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Renewable Energy Development and the Global Energy Transition: A Comparative Analysis (2001–2025)

Mr. K. Boopathiraj[1], Mr. P. Balakrishnan[2]

[1]Assistant Professor, Department of Economics and Centre for Research,
Ayya Nadar Janaki Ammal College (Autonomous), Sivakasi
affiliated Madurai Kamaraj University, Madurai.

[2]Assistant Professor, PG and Research Department of Economics,
Thiagarajar College, Madurai affiliated Madurai Kamaraj University, Madurai.

Abstract- The global energy system is undergoing a significant transformation from fossil-fuel-based energy towards renewable and low-carbon energy sources. This study analyses the growth and structural transformation of global renewable energy capacity during 2001–2025, focusing on solar, wind, hydropower, biomass, geothermal and ocean/marine energy. Secondary data compiled from International Renewable Energy Agency (IRENA) renewable-capacity statistics are examined using five-year periods. Trend analysis, growth-rate analysis, compound annual growth rate (CAGR) and percentage-share analysis are applied to assess changes in renewable energy capacity and identify the major drivers of the global energy transition. The findings indicate a substantial expansion in total renewable capacity, with solar and wind emerging as the fastest-growing renewable sources, while hydropower continues to maintain a significant installed-capacity base but with comparatively slower growth. The study also highlights the economic importance of renewable energy through investment, employment, technological innovation, energy security and reduced dependence on fossil fuels. However, intermittency, energy-storage requirements, grid infrastructure, critical-mineral supply, financing constraints and policy uncertainty remain major challenges. The study concludes that the global energy transition represents both an environmental and economic transformation and requires coordinated investment, technological development and supportive policy measures to achieve a secure, affordable and sustainable energy system.

Keywords- Renewable Energy, Global Energy Transition, Solar Energy, Wind Energy, Hydropower, Energy Capacity, Sustainable Development, Energy Security, Green Investment, Energy Policy.

I. Introduction

The global energy system is undergoing a significant transformation from conventional fossil-fuel-based energy towards renewable and low-carbon sources. Rising concerns over climate change, energy security, environmental pollution and fossil-fuel price volatility have accelerated the adoption of solar, wind, hydropower, biomass, geothermal and ocean energy. Global renewable power capacity has expanded considerably over the past two decades, with solar and wind emerging as major drivers of recent growth. This transition is changing the structure of energy production and consumption across countries. Renewable energy has also become increasingly important from an economic perspective. The expansion of clean-energy technologies is attracting large-scale investment and creating new opportunities in manufacturing, construction, installation, technology and services. In 2025, global energy investment

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was expected to reach around USD 3.3 trillion, with approximately USD 2.2 trillion directed towards clean-energy technologies. Renewable energy can also reduce dependence on imported fossil fuels, improve energy security and support technological innovation. Thus, the energy transition represents not only an environmental transformation but also an important economic and industrial transformation.

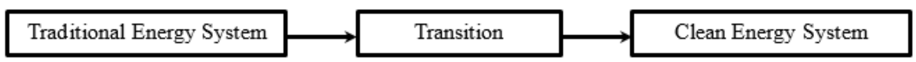
However, the global transition towards renewable energy faces several challenges, including the intermittent nature of solar and wind power, inadequate grid infrastructure, limited energy-storage capacity, critical-mineral supply risks, high initial investment requirements and policy uncertainty. The transition also requires substantial investment in electricity networks, batteries, electric vehicles and other supporting technologies. Therefore, analysing the growth of renewable energy capacity and its changing technological composition is essential for understanding the progress of the global energy transition. This study examines global renewable energy capacity during 2001–2025, focusing on major renewable sources, their growth patterns, economic importance and the challenges affecting the transition.

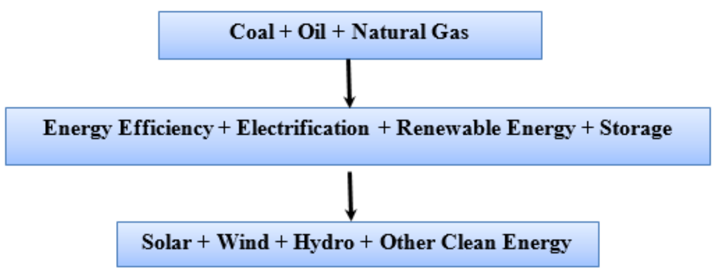
Objectives of the study

- To analyse the growth and trends in global renewable energy capacity by source solar, wind, hydropower, biomass, geothermal and ocean energy during 2001–2025.
- To examine the economic importance and structural transformation associated with the global energy transition, particularly in terms of investment, employment, energy security and fossil-fuel dependence.
- To identify the major challenges and opportunities in accelerating the global transition towards renewable energy and suggest appropriate policy measures for sustainable energy development.

