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REVIEW ARTICLE

The challenges of sustainable energy transition: A focus on renewable energy

Hosam M. Saleh*, Amal I. Hassan

Radioisotope Department, Nuclear Research Center, Egyptian Atomic Energy Authority, Cairo 13759, Egypt

*** Corresponding author:** Hosam M. Saleh, hosam.saleh@eaea.org.eg, hosamsaleh70@yahoo.com

ABSTRACT

Energy is both a fundamental necessity and a driving force behind human activities. Throughout history, energy consumption has steadily risen, evolving from basic needs like food and fire for early humans to complex industrial and technological requirements today. Transitioning to a sustainable energy system requires a policy framework that empowers developing nations to promote green industries, diversify their sectors, and accelerate growth while addressing climate change and related challenges. In response to the urgent need for a global transition towards sustainable energy sources, this research explores the pivotal roles of technology, research, and policy in advancing renewable energy solutions. Motivated by the growing environmental challenges associated with conventional energy sources, the primary goal of this study is to shed light on the multifaceted strategies that facilitate the widespread adoption of renewable energy and contribute to mitigating climate change. Through an extensive analysis of renewable energy technologies, research contributions, and policy frameworks, this research uncovers critical insights. Our findings reveal how technological innovations have revolutionized renewable energy sources, making them more efficient, affordable, and scalable. Furthermore, research efforts have identified new opportunities and addressed technical challenges, while also assessing the environmental and societal impacts of renewable energy adoption. Crucially, this study underscores the indispensable role of policy in driving renewable energy transitions. Governments worldwide play a pivotal role in incentivizing renewable energy development through financial incentives, regulatory mandates, and research and development support. Moreover, these policies aim to promote energy efficiency, conservation, and equitable access to sustainable solutions. The results of this research emphasize that the transition to renewable energy is not only a viable solution to climate change but also an opportunity to create green jobs, enhance energy security, and reduce greenhouse gas emissions. The potential for a sustainable future powered by renewable energy is within reach, and this study serves as a guidepost for realizing this transformative vision.

Keywords: sustainable energy; fuels; energy transition; fossil fuel; biomass; green industries; climate change; renewable energy

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1. Introduction

Energy serves as the lifeblood of modern civilization, powering various facets of our lives, including homes, industries, transportation, and communication systems[1]. However, an excessive dependence on fossil fuels has raised significant environmental and geopolitical concerns. Initiatives like Future Earth emphasize the urgent need for global energy transition towards sustainability.

This paper focuses on the challenges hindering the widespread adoption of renewable energy in sustainable energy transitions, recognizing that this shift is not just a choice but a necessity for the future of our planet.

In the face of pressing challenges such as climate change and environmental degradation, it becomes increasingly evident that our heavy reliance on fossil fuels is unsustainable. The environmental consequences of this dependence are profound, and the geopolitical tensions stemming from competition for these finite resources are concerning. While our need for energy is undeniable, the methods by which we meet this need must evolve[2].

The transition to sustainable energy systems is no longer a matter of choice; it is a global imperative. The future of our planet hinges on our ability to shift away from fossil fuels and embrace cleaner, more sustainable sources of energy. At the core of this transition lies renewable energy—a pivotal force that offers a path to a cleaner and more sustainable energy future[3].

Renewable energy has emerged as a linchpin in sustainable energy transitions. Its potential to reduce our reliance on fossil fuels and mitigate the impacts of climate change has catapulted its significance[4]. Abundant, accessible, and environmentally benign, renewable sources such as solar, wind, geothermal, and hydropower present an attractive alternative to conventional energy.

This paper embarks on a journey to explore the multifaceted challenges that obstruct the widespread adoption of renewable energy in energy transitions. From the intermittency of renewable sources to the high initial costs of implementation, these hurdles necessitate innovative solutions. By gaining a comprehensive understanding of these challenges, we aim to chart a course towards a greener, more sustainable energy landscape.

The journey towards sustainable energy is a collective endeavor, uniting researchers, policymakers, businesses, and communities worldwide. Together, we confront these challenges head-on, leveraging innovation, policy reform, and societal engagement to accelerate the transition to renewable energy and mitigate the dire impacts of climate change.

2. Climate and renewable energy

Recent data unequivocally affirm that the predominant source of greenhouse gas emissions resulting from human activities is the consumption of fossil fuels[5]. The global ramifications of climate change constitute one of the most pressing and formidable challenges faced by both societies and the environment. These effects encompass shifting climate patterns that jeopardize food production, escalating sea levels heightening the risk of catastrophic floods, and a scope and scale of climate change impacts that are truly unprecedented[6]. Failure to take immediate and decisive measures to combat these consequences will not only make adaptation more difficult but also substantially increase the costs associated with doing so. The highest energy-consuming sectors, including transportation, industry, and residential and commercial buildings, collectively contribute to a substantial portion of global energy demand and carbon dioxide (CO_2) emissions. Cement industry occupies a top position in terms of heavy consumption of energy and the generation of carbon dioxide; hence, great attention is dedicated to find alternative sustainable materials to reduce the use of cement in various fields[7–10]. The transportation sector, which relies heavily on fossil fuels, accounts for a significant share of energy consumption and is a major contributor to CO_2 emissions. Similarly, industrial processes and manufacturing facilities are energy-intensive and are responsible for a significant portion of both energy consumption and emissions. Lastly, residential and commercial buildings, driven by heating, cooling, and electrical needs, also represent a significant portion of energy use and emissions. Understanding the energy dynamics and emissions profiles of these sectors is crucial for advancing sustainable energy transitions.

A significant portion of the global energy system currently relies on fossil fuels, which contribute approximately 60% of greenhouse gas emissions responsible for driving climate change[11]. The Middle East, in particular, remains ensnared in an energy policy landscape marked by an imbalanced dependence on non-renewable energy sources, primarily fossil fuels. To address the mounting challenges posed by climate change, actions must be taken. The Paris Agreement, a cornerstone of international climate efforts, sets out the ambitious objective of limiting the rise in average global temperatures to below 1.5 degrees Celsius above pre-industrial levels. Achieving this imperative necessitates a transition to low-carbon energy sources, which account for two-thirds of global emissions[12]. Renewable energy, coupled with energy efficiency enhancements, holds the potential to deliver up to 90% of the required reductions in CO_2 emissions by 2050[13]. Consequently, renewable energy plays a pivotal role in the Nationally Determined Contributions (NDCs) outlined in the Paris Agreement. Currently, the level of detail within NDCs varies across nations, with varying degrees of in-depth research and quantitative information concerning the role of renewable energy in achieving GHG emission reduction targets[14]. The United Nations (UN) Environment has been at the forefront of advocating for innovative developments in solar, wind, geothermal, bioenergy, and various energy storage systems. These efforts aim to encourage leaders in the United States and Canada, both in the private and public sectors, to advance renewable energy adoption and energy conservation. In this context, the imperative of employing alternative energy sources to reduce carbon emissions and greenhouse gases becomes evident[15]. A report from the United Nations Environment Program (UNEP) underscores the transformative potential of energy systems following the COVID-19 crisis. The global response to combat the spread of the pandemic showcased the capacity to create a resilient, prosperous, equitable, and carbon-neutral society[16]. The pandemic disrupted supply chains, affecting the production and distribution of energy-related equipment, including solar panels and wind turbine components[16]. Delays in manufacturing and delivery had repercussions on renewable energy projects. Uncertainty caused by the pandemic made investors cautious, affecting the financing of renewable energy projects[17]. However, some governments introduced stimulus packages that included support for clean energy initiatives. Lockdowns and remote working encouraged discussions about energy efficiency and sustainability. Many individuals and organizations explored ways to reduce energy consumption and adopted remote technologies to monitor and control energy use[18]. Both the energy crisis and the pandemic have prompted discussions about the need for more resilient and sustainable energy systems. Many governments and organizations are considering green recovery plans that prioritize clean energy investments to stimulate economic growth[19]. The pandemic accelerated trends toward remote work and altered transportation patterns. Electric vehicles (EVs) gained more attention as a sustainable mode of transportation, and governments introduced EV incentives as part of their economic recovery plans[20]. The energy crisis and COVID-19 have underscored the importance of energy security, sustainability, and resilience in policymaking. Some countries are reevaluating their energy strategies to ensure they are better prepared for future crises[20].

