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Pathways to Energy Independence in India through Fossil Fuel Substitution: A Techno-Economic, Environmental, and Policy Assessment

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Abstract

Energy independence has become a strategic priority for India owing to the rapid growth in energy demand, increasing dependence on imported fossil fuels, rising greenhouse gas emissions, and the need to ensure long-term energy security. Although fossil fuels have supported India's industrialization and economic development for several decades, their continued dominance has resulted in environmental degradation, energy import vulnerability, and increasing fiscal pressure due to volatile international fuel prices. India's commitment to achieving net-zero emissions by 2070 and expanding non-fossil electricity generation capacity presents a unique opportunity to accelerate the transition toward sustainable energy systems. This review examines the major pathways through which India can reduce fossil fuel dependence by promoting renewable energy technologies, green hydrogen, biofuels, transport electrification, energy efficiency, and supportive policy interventions. The study evaluates these alternatives from techno-economic, environmental, and policy perspectives while discussing recent developments in renewable energy deployment, industrial sustainability, and energy security. Furthermore, recent sustainability assessment frameworks, including integrated environmental and operational performance indicators, are discussed as decision-support tools for evaluating energy transition strategies. The review concludes that a diversified energy portfolio supported by technological innovation, effective governance, industrial participation, and long-term policy commitment can substantially reduce India's dependence on imported fossil fuels and strengthen national energy security while supporting sustainable economic growth.

Keywords: Energy independence; Fossil fuel substitution; Renewable energy; Green hydrogen; Energy security; Sustainable development; India; Energy transition.

1. Introduction

Energy plays a fundamental role in the economic, industrial, and social development of every nation. Reliable and affordable energy supplies are essential for sustaining industrial production, transportation, agriculture, healthcare, communication, urban infrastructure, and overall economic growth. As one of the world's fastest-growing economies and the most populous nation, India is experiencing unprecedented growth in energy demand driven by rapid industrialization, urbanization, expanding infrastructure, rising household incomes, and improvements in living standards [1,2]. According to the International Energy Agency (IEA), India is currently the third-largest energy consumer globally and is expected to contribute significantly to future global energy demand due to its sustained economic expansion and demographic growth [3].

Despite remarkable progress in energy infrastructure, India's energy system remains heavily dependent on fossil fuels. Coal continues to dominate electricity generation, accounting for nearly three-fourths of the country's total electricity production, while crude oil remains the primary source of energy for transportation and several industrial sectors. Natural gas consumption has also increased considerably in fertilizer production, city gas distribution, petrochemical industries, and power generation. Although India possesses substantial domestic coal reserves, more than 85% of its crude oil requirement and a considerable proportion of natural gas demand are met through imports, exposing the economy to fluctuations in international fuel prices, geopolitical uncertainties, and supply chain disruptions [2,4].

Growing dependence on imported fossil fuels has significant economic implications. Rising crude oil prices directly increase transportation costs, manufacturing expenses, inflation, and trade deficits. Moreover, increasing import dependence weakens national energy security by making the economy vulnerable to global political instability and international energy market fluctuations. Abhyankar et al. [5] emphasized that India's long-term economic resilience depends on reducing fossil fuel imports through accelerated deployment of renewable energy technologies, electrification of end-use sectors, and expansion of domestic clean energy manufacturing capabilities.

The environmental consequences of fossil fuel utilization have become equally important. Combustion of coal, petroleum products, and natural gas contributes significantly to greenhouse gas emissions, particulate matter, sulfur dioxide, nitrogen oxides, and other pollutants responsible for climate change, urban air pollution, ecosystem degradation, and adverse public health impacts [6,7]. India is among the countries most vulnerable to climate change due to its large population, extensive agricultural dependence, long coastline, and diverse climatic conditions. Consequently, reducing carbon emissions while ensuring continued economic growth has become one of the country's foremost policy priorities.

Recognizing these challenges, India has adopted ambitious climate and energy policies aimed at transforming its energy sector. Under the Paris Agreement and the updated Nationally Determined Contributions (NDCs), India has committed to increasing the share of non-fossil electricity generation, reducing emission intensity, improving energy efficiency, and achieving net-zero carbon emissions by 2070 [8,9]. During the COP26 summit, India announced its Panchamrit commitments, including achieving 500 GW of non-fossil electricity generation capacity by 2030 and meeting nearly half of its electricity demand through renewable energy sources. These commitments have significantly accelerated investments in renewable energy, battery storage, electric mobility, and green hydrogen technologies.

Energy independence has therefore become a strategic objective extending beyond environmental sustainability. It encompasses energy security, technological self-reliance, economic competitiveness, industrial development, and national resilience. In the Indian context, energy independence refers to the ability to satisfy domestic energy requirements primarily through indigenous and sustainable resources while minimizing reliance on imported fossil fuels. This vision strongly complements the national initiatives of *Atmanirbhar Bharat*, which emphasize self-reliance in manufacturing, innovation, strategic industries, and technological development [5].

Renewable energy represents the most promising pathway toward achieving this objective. India possesses abundant renewable energy resources, including high solar irradiation, extensive wind corridors, significant hydropower potential, and enormous biomass availability. Declining technology costs, supportive government policies, increasing private investments, and continuous technological innovations have accelerated renewable energy deployment during the last decade [10–13]. Solar photovoltaic technology has become one of the lowest-cost electricity generation options worldwide, while improvements in wind turbine technology, energy storage systems, and smart grid infrastructure continue to enhance the reliability and efficiency of renewable energy systems.

Several recent studies have demonstrated that large-scale deployment of renewable energy can substantially reduce India's dependence on fossil fuels while maintaining reliable electricity supply. Gulagi et al. [14] reported that accelerated renewable energy expansion across Indian states could support rapid decarbonization of the power sector through improved transmission infrastructure and energy storage technologies. Similarly, Das et al. [15] developed pathways for achieving net-zero emissions in India's power sector by integrating renewable energy resources, flexible generation technologies, and advanced storage systems. Barbar et al. [16,17] further emphasized that future electricity demand arising from electric vehicles, space cooling, and urbanization can be effectively managed through integrated planning involving renewable electricity generation and energy storage.

Transportation represents another major contributor to fossil fuel consumption in India. Road transport alone accounts for a significant proportion of imported petroleum products, making electrification of transportation an essential strategy for achieving energy independence. Numerous studies have demonstrated that electric mobility can substantially reduce fossil fuel consumption while improving air quality and lowering greenhouse gas emissions [18–22]. Consumer acceptance of electric vehicles has also improved owing to declining battery costs, technological advancements, supportive government policies, and expanding charging infrastructure [23,24]. Furthermore, integration of renewable electricity with electric mobility can significantly reduce lifecycle carbon emissions while strengthening national energy security.

Green hydrogen has recently emerged as another transformative technology for reducing fossil fuel dependence, particularly in difficult-to-decarbonize sectors such as steel, cement, fertilizers, shipping, and heavy transportation. Produced through water electrolysis using renewable electricity, green hydrogen provides a clean alternative to fossil fuels while supporting industrial decarbonization. India's National Green Hydrogen Mission aims to establish the country as a global producer and exporter of green hydrogen by leveraging abundant renewable energy resources and domestic manufacturing capabilities [25,26]. Successful implementation of this mission can substantially reduce imports of natural gas and petroleum-based fuels while creating new industrial and employment opportunities.

In addition to renewable energy deployment, improving energy efficiency remains one of the most cost-effective approaches for reducing fossil fuel consumption. Energy-efficient industrial processes, smart buildings, efficient appliances, advanced cooling technologies, digital energy management systems, and intelligent manufacturing practices reduce overall energy demand without compromising productivity or economic growth [27,28]. Harvey [29] emphasized that investments in energy efficiency often deliver greater environmental and economic benefits than direct financial subsidies for low-carbon technologies. Similarly, Mukherjee et al. [30] demonstrated that efficient cooling technologies can significantly reduce electricity demand while supporting climate change mitigation.

Achieving energy independence also requires comprehensive planning and integrated assessment methodologies capable of evaluating technological feasibility, economic viability, environmental sustainability, and policy effectiveness simultaneously. Modern energy system optimization models enable policymakers to evaluate future energy scenarios, identify least-cost pathways, and optimize interactions among electricity generation, transportation, industrial energy consumption, and energy storage systems [31–35]. Scenario-based planning has become particularly important because future energy systems involve considerable uncertainties related to technology development, economic growth, climate policies, and consumer behavior.

Sustainability assessment has similarly evolved beyond conventional economic indicators. Environmental accountability, operational excellence, digital transformation, and integrated sustainability measurement are increasingly recognized as essential components of industrial competitiveness and long-term development. Patyrykin and Vasyukova [36] emphasized that transparent environmental governance and effective ESG practices are essential for ensuring genuine sustainability improvements rather than symbolic environmental compliance. Digital technologies and intelligent automation further strengthen organizational competitiveness during industrial transformation by improving operational efficiency, resource utilization, and decision-making capabilities [37].

