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Taniya CHOUDHURY, Marek FURMANKIEWICZ, Manu THOMAS

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Taniya CHOUDHURY[a]*, Marek FURMANKIEWICZ[b], Manu THOMAS[c]

[a]* Wrocław University of Environmental and Life Sciences, Institute of Spatial Management
Grunwaldzka 55, 50-357 Wrocław, Poland
taniya.choudhury@upwr.edu.pl, ORCID 0009-0007-3529-2102 *(corresponding author)*

[b]Wrocław University of Environmental and Life Sciences, Institute of Spatial Management
Grunwaldzka 55, 50-357 Wrocław, Poland
ORCID 0000-0001-9715-1056

[c]Wrocław University of Environmental and Life Sciences, Institute of Spatial Management
Grunwaldzka 55, 50-357 Wrocław, Poland
ORCID 0000-0002-3683-8636

Challenges in the Development of Low-Carbon Energy Sources in India

Abstract

India is undergoing an energy transition driven by the dual imperatives of continuing economic growth and the urgent need for climate change mitigation. This article analyzes the planning documents, achievements and future challenges of developing low-carbon energy sources (LCESs) in India. Our considerations are based on the latest statistical data on LCESs development and major government policy documents. India has made significant progress in developing LCESs, focusing on solar, wind, and nuclear power to support economic growth and to mitigate climate change. Between 1990 and 2023, renewable energy production in India increased by 1900 times, from 437 TJ to 830227 TJ. Solar energy has become the cornerstone of India's low-carbon strategy, with aggressive expansion supported by government policy. However, dependence on fossil fuels, especially coal, remains high, increasing from 55% to nearly 63% of the energy production during the same period. The weakness of many planning documents and policies is the lack of measurable goals and dates for their planned implementation, as well as poor analyses of realistic ways to achieve these goals. Key barriers include limited funds for investment, limited energy storage infrastructure, improper energy grid modernisation, regulatory inconsistencies, socioeconomic disparities, and slow policy implementation. A more balanced focus is essential on decentralised energy systems, improved energy efficiency, and just transition strategies.

Key Words: Low-Carbon Economy, Sustainable Development, Energy Sector, Energy Transition, National Policy, India

JEL Classification: **O13, P28, Q48**

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Introduction

According to United Nations (UN) estimates, India overtook China in terms of population in 2023 and became the world's largest country. Economic and population growth, coupled with an improved quality of life, will generate a steady increase in the demand for electricity. This raises an important question: how can economic growth be achieved while avoiding a massive increase in the use of fossil fuels in energy production, which negatively impacts air quality and generates carbon dioxide (CO_2) emissions, thereby increasing the average global temperature?

India was not far behind other large countries in setting a target to reduce CO_2 emissions by approximately 33% between 2005 and 2030 (Fragkos et al., 2021). However, studies on India's development indicate that the share of renewable energy sources (RES) has decreased and CO_2 emissions have increased because energy production growth was based mainly on coal-fired power plants (Ortega-Ruiz et al., 2020; Singh et al. 2023; Uche et al., 2023). These trends contradict national goals and the recommendations of global climate scientists to reduce greenhouse gas emissions (GHG). These data underscore the difficulty in achieving economic development and improving the quality of life of Indian citizens using low-carbon energy sources (LCESs).

This study focuses on the development of LCESs in India, encompassing all energy sources that do not emit CO_2. This includes both renewable and nuclear energy sources. Although the long-term goal should be to achieve a modern circular economy without the use of fossil fuels, the use of non-renewable nuclear energy during the period of energy transition seems necessary owing to the limitations of renewable technologies (the main problem being instability and dispersion). The main goals of this study are as follows:

- To critically analyse the trajectory of India's current LCESs development policies.
- Briefly analyse the current planning documents of the Indian central government related to the development of LCESs

Our analyses and conclusions can be helpful in evaluating existing energy policies in developing countries and shaping future policies.

1. Methods of Research

We primarily rely on the available statistical data on the energy sector's development to date and a qualitative analysis of India's government's strategic documents. Our analysis was divided into two stages. The first examines the real changes in India's energy sector (Section 3). For long-term comparisons (1990-2023), we used data from the International Energy Agency (IRENA, 2025). The year 1990 was selected as a baseline because significant international agreements were negotiated in the 1990s. (such as the UN Framework Convention on Climate Change in 1992 and the Kyoto Protocol in 1997), mentioning the importance of shifting away from fossil fuels as they release greenhouse