Widespread reliance on renewable energy technologies also fosters job opportunities throughout the supply chain. Promoting the transition to renewable energy represents a golden opportunity to align with international climate objectives, stimulate economic growth, and generate millions of jobs, thereby enhancing human well-being[15]. Solar photovoltaics (PV) continued to be the largest employer within the renewable energy sector in 2018, accounting for a third of the workforce, with wind energy supporting an estimated 1.2 million jobs[21].

As of today, renewables contribute approximately 15% of global energy supply. Bioenergy represents approximately 10% of renewable energy, followed by 3% from hydropower, and 2% each from solar energy, wind power, and other renewable sources. According to certain models, renewables could supply nearly a third of the world’s energy by 2040[22].

Nevertheless, the renewable energy share in the energy sector must rise significantly, from 25% in 2017 to an ambitious 86% by 2050[23]. Technically viable and cost-effective solutions exist, providing a unique opportunity to accelerate the transition toward digitized, decentralized, and decarbonized energy systems. A coordinated global effort in this transformative energy endeavor holds the potential to create a more prosperous and inclusive world by facilitating energy transitions in numerous countries. Renewable energy offers a multitude of benefits, including economic growth, job creation, mitigation of climate change, and reductions in air pollution[13].

The transition of the energy sector toward renewables necessitates urgent global action to mitigate the consequences of climate change effectively. The most effective strategy for the future involves a holistic approach, combining renewable energy, energy efficiency enhancements, and secure, reliable, and affordable electricity. This approach has the potential to achieve over 90% of the necessary CO_2-related energy emission reductions required to meet established climate objectives. However, this energy transition requires a comprehensive, all-encompassing approach involving all segments of society[24].

The global pursuit of limiting global warming to 1.5 degrees Celsius above pre-industrial levels demands swift and comprehensive transitions across all sectors, including energy, agriculture, urban infrastructure and buildings, transportation, and industrial systems[25]. These multidimensional transitions necessitate cross-sector emission reductions, an extensive array of mitigation options, and substantial increases in investment. The imperative of sustainable development, balancing social welfare, economic prosperity, and environmental preservation, is intrinsically linked to the critical goal of limiting global warming to 1.5 °C[13].

3. Bioenergy technologies

Bioenergy derives from diverse biomass sources, such as forests, agricultural and animal waste, energy crops, urban solid waste, and other organic materials[26]. These resources can be harnessed for electricity, heat, or converted into gaseous, liquid, or solid fuels through various methods. The development of modern biorefinery systems optimizes biomass utilization, reducing land requirements while also minimizing waste. Integrated biorefineries enhance long-term soil quality through nutrient recycling. Advancements in technology that lower costs and promote comprehensive biomass utilization for food, feed, energy, and chemicals enhance its competitiveness against fossil fuels[27]. Efforts to develop more efficient biomass conversion pathways, particularly for lignocellulosic biomass, expedite the transition toward a competitive bio-based economy[27]. Bioenergy plays a pivotal role in the broader shift toward a bioeconomy, where bioproducts compete in terms of efficiency and cost. Current and emerging bioenergy sectors are influenced by policies, energy pricing, and technological innovations. The increasing utilization of solid biomass and liquid biofuels in international trade has become noteworthy[27].

Biomass stands out as the sole renewable and carbon-neutral resource capable of producing liquid biofuels and carbon-based chemicals, offering a sustainable alternative to fossil fuels in energy production and conversion[28]. Biomass energy conversion methods encompass thermal processes like direct burning, pyrolysis for solid, gaseous, and liquid fuels, gasification for gaseous fuels, and biological processes such as fermentation for ethanol and anaerobic digestion for biogas. For instance, in some countries like Brazil and the United States, ethanol derived from biomass is blended with gasoline as an automobile fuel[28]. The use of biomass for biofuel production has been a subject of debate, with concerns regarding its energy balance, potential competition with food crops, and impacts on water resources[29]. Innovative approaches, such as pyrolysis conducted under inert atmospheres, have been explored to maximize biomass utilization while mitigating environmental impacts[29].

Various forms of biomass, including crop waste, forestry residues, purpose-grown grass, timber crops, algae, organic waste, and municipal wastewater, have found applications across multiple renewable energy sectors[30]. Furthermore, biomass contributes to diverse renewable energy forms, including electrical energy, heat, renewable natural gas, biodiesel, and ethanol[30]. A notable approach involves the concept of biorefineries, similar to petroleum refineries, where biofuels and bioproducts are co-produced, promoting efficiency and cost-effectiveness[31]. Harnessing forest biomass residues for electricity generation supports sustainable resource management and circular production chains[31].

While algae represent a potential biomass source for energy production, challenges such as competition for resources and high production costs persist. Research endeavors aimed at enhancing algae growth and productivity offer promising solutions to these issues[32]. Additionally, the utilization of perennial herbaceous plants, such as Switchgrass, presents a more resource-efficient alternative to annual crops[32].

Switchgrass, abundant in the Great Plains, not only conserves energy and financial resources but also contributes nutrients back to the soil, making it a compelling option for bioenergy production, particularly in the production of liquid fuels like ethanol and methanol[33].

4. Renewable energy's role in sustainable transitions

Renewable energy stands at the forefront of sustainable energy transitions, poised to mitigate greenhouse gas emissions and drive economic growth. Solar, wind, geothermal, and hydropower are gaining global traction as nations seek cleaner, climate-friendly energy alternatives. The advantages extend beyond emissions reduction, encompassing job creation, energy independence, and reduced energy costs[34].

However, the adoption of renewable energy is not without its challenges. Issues like intermittency, grid integration, and the broader socio-political and ethical implications need careful consideration. The transition to renewables has far-reaching consequences for communities and industries alike[34].

