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Economic Perspective of Renewable Energy Sources: Security of Supply, Innovations, and Challenges

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Abstract

Renewable energy sources are crucial for tackling the challenges of energy security and climate change. The mounting concerns about climate change, fossil fuel depletion, and energy security have heightened the focus on renewable energy. The shift to a global energy system that heavily relies on renewable sources, while promising, faces significant barriers that call for coordinated global efforts and innovative solutions. This article examines the technological advancements in renewable energy, evaluates their economic implications, and explores future trends and policy impacts. The core argument of this work is that, despite notable technological advancements, a significant breakthrough and a conducive investment environment are yet to be realised to enable the complete substitution of fossil fuels with renewable energy. It analyses current capacities, technological challenges, economic considerations, and various policies influencing the implementation of renewable energy projects. By conducting a comprehensive examination of the intermittency of energy production, limitations of energy storage, and the need for infrastructure modernisation, the economic implications of investing in renewable energy are assessed, alongside the potential of existing technologies to provide a sustainable alternative to fossil fuels. The article underscores the crucial role of increased investment, ongoing innovation, and global collaboration in overcoming existing challenges and ensuring a sustainable transition to renewable energy sources.

Keywords: renewable energy sources; economic perspective; investments; energy security

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Introduction

Rising concerns about climate change, the depletion of fossil fuels, and energy security have led to an increased focus on renewable energy sources. Renewable energy sources, such as solar power, wind power, hydropower, geothermal energy, and biomass, are crucial for reducing greenhouse gas emissions and achieving sustainable development. According to the International Energy Agency (IEA), fossil fuels still dominate global energy sources, accounting for more than 80% of total energy consumption (IEA, 2021). Although renewable energy has made significant strides, it still constitutes a relatively small share of global energy consumption.

The global transition to renewable energy is not only a technological challenge but also an economic and social endeavour. Growing awareness of the environmental benefits of renewable energy, along with the declining costs of technologies such as solar panels and wind turbines, has spurred governments and the private sector to invest in renewable energy sources. However, this transition requires substantial initial investments, infrastructure modernisation, and the development of new energy storage technologies to ensure a reliable and stable energy supply.

In addition to technological innovations, policies and regulations play a crucial role in encouraging the implementation of various renewable energy projects. Consistent and supportive policies, such as feed-in tariffs, tax incentives, and various subsidies, can attract investment and support the development of renewable energy projects (REN21, 2023).

The transition to renewable energy offers significant economic benefits, including job creation, technological innovation, and reduced dependence on imported fossil fuels, thereby enhancing supply security (IRENA, 2020). It is estimated that renewable energy could create around 42 million jobs by 2050 (IRENA, 2021). Renewable energy reduces greenhouse gas emissions, decreases air pollution, and mitigates the impacts of climate change (Lund, 2009). However, the transition also poses economic challenges, such as the need for substantial initial investments (Sovacool et al., 2020).

With continued technological advancement and decreasing initial investment costs that will encourage further investments, renewable energy will continue to reduce reliance on conventional energy sources and play a crucial role in combating climate change. Governments must play a key role in this transition by providing incentives for renewable energy investments, funding research and development, and implementing policies that promote sustainability. International cooperation is also essential for addressing global challenges like climate change and energy access (Goldemberg, 2007). Increased collaboration between countries could accelerate technology transfer and the sharing of best practices, while global agreements such as the Paris Agreement provide a framework for coordinated efforts to reduce greenhouse gas emissions (UNFCCC, 2015).

The global economic outlook for renewable energy is optimistic, with significant growth in investment in the sector. According to the International Renewable Energy Agency (IRENA), total investment in renewable energy could reach $130 trillion by 2050, laying

the foundation for new business models and innovations (IRENA, 2021). Furthermore, the transition to renewable energy can bring economic benefits that outweigh the investment costs, including savings in healthcare costs due to reduced air pollution and reduced costs associated with climate change (IRENA, 2021).