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gases, especially CO_2. Moreover, a reliable and standardised dataset has been made available from this year (IRENA, 2025). To analyse the regional variation in LCESs capacity, we used the latest statistical data on RES (as of March 2025) published by the Government of India, Ministry of Statistics and Programme Implementation (MSPI, 2025) and data on nuclear power plants (as of June 2025) published by the Nuclear Power Corporation of India Limited (NPCI, 2025). In the analysis of RES, we aggregated small and large hydroelectric sources, which are reported separately in Indian government statistics. We used the QGIS Desktop program (version 3.40.9) to visualise the regional data. In the second stage of the analysis (Section 4), we conducted a concise qualitative analysis of the current strategic, planning, and legal documents prepared by the Indian central government:

1. **Energy Conservation Act** (ECA, passed in 2001, last revised in 2022): It regulates energy consumption in various sectors, promotes energy efficiency, and lays the groundwork for a domestic carbon market.
2. **National Electricity Plan** (NEP, notified in 2007, last revised in 2023): This outlines India's strategy for electricity generation, transmission, and distribution from 2023 to 2032.
3. **National Action Plan on Climate Change** (NAPCC, 2008): This outlines India's approach to addressing climate change, including the energy economic sector.
4. **National Offshore Wind Energy Policy** (NOWEP, 2015): This aims to provide a framework for the development of the offshore wind sector in India.
5. **Long-Term Low-Carbon Development Strategy** (formal acronym LT-LEDS; submitted to the UN in 2022): This outlines a path towards low-carbon development, aiming to decouple economic growth from emissions and foster a sustainable, low-emission economy.
6. **National Green Hydrogen Mission** (NGHM, 2023): It describes India's approach to developing the use of clean hydrogen energy.

In this stage, we focused on finding records in the above-mentioned documents regarding the development of LCESs. To discuss our findings, we used opinions and analyses from other authors, supported by the SCOPUS AI tool, which analyzes abstracts of papers inventoried in the SCOPUS database. We obtained the AI-proposed articles in their full versions and analysed their content in detail, considering only the articles whose content most closely matched our analysis (considering the limit of 20 references in this publication). Articles that could not be obtained because of copyright issues were excluded from the analyses.

2. The Development of LCESs in India

Economic growth, combined with India's growing population, has significantly increased energy demand. Between 2000 and 2023, domestic energy production nearly tripled (Figure 1). However, this growth was predominantly driven by the consumption of coal. According to the International Energy Agency (IRENA, 2025), the share of coal in energy

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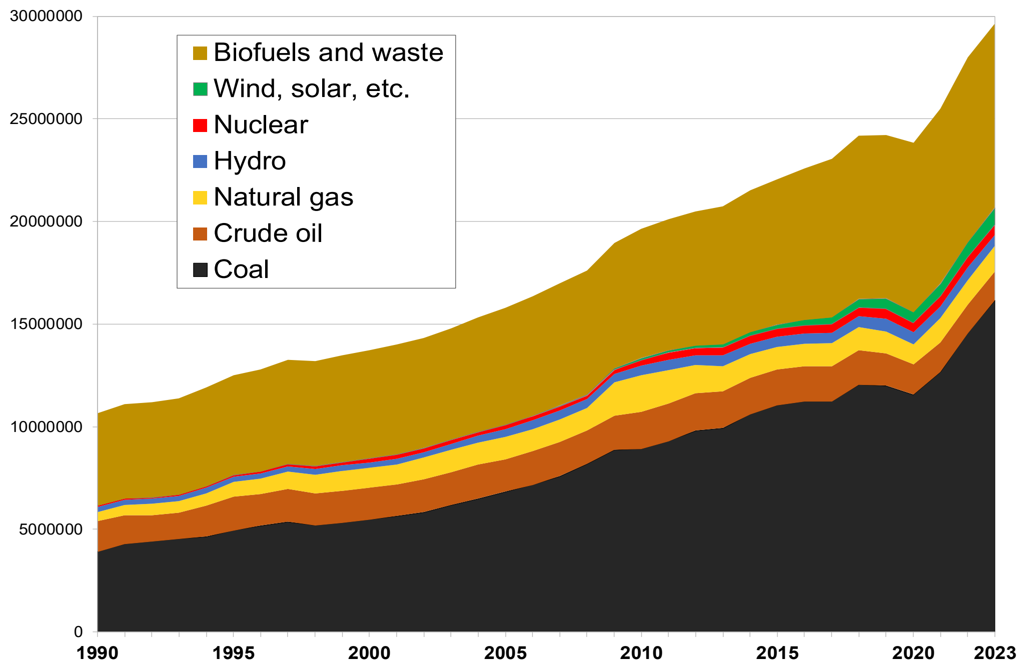
production increased from 34.7% to 54.5% in the years 1990-2023, while the share of renewable energy (RE) decreased from 44,7% to 34,8% (Figure 2). However, RE is dominated by bioenergy from burning wood and waste, which is not an optimal solution for achieving a low-carbon economy in the long term. India is greatly dependent on traditional bioenergy sources for cooking and heating, especially in rural regions. This energy is derived from firewood, crop residues, dried leaves, and animal dung (considered as biofuels in statistics). This is not a sustainable practice and contributes to air pollution, deforestation, black carbon emissions, and health hazards.