Over the last five years, renewable energy markets have witnessed substantial growth, driven by technological advancements and cost reductions. Globally, renewable power output is projected to more than double between 2010 and 2035, with biofuel consumption following a similar upward trajectory[35]. The use of biofuels in aviation is also expected to expand significantly. Additionally, contemporary renewable sources are expected to contribute significantly to heat generation.

Figure 1 illustrates the complex degradation process through which organic matter is transformed into biogas during anaerobic fermentation. Bacteria play a crucial role in this process, breaking down organic material under specific environmental conditions. Biogas is the result of this degradation process, primarily composed of methane (CH_4). Various sources contribute to the production of biogas, including wastewater treatment plants and anaerobic digesters[36]. This valuable fuel source can be harnessed for various applications, including electricity generation and environmental emissions control within the waste industry[37]. Methanol (CH_4), carbon dioxide (CO_2), and nitrogen are the major components of waste gas (N_2) produced during this process[37].

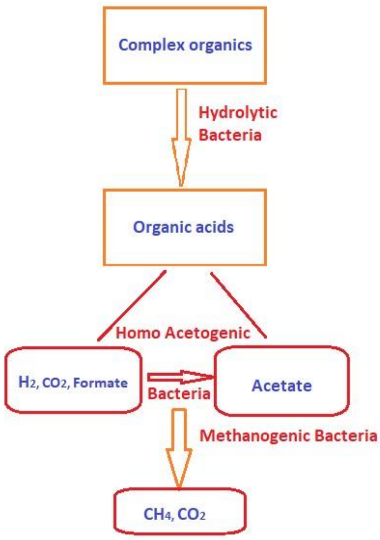

Figure 1. The degradation process of complex organics to generate biogas.

5. Renewable energy and its significance in sustainable energy transitions

In the last five years, the markets for renewable power, heating, and transportation have experienced significant growth. This growth can be attributed to increased confidence in the technologies, reduced prices, and new opportunities. Both well-established technologies, such as hydro, and newer ones, like wind and solar photovoltaic, have seen rapid deployment[6]. Globally, renewable power output is expected to increase by 2.7 times between 2010 and 2035. During the same period, biofuel consumption is expected to more than triple, from 1.3 million barrels of oil equivalent per day (mboe/d) in 2010 to 4.5 mboe/d in 2020. Although the use of biofuels in aircraft has not yet reached its full potential, it is expected to grow significantly by 2035. By 2035, the amount of heat generated by contemporary renewable sources is projected to have almost doubled, from 337 million tonnes of oil equivalent (Mtoe) in 2010 to 604 Mtoe. The percentage of renewables used to produce electricity is much higher than the percentage used for heat production or transportation, as shown in **Figure 2**.

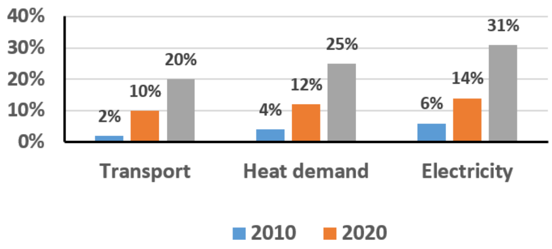

Figure 2. Distribution of renewable energy sources[38].

To address the needs of developing nations and global concerns about climate governance, green development has emerged as an economic model that facilitates the transition from a high-carbon to a low-carbon energy era. Green development offers a twofold benefit: it accelerates economic growth and enhances the prospects of a sustainable development transition. Furthermore, green development presents rapidly developing countries with an opportunity to depart from the traditional development paradigm of pollution-first, treat-later. It provides an alternate path to industrialization for developing nations still in the early stages of their growth trajectory. The potential impacts of adopting green development practices on preserving the planet's natural resources and mitigating climate change are profound[38].

6. The role of minerals in renewable energy

Clean energy technologies, including solar photovoltaics (PV), wind turbines, electric vehicles (EVs), and power storage systems, require significant amounts of minerals as raw materials[39]. With the increasing shift from fossil fuels to renewable energy consumption, global energy transitions have become dependent on these technologies, resulting in a rise in demand for these minerals. However, a country's ability to generate renewable energy is heavily influenced by the availability of mineral resources. Consequently, the demand for minerals has increased, driving the widespread adoption of renewable energy sources, electric cars, and rapid electrification in various economies. In contrast to conventional energy sources, renewable technologies require larger amounts of raw materials. For instance, a solar power plant generates three megawatts, while a conventional power station generates only one megawatt. Copper, indium or tellurium, cadmium, and silver are all critical for solar panel production, while lithium, cobalt, and nickel are essential for electric cars and energy storage batteries[40]. Most of these minerals are found in specific locations worldwide, complicating the clean energy transition process[41]. The renewable energy sector has become an attractive area for economic growth due to the length and complexity of the supply chain involved in its creation and use. Renewable energy usage not only contributes to economic growth but also reduces carbon emissions, generates new employment opportunities, and provides clean energy to society[42]. Low carbon economic development is achievable with the support of renewable energy development, as shown by the strong correlation between the two[43]. Two studies by Adebayo et al.[44] found that renewable energy usage, research spending, and economic development are interrelated. According to Caglar et al.[45], developing renewable energy businesses is the key to achieving sustainable development by reducing national economies' carbon emissions. Shrestha et al.[46] suggest that African nations can increase environmental sustainability and decrease their economies' sensitivity to price swings by adopting renewable energy sources. Kose et al.[47] found that the use of renewable energy contributes to economic development in more nations compared to nonrenewable energy. The use of renewable energy instead of nonrenewable energy also mitigates environmental impacts and reduces carbon emissions[45–49].

7. Renewable energy and economic development

Renewable energy has the potential to spur local manufacturing and economic expansion and can help nations tackle environmental governance challenges. However, the renewable energy sector is characterized by high capital and technology intensity, prolonged project running durations, and substantial initial outlays[49]. Therefore, an effective and robust political and regulatory environment is essential for large-scale investments in renewable energy. The renewable energy sector's high capital and technology intensity, coupled with a long payback cycle, can be a double whammy for developing nations' economy[50]. The objective of this research was to investigate the impact of renewable energy on green development in developing nations, with renewable utilisation as the primary explanatory variable.

Furthermore, in the renewable energy generation market, energy storage technology plays a key role in limiting its diffusion, and developing countries tend to adopt cautious generation policies to avoid high costs[51]. The development and use of renewable energy are also limited by the availability of ancillary facilities, supporting services, and economic conditions. The intermittent nature of renewable energy can have a negative impact on grid operations without technical support[52]. Moreover, the high initial costs and consumption required to develop the market may reduce the incentive for developing countries to invest in and develop renewable energy. In developing countries, the development of renewable energy alone could negatively impact economic growth in the short term[53]. With regards to resource consumption and environmental quality, developing countries face capital and technological constraints, and require financial and technological assistance to achieve low-carbon development[54]. This suggests that developing countries may be impeded by their economic power, technology, and business management practices when developing renewable energy. However, Hsu et al.[55] suggest that the globalization process has helped to develop renewable energy and has been effective in reducing greenhouse gas emissions. According to Li et al.[56], renewable energy and foreign direct investment can help African countries reduce carbon emissions. Africa needs support in the form of technology and skills to take advantage of its abundant renewable resources[57].