Meaning of Global Energy Transition

The global energy transition refers to the transformation of the world's energy system from one dominated by fossil fuels to one increasingly based on renewable and low-carbon energy sources.





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Why is the World Moving towards Renewable Energy?

Climate Change

Renewable energy helps address climate change by reducing dependence on fossil fuels such as coal, oil and natural gas, which are major sources of greenhouse-gas emissions. Solar, wind, hydropower and other renewable sources generate electricity with much lower direct carbon emissions, supporting global efforts to reduce emissions and achieve long-term climate goals.

Energy Security

Renewable energy improves energy security by reducing a country's dependence on imported fossil fuels. Countries that develop domestic solar, wind, hydropower and other renewable resources can reduce their exposure to international fuel-price fluctuations, supply disruptions and geopolitical risks, thereby strengthening the stability of their energy systems.

Falling Costs

The declining cost of renewable-energy technologies is an important factor behind the global transition. Technological improvements, economies of scale, increased manufacturing capacity and stronger competition have reduced the cost of solar panels and wind power in many markets, making renewable electricity increasingly competitive with conventional energy sources.

Energy Access

Renewable energy can improve access to electricity, particularly in remote and rural areas where extending conventional electricity grids may be expensive or technically difficult. Decentralised systems such as solar home systems, mini-grids and small renewable power projects can provide reliable electricity for households, schools, health centres and local businesses.

Employment

The expansion of renewable energy creates employment opportunities throughout the energy value chain, including manufacturing, project development, construction, installation, operation and maintenance. The growth of solar, wind, battery storage and related industries can therefore support new employment and contribute to economic diversification.

Public Health

Renewable energy can improve public health by reducing air pollution associated with the combustion of coal, petroleum and natural gas. Greater use of clean energy can reduce emissions of pollutants such as particulate matter and sulphur dioxide, helping to improve air quality and reduce health risks associated with fossil-fuel-based energy production.

Technological Development

Technological development is accelerating the transition towards renewable energy through improvements in battery storage, smart electricity grids, electric vehicles, digital energy management and renewable-power systems. These innovations help address challenges such as variable solar and wind generation and make it easier to integrate larger amounts of renewable energy into modern energy systems.

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Table 1: Global Renewable Energy Capacity by Source, Five-Year Periods, 2001–2025

S.No.	Period	Solar	Wind	Hydropower	Biomass	Geothermal	Ocean/ Marine	Total Renewable Capacity
1	2001–2005	2.7	39.9	751.4	38.7	8.2	0.2	841.1
2	2006–2010	15.0	122.6	866.5	58.1	9.4	0.2	1,071.8
3	2011–2015	143.5	310.6	1,067.0	88.7	11.0	0.4	1,621.2
4	2016–2020	496.6	600.6	1,172.4	116.8	13.3	0.5	2,400.2
5	2021–2025	1,518.0	1,033.8	1,264.0	146.4	15.2	0.5	3,978.0

Source: Compiled from IRENA renewable power-generation capacity statistics. IRENA's database provides renewable capacity data from 2000 onward and allows data to be selected by year and technology.

II. **CAGR Analysis**

For a dissertation, CAGR is even more powerful because it allows you to compare the long-term growth rates of different renewable technologies.