Fig. 1: Growth in energy production in India between 1990 and 2023 (TJ) and acceleration of investment after 2021.

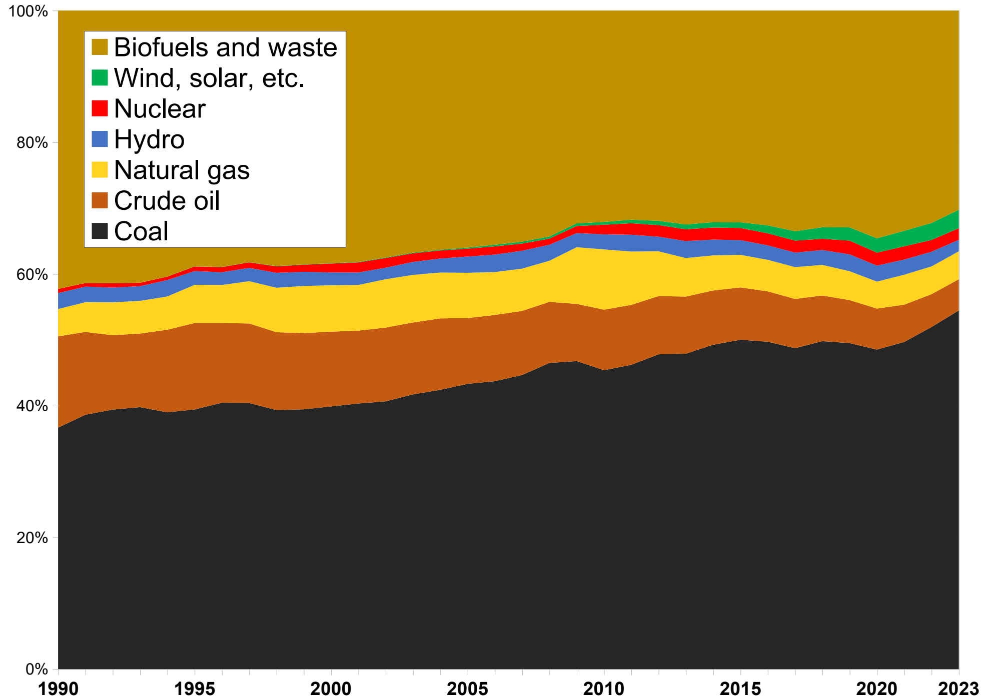


Source: own work, data from the International Energy Agency (IRENA, 2025)

Recently, India has made notable achievements in development of modern LCESs. In the RE sector, the country has experienced rapid growth, with a significant increase in renewable generation, especially solar and wind plants, from approximately 436 TJ in 1990, to 830227 TJ in 2023. According to the IEA, India ranked fourth globally in terms of overall installed RE capacity in 2023 (after China, the USA, and Brazil). Government support through favourable policies and incentives has attracted foreign investment, positioning India as a global leader in clean energy. Furthermore, the RE sector is emerging as a key driver of job creation, contributing to economic development and enhancing the energy security.

DOI: 10.15240/tul/009/lef-2025-02

Fig. 2: Share of sources in national energy production in India (1990–2023). A significant increase in the role of coal is evident, despite the development of modern RES (wind, solar, etc.), which still have a negligible percentage share.