Promoting low-carbon technology and maintaining the global ecological balance are central to the concept of green development[58,59]. This concept aims to maximize economic growth while also protecting the environment and conserving scarce resources. Extensive global research on green development includes the study of green economics, green supply chains, green buildings, and sustainable development. Several investigations have focused on scientific methods for measuring green development[60,61]. Two examples of subjective evaluation methods based on fuzzy evaluation and hierarchical analysis are entropy weighting methods and optimum solution similarity ranking preference approaches. Evaluations are prone to bias because of the need for subjective prioritization of indicators[61]. Data envelopment analysis (DEA) models fall under the category of non-parametric estimation techniques. However, standard DEA models have a few issues. The epsilon-based measure DEA[62], the slack-based measure DEA[63], and the global Malmquist-Luenberger model[64] are some examples of enhanced DEA models that have emerged from these types of investigations. In order to achieve the goal of green development, factors such as economic openness[65], industrial structure, energy consumption structure, urbanization rate, government spending, technological innovation, and environmental regulation need to be investigated. According to Zhang et al.[66] and Zhuo et al.[67], their research found that technology innovation helped promote urban green growth.

The energy transition presents various avenues, difficulties, and prospects, but it also faces several threats. To ensure energy security and a transition towards renewable sources, factors such as sustainability, resilience, and vulnerability are crucial[68]. However, it should be emphasized that the energy transition process will require many nations to go through periods during which carbon-based energy sources will continue to dominate, as further underscored by the geopolitical and energy crises of 2022. Nevertheless, this trend is gradually diminishing, and it is likely that people will increasingly choose sources that cause less pollution and harm to ecosystems, natural resources, communities, and economic systems. Effective resource management is essential to accelerate structural transformation in oil-rich countries, where natural resources refer to technical and economic modernization. Technical training and education in a wide range of domains are necessary for energy transition and energy policy. Many of the analytical and evaluative tools necessary to comprehend the intricate dynamics and occurrences of the energy transition may be found in the social sciences[69]. Fundamental tools include trend analysis, energy demand forecasting, and innovation trajectory analysis. Training in this area is worthwhile since understanding and predicting these dynamics is crucial for competitiveness in terms of employment[70,71]. Investment in retraining and career reorientation, both of which are increasingly important in this field, is also essential. To realize the full potential of renewable energy, policymakers, researchers, and businesses need to work together to address these challenges and facilitate a smooth transition towards a sustainable energy system. This requires a policy framework that supports renewable energy investments, promotes innovation, and fosters international cooperation. Additionally, research and development efforts are needed to improve renewable energy technologies, increase efficiency, and enhance the integration of renewable energy into the grid.

Overall, renewable energy’s significance in sustainable energy transitions cannot be overstated. As the world continues to grapple with climate change and environmental degradation, renewable energy presents a promising pathway towards a more sustainable and resilient future.

8. The global transition towards sustainable energy

The research into energy transitions focuses mainly on the decarbonization of economic activity. It should be noted that more systemic shifts have been linked to new patterns of social and spatial inequality energy transition research[71].

As a result of the increasing diversity of forest uses and public expectations, the concept of sustainable forest management has been central to forest management. However, governments and other organizations have developed Criteria and Indicators systems for sustainable forest management to be defined and described to evaluate the range of forest activities and adapt their management accordingly[72]. These standards and indicators (value measurement) are intended for regional, national and international application. Economic criteria consider employment levels, timber prices, and other forest products. The health, productivity, biodiversity, soil, water, and carbon resources are assessed by environmental criteria. Social criteria consider the public’s participation in decisions on forest management, spiritual and aesthetic use of forests, and other related activities. They are all combined to allow sustainability assessments[73].

Renewable capacity expansion is expected to intensify during the next five years, accounting for about 95 percent of the increase in worldwide electricity capacity through 2026. Global renewable power capacity is expected to grow by more than 60% between 2020 and 2026, reaching moreover 4800 GW, which is the same as the present global power capacity of fossil fuels and nuclear power combined. The trend of renewable capacity growth during the 2021–2026 timeframe suggests that renewable power growth in the European Union as a whole is projected to outperform what the existing National Energy and Climate Plans (NECPs) for 2030 foresee. Using biomass for power generation, hydropower, geothermal energy, and onshore wind can now provide electricity competitively compared to generating electricity from fossil fuels as there are good resources and cost structures[74]. Typical solar photovoltaic (PV) prices in 2015 involve a decrease of 75 percent to 80 percent of their levels by the end of 2009. Between 2010 and 2014, the flat cost of electricity from solar photovoltaic energy was halved at the infrastructure level[75]. The most competitive such energy projects now regularly supply electricity for $0.8 percent per kilowatt-hour without subsidies, compared with $0.045 to $0.14 per kilowatt-hour in the case of energy Fossil fuels. These lower costs are subject to reductions for 2017 and beyond. A recent tender in Dubai for US$0.06/kWh illustrates this shift even in a region with a lot of fossil fuels. Solar PV is likely to lead the way, with competitive auctions aiming to meet the ambitious renewable power target of 500 GW by 2030. Utility-scale solar projects are estimated to account for more than 60% of all solar PV installations worldwide. Global onshore wind installations more than quadrupled in 2020, hitting an all-time high of around 110 GW[76]. **Figure 3** depicts the split of renewables deployment in terms of total final energy consumption according to Renewable Energy Agency 2050[77].

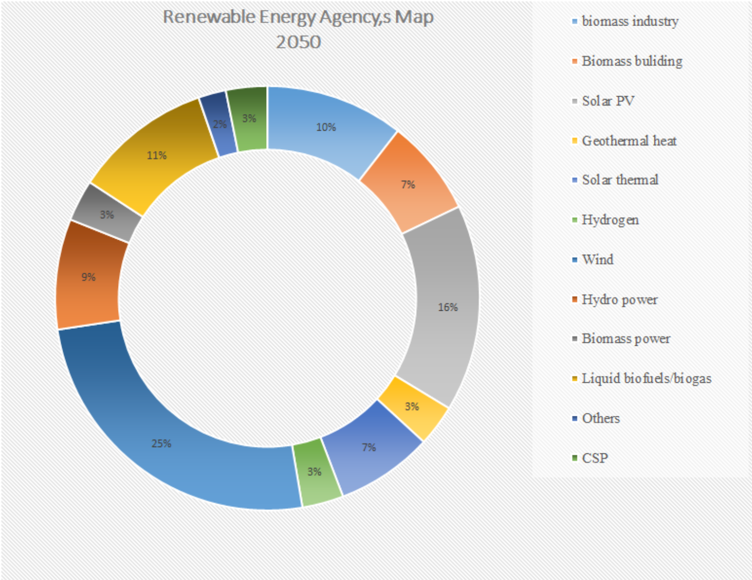

Figure 3. The renewables deployment in terms of total final energy consumption according to Renewable Energy Agency's' 2050[77].