Table 2: Long-Term Growth Results

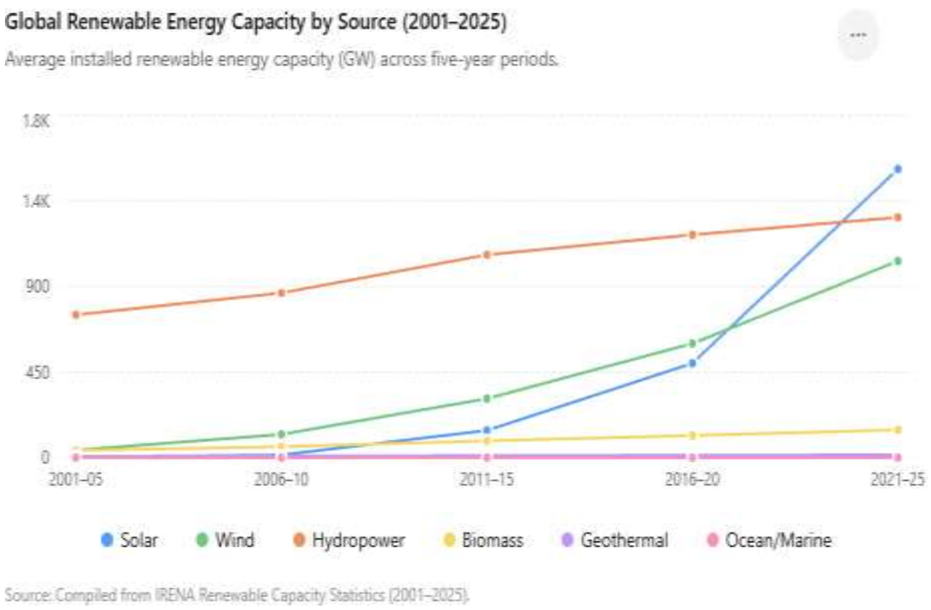
Renewable Source	2001–05 (GW)	2021–25 (GW)	Approx. CAGR (%)	Growth Assessment
Solar	2.7	1,518.0	35.4	Very High
Wind	39.9	1,033.8	17.1	High
Hydropower	751.4	1,264.0	2.6	Low
Biomass	38.7	146.4	6.9	Moderate
Geothermal	8.2	15.2	3.1	Low
Ocean/Marine	0.2	0.5	4.7	Low
Total Renewable	841.1	3,978.0	8.1	Moderate–High

Source: Calculated

The CAGR results demonstrate a fundamental structural change in the global renewable-energy sector. Solar and wind have expanded much faster than established renewable technologies, particularly hydropower. This suggests that the global energy transition is increasingly being driven by variable renewable electricity technologies, especially solar photovoltaic and wind power. The analysis of global renewable energy capacity during the period 2001–2025 reveals a substantial expansion and structural transformation in the renewable energy sector. Total average renewable energy capacity increased from 841.1 GW during 2001–2005 to 3,978.0 GW during 2021–2025, indicating a strong long-term expansion of renewable energy infrastructure. Solar energy recorded the most rapid growth among all renewable sources. Its average installed capacity increased from only 2.7 GW during 2001–2005 to 1,518.0 GW during 2021–2025. The estimated long-term CAGR of approximately 35.4 per cent demonstrates the exceptional expansion of solar energy. Wind energy also experienced rapid growth, increasing from 39.9 GW to 1,033.8 GW, with an estimated CAGR of approximately 17.1 per cent.

Hydropower remained an important component of global renewable capacity, increasing from 751.4 GW to 1,264.0 GW. However, its growth was relatively slow, with an estimated CAGR of approximately 2.6 per cent. Consequently, its share of total renewable capacity declined substantially over the study period. The percentage-share analysis demonstrates the changing composition of renewable energy capacity. Hydropower represented approximately 89.3 per cent of the renewable capacity in 2001–2005, but its share declined to approximately 31.8 per cent by 2021–2025. In contrast, the share of solar increased from approximately 0.3 per cent to 38.2 per cent, while wind increased from approximately 4.7 per cent to 26.0 per cent. Overall, the findings indicate that the global renewable energy transition has involved not only an increase in total renewable capacity but also a significant change in its technological composition. The renewable energy system has gradually shifted from a predominantly hydropower-based structure towards one increasingly dominated by solar and wind energy. Therefore, solar and wind can be identified as the principal drivers of the contemporary global renewable energy transition.

Global Renewable Energy Capacity by Source (Five-Year Periods, 2001–2025)



Solar energy shows the fastest growth, rising sharply after 2011–2015 and reaching 1,518 GW during 2021–2025. Wind energy demonstrates consistent expansion, increasing from 39.9 GW to 1,033.8 GW over the study period. Hydropower remains a major renewable source, but its growth is comparatively gradual, increasing from 751.4 GW to 1,264 GW. Biomass grows steadily throughout the five periods but contributes

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a smaller share than solar and wind. Geothermal and Ocean/Marine energy remain relatively stable with limited global installed capacity.

III. Key Components of the Global Energy Transition

Renewable Power Generation

Renewable power generation is the central component of the global energy transition because it involves replacing conventional fossil-fuel-based electricity generation with cleaner energy sources. Solar, wind, hydropower, biomass, geothermal and ocean energy are increasingly being used to generate electricity. Among these sources, solar and wind have experienced particularly rapid expansion due to technological improvements and declining costs. The development of large-scale renewable power projects can reduce dependence on coal, oil and natural gas. Distributed renewable systems, such as rooftop solar and community-based projects, can also contribute to decentralised electricity generation. Increasing renewable capacity requires investment in transmission networks, energy storage and grid management. Therefore, the expansion of renewable power generation forms the foundation for creating a cleaner, more secure and sustainable global energy system.