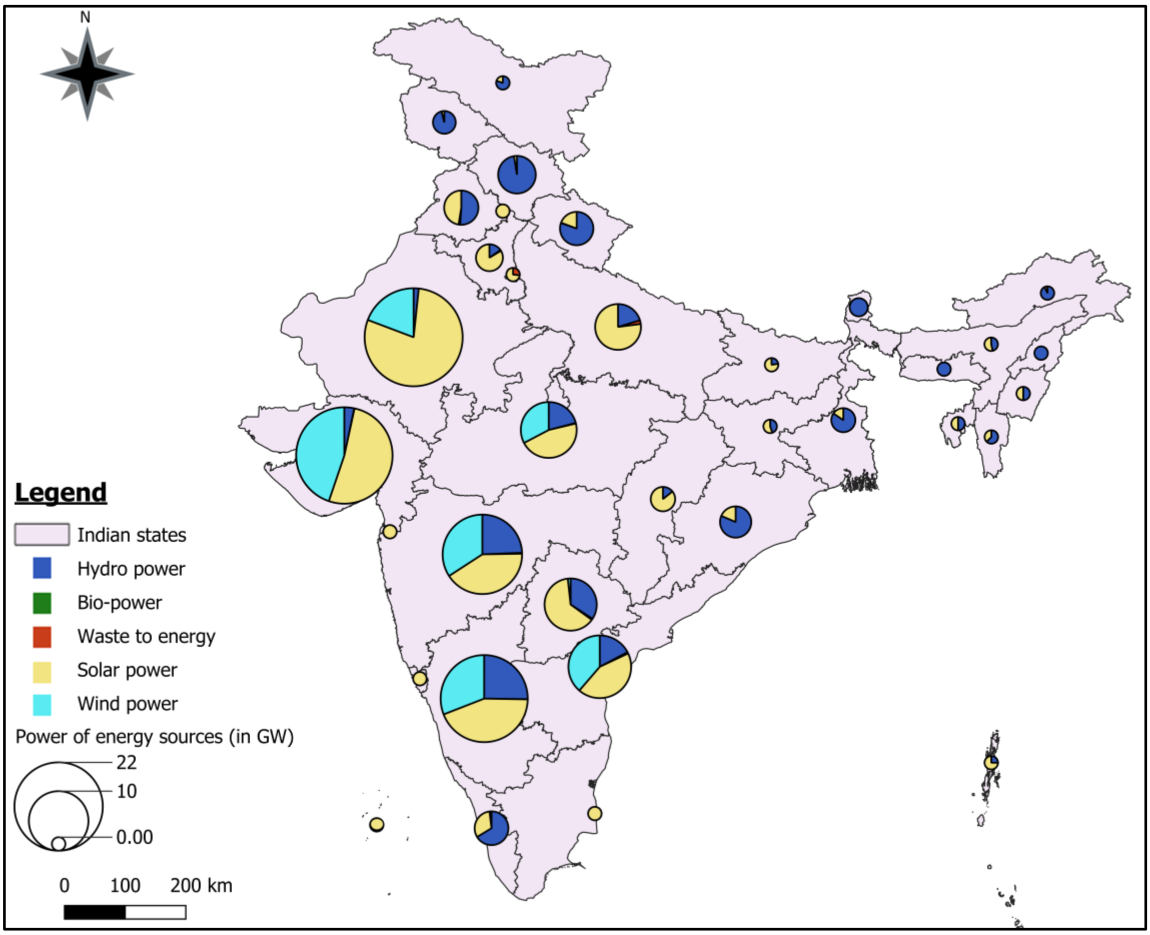
Source: own work, data from the International Energy Agency (IRENA, 2025).

In terms of installed RE capacity in 2024, according to data from the Government of India (MSPI, 2025), solar energy had the greatest importance (81.8 GW of installed capacity, that is, 46.8% of RE), followed by wind energy (45.8 GW, 26.2%), and hydropower (36.1 GW, 20.7%), with solar energy sources experiencing the most dynamic growth. Solar farms mainly operate in western India (Figure 3), with the highest capacities in Rajasthan (21.3 GW), Gujarat (13.5 GW), and Karnataka (8.5 GW).

The largest wind farm capacities were installed in Gujarat (11.7 GW), Karnataka (6.0 GW), and Tamil Nadu (10.6 GW). The largest combined capacities of small and large hydroelectric plants were installed in Karnataka (4.9 GW), Himachal Pradesh (3.9 GW), and Maharashtra (3.7 GW). Bioenergy was dominated in Maharashtra (2.6 GW), Uttar Pradesh (2.1 GW) and Karnataka (1.9 GW). The burning of waste for energy purposes was the highest in Delhi (but only 84 MW). In the northern part of the country, RES are less developed.

DOI: 10.15240/tul/009/lef-2025-02

Fig. 3: Installed RES capacity in Indian states in 2024. There is a visible concentration of investment in the four western Indian states.



