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Electrical Energy Production in India: A Modern History

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ABSTRACT

The past few decades of electrification transformation in India probably mark the most important engineering and technological developments in the history of modern India. From the very first colonial forays into power generation and distribution to the present day of advancements in grid modernization, the entire industry has witnessed diversity and growth at a very rapid pace. As of 2024, India's total installed electricity generation capacity will cross 430 GW, with renewable energy sources accounting for more than 44% of this mix, including more than 180 GW from solar, wind, biomass, and small hydro power. Transmission infrastructure has evolved over almost 470,000 circuit kilometres of high-voltage networks integrating diverse energy sources into the largest synchronized grid in the world. In parallel, developments in smart grid technologies, digital monitoring, and automation allow better energy management in real-time, improved grid stability, and loss reduction across the system. The electrification rate of only slightly above 56% in 2000 crossed almost 100% by 2019, ensuring reliable access to both rural and urban population and maintaining rapid industrial and digital development. Strong policy measures and regulatory reforms have supplemented technological advancement and aided the integration of renewables, demand-side management, and energy storage while addressing the challenges of balancing regional demand-supply variations. The government's thrust on decarbonization and sustainable growth has rightly dovetailed with India's aim of 500 GW of renewable capacity by 2030 and a 45%-reduction in carbon intensity of GDP from the 2005 levels.

Keywords: Electrical energy; demand; generation; distribution; smart grid

INTRODUCTION

One of the nations that is developing the quickest in the globe is India. The need for energy and electricity will rise to maintain such growth. With an estimated population of 1.2 billion and a territory of 3.29 million square mile, India is the 1st most populous nation in the world. Its increasing economy depends on the production and infrastructure of electricity. In India, most of the electricity is generated in coal-fired thermal power plants. Coal continues to be the nation's primary electrical source despite attempts to broaden the possibilities, especially in the field of sustainable energies. The percentage of coal-based electricity generation has been steadily rising during 2000; in the course of that time, it had reached 68%, and by 2017, and has risen to 73%. In India, the electrical sector (both domestic and grid) uses more than 80% of the nation's offtake ((Talhar Belge et al. 2024)). India's energy supply

is tightly controlled as a result of its capitalist and public-benefit traits. Plans and strategies are centered on building ample power and stocks to produce, trade, and consume energy. The total amount of energy that is required as a whole, the type of energy that is desired (who is requesting, where they are requesting, and when), as well as the existence and desire ordering of alternative sources of supply, all influence the demand for coal. As will be further explained, there are several factors that affect electricity demand, some of which have a great deal of ambiguity in the years to come. For instance, expectations of India's GDP growth up to 2030 span 5.7 to 6.5% according to forecasts by the IMF and official sources to approximately 7 to 8 % as anticipated by multiple lenders, economic groups, and academic groups. India consumed 980 TWh of power in 2015 (Figure 1), and its average annual growth rate has been 8.84% (Talwariya et al. 2018). The industrial sector consumes the most electricity; in 2015, its anticipated demand amounted to 450 TWh and it experienced the highest growth rate (11%). The metal, iron, concrete, fuel, paper and pulp products, nutrients, small and medium-sized business, and numerous other industries—all of which are cited as significant because they are overseen by separate ministries are among the most significant sectors of the Indian economy.