Recent research conducted by Jena and co-workers has introduced integrated sustainability assessment methodologies that are particularly relevant for evaluating India's energy transition. Madhab's Environmental–Efficiency–Economic (EEE) Impact Model provides a comprehensive framework for assessing renewable energy alternatives by simultaneously evaluating environmental impacts, operational efficiency, and economic performance [38]. Similarly, the Plant Overall Performance (POP) Index integrates productivity, sustainability, and operational excellence into a single performance indicator capable of supporting industrial decision-making and continuous improvement [39]. These multidimensional assessment tools complement conventional techno-economic analyses by incorporating sustainability into strategic planning and investment decisions. Furthermore, sustainability initiatives implemented across Indian industries have demonstrated positive impacts on stakeholder confidence and organizational performance, highlighting the growing importance of environmental responsibility in achieving sustainable industrial development [40].

Although India has achieved remarkable progress in renewable energy deployment during the past decade, several challenges continue to impede the transition toward complete energy independence. Renewable energy intermittency, energy storage requirements, transmission infrastructure limitations, critical mineral supply chains, financing constraints, land acquisition issues, and technological readiness remain significant barriers requiring coordinated policy interventions. Moreover, balancing rapid economic growth with environmental sustainability requires integrated planning involving government agencies, research institutions, industries, financial organizations, and society.

Against this background, the present review examines the major pathways available for achieving energy independence in India through systematic substitution of fossil fuels with renewable and low-carbon energy resources. The paper provides a comprehensive techno-economic, environmental, and policy assessment of renewable energy technologies, green hydrogen, biofuels, transport electrification, and energy-efficient systems while highlighting recent policy initiatives, industrial sustainability frameworks, and future opportunities for accelerating India's clean energy transition. By synthesizing recent scientific literature and national policy developments, this review aims to provide a holistic understanding of the strategies required for building a secure, resilient, and sustainable energy future for India.

2. India's Energy Scenario and Fossil Fuel Dependence

India has emerged as one of the world's fastest-growing economies, accompanied by a corresponding increase in energy demand across residential, commercial, industrial, agricultural, and transportation sectors. Economic expansion, rapid urbanization, digitalization, improved living standards, and population growth have substantially increased electricity consumption and fossil fuel utilization over the past two decades [41–44]. According to projections by the International Energy Agency (IEA), India's primary energy demand is expected to more than double by 2047, making the country one of the largest contributors to global energy demand growth [3,41]. Consequently, ensuring an affordable, reliable, and sustainable energy supply has become a strategic national priority.

The structure of India's energy system has historically been dominated by fossil fuels. Coal remains the backbone of electricity generation, while petroleum products account for the majority of transportation energy consumption. Natural gas supports fertilizer production, petrochemical industries, power generation, and city gas distribution. Although renewable energy capacity has expanded rapidly during the last decade, fossil fuels continue to account for a significant proportion of India's total primary energy supply [5,15].

The dependence on fossil fuels has enabled rapid industrial development but has simultaneously generated multiple economic and environmental challenges. The country's heavy reliance on imported crude oil and liquefied natural gas exposes it to global supply disruptions, geopolitical conflicts, exchange rate fluctuations, and volatile international energy prices [5,41]. Episodes such as the COVID-19 pandemic, geopolitical tensions in Europe and the Middle East, and disruptions in international supply chains have demonstrated the vulnerability of fossil fuel-dependent economies and highlighted the importance of developing resilient domestic energy systems [45].

Coal continues to play a dominant role in India's electricity sector because of abundant domestic reserves and established thermal power infrastructure. Thermal power plants have historically provided reliable base-load electricity necessary for industrialization and urban development. However, coal combustion is also the largest source of carbon dioxide emissions in India and contributes significantly to particulate matter, sulphur dioxide, nitrogen oxides, and mercury emissions [6,46]. Environmental degradation associated with coal mining, ash disposal, water consumption, and land disturbance further emphasizes the need for gradual diversification toward cleaner energy sources.

Despite possessing one of the world's largest coal reserves, India continues to import coal to satisfy the requirements of specific industries such as steel manufacturing and high-grade thermal applications. Simultaneously, crude oil remains the country's largest imported energy commodity. More than 85% of India's crude oil demand is met through imports, creating a substantial burden on foreign exchange reserves and increasing exposure to international market fluctuations [2,3]. Rising petroleum prices directly influence transportation costs, inflation, industrial production costs, and overall economic competitiveness.

Natural gas has increasingly become an important transition fuel because of its comparatively lower carbon intensity than coal and petroleum products. Domestic natural gas production, however, remains insufficient to satisfy rapidly increasing industrial demand, resulting in growing dependence on imported liquefied natural gas (LNG). Although natural gas contributes to lower emissions relative to coal, continued dependence on imported gas does not fully address India's long-term objective of energy independence [41].

The transportation sector represents one of the largest consumers of imported petroleum products. Road transport dominates passenger and freight movement in India, making diesel and petrol consumption particularly significant. Increasing vehicle ownership, expanding logistics activities, and rapid urbanization have accelerated fuel demand during the past decade [47]. Studies indicate that without substantial policy interventions, transportation-related fossil fuel consumption will continue increasing significantly over the coming decades [18–22].

Electric mobility has therefore become an essential component of India's energy transition strategy. Electrification of passenger vehicles, buses, commercial fleets, and two-wheelers can substantially reduce dependence on imported petroleum while lowering greenhouse gas emissions, particularly when electricity is generated from renewable sources [18–24]. Consumer acceptance of electric vehicles has improved considerably owing to technological improvements, battery cost reductions, expanding charging infrastructure, and government incentive schemes [23,24].

Another major driver of future electricity demand is rapid urbanization combined with increasing cooling requirements. Rising incomes and climate change are expected to significantly increase the adoption of air conditioning and refrigeration systems throughout India. Barbar et al. [16] projected that electricity demand associated with space cooling and electric vehicle charging could become one of the most important factors influencing future power system planning. Consequently, future electricity infrastructure must simultaneously accommodate increased demand while maintaining affordability and sustainability.

The industrial sector also accounts for a substantial proportion of India's energy consumption. Energy-intensive industries including steel, cement, chemicals, aluminium, fertilizer, and manufacturing continue to depend heavily on coal, petroleum products, and natural gas because of their high energy density and well-established industrial infrastructure. Decarbonizing these sectors remains particularly challenging because several industrial processes require high-temperature heat that cannot easily be replaced through direct electrification alone [25]. Consequently, alternative solutions such as green hydrogen, biomass, carbon capture technologies, and advanced electrification are increasingly receiving attention.

The residential sector presents another important dimension of India's energy landscape. Considerable progress has been achieved in expanding electricity access and replacing traditional biomass cooking through initiatives such as rural electrification and clean cooking fuel programmes. Nevertheless, increasing household electricity consumption resulting from improved living standards, digital connectivity, household appliances, and cooling requirements continues to place additional pressure on electricity generation capacity [27,30].

Energy security has therefore emerged as a multidimensional national objective encompassing energy availability, affordability, accessibility, reliability, and environmental sustainability. Traditional definitions of energy security primarily emphasized uninterrupted energy supply. However, contemporary energy systems increasingly recognize the importance of supply diversification, domestic resource utilization, technological innovation, climate resilience, and environmental protection [48]. In India's context, energy security is closely linked with reducing import dependence while simultaneously ensuring economic growth and environmental sustainability.

Recent studies have demonstrated that renewable energy can significantly strengthen India's energy security. Abhyankar et al. [5] estimated that accelerated renewable energy deployment combined with electrification and domestic manufacturing could substantially reduce fossil fuel imports by 2047 while lowering electricity generation costs. Similarly, Gulagi et al. [14] concluded that large-scale renewable electricity deployment supported by transmission expansion and battery storage technologies can reliably meet future electricity demand across Indian states.

Energy storage has become another critical component of future energy systems. Because renewable energy generation from solar and wind sources varies according to weather conditions and time of day, advanced battery technologies, pumped hydro storage, and other storage solutions are necessary to maintain grid stability and ensure reliable electricity supply [17]. Barbar et al. [17] demonstrated that future decarbonization of India's electricity sector will require substantial investments in storage infrastructure alongside renewable generation capacity.

Grid modernization is equally important for supporting renewable energy integration. Expansion of interstate transmission networks, digital grid management systems, demand response technologies, and smart metering enable efficient utilization of renewable electricity while improving overall system reliability [31,35]. Integrated planning approaches combining electricity generation, transportation, industry, and energy storage have therefore become essential for achieving cost-effective decarbonization [32].

In addition to technological considerations, financial investments remain a major determinant of India's energy transition. Renewable energy deployment requires substantial capital investment in generation facilities, transmission infrastructure, battery storage, hydrogen production, and manufacturing capabilities. Public-private partnerships, green financing mechanisms, international climate finance, and supportive regulatory policies therefore play important roles in accelerating clean energy investments [42]. Reports published by the Asian Development Bank and international financial institutions consistently emphasize that long-term policy certainty and stable investment environments are essential for attracting private sector participation in renewable energy development [43].