At the same time, the energy sector faces the challenge of financing and managing the transition to renewable energy. Upgrading and expanding the existing grid infrastructure to accommodate renewable energy sources presents a significant challenge (Sims et al., 2007). Traditional energy systems rely on infrastructure that is already depreciated and integrated into global economic systems. The transition to renewable energy will require substantial investment in new infrastructure, including smart grids, energy storage, and the modernisation of existing power grids (IRENA, 2021).

Literature Review

The transition from fossil fuels to renewable energy sources represents one of the greatest challenges in modern energy and environmental policy. Although renewable energy sources are recognised as key to achieving sustainable development and reducing greenhouse gas emissions, their integration into the global energy system faces numerous technical, economic, and political challenges.

In 2020, the global energy mix was dominated by fossil fuels, accounting for 84% (IEA, 2021). Oil made up 31%, coal 27%, and natural gas 26% of global energy consumption. Renewable energy sources accounted for about 12% of global consumption, with hydropower being the most dominant renewable source (IEA, 2021). Oil, coal, and natural gas form the foundation of the world's energy system due to their relative availability, energy density, and established infrastructure for production and distribution. This dominance has its roots in the Industrial Revolution when fossil fuels enabled rapid industrial and transportation development. However, fossil fuels are also the main source of greenhouse gas emissions, which are the primary driver of climate change.

Solar energy has significant growth potential but currently constitutes only a small share of global energy production. In 2020, solar energy accounted for less than 3% of global electricity generation (IRENA, 2021). Despite this small share, solar energy is the fastest-growing among renewable energy sources. According to IRENA estimates, solar energy could reach 30% of global electricity production by 2050 (IRENA, 2021). Wind energy also has significant growth potential. In 2020, wind power accounted for about 6% of global electricity generation (GWEC, 2021). The global wind power network reached an installed capacity of over 700 GW by the end of 2020, with expected growth to over 2,000 GW by 2030 (GWEC, 2021). Offshore wind power is a key component of this growth, with the installed capacity expected to increase to 230 GW by 2030 (GWEC, 2021). Hydropower currently accounts for the largest share of renewable energy. According to the IEA, hydropower makes up about 16% of global electricity generation (IEA, 2021). However, the potential for further growth in hydropower is limited due to

ecological and social challenges associated with large hydropower projects. Small hydropower, which has a smaller environmental impact, can play a key role in rural areas and developing countries. Geothermal energy accounts for less than 1% of global electricity generation, with an installed capacity of about 14 GW (IRENA, 2020). Despite the small share, geothermal energy has significant growth potential in regions with suitable geothermal resources. Enhanced geothermal systems (EGS) and binary cycles can expand the availability of geothermal energy to a wider area. Biomass energy and biofuels are significant parts of the energy mix in many countries, especially in rural areas and developing countries. According to IRENA, biomass accounts for about 10% of global energy consumption (IRENA, 2021). Second-generation biofuels, derived from non-food biomass, offer a more sustainable alternative to first-generation biofuels.

One of the main challenges in integrating renewable energy sources is their intermittency. Solar power plants produce energy only during the day, depending on the number of sunlight hours, while wind farms depend on the presence of wind. This intermittency can cause instability in the power system, especially when renewable energy sources dominate the energy mix (Zakeri & Syri, 2015). Energy storage technologies, such as lithium-ion batteries and advanced energy storage systems, are crucial to addressing this problem. However, current energy storage technologies are still not sufficiently developed or economically viable on a large scale (IRENA, 2020).

High initial investment costs, the need for infrastructure modernisation, and the lack of consistent policies and incentives are major barriers to investments in renewable energy (Sovacool et al., 2020). Although the costs of renewable energy technologies have significantly decreased over the past few decades, large initial investments with long-term returns are still required. According to IRENA, total investments needed to achieve a global transition to renewable energy could reach $130 trillion by 2050 (IRENA, 2021). These investments include the development and installation of new renewable energy systems, research and development of new technologies, modernisation of existing infrastructure, and the development of smart grids and energy storage systems.

Power grids are designed for centralised energy production from fossil fuels, while renewable energy sources require a decentralised approach. Smart grids, which use advanced technologies to manage and optimise energy distribution, can improve the reliability and stability of the energy system (Gungor et al., 2011). However, modernising power grids requires significant investments.