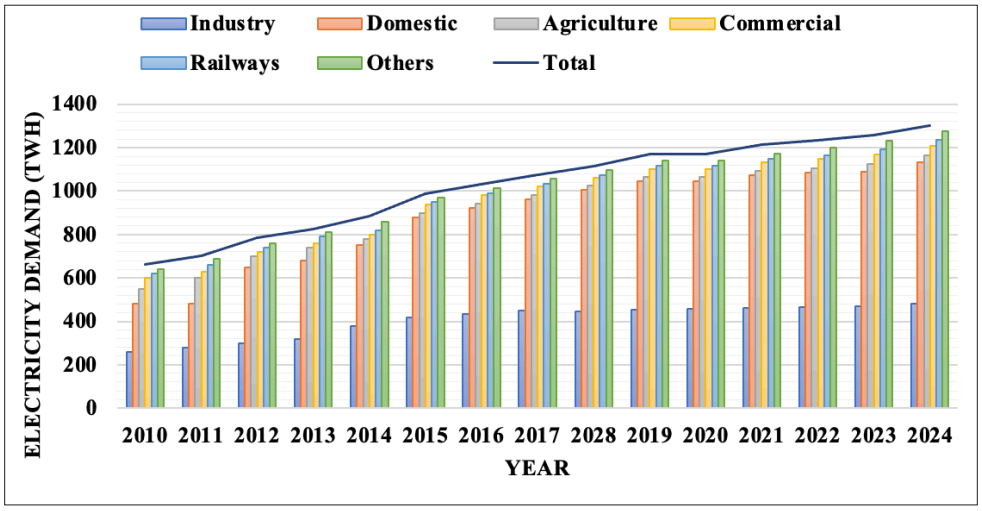

FIGURE 1. Electricity demand by different industries for the year 2001 to 2015

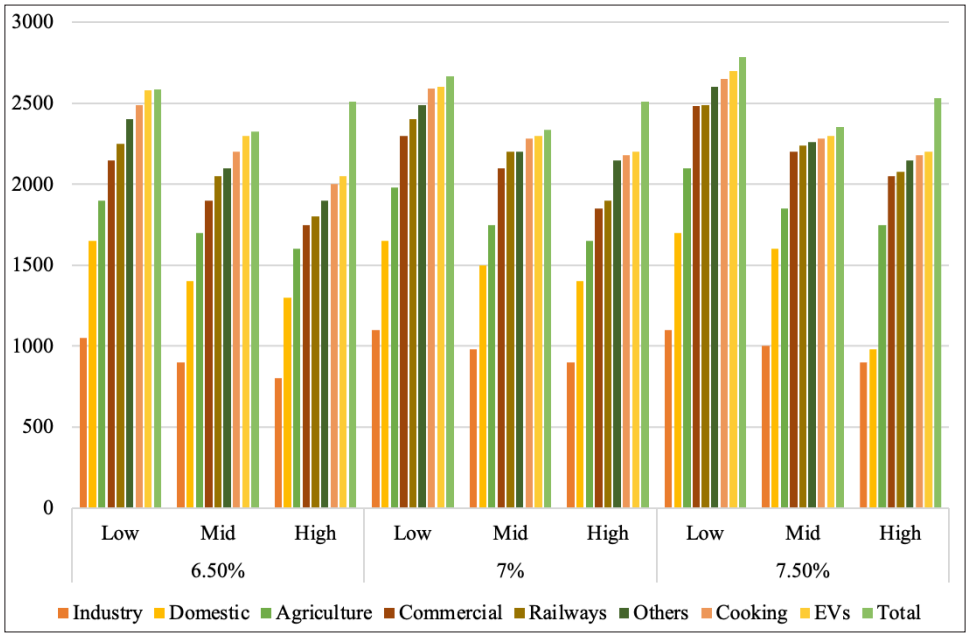

FIGURE 2. Energy efficiency with respect to demand

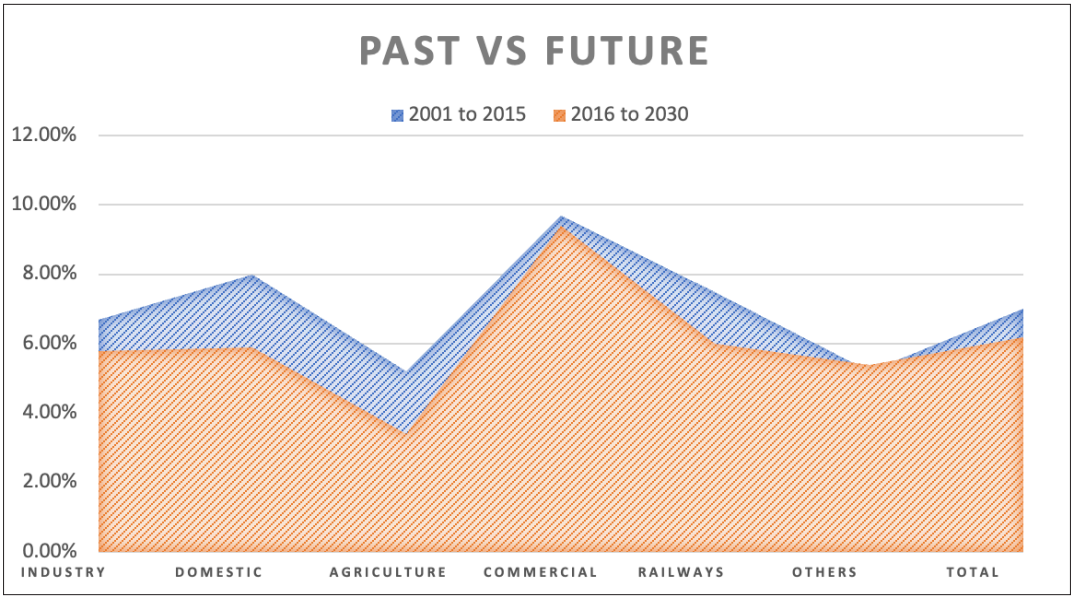

FIGURE 3. Energy prediction analysis past (2001 to 2015) Vs future (2016 to 2030)

Consequently, publicly accountable and measurable result-focused policy interventions have also greatly contributed towards the milestone that India has achieved in power. Competition and private sector participation necessarily characterize the electricity policy environment for generation, and open access provided in the Electricity Act of 2003. Rural electrification has been supported particularly with schemes such as Rajiv Gandhi Grameen Vidyutikaran Yojana (2005) and Saubhagya scheme (2017). This has increased the coverage from a paltry 56% electrification in 2000 to almost 100% by 2019. The landmark launch of the National Solar Mission, 2010 has enabled a great switch to solar power as renewable capacity was built above 180 GW by 2024, while Renewable Energy Development targets of 175 GW by 2022 and 500 GW by 2030 provided a clear roadmap to investors and developers. Ujwal DISCOM Assurance Yojana (UDAY, 2015) reforms, which ensure more robustness for financially distressed power distribution firms, also provide indirect support toward grid stability and renewable integration. The modernization of the grid is being furthered by the development of grid policies with the National Smart Grid Mission (2015) so as to create an environment for digital automation, real-time monitoring, demand-side management, enhanced efficiencies above 20% in the early 2000s declining to below 16 percent by 2024. These could actually be policy-driven incentives for energy storage and green hydrogen, thus paving the way for the next phase of sustainable development (Karthika & Karthikeya 2022).