Environmental sustainability further reinforces the importance of reducing fossil fuel dependence. Fossil fuel combustion remains the dominant source of greenhouse gas emissions in India, contributing to climate change, deteriorating air quality, ecosystem degradation, and adverse human health impacts [6,7]. Lal et al. [49] demonstrated that cleaner industrial pathways involving waste heat recovery and circular resource utilization can simultaneously reduce particulate matter emissions, carbon dioxide emissions, and health-related economic costs. Similarly, Lamb and Steinberger [50] argued that climate mitigation policies should be designed to improve both environmental sustainability and human well-being.

Recognizing these multidimensional challenges, India has adopted a comprehensive strategy emphasizing renewable energy expansion, transport electrification, green hydrogen, domestic manufacturing, battery storage, energy efficiency, and industrial innovation. These initiatives collectively aim to reduce fossil fuel dependence while strengthening national energy security and supporting sustainable economic growth.

Table 1. India's Current Energy Scenario and Fossil Fuel Dependence

Energy Source	Major Applications	Approximate Import Dependence	Key Challenges	Potential Low Carbon Alternativ
Coal	Electricity generation steel, cement	Low–Moderate	High CO_2 emissions particulate pollution mining impacts	Solar PV, Wind Nuclear, Hydropower
Crude Oil	Transportation, petrochemicals, aviation	>85%	Import dependence price volatility, carbo emissions	Electric vehicles Biofuels, Greer hydrogen
Natural Gas	Fertilizers, industry city gas, powe generation	Moderate–High	LNG imports infrastructure constraint	Biomethane, Greer hydrogen
LPG	Domestic cooking	Moderate	Import dependence	Biogas, Electric cooking
Renewable Energy	Electricity generation	Very Low	Intermittency, storage transmission	Battery storage Smart grids, Pumpe hydro

Table 1 highlights that India's greatest strategic vulnerability lies in its dependence on imported crude oil and, to a lesser extent, natural gas. Coal remains predominantly domestically available but carries significant environmental costs due to greenhouse gas emissions and local pollution. Renewable energy technologies offer a pathway to reducing import dependence, although their widespread deployment must be accompanied by investments in storage technologies, grid modernization, and flexible power systems. Consequently, a diversified energy portfolio integrating solar, wind, hydropower, biomass, green hydrogen, and energy storage will be essential for achieving long-term energy independence.

2.1 Renewable Energy Development in India

The transition from a fossil fuel-dependent economy to a sustainable energy system requires large-scale deployment of renewable energy resources. India possesses abundant renewable energy potential owing to its favorable geographical location, diverse climatic conditions, extensive coastline, large agricultural sector, and rapidly expanding technological capabilities. Over the last decade, renewable energy has transformed from an alternative electricity source into one of the principal pillars of India's long-term energy strategy. Government initiatives such as the National Solar Mission, Renewable Purchase Obligations (RPO), Green Energy Corridors, the Production Linked Incentive (PLI) Scheme for solar manufacturing, and the National Green Hydrogen Mission have significantly accelerated renewable energy deployment [41–45].

The renewable energy sector contributes not only to electricity generation but also to economic development, employment generation, technological innovation, industrial competitiveness, and environmental sustainability. Expansion of renewable energy reduces dependence on imported fossil fuels, lowers greenhouse gas emissions, improves air quality, and enhances national energy security [5,14,15].

India has established ambitious renewable energy targets under its updated Nationally Determined Contributions (NDCs), aiming to achieve 500 GW of non-fossil electricity generation capacity by 2030 while meeting nearly half of its electricity demand through renewable sources [8,9]. Achieving these targets requires substantial investments in renewable energy generation, transmission infrastructure, battery storage systems, smart grids, and domestic manufacturing capabilities.

Recent studies indicate that India possesses sufficient renewable energy resources to satisfy future electricity demand if supported by appropriate policy interventions, technological innovation, and energy storage infrastructure [5,14,17]. Consequently, renewable energy has become the primary pathway for reducing fossil fuel dependence while ensuring long-term energy independence.

2.2 Solar Energy Potential

Solar energy represents the most promising renewable energy resource available in India. Owing to its geographical location between the Tropic of Cancer and the Equator, most parts of the country receive annual solar radiation ranging from 4 to 7 $kWh/m^2/day$ with approximately 250–300 sunny days each year [10,11]. This provides enormous opportunities for large-scale deployment of photovoltaic (PV) and concentrated solar power (CSP) technologies.

The Government of India launched the National Solar Mission to promote rapid expansion of solar energy through utility-scale solar parks, rooftop solar systems, floating solar plants, agricultural solar pumps, and decentralized rural electrification programmes. Falling photovoltaic module prices, improvements in conversion efficiency, and supportive financial incentives have significantly improved the economic competitiveness of solar electricity generation [11,13].

India has emerged as one of the world's fastest-growing solar markets. Utility-scale solar projects are now capable of producing electricity at costs comparable to or even lower than conventional coal-fired power plants. Furthermore, distributed rooftop solar installations reduce transmission losses, enhance consumer participation, and improve electricity access in rural and remote regions.

Abhyankar et al. [5] demonstrated that India's abundant solar resource provides the foundation for achieving cost-effective energy independence by 2047. Similarly, Rajesh and Majid [11] emphasized that continued investment in domestic manufacturing, research and development, and grid modernization can further strengthen India's leadership in solar energy deployment. Dey et al. [12] also concluded that solar energy will remain the dominant contributor to future renewable electricity generation owing to its scalability, declining costs, and widespread geographical availability.

Despite these advantages, several challenges remain. Solar electricity generation is intermittent because of seasonal variations, cloud cover, and the day-night cycle. Large-scale deployment therefore requires complementary investments in battery energy storage systems, pumped hydro storage, and flexible grid infrastructure [17]. Land acquisition for utility-scale solar parks and end-of-life management of photovoltaic modules also require careful planning to ensure environmental sustainability.

Nevertheless, solar energy remains the single most important technology for replacing coal-based electricity generation and reducing fossil fuel imports in India.

2.3 Wind Energy Potential

Wind energy constitutes another major component of India's renewable energy strategy. India possesses substantial onshore and offshore wind resources, particularly across Gujarat, Tamil Nadu, Karnataka, Maharashtra, Andhra Pradesh, and Rajasthan. Advances in wind turbine technology have significantly increased electricity generation efficiency while reducing operation and maintenance costs [46].

Wind farms generate electricity without direct greenhouse gas emissions or fuel consumption, thereby contributing simultaneously to climate change mitigation and energy security. Compared with conventional thermal power plants, wind energy requires considerably lower operational expenditure after installation because no fossil fuel is required during electricity generation.

Recent technological developments have substantially improved turbine capacity, rotor diameter, tower height, and power conversion efficiency. Modern wind turbines can generate considerably higher electricity output than earlier generations, thereby improving project economics and reducing the levelized cost of electricity [46].

Hybrid renewable energy systems integrating wind and solar power have become increasingly attractive because they reduce variability in electricity generation. During periods of reduced solar radiation, wind generation often compensates for electricity production, thereby improving overall grid stability. Gulagi et al. [14] demonstrated that integrating wind energy with solar generation, interstate transmission networks, and battery storage enables reliable operation of highly renewable electricity systems across India.

Climate change may influence future wind availability in certain regions. However, Zakari et al. [47] reported that India continues to possess significant long-term wind energy potential despite projected climatic variations. Offshore wind development along India's extensive coastline also presents considerable opportunities for expanding renewable electricity generation over the coming decades.

Several policy initiatives, including competitive bidding mechanisms, transmission infrastructure development, and renewable purchase obligations, have accelerated private investment in wind energy. Continued technological innovation and supportive regulatory frameworks are expected to further strengthen the contribution of wind power toward India's energy independence.

2.4 Hydropower Development

Hydropower has historically played an important role in India's electricity sector and continues to provide one of the most reliable renewable energy sources. Unlike solar and wind energy, hydropower offers dispatchable electricity generation capable of responding rapidly to fluctuations in electricity demand. Consequently, hydropower significantly enhances grid flexibility and facilitates integration of intermittent renewable energy resources.

India possesses considerable hydropower potential, particularly in the Himalayan region and northeastern states. Large hydroelectric projects contribute to electricity generation, irrigation, flood control, water supply, and regional economic development. Small hydropower projects also provide decentralized electricity solutions for remote and mountainous regions where grid connectivity remains challenging.

Pumped-storage hydropower is gaining increasing attention because it functions as a large-scale energy storage technology. During periods of excess renewable electricity generation, water is pumped to elevated reservoirs and subsequently released during peak electricity demand. Such systems improve renewable energy utilization while reducing dependence on fossil fuel-based peaking power plants [17].

Although hydropower offers significant environmental advantages compared with fossil fuel power plants, careful consideration of ecological impacts, biodiversity conservation, river ecosystem protection, land acquisition, and community rehabilitation remains essential for sustainable project implementation.