Offshore wind has emerged as one of the most cost-effective sources of electricity[78]. As technology advances and installation costs fall, the cost of onshore wind is comparable to, if not cheaper than, the cost of fossil fuels. Furthermore, without financial backing, wind projects around the world continue to deliver electricity at a steady price of US$ 0.05 to US$ 0.09/kWh, with the top projects costing even less[79]. Except for onshore winds in island plazas, concentrated solar power and onshore wind are significantly more expensive now among the choices for generating power from and excluding fossil fuels. However, these technologies are still in their infancy in terms of deployment and are essential sources of renewable energy and will play an increasing role in the energy pool in the future as their costs will continue to decline. The costs of more mature technologies in renewable energy generation—biomass for energy, geothermal, and hydropower—have generally been stable since 2010[80]. However, when economic resources remain untapped, these mature technologies can provide some of the cheapest types of electricity compared to any other source. Renewable energy generation has increasingly been competing with fossil fuels without financial support[81].

The energy transition must significantly lower emissions while delivering adequate energy for economic growth. According to the research, the world economic activity's CO_2 emissions intensity must be lowered by 85 percent between 2015 and 2050, and CO_2 emissions must be cut by more than 70 percent compared to the Reference Case in 2050. As a result, yearly energy-related CO_2 emissions are expected to fall by 2.6 percent on average, or 0.6 Gigatonnes (Gt) in absolute terms, culminating in 9.7 Gt of energy CO_2 emissions per year in 2050[82]. The International Renewable Energy Agency examined options for global energy development from two main perspectives: the first is the route set by current and planned policies. The second is a cleaner and more climate-sensitive path that relies on the more ambitious employment of renewables and associated technologies. In the light of this report, the way forward, the first track or current plans provides a baseline comparison for the energy transition[83]. Renewable energy systems with a low starting point necessitate the highest yearly growth rates. The same may be stated for several renewable end-use sector technologies, such as solar heating and hydrogen. This scenario is based on existing energy plans, as well as other established goals and policies in the Paris Agreement's climate commitments[84]. Examine other opportunities to expand or improve low-carbon technologies and approaches, such as renewable energy, energy efficiency, and electrification, as well as the role of other technologies. Develop a viable and realistic energy transition scenario, dubbed the "State of the Renewable Energy Roadmap" in other publications. The scenario focuses primarily on reducing energy-related carbon dioxide emissions, which account for about two-thirds of global greenhouse gas emissions. With cost-benefit analysis and investment needs of low-carbon technologies around the world to achieve the expected transition of the energy sector[85]. Furthermore, lower renewable energy costs generate significant savings through electrification of the transportation and heating sectors. Renewable energy-based heating and transportation solutions alone can provide two-thirds of the energy emissions reductions needed to meet agreed international climate goals[85]. The Renewable Energy Roadmap indicates that renewable energy sources can offset 60% or more of the total final energy consumption for many countries. China's renewable energy proportion in its energy use might expand from 7% in 2015 to 67 percent in 2050, while the European Union's renewable energy share could jump from roughly 17 percent to more than 70%. India and the United States could see a two-thirds increase or more[86].

The cost savings from reduced air pollution, improved public health, and reduced environmental damage will far outweigh these costs. The incremental costs of transforming the global energy system could reach $7.1 trillion annually in 2050, but the cost savings from reduced air pollution, improved public health, and reduced environmental damage will far outweigh these costs[87]. Compared to the current approach to labor, this transformation process will enhance the global energy system's economic, social footprint, and improve welfare, GDP, and employment rates[88]. In the global economy, GDP will rise by 2050 in both the reference and transformational scenarios. As the transformation in the global energy system adds economic activity to the growth that can be expected within the current approved work approach, the cumulative profit resulting from the rise in GDP from 2018 to 2050 will amount to about 52 trillion US dollars[89]. These investments must be infused into an energy system that prioritizes renewables, efficiency, and related infrastructure to ensure a climate-secure future. By adopting a different mix of energy investments and adding only $15 trillion to the total amount of investment, the global energy system can be highly climate-resilient with cost-effective renewable energy technologies focused on efficient use[90]. And $2.3 trillion—about 2% of global GDP-will need to be invested each year to achieve the shift towards low-carbon energy technologies. This is nearly half a trillion dollars more than what is being invested in current plans. While global cumulative investment in energy by 2050 will increase by 16%, its total composition will shift decisively away from fossil fuels[91].

Renewable energy sources like solar, wind, and hydropower have gained significant attention in recent years as a potential solution to the challenges posed by climate change and environmental degradation. While transitioning to renewable energy sources can be challenging, there are several successful case studies of renewable energy implementations and sustainable transitions that can serve as models for others to follow.

One such case study is the city of Copenhagen, Denmark, which has set a goal of becoming carbon-neutral by 2025. To achieve this goal, the city has invested in a range of renewable energy sources, including wind and solar power. Copenhagen also encourages sustainable transportation options, such as bike-sharing programs and electric buses, to reduce emissions from transportation.

Another successful case study of renewable energy implementation is the state of California, which has set ambitious goals for transitioning to renewable energy sources. By 2045, California aims to be powered entirely by renewable energy sources, such as wind and solar power. To achieve this goal, the state has implemented a range of policies and incentives to encourage the development and deployment of renewable energy technologies. In addition to these examples, there are several other successful case studies of renewable energy implementations and sustainable transitions. In Costa Rica, for example, renewable energy sources like hydropower and geothermal power provide more than 99% of the country's electricity. In Germany, the

Energiewende (energy transition) policy has led to significant investments in renewable energy sources like wind and solar power, and the country now generates more than 50% of its electricity from renewable sources.

Successful renewable energy implementations and sustainable transitions share several common characteristics, including political will, strong policies and incentives, and a commitment to community engagement and participation. These factors can help overcome the technical, financial, and institutional barriers to renewable energy adoption, and ensure that the benefits of renewable energy sources are shared widely and equitably. Challenges and Opportunities in Large Economies' Transition to Clean Energy

In the United States, the transition to sustainable energy sources is marked by a series of challenges. These include the need to reconcile substantial energy demands with sustainability goals[92]. Overhauling the nation's energy infrastructure while bridging political divides on environmental policies remains a formidable hurdle. Nevertheless, the U.S. has implemented various policy initiatives, such as federal tax incentives for renewable energy projects and ambitious emissions reduction targets. These policies have contributed to a notable increase in renewable energy adoption rates, with wind and solar energy leading the way. The growth of renewable energy industries has not only advanced environmental objectives but has also generated substantial employment opportunities, underscoring the economic benefits of this transition[93].

Energy policy in the late 20th century underwent a significant shift, primarily aimed at deregulating energy markets to reduce end-user costs. These reforms, though varying in their implementation between federal and state levels, led to the removal of gasoline price regulations, the liberalization of natural gas extraction, and the breakup of integrated utility monopolies[94]. These changes paved the way for independent power producers to enter the electric generation markets, driven by the belief that competition would enhance efficiency and address the well-recognized inefficiencies of regulated monopolies[94].