Policy interventions have also provided quantifiable benefits within the power sector in India in the past few years. The National Solar Mission has propelled solar capacity below 20 MW in 2010 to above 72 GW by 2024 and total renewable capacity has already hit 180 GW with clear government targets of 500 GW by 2030. Ujwal DISCOM Assurance Yojana (UDAY) and the National Smart Grid Mission have increased grid reliability to approximately 16% in aggregate technical and commercial loss in 2024 and has increased stability by means of smart metering and automation. The results point to the direct conversion of targeted policies into increases in capacity, efficiency, and more robust energy system.

India produced 89 million metric tons of crude steel in 2015, and the country has been producing less crude steel per ton of energy intensity since the early 2000s. The strategic objective is 4.5 GCal per metric ton of steel scrap by 2025–2026, up from an average of 6.3 GCal in 2013. With 2.36 million tons of aluminum made, India was predicted to have an electrical intensity ranging from 14,000 to 17,000 kWh per ton. In 2015, India produced 300 million tons of asphalt, with an electrical intensity of 80 kWh per ton. Since power consumption from irrigation pumping is dependent on both external factors (such the strength of the monsoon) and regulatory decisions, economic growth or industry value-added have never been a reliable measure of that growth. As a result, instead of growing at a rate of 5.2% in previous years, the projected future demand for electricity can rise at a rate of 3.9 to 4.2% CAGR. Pump-set control won't be the main limiting factor; rather, service demands—such as consumption requirements and degree of use, among others—will be. The energy prediction analysis of different sectors for the past (2001 to 2015) and future (2016 to 2030) is shown in Figure 3. The findings reveal that the commercial, domestic

and industrial sectors demand increased electricity compared to other fields.