2.5 Biomass and Bioenergy

India generates enormous quantities of biomass through agriculture, forestry, livestock, food processing, and municipal solid waste. Agricultural residues such as rice husk, wheat straw, sugarcane bagasse, cotton stalks, and other crop residues represent valuable renewable energy resources capable of replacing fossil fuels in electricity generation and industrial heating.

Biomass-based energy systems provide multiple socioeconomic benefits. Besides generating electricity and thermal energy, they reduce agricultural waste burning, improve waste management, create rural employment opportunities, and support circular economy principles. Biogas plants convert animal waste and organic residues into clean cooking fuel while simultaneously producing nutrient-rich organic fertilizers.

Compressed biogas (CBG) has emerged as a promising substitute for compressed natural gas in transportation and industrial applications. Government initiatives promoting bioenergy and waste-to-energy technologies contribute to reducing fossil fuel dependence while supporting rural development and sustainable agricultural practices.

Studies have demonstrated that sustainable biomass utilization can significantly reduce greenhouse gas emissions because the carbon released during biomass combustion is largely balanced by carbon absorbed during plant growth [12]. However, ensuring sustainable feedstock availability, efficient collection systems, transportation logistics, and advanced conversion technologies remains essential for maximizing the environmental and economic benefits of biomass energy.

Overall, solar, wind, hydropower, and biomass collectively constitute the foundation of India's renewable energy transition. Their complementary characteristics provide an opportunity to develop a diversified and resilient energy system capable of substantially reducing fossil fuel dependence while improving energy security and supporting sustainable economic development.

2.6 Renewable Energy Manufacturing and the Vision of Atmanirbhar Bharat

Achieving energy independence requires more than expanding renewable electricity generation; it also depends on developing a strong domestic manufacturing ecosystem for clean energy technologies. At present, although India has made significant progress in installing renewable energy capacity, a considerable proportion of solar photovoltaic modules, battery components, advanced power electronics, and critical minerals are imported. Excessive dependence on imported renewable energy equipment may create new strategic vulnerabilities similar to those associated with fossil fuel imports. Therefore, strengthening indigenous manufacturing has become a key objective under the *Atmanirbhar Bharat* initiative and the Production Linked Incentive (PLI) Scheme for high-efficiency solar photovoltaic modules and advanced chemistry cell batteries [5,41].

Domestic manufacturing provides multiple economic benefits, including employment generation, technology transfer, industrial competitiveness, and supply chain resilience. Expanding local production of solar modules, wind turbine components, batteries, electrolyzers, and power electronics can substantially reduce project costs while improving energy security. Jain [48] emphasized that strengthening India's solar manufacturing industry is essential for building a self-reliant renewable energy sector capable of meeting future domestic demand and supporting exports. Similarly, the Shakti Sustainable Energy Foundation highlighted that strategic investments in manufacturing infrastructure, research and development, and skilled human resources are necessary for developing globally competitive renewable energy industries [49].

India has already established itself as one of the world's largest renewable energy markets. Continued policy support, financial incentives, and industrial collaboration can transform the country into a global manufacturing hub for renewable energy technologies. Such a transition would simultaneously reduce import dependence, create employment opportunities, and accelerate economic growth while supporting long-term energy independence [11,12].

2.7 Green Hydrogen: A Future Energy Carrier

Green hydrogen is increasingly recognized as one of the most promising solutions for decarbonizing sectors where direct electrification is technically difficult or economically challenging. Unlike conventional hydrogen produced from fossil fuels, green hydrogen is generated through water electrolysis using renewable electricity, resulting in negligible greenhouse gas emissions during production [25].

The Government of India launched the National Green Hydrogen Mission with the objective of establishing the country as a global producer, consumer, and exporter of green hydrogen. The mission aims to promote domestic manufacturing of electrolyzers, encourage industrial adoption, strengthen research and innovation, and reduce dependence on imported natural gas and petroleum products [25].

Green hydrogen offers significant opportunities for decarbonizing steel production, fertilizer manufacturing, petroleum refining, heavy transportation, shipping, aviation, and chemical industries. Because these sectors require high-temperature heat or energy-dense fuels, hydrogen provides a practical alternative where battery electrification alone may not be sufficient.

Sontakke and Jaju [26] reported that India possesses favorable conditions for large-scale green hydrogen production owing to abundant renewable energy resources and declining solar electricity costs. Lakshmi Priya [50] further emphasized that international collaboration and technological partnerships can accelerate hydrogen infrastructure development while strengthening India's energy security.

Despite its enormous potential, several challenges remain before green hydrogen can achieve widespread commercial adoption. These include high electrolyzer costs, limited hydrogen transportation infrastructure, storage challenges, water availability, and the need for supportive regulatory frameworks. Continued investments in research, demonstration projects, and domestic manufacturing are therefore essential for reducing production costs and improving commercial competitiveness.

2.8 Energy Storage and Smart Grid Infrastructure

Renewable energy technologies such as solar and wind are inherently variable because electricity generation depends on weather conditions and seasonal variations. Consequently, energy storage systems play an indispensable role in ensuring continuous electricity supply and maintaining grid stability [17].

Battery Energy Storage Systems (BESS), pumped hydro storage, compressed air energy storage, thermal energy storage, and emerging hydrogen storage technologies collectively provide flexibility required for integrating high shares of renewable electricity. These technologies store surplus electricity during periods of excess renewable generation and release it during peak demand or low renewable generation periods.

Barbar et al. [17] demonstrated that energy storage becomes increasingly important as renewable penetration rises because storage reduces renewable energy curtailment, enhances transmission efficiency, and improves overall power system reliability. Similarly, Brown et al. [31] showed that combining transmission expansion with sector coupling and storage technologies substantially lowers the cost of highly renewable electricity systems.

Smart grids further strengthen renewable energy integration by incorporating advanced digital communication technologies, artificial intelligence, real-time monitoring, demand response, and automated grid control systems. Smart meters, distributed energy resources, and predictive energy management systems improve electricity utilization while reducing transmission losses and operational costs [32].

The integration of renewable energy, battery storage, electric vehicles, and smart grid technologies creates a flexible and resilient electricity system capable of supporting India's long-term energy transition.

2.9 Challenges in Fossil Fuel Substitution

Although India possesses considerable renewable energy potential, achieving complete fossil fuel substitution remains a complex undertaking involving technological, economic, institutional, and social challenges.

One of the most significant challenges is the intermittency associated with solar and wind energy generation. Electricity production fluctuates according to weather conditions and time of day, requiring substantial investments in storage technologies, flexible generation resources, and modern transmission infrastructure [17,31]. Without adequate storage capacity, high renewable energy penetration may affect grid stability and electricity reliability.

Financial constraints represent another important challenge. Renewable energy projects require significant upfront capital investment despite their relatively low operating costs. Access to affordable financing, risk mitigation mechanisms, and stable policy environments remains essential for accelerating renewable energy deployment [42].

Land acquisition has become increasingly important for utility-scale renewable energy projects. Large solar parks and wind farms require considerable land resources, often leading to conflicts involving agriculture, biodiversity conservation, and local communities. Sustainable land-use planning and stakeholder engagement are therefore necessary to balance energy development with environmental protection.

Supply chain security also presents emerging concerns. Renewable energy technologies depend on critical minerals such as lithium, cobalt, nickel, rare earth elements, and high-purity silicon. Excessive dependence on imported critical minerals could create new geopolitical risks even as fossil fuel dependence declines. Consequently, recycling technologies, material substitution, and domestic mineral exploration should receive greater policy attention.

Technological readiness varies considerably across renewable energy technologies. While solar and wind power have reached commercial maturity, green hydrogen, advanced battery technologies, carbon capture systems, and sustainable aviation fuels require further technological improvements and cost reductions before widespread deployment [15,25].

Institutional coordination among central and state governments also influences the effectiveness of renewable energy policies. Consistent regulatory frameworks, transparent approval processes, efficient grid connectivity, and coordinated planning are essential for achieving long-term investment confidence.

Public awareness and workforce development represent additional challenges. Large-scale renewable energy deployment requires engineers, technicians, project managers, and researchers possessing specialized knowledge in emerging clean energy technologies. Continuous skill development and academic-industry collaboration will therefore play an important role in supporting India's energy transition.

2.10 Transition Outlook

Despite these challenges, India's long-term outlook for achieving energy independence remains highly encouraging. Continuous reductions in renewable energy costs, rapid technological innovation, increasing private investment, supportive government policies, and growing international collaboration have created favorable conditions for accelerating the clean energy transition.

Abhyankar et al. [5] concluded that India possesses sufficient renewable resources to substantially reduce fossil fuel imports and achieve cost-effective energy independence by 2047. Similarly, Das et al. [15] demonstrated that integrated planning involving renewable electricity, energy storage, transmission expansion, electrification, and green hydrogen can enable deep decarbonization of India's power sector while maintaining reliable electricity supply.

Emerging technologies including artificial intelligence, digital twins, advanced forecasting systems, blockchain-enabled energy trading, smart grids, and Internet of Things (IoT)-based energy management systems are expected to further improve renewable energy utilization and operational efficiency. These technologies can optimize electricity generation, transmission, storage, and consumption, thereby enhancing overall system performance.