However, the energy policy landscape of the 21st century faces a different set of challenges. It revolves around the critical issue of global climate change and the urgent need to significantly reduce carbon dioxide (CO_2) emissions and other greenhouse gases linked to the extensive use of fossil fuels as primary energy sources. 36 Concurrently, there is a growing imperative to confront longstanding local environmental damages and disparities associated with energy production and consumption. This means that solutions to climate change must be accompanied by initiatives to rectify environmental injustices.

The complexity of the climate change problem necessitates a collective approach, as private markets alone are unlikely to resolve it. The core challenge arises from the fact that fossil fuels gained dominance as energy sources due to their reliability and low cost. These energy-dense resources are easily storable and transportable over long distances, making them suitable for energy infrastructure that ensures energy availability when and where it is needed[95].

In contrast, current zero-emission technologies lack the favorable characteristics of fossil fuels. Electricity, for instance, is expensive to store with existing technology. Wind and solar power generation are not dispatchable, meaning they produce energy based on weather conditions, which may not align with end-users' demand patterns. Additionally, despite technological advancements, solar and wind generation remains costlier than fossil fuel-fired generation in many regions due to inconsistent resource availability. Even alternative approaches like fossil fuel generation with carbon capture and storage (CCS) and low-carbon fuels like hydrogen pose cost challenges with current technology[96].

Addressing these challenges necessitates a substantial reduction in CO_2 emissions while ensuring a reliable energy supply for on-demand consumption. Achieving these dual objectives will likely require significant policy-driven investments in new energy infrastructure, encompassing generation, transmission, storage, and distribution of zero-emission power. The key policy question then becomes how to incentivize these essential investments without unduly burdening end-users with increased costs.

China faces its own set of challenges on its journey towards sustainable energy. The country grapples with severe air pollution, energy security concerns, and the delicate task of harmonizing rapid economic growth with sustainability imperatives[97]. However, China has responded with significant investments in clean energy, solidifying its position as the world's largest producer of solar panels and wind turbines[98]. Ambitious targets for electric vehicle adoption have also been set. These efforts have led to China's prominent global role in renewable energy capacity, particularly in wind and solar power. Notably, the rapid expansion of the renewable energy sector has translated into substantial emissions reductions and increased energy security. According to the International Energy Agency (IEA), China's energy consumption in 2020 accounted for nearly 90% of the country's total CO_2 emissions[99]. As a result, achieving carbon neutrality hinges on a profound transformation of China's energy sector, making energy transition a linchpin in the broader decarbonization of the economy and society. Despite China's robust targets for energy transition, numerous challenges persist within the energy sector. In terms of energy supply, fossil fuels continue to dominate, and the issue of overcapacity looms large[99]. The distribution of renewable energy resources in China remains mismatched, with renewable energy hubs concentrated in the northwest, while the highest electricity demand resides in the east. Energy consumption patterns are becoming increasingly intricate, demanding greater flexibility in the power system to manage the evolving load profile and diverse regional energy distribution[100]. Furthermore, China's economic growth continues at a substantial pace, and renewable energy alone cannot fulfill the escalating energy demands of the expanding economy. Developing effective incentives to promote renewable energy consumption remains a pending challenge[101]. To address these formidable challenges in the energy transition, renewable energy has emerged as a pivotal instrument of change and has garnered substantial attention. China boasts abundant reserves of renewable energy sources, and recent years have witnessed impressive strides in their development. Currently, renewable energy accounts for nearly 30% of China's electricity generation[102]. China has demonstrated a steadfast commitment to renewable energy, setting ambitious targets, with the aim of renewable energy generation constituting over 50% of the country's total installed power generation by the conclusion of the 14th Five-Year Plan[103]. Projections indicate that by 2060, China intends to invest approximately RMB 122 trillion in establishing a new power system predominantly reliant on clean energy sources[104].

India's sustainable energy transition journey is marked by unique challenges and opportunities. The nation faces issues related to energy access and energy poverty, particularly in rural areas[105]. Grid infrastructure development is essential, as is the delicate balance between economic growth and environmental concerns. India's policy initiatives, such as the National Solar Mission and the UJALA program, aim to drive renewable energy adoption[105]. The country has set ambitious targets, with the goal of achieving 175 GW of renewable energy capacity by 2022. India's progress is particularly notable in the field of solar energy, and it continues to explore wind, hydro, and biomass sources. Innovative financing models and the decreasing cost of solar power have played significant roles in driving renewable energy growth in India. India stands out as the lone major economy making significant strides across all facets of the energy transition[106]. Despite this commendable progress, India's overall ranking remains relatively modest, coming in at 67 out of 120 countries in terms of the comprehensive energy transition. The WEF underscores the critical importance of maintaining this transition momentum in India, particularly to align with its international commitments for carbon reduction[107,108].

India has committed to achieving net-zero emissions by 2070 and has heightened its ambitions in its revised Nationally Determined Contribution (NDC) by aiming to reduce emission intensity by 45% compared to 2005 levels. Additionally, the nation targets generating 50% of its power from non-fossil fuel sources by 2030[108].

India's energy landscape has shown signs of improvement in sustainability despite its predominant reliance on carbon-intensive sources. Over the last two decades, India's energy consumption has more than doubled, fueled by its status as the fastest-growing major economy. This upward trajectory in energy demand is expected to persist, resulting in a continued need for increased energy imports to meet this growing demand[109].

To accomplish its ambitious goal of installing 500 GW of non-fossil fuel power generation capacity by 2030, India will need substantial investments and modernization of its grid infrastructure. Accelerating the energy transition can unlock a myriad of opportunities for India, including the creation of millions of jobs, enhanced energy security, and a tangible reduction in nationwide greenhouse gas emissions[110].

Globally, the renewable energy sector already employs 11.5 million individuals, with an estimated 24 million new jobs anticipated by 2030. India has the potential to lead the world by fostering one of the largest green workforces and by establishing a domestic supply chain for critical battery materials through recycling, thereby making significant contributions to the fight against climate change, both at the national and international levels[111].

India has already made substantial headway in green energy production and aspires to become a net-zero emitter of CO_2 by 2070, with at least half of its power generated from non-fossil sources by 2030. The country's abundant resources, including its extensive coastline, ample sunshine, and vast expanses of unused land, position it as a potential global leader in wind and solar energy production[97].

The urgency of reducing carbon emissions necessitates swift action and substantial investments. Although fossil fuels currently maintain a price advantage over renewables, governments can play a pivotal role in making renewables economically viable by investing in the sector and scaling up circular energy practices. India's progress in renewable energy production, combined with its potential in sustainable energy storage and the burgeoning battery recycling and reuse industry, places it in a prime position to steer the world towards a future with net-zero carbon emissions, setting an example for others to follow[112].

Large economies confront the intricate task of harmonizing massive energy demand with sustainability objectives. The scale of infrastructure requirements necessitates substantial investments in grid upgrades and clean energy projects[97]. The economic ramifications of transitioning away from fossil fuels are multifaceted, encompassing potential job displacements in traditional sectors alongside job creation in clean energy industries. Leveraging economies of scale presents an opportunity, as does fostering innovation in technology and financing models.