AVAILABILITY OF MODERN, RELIABLE, AND INEXPENSIVE POWER SUPPLIES

India's Saubhagya Scheme, which is working for 100% rural electrification, the Government of India also emphasized on energizing all un-electrified residences across the country. Research indicates that household electrification is hindered by factors such as low awareness, high expenses, intricacy, and logistical obstacles. It has substantially enhanced the provision of electricity in recent years; according to official data, over 99% of residences had access to power in 2019. However, studies show that just over 80% of commercial consumers, 65% of entrepreneurs, and 50% of agricultural patrons were successfully connected to the electrical grid in the year 2018 (Sharma & Singh, 2019). These findings highlight persistent issues with the level of service and predictability of electricity supply for both connected homes and non-household consumers. It is possible that the COVID-19 pandemic and its financial ramifications will undo recent progress and force certain linked homes to fall into previous energy deprivation.

An enlarged bundle of electrical services could become unaffordable for up to 40 million individuals in India who have access to electricity. Due to the necessity of balancing their energy requirements with other demands, some low-income households may return to using outdated and costly fuels. With approximately 99% of associations made under the Saubhagya Scheme, on-grid electrical power continues to be the most cost-effective way for the majority of Indian customers to obtain cutting-edge electricity services, particularly in light of rising household consumption due to growing appliance ownership. Nonetheless, independent networks and small-scale grids provide a workable substitute for dependable access to electrical services in some circumstances, particularly in isolated remote regions, to supplement the main grid.

The booming demand due to industrialization, urbanization, and near-universal electrification has been the largest historical trend in the electrical energy sector in India; per capita electricity consumption increased by approximately 700 kWh in 2000 to more than 1,300 kWh in 2024. In the future, by far the most important forecast is that demand will keep surging and by 2040 it will be almost twice as large as today due to electric mobility, the digital infrastructure and the increase in living standards, and renewable energy will become the dominant element of the supply mix, which will correspond to the goal of 500 GW of renewable capacity by 2030 and a net-zero pathway by 2070 in India.

RECENT ACTS AND REGULATIONS

Boosting the proportion of renewable energy sources in the energy portfolio of India is the foundation for sustainable resource policy's long-term objective. The government sets certain energy-related regulations, which are listed in below:

NATIONAL ELECTRICITY POLICY AT 2005

The National Electricity Policy seeks to meet a number of objectives: ensuring that everyone has a reliable supply of electricity; meeting all electrical demand from 2012; beating energy along with rising shortages while preserving an unlimited retain; supplying stable, reliable power that meets the regulations in an affordable and effective manner; increasing the amount of electricity available per person to more than 1000 units in that same year; and preserving the best interests of customers.

ELECTRICITY ACT AT 2003

The following rules concerning alternative sources of energy are stipulated in the Electricity Act. According to the statement, the Central Government is responsible for periodically drafting and releasing the National Electricity Policies and tariffs. The state commissions are expected to carry out the following duties: they will encourage cogeneration and the production of electricity from renewable energy sources by offering feasible options for grid connectivity and the provision of electricity to any individual. They will additionally allocate a portion of the total electricity consumption in the area covered by the distribution permit for the acquisition of electricity from these sources.

TARIFF POLICY AT 2006

A minimum percentage for the procurement of electrical power from these sources must be determined by the Appropriate Commission, who will consider the impact on retail pricing and the accessibility of such resources in the area. Non-conventional technologies will need some time to catch up to conventional sources in terms of electricity cost. Transmission businesses have to purchase goods at favorable tariffs that have been established by the Appropriate Commission. In the event that non-firm electricity is procured through non-competitive auctions, the Central Commission ought to create standards for selling non-firm power, especially those coming from alternative sources, within a span of three months.

NATIONAL RURAL ELECTRIFICATION POLICIES AT 2006

All households must have access to electricity in the year 2009, and by the year 2012, every home must have a minimum lifeline usage of one unit per household per day as a reward item. Off-grid solutions based on independent systems may be used to provide energy to tribes and other settlements where grid connectivity would not be practical or affordable. Within a period of six months, the state government is required to come up with and publish a rural electrification plan that includes a map and specifics of the delivery system for electricity. Every year on March 31st, the village's electricity status must be recognized and reaffirmed by the Gramme Panchayat.