In addition, integrated sustainability assessment frameworks such as Madhab's Environmental–Efficiency–Economic (EEE) Impact Model [38] and the Plant Overall Performance (POP) Index [39] provide valuable decision-support tools for evaluating renewable energy projects from environmental, operational, and economic perspectives. Their application can assist industries and policymakers in identifying the most sustainable pathways for energy transition while ensuring continuous performance improvement.

Overall, India's transition toward energy independence will depend upon coordinated implementation of renewable energy expansion, domestic manufacturing, green hydrogen, transport electrification, energy efficiency, smart infrastructure, and effective governance. With sustained policy support and technological innovation, fossil fuel substitution can become the cornerstone of a resilient, secure, and sustainable national energy system.

3. Pathways for Fossil Fuel Substitution

The transition towards energy independence requires the gradual replacement of fossil fuels with cleaner, sustainable, and domestically available energy resources. Fossil fuel substitution is not limited to replacing coal-fired power plants with renewable electricity; rather, it involves transforming the entire energy ecosystem, including electricity generation, transportation, industrial production, residential energy use, and agricultural operations. Successful substitution depends on technological maturity, economic feasibility, environmental performance, policy support, and social acceptance [31,33].

India possesses one of the world's most diverse renewable energy portfolios, including abundant solar radiation, extensive wind corridors, significant hydropower resources, vast biomass availability, and emerging green hydrogen potential. These resources provide a strong foundation for reducing dependence on imported crude oil, coal, and natural gas while supporting economic development and environmental sustainability [5,14].

The following sections critically examine the major pathways available for fossil fuel substitution in India.

3.1 Solar Energy as the Primary Driver of Energy Independence

Solar energy has become the cornerstone of India's renewable energy transition because of its enormous resource availability, rapidly declining technology costs, modular installation capability, and minimal environmental impact during operation. India receives annual average solar radiation ranging from 4 to 7 $kWh/m^2/day$ over most geographical regions, making it one of the most favorable countries for photovoltaic electricity generation [10,11].

Unlike fossil fuels, solar energy is indigenous, inexhaustible, and free from geopolitical supply risks. Every additional megawatt of solar capacity installed reduces dependence on imported coal, petroleum products, and natural gas while lowering greenhouse gas emissions and improving energy security [5].

The Government of India has launched several initiatives to accelerate solar deployment, including the Jawaharlal Nehru National Solar Mission, Ultra Mega Solar Parks, PM-KUSUM Scheme for agricultural solar pumps, rooftop solar programmes, and Production Linked Incentive (PLI) schemes for domestic solar manufacturing [41,42]. These initiatives have transformed India into one of the fastest-growing solar energy markets globally.

Economic Benefits

One of the principal reasons for rapid solar expansion is the continuous decline in photovoltaic module prices. During the past decade, the levelized cost of electricity generated from solar photovoltaic systems has decreased dramatically, making utility-scale solar plants economically competitive with conventional thermal power plants [12].

Solar power also offers relatively low operation and maintenance costs because electricity generation does not require fuel transportation, mining activities, or combustion processes. Consequently, long-term electricity price stability improves, reducing exposure to fluctuations in international fossil fuel prices [15].

Furthermore, expansion of domestic solar manufacturing creates employment opportunities throughout the value chain, including silicon processing, module manufacturing, inverter production, installation, maintenance, and recycling. Development of indigenous manufacturing capacity also supports the objectives of *Atmanirbhar Bharat* by reducing dependence on imported photovoltaic components [48,49].

Environmental Benefits

Solar photovoltaic systems generate electricity without emitting carbon dioxide, sulphur dioxide, nitrogen oxides, or particulate matter during operation. Large-scale deployment therefore contributes significantly to climate change mitigation while improving urban and regional air quality [6,7].

Compared with coal-fired thermal power plants, solar installations require considerably less water during operation, making them particularly advantageous in water-stressed regions. Reduced mining activities also minimize land degradation, ecosystem disturbance, and occupational health hazards associated with fossil fuel extraction.

Several studies have demonstrated that replacing conventional coal-fired electricity generation with solar energy substantially lowers lifecycle greenhouse gas emissions while supporting India's climate commitments under the Paris Agreement [14,15].

Technological Developments

Rapid technological advancements continue to improve photovoltaic conversion efficiency, module durability, tracking systems, and power electronics. Bifacial photovoltaic modules, floating solar installations, building-integrated photovoltaics (BIPV), agrivoltaics, and concentrated solar power technologies further expand the applicability of solar energy across different sectors.

Artificial intelligence, drone-based inspection systems, predictive maintenance, digital twins, and Internet of Things (IoT)-based monitoring have significantly enhanced operational efficiency and reduced maintenance costs for large-scale solar farms.

Battery Energy Storage Systems (BESS) are increasingly integrated with photovoltaic plants to address intermittency and provide firm electricity supply during evening peak demand periods [17].

Challenges

Despite remarkable progress, several challenges remain.

Solar electricity generation depends on weather conditions and daylight availability, requiring complementary storage technologies or hybrid renewable systems to maintain supply reliability. Utility-scale projects also require considerable land resources, sometimes leading to land acquisition conflicts and ecological concerns.

Another emerging issue is end-of-life management of photovoltaic modules. As early-generation solar panels approach retirement, effective recycling infrastructure will become increasingly important for recovering valuable materials and minimizing environmental impacts.

Nevertheless, the advantages of solar energy substantially outweigh these limitations, making it the most important contributor to India's future energy independence.

3.2 Wind Energy: Complementing Solar Power

Wind energy represents the second major pillar of India's renewable energy strategy. Unlike solar energy, which generates maximum electricity during daytime hours, wind energy frequently exhibits complementary generation patterns, particularly during monsoon seasons and nighttime periods. This complementary behavior improves overall renewable energy reliability and reduces dependence on fossil fuel-based backup generation [14].

India possesses one of the largest onshore wind potentials in the world, particularly across Gujarat, Tamil Nadu, Karnataka, Maharashtra, Andhra Pradesh, Rajasthan, and several coastal regions [46]. Offshore wind resources along the western and southern coastlines provide additional long-term opportunities for renewable electricity generation.

Contribution to Energy Security

Wind energy directly contributes to energy independence by replacing electricity generated from coal and natural gas. Because wind turbines require no fuel during operation, electricity generation costs remain largely independent of international energy markets.

Expansion of wind farms therefore improves energy price stability while reducing greenhouse gas emissions and dependence on imported fossil fuels.

Abhyankar et al. [5] reported that integrating large-scale wind and solar generation can substantially reduce India's fossil fuel imports while maintaining affordable electricity prices.

Technological Improvements

Modern wind turbines differ significantly from earlier designs. Larger rotor diameters, taller towers, advanced composite materials, improved aerodynamic blade profiles, and intelligent control systems have substantially increased electricity generation efficiency.

Digital technologies including artificial intelligence, condition monitoring, predictive maintenance, and remote diagnostics further improve operational reliability while reducing maintenance costs.

Hybrid renewable projects combining solar photovoltaic systems, wind turbines, and battery storage have become increasingly attractive because they provide more consistent electricity generation than individual technologies operating independently [14].

Economic Advantages

Wind energy projects require relatively high initial capital investment but very low operating expenditure because no fuel costs are incurred during electricity generation.

Over the operational lifetime of a wind farm, electricity generation costs become highly competitive with conventional thermal power plants.

Domestic manufacturing of wind turbines, blades, towers, generators, and associated electrical equipment also contributes significantly to industrial development and employment generation.

Environmental Performance

Wind energy produces virtually no greenhouse gas emissions during electricity generation and requires minimal water consumption compared with thermal power stations.

Furthermore, wind farms occupy comparatively small permanent land areas because agricultural activities can continue beneath turbine installations, thereby minimizing conflicts with food production.

However, environmental planning remains necessary to reduce potential impacts on bird migration, bats, and sensitive ecological habitats. Appropriate site selection and environmental impact assessments are therefore essential components of sustainable wind farm development.

Future Potential

Recent climate assessments indicate that although localized changes in wind patterns may occur because of climate change, India's overall wind energy potential remains substantial [47]. Expansion of offshore wind farms, improved transmission infrastructure, digital forecasting systems, and advanced storage technologies are expected to further increase the contribution of wind power toward India's energy independence.

Consequently, solar and wind energy should not be viewed as competing technologies but rather as complementary resources capable of jointly forming the foundation of India's future renewable electricity system.

3.3 Hydropower: Supporting Grid Stability and Renewable Energy Integration

Hydropower has been one of India's oldest and most reliable renewable energy resources, contributing significantly to electricity generation for several decades. Unlike solar and wind energy, which are weather dependent, hydropower provides dispatchable electricity and can rapidly respond to fluctuations in electricity demand. This operational flexibility makes hydropower an indispensable component of India's future renewable electricity system, particularly as the share of intermittent renewable energy continues to increase [31,33].