9. The challenges of sustainable energy transitions

Renewable energy is growing steadily globally, driven by the falling cost of technologies and the need to reduce greenhouse gas emissions. Renewable energies in 2016 accounted for 17.5% of global final energy consumption and are expected to reach 50% by 2040. Solar and wind energy capacities have evolved, and between 2009 and 2018, the actual installed capacity of renewable energy in the world increased by 100 gigawatts annually. In 2018, it reached 1179 gigawatts[113]. This growth is expected to continue between 2019 and 2030, reaching an additional capacity of 2000 GW, of which solar energy represents 60%[114].

As solar and wind energy production increases, grid operators need new equipment to bring flexibility into the operation of the entire power system. While some solutions are market-based, others require investment in modern technology solutions. The rapidly growing reserves are in thermal generation, pumped hydropower, reinforced transmission and distribution networks, and control devices[115]. Digital, greatly expanded storage capacity and demand-side management with heat pumps, electric boilers, and battery systems to store energy from renewable sources are just some of the energy system investment areas[116]. The energy system transformation will involve more than one billion electric vehicles worldwide by 2050[116].

Investments in charging infrastructure and electrification of rail systems could total $298 billion annually. To further strengthen the system's synergies, renewable hydrogen—that is, hydrogen produced from renewable energy sources—can meet approximately 19 exajoules' (1018 joules) of global energy demand. But this would mean adding one terawatt of electrolyzes capacity by 2050 at an average investment cost of $16 billion annually globally. Renewable heating, fuels, and direct use investments, which were around $25 billion in 2019 (IEA, 2019), will need to triple to $73 billion per year over the next three decades. The biggest problem facing the Middle East and North Africa region is adhering to the Paris climate agreement's obligations to reduce greenhouse gas emissions[117]. The Middle East and North Africa region witnessed a more than 100% increase in carbon dioxide emissions from 2000 to 2010. Decarbonization of the electric power and transportation sectors are the key sources of greenhouse gas emissions in the region, which can help limit these emissions[118]. However, the best way to achieve the desired rate of decarbonization is to increase the proportion of sustainable energy sources. Although the Middle East and North Africa region is one of the regions most affected by climate change, only 6.3% of global investments in renewable energy in 2017 were allocated to Africa and the Middle East combined[119]. In addition, the IEA estimates that the Middle East and North Africa (MENA) will account for a large share of the growing global energy, but lacking sustainable, reliable, and earmarked funds in the MENA region is an obstacle to stimulating and encouraging sustainable energy markets. The scarcity of funding is owing to higher investment risks, a lack of local SMEs, and local banks' experience with boosting the viability of sustainable energy projects[120].

The optimization findings show that including biomass in the power generating mix can result in base-load behavior with moderate fluctuations, even when solar and wind power output is high. This renewable energy source offers operational and economic benefits, with the potential to reduce power costs by up to 20%. In this study, biomass has been evaluated due to its well-developed state of the art. Future research can explore the feasibility of alternative non-intermittent energy sources, such as geothermal, which have a smaller footprint. Furthermore, using ammonia as an energy storage option could be an attractive and practical solution in a future economic system that is free of CO_2 emissions.

The availability of infrastructure to support renewable energy sources this includes the development of transmission lines, energy storage systems, and smart grids is considered a challenge[121]. Without these infrastructure developments, renewable energy sources cannot be effectively integrated into the energy grid. Governments and energy companies can work together to invest in infrastructure development to support renewable energy sources. Policy and regulatory frameworks can also pose a significant obstacle to sustainable energy transitions. For example, subsidies for fossil fuel industries can create an uneven playing field and hinder the growth of renewable energy. In addition, regulatory barriers can limit the ability of renewable energy companies to enter the market. Governments can address these challenges by implementing policies that promote renewable energy and phase out subsidies for fossil fuels[122].

The intermittency of renewable energy sources such as wind and solar is another obstacle to achieving sustainable energy transitions. Energy storage systems such as batteries can help mitigate the intermittency issue by storing excess energy during times of high production and releasing it during times of low production. Additionally, the integration of complementary renewable energy sources such as wind and hydropower can help address the intermittency issue[123].

Achieving universal sustainable energy is a daunting task that requires a range of solutions and strategies. In this article, we explore several possible scenarios that can help achieve this goal. One of the most promising approaches is the expansion of renewable energy sources such as solar, wind, hydropower, and geothermal. This can be achieved through a combination of technology development, investment, and policy incentives. Another key aspect of achieving sustainable energy is improving energy efficiency. This can be done through the adoption of energy-efficient technologies, building codes, and public awareness campaigns. Additionally, modernizing the power grid is essential to accommodate the growing share of renewable energy in the energy mix. Carbon capture and storage technologies can also play a role in reducing carbon emissions from fossil fuel power plants.

While some experts argue that nuclear energy can help bridge the gap to a fully renewable energy system, others have concerns about nuclear waste and safety. Ultimately, achieving universal sustainable energy will require a combination of solutions tailored to the specific needs and challenges of each region and country. This will involve collaboration between governments, businesses, and civil society to drive the necessary changes and investments. Additionally, promoting sustainable practices at the individual, community, and institutional levels will be crucial to achieve this goal.

Finally, public awareness and education can also be a significant challenge. Many people are not aware of the benefits of renewable energy or the impact of traditional energy sources on the environment. Governments and organizations can work to educate the public about renewable energy and its benefits, as well as encourage public participation in renewable energy projects.

10. The role of technology, research, and policy in advancing renewable energy and sustainable transitions

Mitigating climate change requires an immediate shift to a worldwide, low-carbon, renewable energy economy. From the land degradation, ecological disruption, and community displacement often associated with fossil fuel extraction to the serious and inequitably distributed environmental and health impacts of fossil fueled transport and electricity generation, switching to renewables is essential for alleviating the many conservation, health, environmental justice, and distributive problems associated with conventional energy use and extraction[124]. Renewable energy and sustainable transitions are critical to achieving a more sustainable and resilient future for our planet. Technology, research, and policy play essential roles in advancing these goals[125].

Technology has been a major driver of renewable energy development and deployment. Innovations in solar, wind, hydropower, and geothermal technologies have made them more efficient, affordable, and scalable[126]. For example, advancements in solar technology have led to the development of photovoltaic cells that are more efficient and can generate electricity even in low light conditions. Similarly, the use of offshore wind turbines has expanded the potential for wind energy generation, particularly in areas with high wind speeds. Research also plays a crucial role in advancing renewable energy and sustainable transitions. Research can help identify new opportunities for renewable energy development, as well as address technical and engineering challenges[127]. It can also help to better understand the potential impacts of renewable energy on the environment and society, and identify ways to mitigate those impacts. For example, research is ongoing in the areas of energy storage, smart grids, and electric vehicles to address the challenges associated with integrating renewable energy into the power grid[128].

Policy is also a critical factor in advancing renewable energy and sustainable transitions. Governments can incentivize renewable energy development through tax credits, subsidies, and regulatory mandates. Policies can also promote energy efficiency and conservation, as well as support research and development of renewable energy technologies[129]. Additionally, policy can help to promote equity and social justice by ensuring that communities that are disproportionately affected by environmental degradation have access to renewable energy and other sustainable solutions[130].