Consistent and supportive policies are crucial for encouraging investments in renewable energy. However, policies must be stable and long-term to ensure investment security. Germany's "Energiewende" program's success demonstrates how consistent policy can drive significant growth in renewable energy and the development of related industries. However, it also highlights the need to address challenges such as high energy costs and the integration of renewables into the power grid (Agora Energiewende, 2021).

The transition to renewable energy can bring significant economic benefits. According to IRENA, the transition to renewable energy could result in the creation of around 42 million jobs by 2050 (IRENA, 2021). These jobs include not only direct employment in the sectors of production, installation, and maintenance of renewable energy systems but also indirect jobs in supporting industries such as component manufacturing, research and development, and support services. Additionally, reducing air pollution associated with the transition to renewable energy can result in significant savings in healthcare costs. The World Health Organization (WHO) estimates that air pollution causes millions of premature deaths each year, and the transition to renewable energy can significantly reduce these health costs (WHO, 2016).

Examples of successful transitions to renewable energy can provide valuable lessons for other countries. Germany, with its ambitious "Energiewende" program, has made significant progress in increasing the share of renewable energy in its energy mix and developing a supporting industry. Germany has introduced various incentives, including feed-in tariffs, to encourage investment in renewable energy. As a result, significant growth in the installed capacity of solar and wind power has been achieved. However, challenges such as high energy costs and the integration of renewable energy into the power grid remain (Agora Energiewende, 2021).

California is a leader in the United States when it comes to renewable energy. The state has set a goal of achieving 100% clean energy by 2045. California's solar energy incentive programs, such as the California Solar Initiative, have significantly increased the installation of solar systems on residential and commercial rooftops. California is also investing in the development of smart grids and energy storage technologies to improve the reliability and integration of renewable energy (California Energy Commission, 2021). Programs such as clean energy incentives and infrastructure laws are aimed at encouraging investment in renewable energy and modernising infrastructure (White House, 2021).

China, the world's largest emitter of greenhouse gases, plans to achieve climate neutrality by 2060 and is investing significant resources in the development of solar, wind, and hydropower. China is also a leader in the production of solar panels and wind turbines, allowing it to rapidly expand renewable energy domestically and export these technologies (China National Energy Administration, 2021).

Technological advancements play a crucial role in the transition to renewable energy. Solar and wind power plants have made significant strides in increasing efficiency and reducing costs. For example, perovskite solar cells represent a promising new solution that can significantly reduce costs and increase the efficiency of solar P.V. systems (Yang et al., 2020). Similarly, innovations in wind turbine blade design and materials have increased the efficiency and lifespan of wind turbines (Hau, 2013). Concentrated solar power (CSP) is also an important technology that can help address the issue of intermittency in energy production. CSP systems use solar heat to generate electricity, and advanced technologies like the use of molten salt for thermal energy storage allow for electricity generation even when the sun is not shining (Sharma et al., 2017). Despite these innovations, CSP technologies currently make up a smaller part of solar

installations but offer significant advantages in terms of energy storage. Geothermal energy also has significant growth potential. Enhanced geothermal systems (EGS) allow for the creation of fractures in hot rock formations, expanding the geographical availability of geothermal energy (Tester et al., 2006). Binary cycle plants enable the use of lower-temperature resources, making geothermal energy viable in more locations (DiPippo, 2012).

Smart grids are crucial for integrating renewable energy into the power system. They use advanced technologies to manage and optimise energy distribution, allowing for greater flexibility and stability in the grid. Smart grids also enable better integration of decentralised energy sources, such as rooftop solar panels and small wind turbines (Gungor et al., 2011). Smart grids include the use of advanced measurement and monitoring systems, as well as demand management systems that allow for real-time energy consumption adjustments. These technologies can improve the reliability and stability of the energy system, reducing the risk of power outages and allowing for more efficient integration of renewable energy sources; however, they require significant investments that are not sufficiently incentivised for the private sector.