Electrification

Electrification refers to replacing direct fossil-fuel use with electricity in sectors such as transport, buildings and industry. The process is particularly important when electricity is generated from renewable sources because it can reduce the carbon intensity of energy consumption. Electric vehicles are replacing petrol and diesel vehicles in many markets, while heat pumps and electric heating systems are increasingly being used in buildings. Industries are also exploring electricity-based technologies for processes that traditionally depend on coal, oil and natural gas. Greater electrification increases demand for reliable electricity generation and requires expansion and modernization of electricity grids. It also creates stronger connections between renewable energy development and energy consumption. Thus, electrification is an important mechanism for transferring the benefits of renewable energy from the power sector to the wider economy.

Energy Storage

Energy storage is a critical component of the energy transition because renewable sources such as solar and wind are variable in nature. Solar power is mainly available during daylight hours, while wind generation depends on weather conditions. Batteries and other storage technologies can store electricity when renewable generation is high and release it when demand increases or renewable production declines. Large-scale battery storage can therefore improve electricity-system flexibility and reliability. Other technologies, including pumped-storage hydropower, thermal storage and hydrogen, can provide additional forms of energy storage. Improvements in battery technology are also supporting the expansion of electric vehicles and decentralised energy systems. Consequently, energy storage helps overcome the intermittency challenge and enables electricity systems to accommodate a higher share of renewable energy.

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Energy Efficiency

Energy efficiency involves providing the same level of economic output, comfort or services while using less energy. It is one of the most cost-effective components of the global energy transition because reducing energy demand can decrease the amount of new energy infrastructure required. Improvements can be achieved through energy-efficient buildings, industrial equipment, appliances, vehicles and production processes. Energy-efficient technologies can reduce electricity consumption and lower energy expenditure for households and businesses. In industry, efficient machinery and improved production processes can reduce both energy use and production costs. Governments can encourage efficiency through building standards, appliance standards, energy-management programmes and financial incentives. Therefore, energy efficiency complements renewable energy by reducing overall energy demand while supporting economic productivity and environmental sustainability.

Green Hydrogen

Green hydrogen is hydrogen produced by using renewable electricity to split water into hydrogen and oxygen through electrolysis. It is considered an important component of the energy transition because some industrial activities are difficult to electrify directly. Green hydrogen has potential applications in industries such as steel, chemicals, refining and long-distance transport, where conventional fossil fuels currently play an important role. It can also potentially be used as an energy-storage medium when renewable electricity production exceeds immediate demand. The development of green hydrogen depends on the availability of low-cost renewable electricity, electrolyser technology, water resources and appropriate infrastructure. Investment in hydrogen production, transportation and storage is therefore necessary for large-scale adoption. Although green hydrogen remains relatively expensive in many applications, technological progress and increasing renewable capacity could improve its economic viability.

Smart Grids

Smart grids are modern electricity networks that use digital technologies, sensors, communication systems and automated controls to manage electricity generation, transmission, distribution and consumption more efficiently. They are particularly important for integrating large quantities of variable renewable energy into electricity systems. Smart grids can monitor electricity demand and supply in real time and help balance fluctuations in solar and wind generation. They can also coordinate distributed energy resources such as rooftop solar panels, batteries, electric vehicles and local energy systems. Advanced metering and demand-response technologies allow consumers to adjust electricity consumption according to system conditions. Modern grid management can improve reliability, reduce transmission losses and support efficient use of available electricity. Therefore, smart grids provide the digital and infrastructure foundation required for a flexible, resilient and renewable-based energy system.

IV. Major Challenges of the Global Energy Transition

Intermittency of Renewable Energy

The variable nature of solar and wind generation creates a major challenge for electricity-system reliability because their output depends on sunlight, wind conditions and weather patterns. Solar PV cannot generate electricity at night, while wind generation can fluctuate considerably within short periods. The IEA projects that variable renewables could provide almost 30% of global electricity generation by 2030, approximately twice their current share, increasing the need for system flexibility. Rising levels of curtailment and periods of negative electricity prices in several markets indicate that renewable generation can sometimes exceed the ability of electricity systems to absorb it. Therefore, the rapid growth of solar and wind capacity must be accompanied by demand-side flexibility, storage, stronger grids and other dispatchable resources.