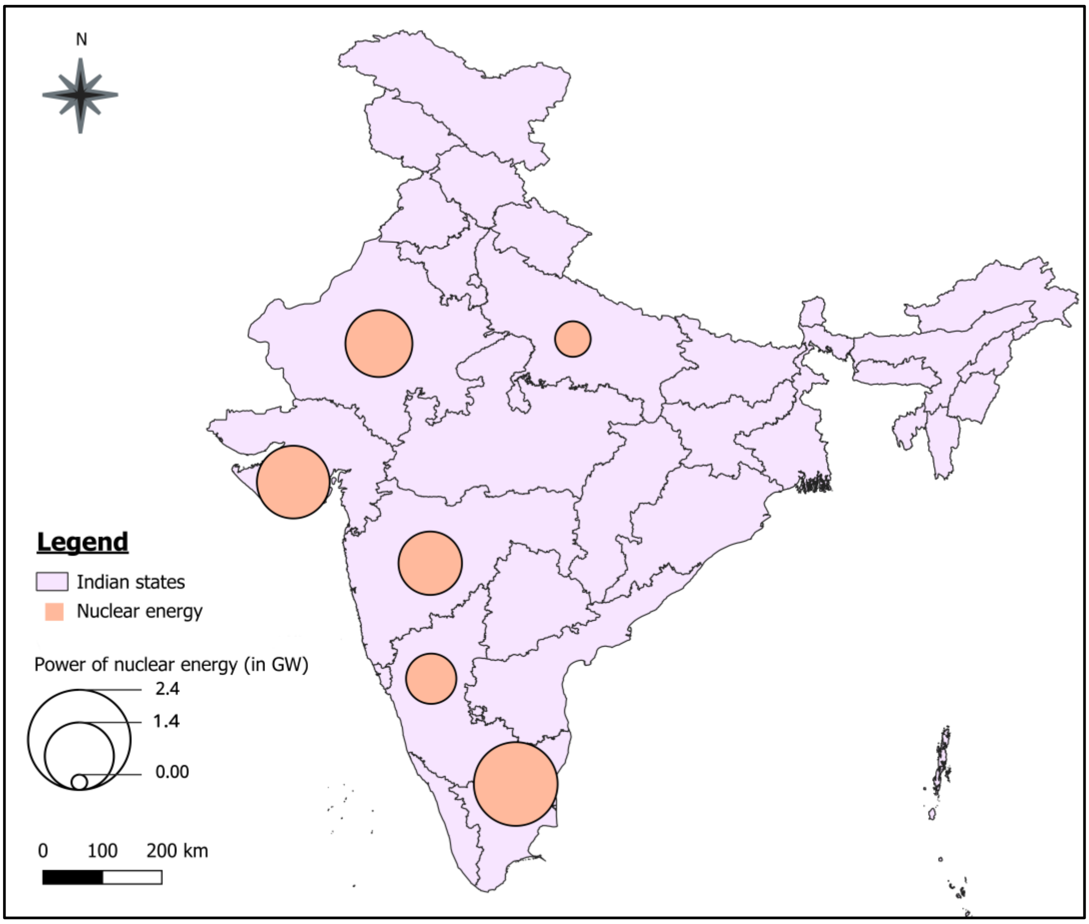
Source: own work, data from (MSPI, 2025)

In the nuclear energy sector, India has 25 reactors in operation in eight nuclear power plants located in six states (Figure 4). Their capacity was 8.9 GW as of June 2025, which is a very low figure in relation to India's energy needs. Nuclear power produced 57 TWh in the fiscal period 2024/2025[1], contributing to approximately 3% of the total power generation in India. Eleven reactors are under construction, with a combined generation capacity of 8.7 GW.

[1] In India, the government's financial year (financial period), often used in statistics, runs from 1 April to 31 March the following year.

DOI: 10.15240/tul/009/lef-2025-02

Fig. 4: Nuclear energy installed capacity in Indian states in 2025. Nuclear power plants are located in only six states in India, which hinders energy distribution.



Source: own work, data from (NPCI, 2025)

3. The Analysis of Documents Related to Energy Policy in India

India's transition to a low-carbon energy economy is guided by a series of national rules, plans, and strategies, such as the Energy Conservation Act (ECA), National Electricity Plan (NEP), National Action Plan on Climate Change (NAPCC), National Offshore Wind Energy Policy (NOWEP), Long-Term Low-Carbon Development Strategy (formal acronym LT-LEDS), and National Green Hydrogen Mission (NGHM).

The Energy Conservation Act (ECA) drives India's energy structure towards a low-carbon trajectory. It defines the regulatory and institutional framework of the Carbon Credit Trading Scheme (CCTS, last detailed regulations in 2024), which offers companies financial incentives to invest in clean technologies. To ensure accurate measurement of carbon emissions and energy consumption, this act introduced energy auditor professionals to verify and evaluate commercial units, appliances, industries, academic institutions, residences and vehicles for carbon trading certificates. Alongside market-

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based mechanisms, this amendment also mandates the Energy Conservation and Sustainable Building Codes (ECSBC, last detailed regulations in 2024), a responsibility of both the central and state governments. This strategy empowers audit agencies and imposes penalties for non-compliance. Stringent energy norms and strict financial retribution are applied in cases of failure to meet the mandatory regulations. Furthermore, the State Energy Conservation Fund and financial budget planning support local energy initiatives. Strengthening intergovernmental collaboration is another objective of enhancing project efficiency. Together, these measures will help India join the global climate movement by advancing greener practices. However, the Act fails to address small-scale enterprises and household energy efficiency. From a low-carbon economy perspective, it supports all energy sources simultaneously, whereas the slow adaptation of market-based mechanisms may constrain progress.