Global cooperation is crucial for addressing the challenges of transitioning to renewable energy. International agreements like the Paris Agreement provide a framework for coordinated efforts to reduce greenhouse gas emissions and promote sustainable development (UNFCCC, 2015). Regional initiatives, such as the European Green Deal, also play an important role in achieving climate goals through coordinated efforts and joint investments (European Commission, 2020). Consistent and supportive policies are key to encouraging investment in renewable energy. Successful policy examples include feed-in tariffs, tax incentives, and various incentive programs to encourage private-sector investment. These policies can attract investment and support the development of renewable energy, but they must be stable and long-term to ensure investment security (Sovacool, 2009).

Despite significant progress, numerous challenges and barriers must be overcome to enable a successful transition to renewable energy. The intermittency of energy production from renewable sources, underdeveloped energy storage technologies, high initial investment costs, and the need for infrastructure modernisation are major challenges we face (Lund & Mathiesen, 2009). In addition to technological and economic challenges, there is the issue of public acceptance. Gaining public support for investments in renewable energy projects is crucial, especially for wind and hydroelectric power, which can have significant local environmental and social impacts (Wüstenhagen et al., 2007). Education and transparent communication with local communities can improve acceptance and reduce resistance (Devine-Wright, 2011).

The theoretical background provides an overview of the main elements that led to the hypothesis that despite significant technological progress, there have not yet been sufficient technological breakthroughs and an encouraging investment environment to enable the complete replacement of fossil fuels with renewable energy sources.

An analysis of the current capacities of renewable energy sources, technological challenges, economic and political factors, and examples of successful transitions to

renewable energy indicates the need for further investment incentives, continuous innovation, and global cooperation to overcome existing challenges and ensure a sustainable transition to renewable energy. The long-term success of this transition will depend on society's ability to adapt to new technologies and energy management models, as well as the willingness of governments and the private sector to invest in a future that is environmentally, economically, and socially sustainable. The transition from fossil fuels to renewable energy sources represents one of the biggest challenges of contemporary energy and environmental policy. Although renewable energy sources are recognised as key to achieving sustainable development and reducing greenhouse gas emissions, their integration into the global energy system faces numerous technical, economic, and political challenges.

Methodology

To quantitatively prove the research hypothesis, several key indicators must be analysed, including the current capacities of renewable energy sources and their share in the global energy mix, the intermittency of production, the efficiency of energy storage technologies, and economic aspects and political measures.

The methodology of this research includes an analysis of the current capacities and share of renewable energy sources in the global energy mix through a review of the literature and available statistical data. By using data from sources such as the International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA), trends in the growth of solar photovoltaic systems, wind power, hydropower, geothermal energy, and biomass capacity were examined. The challenges of the intermittency of energy production from renewable sources and the efficiency of existing energy storage technologies were analysed. The economic implications of the transition to renewable energy sources were also reviewed, including the costs of technologies, financial incentives, and the impact on employment and macroeconomic effects. Data from various studies, reports, and forecasts were used to gain a comprehensive insight into the current situation and future trends. In order to quantitatively prove the set research assumption of the work, it is necessary to analyse several key indicators that include the current capacity of renewable energy sources and their share in the global energy mix, the periodicity of production and the efficiency of energy storage technologies, as well as economic aspects and political measures.

Results

Current Capacity and Share of Renewable Energy in the Global Energy Mix

Global renewable energy capacities have significantly increased over the past decade. Solar photovoltaic (P.V.) systems grew from 40 G.W. in 2010 to over 580 GW in 2019 (IRENA, 2020). The global capacity of wind power reached over 700 GW by the end of 2020 (GWEC, 2021). However, despite these impressive numbers, solar and wind

energy together account for less than 10% of the global electricity production share (IEA, 2021).

Fossil fuels still dominate the global energy mix, comprising more than 80% of total energy consumption (IEA, 2021). Hydropower, the oldest and most widely used renewable energy source, makes up about 16% of global electricity production, while solar and wind energy together account for around 9% (IEA, 2021). Other renewables, such as geothermal energy and biomass, have an even smaller share. These figures clearly demonstrate that despite rapid growth, renewable energy sources still cannot fully replace fossil fuels in electricity production or the global energy mix.

Table 1 illustrates the projected growth in renewable energy capacities by 2050. Solar capacities are expected to rise from 580 GW in 2020 to 30,000 GW by 2050, while wind power capacities are projected to increase from 700 GW to 10,000 GW. Despite these impressive forecasts, current capacities are still insufficient to achieve the complete replacement of fossil fuels (IRENA, 2021).