Energy Storage

Energy storage is becoming increasingly important because electricity generation from solar and wind does not always coincide with electricity demand. Battery energy storage systems can store surplus renewable electricity during periods of high generation and release it when demand rises or renewable output falls. IRENA reports that energy shifting accounted for 67% of total electricity-storage capacity additions in 2024, demonstrating the growing importance of storage for balancing renewable electricity supply and demand. Battery storage is particularly useful for shifting solar electricity from daytime to evening demand periods. However, large-scale deployment requires investment in batteries, transmission systems, market mechanisms and supportive regulations. Consequently, inadequate storage capacity can limit the effective integration of rapidly expanding renewable generation.

Grid Infrastructure

Insufficient transmission and distribution infrastructure is one of the most significant physical constraints on the global energy transition. Unlike many conventional power stations, solar and wind projects are geographically distributed and are often located far from major electricity-demand centres. This requires new transmission lines, substations, distribution networks and digital grid-management systems. IRENA estimates that global power systems will require 2.5 to 3 times more flexibility than in 2019 to manage variable renewable generation effectively, while its 1.5°C scenario estimates that annual grid investment needs to reach approximately USD 671 billion up to 2030. Delays in grid expansion can therefore result in renewable projects waiting for connection, electricity congestion and increased curtailment. Grid modernization is consequently not a secondary requirement but a fundamental infrastructure condition for the energy transition.

Critical Minerals and Supply-Chain Risks

The rapid expansion of renewable energy, electric vehicles, batteries and electricity grids is increasing demand for critical minerals such as lithium, copper, nickel, cobalt, graphite and rare earth elements. According to the IEA, global lithium demand increased by nearly 30% in 2024, while demand for nickel, cobalt, graphite and rare earth elements increased by approximately 6–8%. These minerals are essential for batteries, electric vehicles, renewable technologies and grid infrastructure. Supply-chain concentration creates additional risks because mining, processing and manufacturing are geographically concentrated in a limited number of countries. The IEA also reports that China accounts for around 90% of rare-earth refining used in many clean-energy supply chains. Therefore, mineral availability, processing capacity, geopolitical risks and supply-chain diversification have become important determinants of the speed and security of the global energy transition.

High Initial Investment and Financing Gap

Although renewable technologies have become increasingly cost-competitive, renewable energy projects generally require substantial upfront investment in generation capacity, transmission, storage and supporting infrastructure. Global energy-transition investment reached a record USD 2.4 trillion in 2024, while renewable-energy investment alone reached approximately USD 807 billion. However, around 90% of energy-transition investment remained concentrated in advanced economies and China, leaving many emerging and developing economies with limited access to affordable finance. IRENA also notes that financing conditions in developing economies are affected by higher capital costs, currency risks, macroeconomic instability and policy uncertainty. This creates a significant investment gap between countries with strong financial systems and those that require external finance. Therefore, mobilising concessional finance, development finance and private investment is essential for achieving a globally inclusive energy transition.

Land Use and Environmental Issues

Large-scale renewable-energy projects can create land-use and environmental challenges even though renewable technologies generally have much lower operational emissions than fossil fuels. Solar farms, wind farms, hydropower projects and transmission infrastructure require land and may compete with agriculture, conservation and other economic activities. Hydropower projects can affect river ecosystems and local communities, while wind and solar projects may create concerns relating to biodiversity, landscape and land availability. The rapid expansion of renewable capacity therefore requires careful environmental assessment and spatial planning. These challenges become particularly important as renewable deployment accelerates and projects increasingly occupy larger areas. Consequently, the energy transition must balance rapid decarbonisation with biodiversity protection, responsible land management and community participation.

Just Transition and Employment

The shift away from fossil fuels creates social and regional challenges because coal mining, oil production, gas extraction and conventional power generation support millions of workers and local economies. A rapid reduction in fossil-fuel activity can therefore affect employment, household incomes, government revenues and regional economic structures. At the same time, renewable-energy industries create new employment opportunities in manufacturing, construction, installation, operation and maintenance. The key issue is whether workers displaced from declining fossil-fuel industries can obtain the skills and opportunities required in emerging clean-energy sectors. A successful transition therefore requires retraining, reskilling, social protection and regional economic diversification. Without such measures, the economic benefits of decarbonisation may be distributed unevenly and generate resistance among affected communities.

Policy Uncertainty

Policy uncertainty can influence the scale and timing of renewable-energy investment because energy projects normally involve large capital commitments over long periods.

