 10 nations' influence, and varied regional contributions. In India, the wind sector ranks second in Asia and fourth globally, contributing 64.09percent to the nation's total renewable energy capacity, supported by unwavering government commitment.

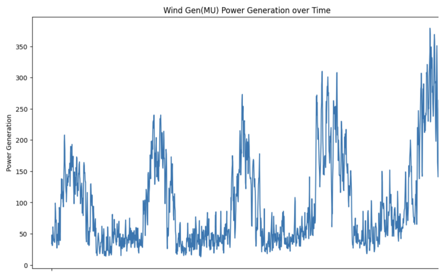

Fig. 9. Wind power

The Indian government aims for ambitious wind energy development, targeting the addition of 15,000 MW during the 12th Five-Year Plan (2012-2017). Efforts to promote offshore wind development began with a policy framework in 2015, results of this thrust by GOI can be found in Fig. 9.

India boasts vast wind energy potential, estimated at 302 GW at 100m hub-height. The government is assessing this potential and fostering wind energy projects nationwide, including in the North-Eastern Region.

The growth of wind energy in India addresses the country's energy needs and environmental challenges positively. As a clean and renewable source, wind energy helps reduce reliance on fossil fuels and mitigate climate change [13].

V. Energy Demand by Source and Region

India's energy demand paints a diverse picture across its vast geographical expanse. Each region boasts unique consumption patterns and presents distinct challenges and opportunities for future development. Here's a closer look:

A. Northern and Western Regions-*'Heavyweights'*

In Fig. 10, regions such as Gujarat, Maharashtra, and Uttar Pradesh emerge as India's industrial and agricultural hubs with the highest energy consumption. They heavily rely on coal, oil, and hydro-power from the Indo-Gangetic plains to fuel factories, farms, and urban areas.

Challenges: Balancing industrial growth with environmental concerns is essential. Air pollution and water scarcity underscore the need to shift towards cleaner sources like wind and solar, increasingly prevalent in states like Gujarat.

Opportunities: Upgrading grids and promoting distributed renewables are key for efficient energy use and cutting carbon footprints.

B. Southern Region-*'Renewable Champions'*

Tamil Nadu and Karnataka lead in harnessing solar energy for large-scale projects, while wind energy also plays a significant role. This results in a comparatively cleaner energy mix compared to the northern states, as depicted in Fig. 11.

Challenges: Integrating intermittent renewables into the grid is challenging. Storage solutions and robust management systems are crucial for grid stability.

Opportunities: TThe region's commitment to renewables drives technological innovation and attracts investments in grid modernization and green energy solutions.

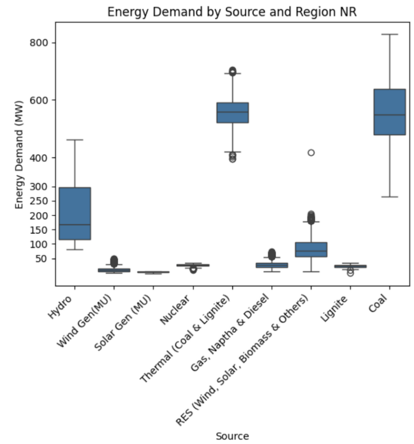

Fig. 10. Northern Region and Western Region

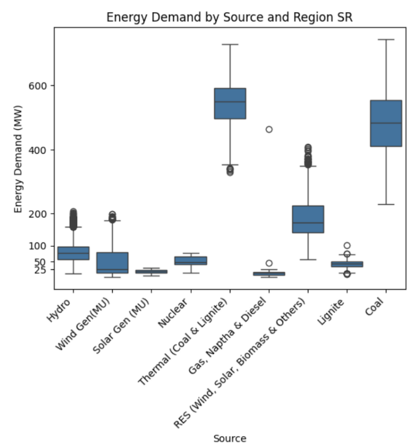

Fig. 11. Southern Region

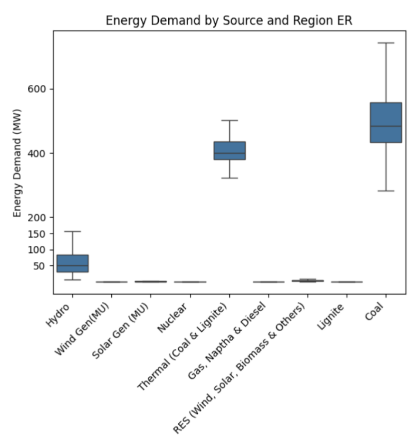

Fig. 12. North-East Region

C. Eastern and Northeastern Region-*'Hydropower Potential'*

Abundant rivers and mountainous terrain offer significant hydropower potential reflected in first column of Fig. 10 and 11, yet challenges persist due to geographical accessibility and environmental concerns related to dam construction.

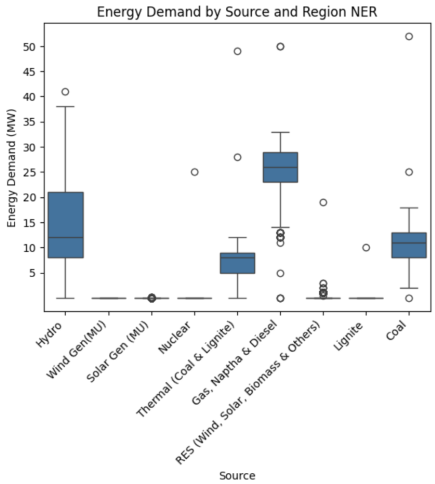

Fig. 13. Eastern Region

Challenges: Balancing hydropower development with ecological protection and equitable benefit distribution to local communities is crucial.