Table 1 Projected Growth of Renewable Energy Capacity by 2050

Capacity (G.W.)	2020	2030	2050
Solar	580	2000	30000
Wind	700	2000	10000
Hydro energy	1200	1500	2000
Geothermal	14	100	1000
Biomass	100	300	1000

Source: IRENA (2021)

Intermittency of Production and Efficiency of Energy Storage Technologies

The intermittency of energy production from renewable sources is one of the main challenges. Solar power plants generate energy only during the day, depending on the number of sunlight hours, while wind power plants rely on the presence of wind. The study by Zakeri and Syri (2015) indicates that intermittency can cause instability in the power system, particularly when renewable energy sources dominate the energy mix. Currently, energy storage technologies, such as lithium-ion batteries, can store energy for several hours to a few days. However, they are not capable of long-term storage needed to compensate for intermittency (IRENA, 2020) fully.

The intermittency of energy production from solar and wind power is a significant challenge. Solar energy is available only during the day and depends on the number of sunlight hours, while wind energy is subject to weather conditions. Energy storage technologies, like lithium-ion batteries, provide partial solutions to this intermittency. Table 2 shows the reduction in energy storage costs with lithium-ion batteries from 2010 to 2020. Despite the significant cost reductions, current storage capacities are still insufficient to address all the challenges of intermittency and the storage of electricity generated from renewable sources.

Table 2: Energy Storage Costs with Lithium-Ion Batteries

Year	Cost per kWh (USD)
2010	1100
2012	800
2014	600
2016	400
2018	250
2020	137

Source: IRENA (2021)

Lithium-ion batteries, which are the most widespread energy storage technology, have a limited lifespan and storage capacity. According to research conducted by Lund (2009), current energy storage technologies are still not sufficiently developed or economically viable on a large scale. Although new technologies, such as hydrogen fuel cells and advanced batteries, are being developed, they are not yet ready for widespread commercial application. The costs of energy storage continue to present a significant barrier to the mass adoption of renewable energy sources.

Economic Aspects and Political Measures

The transition to renewable energy sources has profound economic implications, ranging from costs and benefits at the macroeconomic level to specific sectors within the economy. Therefore, it is essential to consider the economic aspects of renewable energy, including the costs of technologies, financial incentives, economic benefits, funding challenges, employment impacts, and broader macroeconomic effects.

The costs of renewable energy sources have significantly decreased over the past few decades. According to IRENA, the average cost of installed solar photovoltaic systems fell from $4.8 per watt in 2010 to $0.68 per watt in 2020 (IRENA, 2021). Similarly, the costs of onshore wind turbines have dropped by about 40% over the same period, while offshore wind costs have decreased by approximately 30% (IRENA, 2021). Despite this reduction in costs, the high initial investment costs for renewable energy sources remain a significant barrier. These costs include not only the procurement and installation of equipment but also the expenses associated with infrastructure modernisation, such as smart grids and energy storage systems. Investments are high with long-term returns and may not be attractive enough for the private sector, which often prioritises rapid returns when evaluating investments in various projects.

Governments around the world use various financial incentives to encourage investments in renewable energy and make such investments attractive to the private sector. Feed-in tariffs, tax incentives, subsidies, and various clean energy incentive programs are examples of policies that have proven effective in increasing investments in renewable energy (REN21, 2023). Feed-in tariffs are fixed prices offered to renewable energy producers for each kilowatt-hour of energy produced. This ensures payment at prices slightly above market rates for a longer period, making investments profitable. This approach provides stable income for energy producers, reducing financial risk and

encouraging investments. Germany has successfully used feed-in tariffs as part of its "Energiewende" program, leading to a significant increase in installed solar and wind energy capacities (Agora Energiewende, 2021). Tax incentives and subsidies also play a crucial role in encouraging investment. For example, the U.S. government offers tax credits for investments in renewable energy through the Investment Tax Credit (ITC) program. These measures reduce the overall costs of renewable energy projects, making them economically viable (IRENA, 2021).