The National Electricity Plan (NEP), under the Ministry of Power, outlined a 15-year roadmap for electricity generation, forecasting a demand of 277 GW by the Indian fiscal period 2026/2027 and 366 GW by 2031/2032. The ministry is strategically planning to generate additional electricity to meet future energy requirements of the country. A large part of this mission is devoted to demand-side management (DSM) to reinforce low-carbon policies across various sectors, led by the Bureau of Energy Efficiency (BEE). It includes emission laws to decarbonise fossil fuel-based power plants by implementing cleaner technologies, such as fuel-gas desulfurisation. The total generation capacity is expected to increase through a diversified mix of renewable and nuclear sources by 2027-2032, aiming for 80% of capacity from clean sources. The improvement of battery and pumped hydro storage is prioritised to reduce the dependency on conventional sources. The plan also supports low-emission technological research, including waste-to-energy, stabilised grids, demand management and knowledge transfer. However, it lacks incentives for private-sector investment in low-carbon projects.

The National Action Plan on Climate Change (NAPCC) is closely linked to sustainable development goals (SDGs), including poverty alleviation (SDG 1) and climate action (SDG 13). India acknowledges its shared responsibility to address climate change through global cooperation, framed under the 'common but differentiated responsibilities' of the United Nations Framework Convention on Climate Change (UNFCCC) for equitable mitigation of climate change. The NAPCC launched eight National Missions for climate-resilient, low-carbon economic development without environmental harm: (1) the National Solar Mission to boost solar energy uptake; (2) the National Mission for Enhanced Energy Efficiency to strengthen energy security; (3) the National Mission on Sustainable Habitat to plan urbanisation and waste management; (4) the National Water Mission for water resources conservation; (5) the National Mission for Sustaining the Himalayan Ecosystem to protect natural habitats and glaciers; (6) the National Mission for a Green India to safeguard biodiversity; (7) the National Mission for Sustainable Agriculture to build climate resilience in agriculture; and (8) the National Mission on Strategic Knowledge for Climate Change to advance research. Together, these offer a platform for India to meet its environmental goals, protect vulnerable communities, promote market-based tools, and build a low-carbon economy with international partnerships. However, the NAPCC sets no carbon reduction target, lacks strong central–

DOI: 10.15240/tul/009/lef-2025-02

state coordination, faces funding shortfalls in some sub-missions, and suffers from limited outcome reporting. Solar energy has shown the fastest growth, although the distributed solar potential remains underdeveloped.

The National Offshore Wind Energy Policy (NOWEP) attempts to utilise the country's 7600 km coastlines to produce cost-effective, sustainable renewable energy. The goal is to promote the establishment of offshore windfarms along the Exclusive Economic Zone (EEZ) through Foreign Direct Investments, public-private partnerships, and international collaborations. In accordance with this strategy, the Ministry of New and Renewable Energy would serve as India's key ministry for the development of offshore wind energy and collaborate closely with other governmental organisations to develop and utilise maritime space. However, the government document on this policy, beyond generally formulated goals, does not contain any specific analyses, measurable goals, or dates for achieving them. According to preliminary assessments, eight locations in Gujarat and Tamil Nadu have been identified as possible offshore zones for the development of offshore wind energy, which is estimated to generate approximately 71 GW. However, by mid-2025, no offshore wind farms had been built.

In 2022, the Government of India submitted a Long-Term Low-Carbon Development Strategy (LT-LEDS) to the UN. This document outlines a vision to expand low-carbon energy pathways by emphasising both renewable and nuclear power as critical pillars of its transition strategy. LT-LEDS reaffirms the target of achieving 50 % of installed power capacity from non-fossil sources—primarily renewables—by 2030, alongside a 45 % reduction in the emission intensity of GDP from 2005 levels. This renewables push builds on substantial growth in solar, wind, hydro, and bioenergy, supported by massive capacity additions and policy-support mechanisms. Simultaneously, this strategy underscores the long-term potential of nuclear energy to provide firm, carbon-free, baseload power. It envisions leveraging India's three-stage nuclear programme to bolster energy security and decarbonisation. The approach considers nuclear and renewable sources as complementary: renewables offer rapid scalability, whereas nuclear energy delivers reliability and deep decarbonisation. Collectively, these energy pathways form a dual strategy designed to meet India's development needs while aligning with its net-zero by 2070 goal. Nuclear power is a significant pillar of the long-term energy transition in India's Union Budget and has ignited hope for India's low-carbon development. It complements the RES and is suitable for factory-based manufacturing and provides grid stability. The Nuclear Power Corporation of India Limited (NPCIL) aims to generate 500 GW of clean energy by 2030. The Nuclear Energy Mission for '*Viksit Bharat*' (Developed India) seeks to make India a nuclear leader by increasing capacity from 8180 MW to 22480 MW (by 2031/2032) and 100 GW by 2047. Ten additional reactors will be built in Gujarat, Rajasthan, Tamil Nadu, Haryana, Karnataka, and Madhya Pradesh, and construction of the previously approved ten has already begun. The Prototype Fast Breeder Reactor at Kakrapar and the Jaduguda uranium deposit are notable advances. High hopes are pinned on the R&D of small modular reactors (SMR), with indigenous SMRs planned in remote areas by 2033. The government encourages public-private partnerships through legislative changes. Safety remains the top priority, supported by stringent nuclear policies in the country. While SMR commercialisation and thorium