Opportunities: Investing in mini-hydro projects and sustainable hydropower practices unlocks clean energy potential while minimizing environmental impact.[14]

D. Demand and shortage.

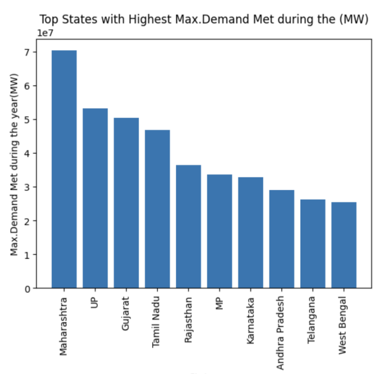

Fig. 14. State-wise highest demands

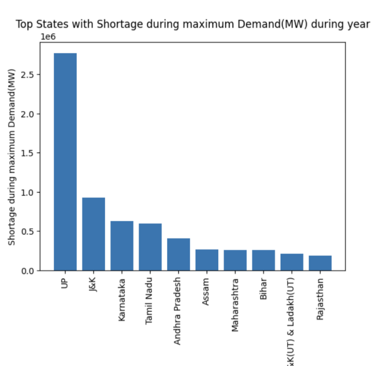

Fig. 15. States with maximum shortages

From Fig. 14, it can be clearly understood that the states with the Highest demand are industrial power-houses of the country and also one of the most population-dense areas of the country which puts the grid to a test. Similarly from Fig. 15 , the states with maximum shortages are where there is still old grid-lines, illegal connections , remote and backward areas of the country like Bihar,Assam,Jammu and Kashmir(shortage also due to national security issues).

E. Regression and statistics

Using python libraries like sklearn, the authors of the paper intended to find the connection or in mathematical terms a correlation between the Maximum Demand Met and Energy Met, the results as depicted in Fig. 16 can be understood as:

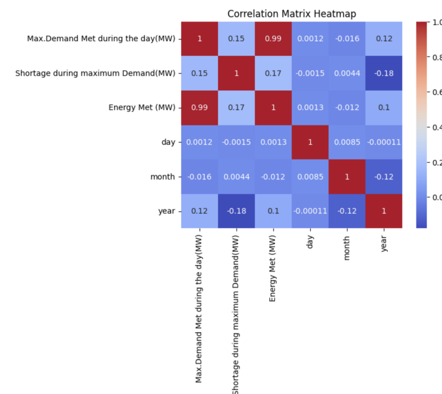

Fig. 16. Correlation matrix

1) The correlation matrix analysis conducted in this research paper sheds light on intricate relationships within the domain of electricity demand and supply.
2) A robust and highly significant positive correlation (0.992330) is found between the maximum demand met during the day and the actual energy met, emphasizing their closely intertwined dynamics.
3) Conversely, a positive correlation (0.153828) exists between the maximum demand met and the shortage during maximum demand, indicating a somewhat weaker but still discernible connection.
4) Temporal factors, including day (0.001178), month (-0.015992), and year (0.116664), exhibit weak correlations with the maximum demand met during the day, suggesting minimal influence on its variability.

To delve deeper into the relationship between the two variables, a scatter plot shown in Fig. 17 was created to visually depict their correlation. Subsequently, a linear regression analysis was performed using the sklearn library to derive a regression line that best fits the data points on the scatter plot. This regression line in Fig. 18 represents the mathematical equation that describes the relationship between the variables.

After conducting the linear regression analysis, predictions were made using the model on both the x and y values. The accuracy of these predictions was measured, and the

$$y\left(quantity\,produced\ (MW)\right) = 20.8756 \times \left(units\,met\left[MW\right]\right) - 861.0183190705575$$

Fig. 17. Regression equation

model performed exceptionally well, achieving an accuracy of 0.9792894593897667, which translates to nearly 98 percent. This high level of accuracy indicates that the regression model effectively captures the relationship between the variables and can make reliable predictions.

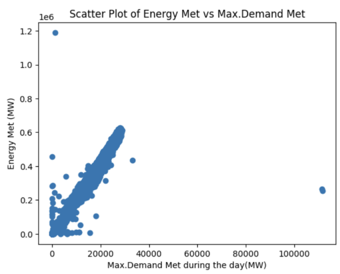

Fig. 18. Scatter Plot to generate regression line

VI. Conclusion

Through this research paper , the authors aimed to reflect on the journey which India has made in the electricity generation throughout the Decade . Taking insights from Graphs and visualisation generated through data science and analytics methods, we see India‘s remarkable journey towards a cleaner and greener future. India‘s renewable journey is marked with speed-breakers and potholes like skewed Energy-demand , low revenues of Transmission and Generation companies , Cheap coal energy , lack of renewable infrastructure and Research and Development in the field of green energy. [15] The authors of this paper in conclusion underscore the importance of a multifaceted approach to facilitate India’s transition from a coal-dependent energy system to a renewable energy leader. The strategies outlined, including promoting hybridization of solar and wind energy, investing in enhanced evacuation infrastructure and digitalization, developing battery storage solutions, and reforming distribution companies, are essential components of a comprehensive renewable energy transition plan. Moreover, policy measures to phase out fossil fuel subsidies, encourage research and development in innovative technologies, foster collaboration among stakeholders, establish renewable energy parks, and prioritize energy efficiency play pivotal roles in driving India’s renewable energy transformation. Additionally, incentivizing decentralized energy generation, enhancing public awareness, supporting capacity building, and engaging in international partnerships are crucial steps towards achieving sustainable energy goals. By integrating these strategies into our research findings, we contribute to the discourse on India’s renewable energy transition, advocating for a holistic approach to address the challenges and opportunities in this critical endeavor.

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