The transition to renewable energy sources brings numerous economic benefits. Besides reducing greenhouse gas emissions and improving air quality, renewable energy can stimulate economic growth by creating new jobs and developing new industries. Job creation is one of the most important economic effects of the transition to renewable energy. According to IRENA estimates, the transition to renewable energy could result in the creation of approximately 42 million jobs by 2050 (IRENA, 2021). These jobs include not only direct employment in the sectors of production, installation, and maintenance of renewable energy systems but also indirect jobs in supporting industries such as component manufacturing, research and development, and support services.

Additionally, the development of new industries and innovations in renewable energy technologies can drive economic growth. For example, China has become a leader in the production of solar panels and wind turbines, enabling rapid expansion of renewable energy in the domestic market and export of these technologies. This has created new jobs and increased economic growth in regions previously dependent on traditional fossil fuel industries (China National Energy Administration, 2021). Reducing healthcare costs is another significant economic benefit of the transition to renewable energy. Reducing air pollution associated with the transition to renewable energy can result in significant savings in healthcare costs. The World Health Organization (WHO) estimates that air pollution causes millions of premature deaths each year, and the transition to renewable energy can significantly reduce these healthcare costs (WHO, 2016).

Despite the numerous economic benefits, the transition to renewable energy faces funding challenges. The high initial investment costs require access to favourable financial mechanisms. Traditional funding sources, such as commercial loans, are often not flexible enough to finance large renewable energy projects. Green bonds and clean energy funds represent innovative financial mechanisms that can help mobilise capital for renewable energy projects. Green bonds are long-term financial instruments that allow investors to invest in projects with positive environmental impacts (IRENA, 2021). Clean energy funds, often established by governments and international financial institutions, can provide additional capital for the development and implementation of renewable energy projects (IRENA, 2021). Public-private partnerships (PPPs) also play an important role in financing renewable energy projects. These models allow for risk and benefit-sharing between the public and private sectors, increasing the financial sustainability of projects. Governments can use PPP models to attract private investments in infrastructure projects, including smart grids and energy storage systems (IRENA, 2021).

The transition to renewable energy can have a significant impact on employment. The global renewable energy industry employed around 11.5 million people in 2019, and that number continues to grow (IRENA, 2021). These jobs encompass a wide range of sectors, from manufacturing and installation to maintenance and management of renewable energy systems. However, the transition to renewable energy can also lead to worker displacement from traditional fossil fuel industries. Governments and industries need to develop retraining and support programs for workers who lose their jobs in fossil fuel sectors to facilitate their transition into new industries.

The transition to renewable energy can have broad macroeconomic effects, including increased energy security, reduced dependence on imported fossil fuels, and the promotion of sustainable economic growth. Increasing energy security is one of the key macroeconomic effects of the transition to renewable energy. Utilising domestic energy sources reduces dependence on imported fossil fuels and increases the resilience of energy systems to external shocks, such as geopolitical conflicts or oil price volatility (IRENA, 2021). This can have positive effects on national security and economic stability. Reducing dependence on fossil fuels can also yield significant economic benefits. Countries highly dependent on fossil fuel imports often face high import costs and price volatility. The transition to renewable energy can reduce these costs and provide a more stable and predictable energy supply (IRENA, 2021). This is particularly important for developing countries, which are often most vulnerable to changes in fossil fuel prices and geopolitics related to energy resources. Promoting sustainable economic growth is another important macroeconomic effect of the transition to renewable energy. The development of new technologies and industries associated with renewable energy can stimulate innovation, increase productivity, and create new markets. Moreover, investments in renewable energy often have multiplier effects on the economy, generating additional economic activity and employment in related sectors (IRENA, 2021).

While the transition to renewable energy brings numerous economic benefits, it also carries certain risks and challenges. Financial risks include market volatility, policy and regulatory changes, and uncertainties associated with technological advancements. Economic risks may include high initial investment costs, uncertainties related to returns on investment, and potential changes in energy demand. Technological challenges include the intermittency of energy production from renewable sources and the need to develop efficient energy storage technologies. These challenges require continuous investment in research and development and innovation to ensure a stable and reliable energy supply.