India possesses an estimated hydropower potential exceeding 145 GW, with major resources concentrated in the Himalayan states, northeastern India, and the Western Ghats [41]. Large hydroelectric projects have traditionally supplied base-load electricity while simultaneously supporting irrigation, flood control, drinking water supply, and regional economic development.

From the perspective of fossil fuel substitution, hydropower provides several advantages. First, electricity generation does not require coal, petroleum, or natural gas, thereby directly reducing greenhouse gas emissions and dependence on imported fuels. Second, hydroelectric stations exhibit relatively long operational lifetimes, often exceeding 50–100 years with appropriate maintenance. Third, hydropower plants have comparatively low operating costs because fuel procurement is unnecessary after project commissioning.

Hydropower also plays a crucial role in balancing renewable electricity generation. During periods of low solar radiation or reduced wind speeds, hydroelectric stations can rapidly increase electricity output to maintain grid stability. Conversely, during periods of surplus renewable electricity generation, hydroelectric reservoirs conserve water for future electricity production. This operational flexibility substantially enhances renewable energy integration [17].

An increasingly important technology is pumped-storage hydropower (PSH). Pumped-storage systems function as large-scale electricity storage facilities by pumping water from lower reservoirs to upper reservoirs during periods of excess renewable electricity generation. The stored water is subsequently released through turbines during peak electricity demand, effectively functioning as a giant rechargeable battery [31].

Studies have shown that large-scale deployment of pumped-storage systems significantly improves renewable electricity utilization while reducing renewable energy curtailment and minimizing dependence on fossil fuel-based peaking power plants [17]. Consequently, pumped-storage hydropower is expected to become a key component of India's future energy infrastructure.

Despite these advantages, hydropower development faces several environmental and social challenges. Construction of large reservoirs may affect river ecosystems, aquatic biodiversity, forest resources, and local communities through land acquisition and resettlement. Comprehensive environmental impact assessments, stakeholder participation, and sustainable watershed management are therefore essential for balancing electricity generation with ecological conservation.

Climate change also introduces uncertainty regarding long-term river flows and glacier-fed water availability. Future hydropower planning should therefore incorporate climate resilience and adaptive water resource management to ensure reliable electricity generation under changing climatic conditions [47].

Overall, hydropower remains an important complementary renewable energy source capable of supporting India's transition toward a low-carbon and energy-independent economy

3.4 Biomass and Bioenergy

Biomass represents one of India's most abundant renewable energy resources because of its extensive agricultural activities, forestry operations, livestock production, and municipal waste generation. Unlike solar and wind energy, biomass provides a storable and dispatchable renewable fuel capable of generating electricity, heat, and transportation fuels throughout the year [12].

India produces enormous quantities of agricultural residues, including rice straw, wheat straw, sugarcane bagasse, cotton stalks, maize residues, coconut shells, and other crop wastes. Traditionally, a significant proportion of these residues has been openly burned, contributing to severe air pollution, greenhouse gas emissions, and loss of valuable biomass resources. Converting agricultural residues into useful energy therefore provides simultaneous environmental, economic, and social benefits.

Biomass-based electricity generation substitutes coal-fired thermal power while simultaneously reducing agricultural waste disposal problems. Combined heat and power (CHP) systems utilizing biomass are particularly suitable for sugar industries, food processing industries, paper mills, and other agro-based industries where process heat and electricity are simultaneously required.

Biogas production represents another important biomass application. Organic wastes, livestock manure, sewage sludge, and food waste undergo anaerobic digestion to produce methane-rich biogas suitable for cooking, electricity generation, and transportation fuel applications. Digestate remaining after biogas production can be utilized as an organic fertilizer, thereby supporting sustainable agricultural practices and circular economy principles [49].

Compressed Biogas (CBG) has recently received considerable policy attention under India's Sustainable Alternative Towards Affordable Transportation (SATAT) initiative. CBG provides a renewable substitute for compressed natural gas in transportation and industrial applications while reducing dependence on imported natural gas.

The environmental benefits of biomass extend beyond fossil fuel substitution. Sustainable biomass utilization reduces methane emissions from uncontrolled decomposition, minimizes crop residue burning, decreases landfill waste, and contributes to carbon neutrality because carbon released during biomass combustion is largely offset by carbon absorbed during plant growth [12].

However, biomass utilization also requires careful management to ensure sustainability. Excessive biomass extraction may reduce soil fertility, increase transportation costs, and compete with alternative agricultural uses. Consequently, efficient biomass collection systems, decentralized processing facilities, and advanced conversion technologies are essential for maximizing economic viability.

Modern biomass conversion technologies, including gasification, pyrolysis, torrefaction, and advanced bio-refineries, significantly improve energy conversion efficiency while producing valuable by-products such as biochar, renewable chemicals, and synthetic fuels. Continued technological innovation is therefore expected to strengthen the contribution of biomass toward India's long-term energy independence.

3.5 Green Hydrogen: Decarbonizing Difficult-to-Abate Sectors

Although renewable electricity can replace fossil fuels in many applications, several industrial sectors require high-temperature heat or energy-dense fuels that cannot easily be supplied through direct electrification. These include steel manufacturing, cement production, fertilizer industries, petroleum refining, shipping, aviation, and heavy commercial transportation. Green hydrogen has therefore emerged as one of the most promising technologies for achieving deep decarbonization while reducing fossil fuel dependence [25].

Green hydrogen is produced by splitting water into hydrogen and oxygen using electricity generated from renewable sources such as solar and wind power. Unlike conventional grey hydrogen produced from natural gas, green hydrogen produces virtually no direct carbon emissions during production.

India's National Green Hydrogen Mission recognizes hydrogen as a strategic energy carrier capable of transforming industrial production while supporting national energy security. The mission promotes domestic manufacturing of electrolyzers, renewable electricity integration, hydrogen infrastructure development, research and development, and industrial adoption [25].

One of the greatest advantages of green hydrogen is its versatility. Hydrogen can be utilized directly as an industrial fuel, converted into ammonia for fertilizer production, blended with natural gas, utilized in fuel-cell electric vehicles, or stored for long durations to support seasonal renewable energy balancing.

Sontakke and Jaju [26] concluded that India possesses significant comparative advantages for green hydrogen production because of abundant renewable energy resources, declining solar electricity costs, and growing industrial demand. Similarly, Lakshmi Priya [50] emphasized that green hydrogen could become a major driver of India's future energy diplomacy through international partnerships and export opportunities.

Green hydrogen also contributes to energy storage. Excess renewable electricity generated during periods of high solar or wind production can be converted into hydrogen through electrolysis and stored for future electricity generation or industrial utilization. Such "power-to-hydrogen" systems improve renewable energy utilization while enhancing grid flexibility.

Despite enormous potential, green hydrogen remains comparatively expensive compared with conventional fossil fuels. Electrolyzer costs, renewable electricity requirements, hydrogen storage infrastructure, transportation systems, and distribution networks continue to limit widespread commercialization.

Nevertheless, declining renewable electricity costs, technological improvements, economies of scale, and supportive government policies are expected to significantly reduce production costs during the coming decades. Consequently, green hydrogen is widely regarded as one of the most important technologies for achieving complete fossil fuel substitution in hard-to-decarbonize sectors.

3.6 Biofuels: A Sustainable Alternative for Liquid Transportation Fuels

The transportation sector is one of the largest consumers of petroleum products in India, accounting for a substantial proportion of crude oil imports. Since complete electrification of heavy-duty vehicles, aviation, shipping, and certain agricultural applications will require considerable time, biofuels provide an important intermediate solution for reducing dependence on conventional fossil fuels. Biofuels are renewable fuels derived from biological resources such as sugarcane, maize, crop residues, used cooking oil, algae, and municipal organic waste. Their utilization contributes to fossil fuel substitution while simultaneously supporting agricultural development, waste management, and rural employment [18,21].

India has adopted an ambitious National Biofuel Policy promoting ethanol blending, biodiesel production, compressed biogas, and advanced biofuels. Ethanol blending with petrol has emerged as one of the country's most successful renewable fuel programmes. Increasing ethanol blending reduces crude oil imports, improves fuel combustion characteristics, and lowers greenhouse gas emissions. The Government of India has accelerated the Ethanol Blended Petrol (EBP) Programme with the objective of increasing blending levels while encouraging domestic feedstock production.

Second-generation (2G) biofuels have attracted considerable attention because they utilize agricultural residues rather than food crops, thereby minimizing concerns regarding food security. Technologies capable of converting rice straw, wheat straw, sugarcane bagasse, and other lignocellulosic biomass into ethanol provide an environmentally sustainable solution for utilizing agricultural waste while reducing open-field burning and associated air pollution.

Biodiesel production from non-edible oil seeds, waste cooking oil, and algae also offers opportunities for reducing diesel consumption in heavy transportation and agricultural machinery. Furthermore, sustainable aviation fuel (SAF) derived from biomass is increasingly recognized as an important strategy for decarbonizing the aviation sector.