DOI: 10.15240/tul/009/lef-2025-02

reactor development remain in the early stages of research, falling RE costs may heighten competition. Past nuclear disasters have raised concerns, and community acceptance remains challenging. Despite these hurdles, the mission aims to strengthen domestic nuclear capacity and boost energy efficiency in India.

The National Green Hydrogen Mission arose from India's goal to be Net Zero by 2070 and energy efficient by 2047. Its aim is not only energy independence but also surplus generation for export, helping to shift from carbon-intensive energy to clean fuels. Governed by the Ministry of New and Renewable Energy (MNRE), the mission has a standardised regulatory framework to ensure efficiency, interoperability, and global alignment, promoting cross-border trade. A national portal will monitor the efficacy, safety certifications, and regulatory clearances. Coordination among governments, businesses, academia, and international partners is encouraged, with private sector involvement to overcome market barriers being necessary. Green hydrogen can be crucial for decarbonising steel, fertilisers, and heavy industries, with a 2030 target of five million metric tons annually. Cost reduction is pursued via pipelines, electrolysers, small hydro systems, rooftop solar systems, and wastewater electrolysis. International R&D collaboration supports electrolyser development. Phase one (2022–2026) focuses on infrastructure, pilots, compliance, investment risk assessment, policy improvement, and safety. Phase two (2026–2030) expands adoption to carbon-intensive sectors, mandates consumption under the ECA, develops skills, transitions the workforce, promotes partnerships, and raises public awareness. Despite progress, achievements are unassessable due to the early research phases, high production costs, and limited hydrogen technology.

4. Discussion

Despite the ambitious goals and policy frameworks listed in national documents, energy transition faces several critical challenges. Policies often fail to achieve their intended targets. For example, according to the Ministry of New and Renewable Energy, in the Indian rooftop solar initiative, '*PM Surya Ghar Muft Bijli Yojana*' (2024/2025), only about 613,000 people out of 4,700,000 applicants received government-provided subsidies. This is an example of a policy gap between planning and execution, resulting from a lack of sufficient funds for this type of investment. Despite significant achievements in RES investments, India's current efforts towards a low-carbon economy have not been sufficient to reduce CO_2 emissions. The growing energy demand is also driving the use of traditional energy sources based on the combustion of non-renewable energy sources.

The authors listed several social, political, and economic barriers to the development of LCESs (Lawrenz et al., 2018). The main social barrier is poverty, which prevents investment in energy efficiency and distributed energy sources at the local level. The coal mining and energy sectors employ over 400,000 people. These employees and their families constitute an important political lobby that supports this economic sector. In the nuclear sector, the major social obstacle is public opposition stemming from safety

DOI: 10.15240/tul/009/lef-2025-02

concerns, especially in light of past industrial disasters, such as the Fukushima nuclear accident in Japan (Vidyarthi, 2015). Societal resistance and stringent regulations continue to delay project implementation and reduce public trust in nuclear energy as a viable low-carbon solution (Selvam et al., 2025). Challenges in nuclear waste management, regular uranium supply, and the complexity of regulatory approval processes further slow down progress. These issues are compounded by the difficulty in fully realising RE goals, indicating the need for more aggressive and coherent policy execution. Both nuclear energy and RE require huge capital expenditures, which are lacking in India's budget. Inadequate storage facilities, underdeveloped technology, grids, and infrastructural energy transmission to rural areas are considerable problems for RE development. In this sector, a significant gap remains between the estimated potential, national goals, and actual deployment of technologies. Factors such as inadequate dissemination strategies, technological limitations, and inconsistent implementation hinder progress (Chandrasekar and Kandpal, 2007). Without strong measures to curb coal use, the rapid adoption of renewable technologies may still fall short of the carbon reduction targets required to meet climate goals by 2050 (Barbar et al., 2023). Effective decision support systems are required for RES development, for example, by effectively assessing the feasibility of locations for RES (Kazak et al., 2023). There is also the potential to increase waste-to-energy generation in India, but this is controversial from an environmental perspective, and it is recommended to reduce the amount of waste and recycle it rather than incinerating it.