INTEGRATED ENERGY POLICY REPORT AT 2006

Provide a plan for integrating the nation's energy demands until 2031 to 2032. It suggested placing extra emphasis on the development of renewable energy.

ACHIEVEMENTS OF SIGNIFICANCE

India has made significant progress in developing renewable energy, which can be summed up as follows:

1. Grid energy from wind, hydroelectric plants, biomass, and solar energy totaling more than 4200 MW.
2. Approximately 3600 isolated villages and hamlets, such as those in the North East, Bangladesh, Ladakh, and the Sunderbans, are powered by solar energy.
3. Set up at Tirupati Tirumala Devasthanam, the biggest solar-steam heating facility can accommodate 15,000 people per day.
4. Around 7 lakhs solar water heating systems with collection area have been deployed.
5. There are 3.5 million biogas plants operational for heating and culinary needs.
6. In rural residences, there are 35 million upgraded fire heaters.
7. Blocks with 860 installations of the Integrated Rural Energy Project.
7. Solar power plants with a capacity of around 30 MW are exported to nations that are both industrialized and developing.
8. Approximately 280 Energy Parks have been set up by educational facilities to exhibit green energy sources and technologies.
9. The total amount of direct subsidies granted to consumers and recipients of clean energy systems and components, including grid-connected solar power plants, are a total of 25,000 rupees million.
10. The Indian Renewable Energy Development Agency Limited has so far financed Rs. 32,000 million for 1600 green energy developments.
11. Founded in Chennai, Tamil Nadu, the Centre for Wind Energy Technology is a scientific and industrial research organization dedicated to wind resource assessment, technology certification, and research & development.
12. In Gurgaon, Haryana, a Solar Energy Centre has been established to develop solar energy equipment and systems.

ELECTRICITY ANALYSIS OF THE MARKET IN 2023

In 2022, the need for electricity globally did not decline despite the worldwide shortage of energy brought on by the Russian bombardment of Ukraine (Bhattacharjee et al. 2024). In comparison to the 2.4% average rate of expansion observed between the years 2015 and 2019, demand increased by over 2%. On a global scale the electrically powered transformation of the transportation and heating industries is growing faster, with record sales of electric automobiles and heating systems in 2022 fueling the expansion. However, record-high energy costs wrecked economies all over the world, which were still recuperating from the effects of COVID-19. Inflation increased quickly as a result of the dramatic increase in energy production costs brought on by the soaring costs of basic commodities like coal and natural gas. In most parts of the world, economic recessions and high electricity costs inhibited the rise of the demand for electricity (Kumar & Trivedi 2025).

The historical demand, forecasting results, and previous forecasting results are represented in Figure 4. Power consumption in India was above 8.4% in 2022, a significant increase over the 5.3% yearly average growth rate observed from 2015 to 2019. This was made possible by the country's strong post-pandemic recovery. In 2022, the hottest March in more than a century occurred as a result of the early arrival of the peak summer season. Demand for electricity increased by 12% between March and July compared to the identical year in 2021. Researchers predict considerably lower growth, about 5.6% annually, for the 2023–2025 timeframe (Das et al. 2025).