Although biofuels cannot completely replace petroleum products, they provide a practical transition pathway capable of reducing import dependence while supporting rural economic development and circular resource utilization. Continued research into advanced bio-refineries, feedstock diversification, and process optimization will further improve the economic viability and environmental performance of biofuel technologies.

3.7 Nuclear Energy: Reliable Low-Carbon Base-Load Power

Nuclear energy provides another important pathway for reducing fossil fuel dependence while ensuring continuous electricity supply. Unlike solar and wind energy, nuclear power plants generate electricity continuously irrespective of weather conditions, making them valuable sources of reliable base-load electricity.

India has pursued nuclear power development for several decades through indigenous reactor technologies and international cooperation. Nuclear electricity generation contributes to energy security by reducing dependence on imported fossil fuels while producing negligible greenhouse gas emissions during operation [15].

One of the principal advantages of nuclear energy is its extremely high energy density. A comparatively small quantity of nuclear fuel generates enormous amounts of electricity, reducing fuel transportation requirements and minimizing land use relative to many conventional energy systems.

Nuclear energy also complements renewable electricity generation. While renewable energy supplies variable electricity depending upon climatic conditions, nuclear plants provide stable electricity generation that supports industrial production and maintains grid stability. Such complementary operation reduces dependence on coal-fired thermal power plants for base-load electricity generation.

Nevertheless, nuclear power development faces several challenges, including high capital investment requirements, long construction periods, radioactive waste management, public acceptance, safety concerns, and complex regulatory procedures. Continuous improvements in reactor safety, waste management technologies, and small modular reactor (SMR) development are expected to enhance the future role of nuclear energy within India's diversified energy portfolio.

Accordingly, nuclear energy should be viewed as a complementary low-carbon technology supporting renewable energy rather than as a direct competitor

3.8 Transport Electrification

The transportation sector contributes significantly to India's petroleum consumption and greenhouse gas emissions. Road transport alone accounts for a major share of imported crude oil utilization, making transportation electrification one of the most effective strategies for achieving energy independence [18,19].

Electric vehicles (EVs) replace internal combustion engines powered by petrol or diesel with electric motors supplied by rechargeable battery systems. When charged using renewable electricity, electric vehicles substantially reduce lifecycle greenhouse gas emissions while decreasing dependence on imported petroleum products [20,21].

Several studies have demonstrated that widespread adoption of electric mobility can significantly improve urban air quality, reduce carbon emissions, and strengthen national energy security [18–24]. Hossain et al. [20] concluded that large-scale deployment of electric passenger vehicles across Indian states can contribute substantially toward achieving carbon neutrality while improving public health through reduced air pollution.

India has introduced several policy initiatives supporting electric mobility, including Faster Adoption and Manufacturing of Electric Vehicles (FAME), Production Linked Incentive schemes for Advanced Chemistry Cells, battery manufacturing programmes, and expansion of charging infrastructure.

The rapid growth of electric two-wheelers is particularly significant because motorcycles and scooters constitute the largest segment of India's vehicle population. Consumer acceptance studies indicate that declining battery costs, improved charging infrastructure, financial incentives, and technological improvements continue to accelerate electric vehicle adoption [22,23].

Despite substantial progress, challenges remain. Battery costs, charging infrastructure availability, charging duration, recycling systems, and supply chains for lithium and other critical minerals require continued policy attention. Development of domestic battery manufacturing and recycling infrastructure will therefore play a vital role in ensuring long-term sustainability.

Integration of electric vehicles with renewable electricity and smart grids also presents opportunities for Vehicle-to-Grid (V2G) services, where parked vehicles function as distributed energy storage resources capable of supporting grid stability during peak demand periods [34].

3.9 Energy Efficiency: The First Fuel

Among all energy transition strategies, improving energy efficiency is frequently regarded as the most economical approach because the cleanest unit of energy is the energy that is never consumed. Increasing efficiency reduces energy demand across industrial, commercial, residential, and transportation sectors without compromising productivity or economic development [27,29].

Industrial energy efficiency can be improved through waste heat recovery, high-efficiency motors, variable frequency drives, digital manufacturing systems, predictive maintenance, process optimization, and energy management systems. Such improvements simultaneously reduce operating costs, greenhouse gas emissions, and fossil fuel consumption.

Building energy efficiency also plays an increasingly important role because urbanization and rising living standards continue to increase electricity demand for lighting, air conditioning, refrigeration, and appliances. Efficient building envelopes, LED lighting, high-efficiency cooling systems, smart building controls, and energy-efficient appliances substantially reduce electricity consumption [30].

Digitalization further strengthens energy efficiency through artificial intelligence, Internet of Things (IoT), digital twins, cloud computing, and advanced analytics. These technologies enable real-time monitoring, predictive maintenance, demand forecasting, and optimized energy utilization across industrial and commercial facilities.

Harvey [29] argued that investments in energy efficiency frequently provide greater long-term environmental and economic benefits than technology subsidies alone because efficiency improvements permanently reduce energy demand.

Furthermore, energy efficiency complements renewable energy by reducing the overall electricity generation capacity required to satisfy future demand. Consequently, efficient utilization of energy should be considered an integral component of India's strategy for fossil fuel substitution rather than an independent policy objective.

3.10 Integrated Approach to Fossil Fuel Substitution

The preceding discussion demonstrates that no individual technology can independently achieve complete energy independence. Instead, successful fossil fuel substitution requires an integrated energy system combining renewable electricity generation, transport electrification, green hydrogen, sustainable biofuels, hydropower, biomass, nuclear energy, battery storage, smart grids, and energy-efficient technologies [15,31–35].

Integrated planning enables policymakers to optimize technology deployment according to regional resource availability, economic conditions, industrial demand, and environmental priorities. For example, solar-rich states may prioritize photovoltaic generation and green hydrogen production, whereas mountainous regions may emphasize hydropower and pumped-storage facilities. Agricultural regions can exploit biomass and bioenergy resources, while coastal regions possess considerable offshore wind potential.

Recent optimization studies demonstrate that coordinated planning significantly reduces total system costs while improving energy reliability and reducing greenhouse gas emissions [14,15,31]. Such integrated approaches are therefore essential for balancing affordability, sustainability, and energy security.

Moreover, comprehensive sustainability assessment frameworks such as Madhab's Environmental–Efficiency–Economic (EEE) Impact Model [38] and the Plant Overall Performance (POP) Index [39] provide practical tools for evaluating renewable energy projects beyond traditional financial indicators. By simultaneously considering environmental performance, operational efficiency, and economic viability, these methodologies enable policymakers and industries to prioritize investments that maximize long-term sustainability. Combined with transparent environmental governance and ESG accountability frameworks [36], these approaches can support evidence-based decision-making throughout India's energy transition.

4. Policy Framework and Strategic Roadmap for Energy Independence

The successful transition from a fossil fuel-dependent economy to an energy-independent nation requires more than technological advancement. It demands a comprehensive policy framework integrating renewable energy development, industrial modernization, financial incentives, institutional coordination, technological innovation, and environmental governance. India's energy transition must therefore be viewed as a multidimensional transformation involving electricity generation, transportation, manufacturing, agriculture, urban infrastructure, and research ecosystems. A coordinated policy approach will determine the pace at which fossil fuel substitution contributes to national energy security and sustainable economic growth [5,15].

Over the past decade, the Government of India has introduced several policies that collectively support the clean energy transition. The National Solar Mission, National Wind-Solar Hybrid Policy, National Green Hydrogen Mission, Faster Adoption and Manufacturing of Electric Vehicles (FAME), Production Linked Incentive (PLI) schemes for renewable energy manufacturing, Perform Achieve and Trade (PAT) programme, Renewable Purchase Obligations (RPOs), Green Energy Corridors, and updated Nationally Determined Contributions (NDCs) have created a favorable institutional environment for renewable energy deployment [8,9,41,42]. These initiatives demonstrate India's commitment to reducing fossil fuel dependence while strengthening domestic industrial capability.

However, achieving energy independence by 2047 requires further strengthening of policy integration across sectors. Renewable electricity generation alone cannot ensure energy security unless accompanied by domestic manufacturing of photovoltaic modules, wind turbines, battery systems, electrolyzers, smart grid components, and power electronics. Expanding indigenous manufacturing under the *Atmanirbhar Bharat* initiative will reduce import dependence, improve supply-chain resilience, generate skilled employment, and enhance industrial competitiveness [5,48,49].

4.1 Strengthening Renewable Energy Manufacturing

India has become one of the largest renewable energy markets globally, yet a considerable proportion of advanced renewable energy components continues to be imported. Developing a complete domestic manufacturing ecosystem should therefore become a strategic priority. Government support should focus on:

- expanding domestic manufacturing of solar photovoltaic modules, inverters, batteries, and electrolyzers;
- promoting indigenous wind turbine component manufacturing;
- encouraging public-private partnerships for advanced clean energy technologies;
- strengthening research collaboration among universities, research institutions, and industries; and
- developing recycling industries for photovoltaic modules and lithium-ion batteries.

Such measures would simultaneously strengthen energy security and industrial development while reducing future dependence on imported clean energy technologies.