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Changes in subsidies, taxation, permitting rules, renewable-energy targets, electricity-market regulations and trade policies can alter expected project returns. The IEA's 2025 renewable-energy outlook revised its forecast for global renewable capacity additions during 2025–2030 downward by 5%, equivalent to 248 GW less capacity, partly reflecting policy, regulatory and market changes. The report also highlights the importance of reducing policy uncertainty, shortening permitting periods, increasing grid investment and improving financing conditions to accelerate deployment. Therefore, stable and predictable policy frameworks are essential for reducing investment risk and maintaining the momentum of the global energy transition.

Economic Importance of the Global Energy Transition

Reduction in Fossil-Fuel Price Exposure

Renewable energy reduces dependence on imported fossil fuels and exposure to international price fluctuations. This can improve energy-price stability and reduce pressure on import bills. The increasing investment in domestic renewable resources strengthens long-term energy security. The IEA expects clean-energy investment to reach USD 2.2 trillion in 2025, twice the investment in fossil fuels.

Green Investment and Technological Innovation

The energy transition is redirecting global capital towards renewable energy, batteries, electrification, grids and other clean technologies. Global energy investment is expected to reach USD 3.3 trillion in 2025, with about USD 2.2 trillion going to clean-energy technologies. This investment promotes technological innovation, productivity improvements and new industrial supply chains.

Employment and New Industries

Renewable energy is creating employment in solar, wind, hydropower, bioenergy, manufacturing, installation and maintenance. Global renewable-energy employment reached 16.6 million jobs in 2024, the highest level recorded. However, employment growth was only 2.3% from 2023 because automation and productivity improvements reduced labour requirements.

Changes in International Trade

The energy transition is changing global trade from traditional fossil fuels towards solar panels, batteries, electric vehicles, critical minerals and other clean-energy technologies. Countries with strong manufacturing capacity can gain export opportunities and develop domestic industries. At the same time, dependence on imported critical minerals creates new supply-chain risks. Thus, energy transition is reshaping global trade patterns.

Reduction in Energy-Import Dependence

Countries with abundant solar, wind or hydropower resources can reduce their dependence on imported coal, oil and natural gas by expanding domestic renewable capacity. This can improve the trade balance and reduce vulnerability to international energy-price shocks. Renewable energy therefore provides both an environmental benefit and an important energy-security benefit. The growing emphasis on domestically available energy resources is also influencing investment decisions globally.

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Infrastructure Investment and Economic Growth

The transition requires large investments in renewable generation, electricity grids, battery storage, electric vehicles and energy-efficient infrastructure. The IEA estimates that global energy investment will reach USD 3.3 trillion in 2025, with clean-energy investment accounting for around USD 2.2 trillion. Such investment can stimulate construction, manufacturing, employment and technological development. Therefore, energy transition can become an important source of long-term economic growth.

Suggestions

- Governments should promote large-scale and decentralised solar and wind projects through stable policies, competitive financing and faster project approvals.
- Greater investment should be directed towards transmission, distribution and smart-grid systems to integrate increasing renewable electricity capacity efficiently.
- Countries should increase investment in battery storage, pumped-storage hydropower and other flexible technologies to manage fluctuations in solar and wind generation.
- International institutions and governments should provide concessional finance, guarantees and risk-sharing mechanisms to improve renewable-energy investment, particularly in developing economies.
- Countries should diversify mineral supplies, promote recycling and develop domestic processing capabilities to reduce dependence on concentrated global supply chains.
- Governments should provide reskilling, retraining and alternative employment opportunities for workers and communities affected by the decline of fossil-fuel industries.
- Long-term renewable-energy targets, transparent regulations and predictable incentives are necessary to reduce investment uncertainty and accelerate private-sector participation.
- Renewable expansion should be combined with energy-efficient buildings, industries and electric transport to maximise the economic and environmental benefits of the energy transition.

V. Conclusion

The analysis shows that the global energy system has undergone a significant shift towards renewable energy during 2001–2025. Total renewable capacity increased substantially, while solar and wind emerged as the fastest-growing sources. Hydropower continued to provide a major share of renewable capacity, but its relative dominance declined as solar and wind expanded rapidly. The transition is also generating economic opportunities through investment, employment, technological innovation and improved energy security. However, challenges related to energy storage, grid infrastructure, critical minerals, financing and policy stability remain important. Overall, the evidence indicates that renewable energy has become a central pillar of the global energy transition and future sustainable development.

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