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Review

Economic and Technological Challenges in Zero-Emission Strategies for Energy Companies

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Abstract: The energy transition requires substantial financial investments and the adoption of innovative technological solutions. The aim of this paper is to analyze the economic and technological aspects of implementing zero-emission strategies as a key component of the transition toward a carbon-neutral economy. The study assesses the costs, benefits, and challenges of these strategies, with a particular focus on wind farms and nuclear power, including small modular reactors (SMRs). The paper presents an in-depth examination of key examples, including onshore and offshore wind farms, as well as nuclear energy from both large-scale and small modular reactors. It highlights their construction and operating costs, associated benefits, and challenges. The investment required to generate 1 MW of energy varies significantly depending on the technology: onshore wind farms range from $1,300,000 to $2,100,000, offshore wind farms from $3,000,000 to $5,500,000, traditional nuclear power plants from $3,000,000 to $5,000,000, while small modular reactors (SMRs) require between $5,000,000 and $10,000,000 per MW. The discussion underscores the critical role of wind farms in diversifying renewable energy sources while addressing the high capital requirements and technical complexities of nuclear power, including both traditional large-scale reactors and emerging SMRs. By evaluating these energy solutions, the article contributes to a broader understanding of the economic and technological challenges essential for advancing a sustainable energy future.

Keywords: cost of renewables; renewable energy; small modular reactors; nuclear energy; wind energy; net-zero emission

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1. Introduction

The pursuit of zero emissions has become a priority for energy companies worldwide, driving them to implement various strategies aimed at reducing greenhouse gas emissions [1]. To achieve reduction plans targeting net-zero emissions by 2050, companies, including energy providers, must adopt and strengthen policies promoting the production of clean energy. However, the transition to a low-emission economy requires substantial financial investments and advanced technological solutions [2]. Companies are adopting different strategies to meet these challenges, including adaptation strategies, prosumer strategies, and strategies for integrating sustainable technologies [3,4].

The study aims to analyze zero-emission strategies adopted by energy companies in their efforts to achieve carbon neutrality by 2050, assess their economic impact, assess the impact of national and international regulations, and identify key technological solutions. Depending on geographical location and climatic conditions, the strategies implemented may differ. In regions with low daily and annual solar radiation, investments in photovoltaics may not be an optimal solution, similarly to wind farms in areas with low wind

intensity. It is important to locate the wind turbines in windy areas with the appropriate positioning of the blades so that the energy production is most effective [5]. The choice of emission reduction technologies is also influenced by factors such as the availability of natural resources, the structure of the power grid, and local economic and social conditions. In addition, the structure of energy consumption and the level of development of energy infrastructure may determine whether distributed prosumer systems or large, central renewable sources should be the priority.

The adaptation strategy involves adjusting existing infrastructure and production processes to meet new environmental, legal, and social requirements, playing a key role in the transformation of energy companies toward zero emissions. In practice, this means not only modernizing technology but also implementing comprehensive organizational and operational changes that allow companies to meet increasing stakeholder expectations. Legal requirements, such as EU regulations on reducing greenhouse gas emissions and national emission standards, force companies to invest in technologies that reduce their carbon footprint. In the context of the energy crisis, EU regulations on solidarity mechanisms have emerged, which involve cooperation between states and businesses for sharing energy resources and jointly funding clean energy investments. This aims to ensure both energy security and the achievement of climate goals [6].

An example of infrastructure that helps reduce emissions is carbon capture and storage (CCS) systems in power plants, which can significantly lower CO_2 emissions. Carbon Capture and Storage (CCS) systems play a crucial role in the energy transformation process by significantly reducing greenhouse gas emissions. These technologies capture CO_2 emissions directly from power plants and industrial facilities, preventing them from being released into the atmosphere. Once captured, the CO_2 is transported and securely stored underground in geological formations, such as depleted oil and gas fields or deep salt caves. However, the costs associated with such investments are high. According to an IEA report, the implementation of CCS technology is estimated to cost between \$50 to \$350 per ton of captured CO_2, depending on the sector and the concentration of CO_2 [7]. In a typical coal-fired power plant, the process of capturing and compressing CO_2 can consume around 250 kWh of energy per ton of CO_2 captured. Since such a power plant generates approximately 1200 kWh of electricity per ton of CO_2 emitted, the CCS process would consume about 20% of the generated energy. This high energy demand reduces the overall efficiency of electricity production. Therefore, it is valuable to consider not only the direct costs of CCS technology but also the additional energy required to capture the CO_2, as it can significantly impact the overall energy efficiency and economic feasibility of the system [8]. Batteries used in renewable energy systems storage pose several challenges in terms of utilization and disposal due to their limited lifespan, resource-intensive production, and difficulties with recycling. These issues not only affect the economic viability of energy storage solutions but also present significant environmental concerns. Effective solutions are needed to minimize these impacts and improve sustainability. One approach is the development of second-life applications, where used batteries are repurposed for other energy storage functions, thus, extending their lifespan. Another solution is advancing battery recycling technologies, which can reduce the demand for raw materials and decrease waste.