4.2 Accelerating Green Hydrogen Deployment

Green hydrogen is expected to become one of the most important technologies for decarbonizing heavy industries and long-distance transportation. To accelerate commercialization, policy interventions should include:

- financial incentives for electrolyzer manufacturing;
- dedicated renewable electricity projects for hydrogen production;
- development of hydrogen transportation and storage infrastructure;
- industrial demonstration projects in steel, fertilizer, and refining sectors; and
- international cooperation for technology transfer and export development [25,26,50].

Early commercialization of green hydrogen will substantially reduce dependence on imported natural gas and fossil fuels in difficult-to-decarbonize industries.

4.3 Grid Modernization and Energy Storage

The future electricity system will contain substantially higher shares of intermittent renewable energy. Consequently, transmission expansion, battery storage deployment, pumped-storage hydropower, smart grid technologies, and digital energy management systems should receive priority investment [17,31].

Advanced forecasting algorithms, artificial intelligence, Internet of Things (IoT), digital twins, and automated demand-response systems can improve renewable energy integration while minimizing electricity curtailment. Policy frameworks should encourage deployment of distributed energy resources, community energy systems, and vehicle-to-grid (V2G) technologies to improve grid flexibility.

4.4 Financial and Institutional Support

One of the principal barriers to renewable energy deployment remains the high initial capital requirement associated with renewable electricity generation, storage systems, hydrogen infrastructure, and transmission expansion. Although operating costs are comparatively low, access to affordable finance remains critical.

Government policies should therefore encourage:

- green bonds and climate finance;
- concessional financing for renewable energy projects;
- carbon pricing and market-based incentives;
- risk-sharing mechanisms for emerging technologies;
- international climate investment partnerships; and
- simplified regulatory approval processes.

Stable policy environments improve investor confidence and accelerate private sector participation in renewable energy development [42].

4.5 Human Resource Development and Research

Technological transformation requires an equally significant transformation of human capital. Universities, technical institutions, and industrial training centers should expand educational programmes related to renewable energy engineering, battery technologies, hydrogen systems, artificial intelligence, digital energy management, and sustainability assessment.

Research funding should prioritize:

- next-generation photovoltaic technologies;
- high-efficiency batteries;
- hydrogen production and storage;
- carbon capture technologies;
- circular economy solutions;
- critical mineral recycling; and
- integrated energy system optimization.

Academic-industry collaboration will accelerate technology commercialization while improving national innovation capability.

Table 3. Strategic Roadmap for Achieving Energy Independence in India

Strategic Area	Key Actions	Expected Outcomes
Renewable Electricity	Expand solar, wind, hydropower, and biomass capacity	Reduced coal-based electricity generation

Domestic Manufacturing	Solar modules, batteries, electrolyzers, wind turbines	Reduced technology imports and increased employment
Transport Electrification	EV adoption, charging infrastructure, public transport electrification	Reduced petroleum imports and improved air quality
Green Hydrogen	Industrial deployment, hydrogen infrastructure, electrolyzer manufacturing	Decarbonization of hard-to-abate sectors
Energy Storage	Battery systems, pumped hydro, smart grids	Improved renewable integration and grid stability
Energy Efficiency	Industrial modernization, efficient buildings, digital energy management	Lower overall energy demand and operating costs
Policy and Governance	Financial incentives, regulatory reforms, research funding	Accelerated clean energy transition and investment
Sustainability Assessment	EEE Impact Model, POP Index, ESG monitoring	Improved decision-making and long-term sustainability

4.6 Discussion

The present review demonstrates that India's pathway toward energy independence cannot rely on a single technology. Instead, a diversified energy portfolio integrating renewable electricity, energy storage, transport electrification, green hydrogen, biofuels, hydropower, biomass, and nuclear energy is required to achieve long-term sustainability. The complementary characteristics of these technologies improve system resilience while reducing dependence on imported fossil fuels.

Solar and wind energy will likely remain the primary contributors to electricity generation because of their abundant resource availability and rapidly declining costs. However, large-scale deployment must be accompanied by investments in battery storage, pumped-storage hydropower, smart transmission infrastructure, and digital energy management systems to overcome intermittency challenges [14,17,31].

Similarly, electrification alone cannot decarbonize all economic sectors. Green hydrogen, sustainable biofuels, and biomass-based energy systems provide practical solutions for heavy industries, aviation, shipping, and long-distance transportation where direct electrification remains technically challenging [25,26].

The review also highlights the growing importance of integrated sustainability assessment. Conventional financial evaluation methods alone are insufficient for selecting future energy technologies. Decision-makers should simultaneously evaluate environmental performance, operational efficiency, economic viability, and long-term sustainability. Frameworks such as Madhab's Environmental–Efficiency–Economic (EEE) Impact Model [38] and the Plant Overall Performance (POP) Index [39] provide valuable tools for comprehensive sustainability assessment and strategic decision-making.

Furthermore, environmental accountability and transparent ESG reporting are becoming increasingly important for ensuring that industrial sustainability initiatives produce measurable environmental improvements rather than symbolic compliance [36]. Integration of digital technologies, artificial intelligence, predictive analytics, and intelligent automation further enhances operational performance while supporting evidence-based policy implementation [37].

Overall, India's abundant renewable resources, strong policy commitment, expanding industrial capability, and growing research ecosystem provide favorable conditions for achieving energy independence. Continued technological innovation, institutional coordination, and stakeholder participation will determine the pace and success of this transition.

5. Conclusion

India's pursuit of energy independence represents one of the most significant national priorities for achieving sustainable economic growth, environmental protection, and long-term energy security. The country's increasing energy demand, coupled with heavy dependence on imported fossil fuels, has created economic and strategic challenges that necessitate a rapid transition toward cleaner and domestically available energy resources. Fossil fuel substitution is therefore not only an environmental imperative but also a critical component of national development and self-reliance.

This review demonstrates that India possesses abundant renewable energy resources capable of supporting a diversified and resilient energy system. Solar energy, owing to its vast resource availability and declining generation costs, is expected to remain the primary driver of the country's clean energy transition. Wind energy complements solar power by improving generation reliability, while hydropower contributes operational flexibility and grid stability. Biomass and bioenergy provide sustainable alternatives for electricity generation, industrial heating, and rural energy applications by utilizing agricultural and organic waste resources. Together, these renewable energy sources can substantially reduce dependence on coal, petroleum, and natural gas while enhancing energy security.

The study further highlights that achieving complete fossil fuel substitution requires a comprehensive and integrated approach. Green hydrogen has emerged as a promising solution for decarbonizing energy-intensive industries and heavy transportation where direct electrification remains difficult. Biofuels offer practical alternatives for reducing petroleum consumption in sectors that continue to rely on liquid fuels, whereas nuclear energy provides reliable low-carbon base-load electricity that complements intermittent renewable energy generation. Transport electrification, supported by renewable electricity and advanced battery technologies, represents another major opportunity for reducing oil imports and improving air quality. Simultaneously, improvements in energy efficiency across industrial, commercial, residential, and transportation sectors can significantly reduce overall energy demand while enhancing economic productivity.

The review also emphasizes that technological advancement alone cannot ensure successful energy transition. Effective policy implementation, domestic manufacturing capability, financial support, institutional coordination, research and innovation, and skilled human resources are equally important for accelerating fossil fuel substitution. Strengthening indigenous manufacturing of renewable energy technologies, battery systems, electrolyzers, and smart grid infrastructure will reduce import dependence, create employment opportunities, and improve industrial competitiveness. Investments in digital technologies, artificial intelligence, advanced energy management systems, and modern transmission infrastructure will further improve the reliability and efficiency of future energy systems.

Another important finding of this review is the growing significance of integrated sustainability assessment in energy planning. Future energy projects should be evaluated not only on economic performance but also on environmental impacts, operational efficiency, resource utilization, and long-term sustainability. Such multidimensional assessment approaches provide policymakers and industries with more comprehensive information for selecting the most effective and sustainable energy transition pathways.

Although significant progress has been achieved in renewable energy deployment, several challenges continue to influence the pace of India's energy transition. Renewable energy intermittency, large-scale energy storage requirements, transmission infrastructure expansion, financing constraints, land availability, critical mineral supply, and technological readiness remain important issues requiring continuous policy attention and strategic investment. Addressing these challenges will require close collaboration among government agencies, industries, research institutions, financial organizations, and society to ensure that the transition remains economically viable, socially inclusive, and environmentally sustainable.

Overall, India possesses the natural resources, technological capability, industrial potential, and policy commitment necessary to achieve substantial energy independence in the coming decades. A diversified energy portfolio integrating renewable electricity, hydropower, biomass, green hydrogen, biofuels, nuclear energy, transport electrification, energy efficiency, and intelligent energy management systems provides the most effective pathway for reducing fossil fuel dependence. By adopting an integrated techno-economic, environmental, and policy approach, India can strengthen national energy security, improve environmental quality, enhance industrial competitiveness, and support sustainable economic development while progressing toward the vision of a self-reliant and energy-independent nation.

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