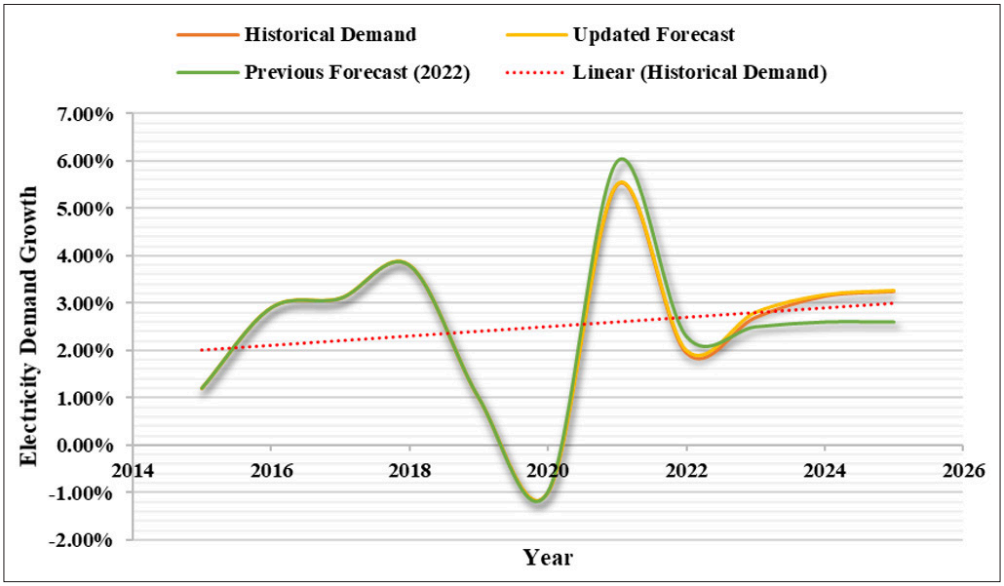

FIGURE 4. Electrical change analysis year wise (2015 to 2025)

India's GDP is predicted to expand by a mere 6.8% in 2022.The forecast for 2023 had been lowered in January from 6.9% to 6.1%, mostly as a result of the trading partner countries' sluggish economic growth. The 6.8% GDP growth rate for 2024 remained same. The prior October assessment yielded growth 2025 estimate of 6.8%. Peak summer temps combined with a protracted economic rebound following the Covid-19 pandemic had a major impact on India's electrical consumption in 2022, increasing it by 8.4%. Between 2023 and 2025, researchers anticipate that demand will expand at a rate of about 5.6% annually on aggregate. In 2022, there were severe heat waves in India. It had been the driest March in more than a century since the warmer season started before than expected. Heat waves caused an unprecedented peak electrical use of 211 GW on June 10, 2022, despite the fact that the demand for electricity from April to July had been 14% greater than what it was in 2021.The main method of meeting the substantial rise in summer need remained coal fired power, which saw a notable year-over-year gain of 21.3% during April 2022 to July 2022 compared to April 2021 to July 2021. The Ministry of Power then ordered government utilities and private generators to meet a 10% blending requirement, which implies that 10% of the nation's coal demand should be met by imports of coal.

As a result, India encountered difficulties in the supply of coal. Before the monsoon season began, it became necessary to guarantee sufficient coal reserves. The government abolished these regulations for merging in August 2022 once electricity locations had enough fuel stocks. With 410 GW of total capacity at the year of 2022, India is mostly dependent on nuclear power plants for the remainder of 236 GW, which originates from fossil-fired power plants (coal, gas, and oil), 52 GW through hydropower, and 115 GW through PV and wind sources. Coal power plant retirements have been slower than expected; currently, 14 GW of the capacity that had been scheduled for completion between 2017 and 2022 is still in use for regulating. Following the public disclosure of the revised Nationally Determined Contributions of 500 GW of non-fossil production in 2030, the government is moving to expedite the growth of energy from renewable sources. To incorporate this additional power into the power grid, the government developed an agenda that calls for both grid extensions and more storage facilities. In addition, the Central Electricity Authority (CEA) states that comparable renewable energy generation might substitute approximately 3 GW of thermal electrical power that is scheduled to be discontinued before 2030.

To provide continuously electricity from sources of renewable energy, steps to speed up the development of green power include raising solar power procurement requirements (to 2029–2030) and focusing greater emphasis on wind, hydropower, and energy storage. Secondly, it is anticipated that procurement of clean energy is going to rise as a result of the sustainable accessible strength regulations, which were announced in June 2022 and put into effect in November 2022. Following that, the Energy Conservation (Amendment) Bill 2022 creates carbon markets and requires specific industrial and commercial customers to use non-fossil sources. As part of its green hydrogen policy, India waives interstate gearbox fees for 25 years, which further promotes the fabrication of green hydrogen and ammonia. Currently, 74% of India's electricity comes from coal. Nuclear output is predicted to increase by more than 80% throughout the

projected period, to 83 TWh, but it will still only make up 4% of the total energy mix in 2025. In 2022, gas-fired output decreased by 36% as a result of increasing import petrol prices, whereas the generation using coal increased by 7.7%. Although total power generated by coal is predicted to increase through 2025, researchers anticipate that once renewable energy reaches 25% of the generation mix, coal's share will decline to 69%. Even though CO2 intensity is declining, total power generating CO2 emissions increase to 8% on 2022 levels by 2025 due to increased coal-fired output.