Recent years have seen a surge in the generation of renewable energy as a direct result of the pressing need to reduce emissions and transition away from the fossil fuels that now power the world's majority of power plants and transportation networks. A wide variety of renewable energy technologies, infrastructure, markets, and institutional frameworks have advanced and been made more accessible as a result of this. The International Energy Outlook 2017 predicts that, between now and 2040, the usage of renewable energy will expand more than any other energy source[131]. Over the period of 2015–2040, hydropower and other renewables are expected to expand at a faster rate than any other type of energy production, by an average of 2.8% year, thanks to technology advancements and government incentives in many nations[132]. As renewable energy technology develops, its price drops and its market share grow in many nations. Transitioning to modern, efficient, low-carbon energy systems at the lowest possible cost requires constant technological innovation[133]. Energy systems consist of supply technologies, demand technologies, and the infrastructures that link them.

Facilitating technologies aid in increasing the use of renewable energy across various industries. Technology and innovation are often discussed, however it is usually in the context of power systems[134]. However, there are substantial chances to offer further advantages by developing new markets for renewable energy in buildings, industry, and transportation, and none of these technological groupings has been designed with that objective in mind[135]. Electrifying automobiles, for instance, has several benefits, including the reduction of local air pollution and the opening of the transportation industry to renewable power sources, which are increasing quickly but were previously prohibited from displacement of fossil fuels. Expanding the use of renewable energy sources has several advantages, including improved air quality[136].

The physical infrastructure and automation technology needed to allow things like increased system integration, data collecting and dissemination, and efficient and effective demand response are together referred to as "enabling technologies". This has the potential to improve energy system performance, leading to wider usage of renewable sources[137]. It is commonly held that a country's technical development is crucial for the promotion and implementation of renewable energy consumption. In order to reduce the external cost and, by extension, the pollution caused by the production of renewable energy, better technologies are essential[138].

Long-term renewable energy consumption in OECD nations is highly influenced by technology improvement, according to a research by Alam and Murad[139]. Most OECD countries are wealthy, technologically advanced, and heavily engaged in international commerce, thus it is simpler for them to acquire and put to use cutting-edge resources for renewable energy production[140].

Energy efficiency may be increased thanks to technological advancements, according to studies[141]. However, development in technology is essential for improving energy efficiency, which in turn encourages the adoption of renewable energy sources.

Until renewable energy technologies mature and can compete with current energy technology alternatives, financial support mechanisms are vital tools to stimulate their adoption and innovation[142]. Cost reductions in renewable energy cannot be achieved as effectively via demand subsidies as they can through research and development[143]. Instead of directly subsidizing renewable energy equipment, many European countries offer feed-in tariffs as a subsidy on clean electricity. However, even when adjusted optimally, feed-in tariffs are much less effective than a first-best policy, leading to significant welfare losses in the case of too low an emission tax or large market power in the fossil-fuel sector[144]. When used as effective tools to accomplish mitigation, subsidies for continuously renewable energy result in substantially larger welfare losses than a carbon price regime. Because even a minor variation from the best value would lead to a quick increase in emissions or a loss of welfare, permanent subsidies for renewable energy are not only an expensive option to fulfill mitigation objectives, but also a highly dangerous tool[145]. As a result, it is clear that subsidy policy is not the best option for the future. Instead of relying on subsidies to the renewable energy industry, governments should implement carbon pricing, improve stable and predictable regulatory and investment environments, and create fair competitive environments for clean energy investment in order to successfully promote the low-carbon transformation of the global economy.

Table 1 provides a concise overview of how technology, research, and policy interact to drive the advancement of renewable energy and sustainable transitions while considering various aspects essential for success.

Table 1. Roles and aspects of renewable energy advancement: technology, research, and policy.

Aspect	Role
Technology advancements	1. Enhance the efficiency, affordability, and scalability of renewable energy technologies. 2. Drive innovations in solar, wind, hydropower, and geothermal systems. 3. Develop breakthroughs in energy storage and grid integration technologies.
Research and development	1. Identify new opportunities for renewable energy development. 2. Address technical and engineering challenges in renewable energy systems. 3. Understand and mitigate potential environmental and societal impacts. 4. Advance areas like energy storage, smart grids, and electric vehicles.
Policy framework	1. Incentivize renewable energy adoption through tax credits, subsidies, and mandates. 2. Promote energy efficiency, conservation, and renewable technology investment. 3. Ensure equitable access to renewable energy solutions for marginalized communities.
Enabling technologies	Develop physical infrastructure for system integration and efficient demand response. 2. Enable data collection and dissemination for improved energy system performance.
Market development	1. Create new markets for renewable energy in sectors like buildings, industry, and transportation. 2. Promote the electrification of transportation to replace fossil fuels.
Global collaboration	1. Facilitate international cooperation to share best practices and resources. 2. Harmonize standards and agreements to address climate change on a global scale.
Education and awareness	1. Raise public awareness and educate citizens on renewable energy benefits. 2. Mobilize support for policy changes and sustainable choices.
Investment and funding	1. Secure funding and investments from both the public and private sectors. 2. Fund research, development, and infrastructure projects in renewable energy.
Regulatory framework	1. Create stable and predictable regulatory environments to attract investments. 2. Build investor confidence for long-term planning and development.
Infrastructure development	1. Develop energy storage, transmission, and distribution systems for renewable energy integration. 2. Ensure seamless incorporation of renewables into existing grids.
Circular economy	1. Promote recycling and reusing materials to reduce waste and environmental impact.
Carbon pricing	1. Implement carbon pricing mechanisms to incentivize the transition to renewable energy.
Ecosystem restoration	1. Complement renewable energy transitions with ecosystem restoration efforts. 2. Enhance carbon sequestration and biodiversity for overall sustainability.

11. Conclusion

Renewable energy and energy efficiency are the two main pillars for achieving the desired transformation in the energy sector. Although the various paths are capable of reducing the climate changes, renewable energy and energy efficiency constitute the optimal path to fulfill the majority of the reduction, accomplishing more than 90% of the required emissions reductions in gas emissions with the necessary speed. Together, they can carbon-related energy, using safe, reliable, affordable, and widely available technologies. The negative consequences of fossil fuel use will hasten climate change and affect the economy and civilized security. As a result, establishing a regional cooperation relationship must include energy security and diversity, with a focus on renewable energy as the ultimate goal The World Energy Scenarios, as exploratory scenarios, show an increased decoupling of economic development and energy consumption in the future, which is most evident when innovation connected to new energy technology materializes at a faster rate One of the most prominent of these challenges is how to store renewable energy sources such as wind and solar energy. Developments in this field may allow consumers in the future to generate and store energy without the need for electricity companies.

Author contributions

Conceptualization, HS and AH; validation, HS and AH; formal analysis, HS and AH; data curation, HS and AH; writing—original draft preparation, AH; writing—review and editing, HS and AH. All authors have read and agreed to the published version of the manuscript.

Conflict of interest.

The authors declare no conflict of interest.

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