Conclusion

Harnessing the potential of renewable energy can achieve a sustainable energy transition that benefits both the economy and the environment. However, to reach these goals, coordinated efforts from all stakeholders in the process—governments, the private sector, and international organisations—are essential. There is a need further to encourage investment in research and development, support innovations,

and create incentive policies that will facilitate the faster integration of renewable energy sources into the energy mix. At the same time, it is crucial to work on educating and raising public awareness about the benefits of renewable energy to increase support and participation in projects. Only through a comprehensive and coordinated approach can we achieve a sustainable transition to renewable energy sources and ensure an energy system that is environmentally, economically, and socially sustainable.

Renewable energy is a key component of the global strategy to combat climate change and ensure sustainable development. In recent decades, renewable energy technologies have made significant advances, enabling substantial cost reductions and increased efficiency. Despite this, the transition from fossil fuels to renewable energy faces numerous challenges that must be overcome to achieve the complete replacement of fossil fuels. The first and perhaps most critical challenge is the intermittency of energy production from renewable sources like solar and wind power plants. This intermittency can cause instability in the power system, especially when renewable energy sources dominate the energy mix. Energy storage technologies, such as lithium-ion batteries and advanced storage systems, are crucial for addressing this issue. However, current energy storage technologies are still not sufficiently developed or economically viable on a large scale. According to research by Zakeri and Syri (2015), the costs of energy storage remain a significant barrier to the widespread adoption of renewable energy sources.

The second significant challenge is the need to modernise existing energy infrastructure. Power grids are designed for centralised energy production from fossil fuels, whereas renewable energy sources require a decentralised approach. Smart grids, which use advanced technologies for managing and optimising energy distribution, can enhance the reliability and stability of the energy system. However, modernising power grids requires substantial investments. The third challenge is the high initial investment costs associated with renewable energy sources. Although the costs of renewable energy technologies have significantly decreased over the past few decades, substantial initial investments are still required.

In addition to technical and economic challenges, the transition to renewable energy requires political support. Consistent and supportive policies are essential to encourage investment in renewable energy sources. Successful policy examples include feed-in tariffs, tax incentives, and clean energy incentive programs. However, policies must be stable and long-term to ensure investment security. It is also important to note that the transition to renewable energy can bring significant economic benefits. The economic aspects of the transition to renewable energy are complex and multifaceted. Although there are significant costs associated with installing new capacities and modernising infrastructure, the long-term economic benefits are substantial. Job creation, the development of new industries, reduced healthcare costs, and increased energy security are just some of the positive effects of the transition to renewable energy. To capitalise on these economic benefits, innovative financial solutions, consistent and supportive policies, and global cooperation are needed. Governments, the private sector, and international

organisations must work together to develop and implement strategies that will enable a sustainable and economically viable transition to renewable energy sources.

The long-term success of this transition will depend on our ability to adapt to new technologies and energy management models and our willingness to invest in a future that is environmentally, economically, and socially sustainable. Although there are significant challenges, continuous innovation, policy support, and global cooperation can enable a successful transition to renewable energy sources. Through a comprehensive and coordinated approach, we can achieve a sustainable energy system that benefits both the economy and the environment, ensuring a better future for all. By leveraging the potential of renewable energy while addressing the technical, economic, and social challenges, we can achieve the goals of reducing greenhouse gas emissions and achieving climate neutrality. A sustainable energy transition requires continuous investment in research and development, fostering innovation and public education, and the implementation of effective policies that support the development and integration of renewable energy sources.

The analysis clearly shows that despite significant progress, the current capacities of renewable energy sources, energy storage technologies, and political measures are still insufficient for the complete replacement of fossil fuels. The current share of renewable energy in the global energy mix, the issues of production intermittency, and the high investment costs confirm the hypothesis that a sufficient technological breakthrough has not yet been achieved. Additional investments, continuous innovation, and global cooperation are needed to overcome existing challenges and ensure a sustainable transition to renewable energy sources. The long-term success of the transition to renewable energy will depend on society's ability to adapt to new technologies and energy management models and the willingness of governments and the private sector to invest in a future that is environmentally, economically, and socially sustainable.

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