Although energy markets account for 6% of the overall production and short-term platforms (exchanging agreements between parties with a duration of less than a year) account for 14% of it, these financial markets are predicted to expand. In the financial year 2022 (from April 2021 to March 2022), the amount of energy traded on the Indian Energy Exchange (IEX) rose by 38% year over year in every segment of the market. Hindustan Power Exchange began operations in July 2022, joining IEX and Power Exchange India Ltd (PXIL) as the third power marketplace. Prices surged as a result of the twofold demand for power transfers in the summertime supply constraints of 2022. The Central Electricity

Regulatory Commission (CERC) established a limit of INR 12/kWh on the electricity market closing price to protect the interest of customers. The price cap had been scheduled to expire on September 30, 2022, but the deadline ended up being postponed to the end of the year to account for increased demand around the holidays and the start of winter. In southern Asia, India is crucial to regional connectivity and cross-border trade. India now imports hydropower from Bhutan, and given Nepal's 5,000 MW of excess hydropower, importation from Nepal are anticipated to rise in the span of 2 to 3 years. Nepal boosted its market capacity to roughly 364 MW of electricity in June 2022 after beginning to trade hydropower on India's power market in 2021. A deal to invest in the creation of additional hydro projects (pertaining to 1,200 MW) has been signed in the summer of 2022.The distribution industry is still under pressure, as demonstrated by the rise in total cumulative losses from INR 300 billion in the financial year 2019-2020 to INR 500 billion during the financial year 2020/2021. In response, the government introduced the redesigned distribution sector scheme, which provides financial support for improving facilities and the green electricity authority issued standards for establishing a plan while ensuring resources availability.

OUTLINE OF ENERGY STABILITY AND SUSTAINABILITY

The COVID-19 pandemic has obstructed India's path towards progress. The length of the crisis, the form of recovery, and the potential future energy associated stimulus efforts that the government may implement are all still very much up in the wild. The epidemic is progressively pursuant to control during 2021. A strengthening economy creates the conditions for acceleration to substantial growth in GDP throughout the rest of the year. India is the main contributor of worldwide energy use development during the Outlook period, which renders it the most important nation for market developments involving all forms of energy and technology. India's CO2 emissions per person are still significantly below the world average, but by 2040, overall emissions will rise almost 50%, substantially keeping up with the development in demand. By 2040, India will be the world's second-biggest source of greenhouse gas emissions, surpassing the predicted decrease in pollution in Europe due to its rising emissions.

CONCLUSION

In the past few decades, India has connected countless millions of people to electricity, pushed most homes to upgrade to extremely efficient fluorescent lighting, and significantly increased the amount of energy coming from sustainable sources, mainly solar power. It is evident that the level of living of Indians has increased. However, the COVID-19 pandemic has attempted to address some important issues that are more difficult to resolve.

In this study, the historical analysis and prediction of India's electrical energy demand are presented. This unique research lays out India's potential energy futures, the choices and factors that affect them, and the dynamics that occur throughout an intricate energy system. One key element guiding the international reaction to the impact of climate change is the growing urgency of the situation. Even though India hasn't made significant improvements to global greenhouse gas emissions to date, the country is already suffering from its impacts. The study presented in this article is predicated on a thorough examination of current or declared energy targets and changes. These include plans to over double the proportion of natural gas in the energy mix, increase the output from domestic coal,

decrease dependency on imports, improve energy conservation and transportation systems, and quadruple the capacity of renewable electricity by 2030.

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DECLARATION OF COMPETING INTEREST

None.

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