Furthermore, India continues to grapple with an energy crisis characterised by unreliable power supply, transmission losses, and increasing demand, particularly in the rapidly growing building sector (Joshi and Pathak, 2014). Although increasing RE is vital, its rapid integration into India poses significant challenges to the existing coal-based infrastructure and has major socio-economic implications for the country. There are also opinions that express concerns about abandoning traditional fossil fuels too quickly. Pandey and Kumar (2025) believe that if India moves away from coal too quickly, there could be several serious economic risks, including threats to energy security, the creation of stranded assets, loss of livelihoods, technological complexities of transitioning to low-carbon technologies, an increase in import dependency, and significant financial losses to the government's exchequer. Therefore, policy must adopt a holistic socio-technical approach at the local and central levels that supports flexible coal-fired power plant operations, invests in new technologies, and manages the transition justly to mitigate potential disruptions (Debnath et al., 2021). However, excessive climate change caused by CO_2 emissions could trigger even more costly and disruptive changes in the future. However, these changes are difficult to predict. Consequently, the development of nuclear infrastructure is crucial for decarbonising India's power sector (Selvam et al., 2025).

Efforts to achieve a low-carbon economy cannot be confined to national energy policies that focus solely on large-scale production. Equally intensive action is needed to improve energy efficiency in the economy and households. Using current technologies, single-family households in most parts of India can become annual producers rather than consumers of energy. However, this requires financial backing for grassroots initiatives, as residents often lack resources for relatively costly energy efficiency investments.

DOI: 10.15240/tul/009/lef-2025-02

Research in some countries shows that local communities dependent on traditional household energy sources (e.g. fossil fuel stoves) are often not strongly inclined to develop RE sources (Furmankiewicz et al., 2021). Therefore, development must consider both centralised and locally distributed energy sources while maximising energy efficiency in industry, agriculture, services, and households, alongside societal education.

A comparison of the projected reduction in CO_2 emissions associated with investments in LCESs suggests less favourable outcomes for India than for many other countries. Compared to 2015 levels, emissions are anticipated to fall across many countries by 2050, except India. Projections indicate that developing nations, such as Brazil, China, India, and Indonesia, will see a sharp rise in greenhouse gas emissions, whereas developed nations, such as Canada, Japan, and the United States, are expected to experience relative stabilisation (Fragkos et al., 2021). The European Union is an exception because emissions in this area could continue to decline through 2050 (Fragkos et al., 2021; Manowska et al., 2024). Under a low-emission pathway, many countries are projected to cut emissions from reference levels, with reductions ranging from approximately 10% in Brazil to over 60% in Canada, the EU, and the USA. However, the emphasis on developing particular types of energy varies from country to country, depending on financial and technological resources, natural conditions, and national policies. Labour-intensive RE projects favour emerging economies such as India, but in mature markets like Germany, future RE growth can be more difficult due to high saturation (Murgan et al. 2025).

Conclusion

Despite its significant achievements in the development of LCESs (Singh et al., 2023), India continues to increase its consumption of fossil fuels that emit CO_2. Presumably, without the development of nuclear energy, reducing the role of fossil fuels will not be possible over a long period. Based on the analyses presented, we can identify three main recommendations for India's energy policy at the national, federal, state, and local (districts and municipalities) levels.

(1) At the national level: The central government should define quantifiable LCESs development goals for all national and state energy plans to improve monitoring and accountability. It should also address nuclear energy concerns, such as safety and nuclear waste management. Central subsidies should be designed to encourage activity, for example, by offering bonuses in subsidies to the most active states. Mandating rooftop solar installations for new building construction can be included as a policy measure. Extending the deadline of the Production-Linked Incentive (PLI) scheme up to 2030 is required to encourage the private sector to invest in the production of high-efficiency PV modules, as the development did not meet expectations. India must support public-private partnerships in the energy sector, and facilitate access to individual bank credits or subsidies for decentralised RES installations in households and medium-sized enterprises. Significant efforts are needed to modernise energy grids to integrate RES into

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the existing system. The future development of Small Modular Reactors (SMRs) is also an opportunity.

(2) At the state level: States should be required to prepare regional strategies and plans for the development of LCESs in accordance with their physical and geographical conditions, considering measures to save energy, not just produce it.

(3) At the local level: Initiatives for developing urban low-emission development strategies (Staden et al., 2014) should be further expanded, and energy saving should be promoted. Greater emphasis should be placed on modern, dispersed RE sources, energy efficiency, and recycling rather than waste incineration. In the event of problems with the development of the energy network, local off-grid systems with battery storage should be supported. It is also necessary to educate residents on behaviours that promote low-carbon economies.

Finally, coordination between the central and state governments must be improved. Greater attention should be paid to increasing energy efficiency, particularly in industries and households. Traditional economic development focuses on energy development and supply, generating profits for energy companies. However, energy efficiency can significantly reduce the increase in energy demand, thereby contributing to the achievement of sustainable development goals.

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