The prosumer strategy focuses on involving energy consumers in energy production and consumption, such as through the development of photovoltaic micro-installations or energy storage systems for individual customers. Prosumer strategies promote local production of renewable energy, reducing dependence on fossil fuels and increasing energy efficiency. The prosumer strategy empowers individual customers, turning them from passive energy consumers into active participants in the energy market [9]. Through this

strategy, consumers can not only use energy provided by traditional suppliers but also produce it themselves, for example, through photovoltaic installations, small wind turbines, or other micro-installations [10]. A prosumer has the ability to meet their own energy needs and sell excess energy back to the grid, making them an equal participant in the market [11]. This type of activity promotes the decentralization of the energy system, increases its flexibility, and contributes to the reduction in greenhouse gas emissions. At the same time, this strategy requires investments in infrastructure, such as smart meters, energy storage systems, and digital platforms for managing energy flow, which generates additional costs but also creates new opportunities for savings and profits for prosumers [12]. This strategy requires modernization investments in infrastructure to integrate decentralized energy sources with the grid, which can cost up to $1–2 million per installed MW [13]. However, companies also benefit from reduced needs for expanding large power plants and lowering energy transmission costs over long distances.

The strategy of integrating sustainable technologies involves building new renewable energy sources, such as wind and solar farms, and developing advanced energy storage technologies. Although investment costs for offshore wind farms or battery energy storage systems are high—ranging from $2.5 to $4 million per MW for wind farms and $300 to $500 per kWh of capacity for battery storage systems—the long-term economic benefits, such as stable energy prices and the elimination of CO_2 emission-related costs, make this strategy economically viable.

The economic and technological challenges primarily relate to the need to incur high upfront costs for implementing advanced technologies, integrating networks and providing energy storage to ensure the reliability and continuity of energy supply. The research presented in this paper discusses key economic aspects related to choosing these strategies and technologies that play a decisive role in this transformation. Each of these paths requires not only financial investments but also careful planning to ensure that investments bring both environmental and economic benefits [14].

2. Literature Review

In the ongoing research on the economic and technological challenges of energy companies in the area of zero-emission strategies, the scientific literature offers many valuable studies. International scientific journals publish extensive analyses related to energy transformation, technological innovations and the costs of adapting companies to zero-emission requirements. Articles often focus on the integration of renewable energy sources and solutions that increase energy efficiency, which is a key element of energy companies' strategies.

Energy economics journals provide in-depth financial and economic analyses, indicating the long-term benefits of investing in clean energy. The literature also includes interdisciplinary studies that combine environmental, technological, and social aspects. These diverse sources provide energy companies with comprehensive knowledge necessary to develop and implement effective zero-emission transformation strategies.

The results of the literature review related to the discussed topic have been summarized and presented in Table 1, which allows for a synthetic comparison of key conclusions and the most important sources.

Table 1. Selected scientific articles discussing issues related to the transformation towards zero emissions.

Title of the Scientific Paper	The Most Important Issues Presented in the Paper
Achieving net zero emissions in Italy by 2050: challenges and opportunities.	An energy mix based primarily on renewable energy sources (at least 80–90% by 2050) is essential for achieving decarbonization in final energy consumption. Green fuels, produced from renewable sources, represent a crucial energy supply for sectors where electrification faces technical and economic barriers, such as heavy transport, aviation, and the chemical industry. However, the introduction of sustainable technologies in these areas requires substantial investments in research and development, as well as the construction of appropriate infrastructure, such as networks for the production and distribution of green hydrogen. At the same time, the European principle of "energy efficiency first" remains pivotal, emphasizing the priority of reducing energy consumption before developing new energy sources. Achieving climate neutrality also demands international cooperation and the implementation of policies supporting the transition, such as financial mechanisms or regulations promoting renewable energy sources. Equally important is raising public awareness and education about the benefits of the energy transition, which will contribute to greater acceptance and support for these initiatives [15].
Economic analysis of measures for GHG emission reduction.	Analyses conducted in studies have indicated that, through the reconstruction of thermal power plants, increased utilization of renewable energy sources, and measures aimed at enhancing energy efficiency, the largest reduction in greenhouse gas emissions is expected in the energy sector. The modernization of existing installations and the integration of energy storage systems, such as batteries and hydrogen technologies, play a crucial role in achieving these objectives. Additionally, the development of smart energy grids enables more efficient energy management and minimizes transmission losses, which also contributes to emission reductions. An important element of the strategy is the implementation of mechanisms supporting the growth of renewable micro-installations, such as photovoltaic panels and small wind turbines, which can significantly contribute to decentralizing energy production. Research findings clearly indicate that the energy sector, as the primary emitter of greenhouse gasses, has the greatest transformational potential, making it a priority area for decarbonization efforts [16].
Challenges in the decarbonization of the energy sector.	Challenges on the path to a decarbonized energy sector are identified in relation to environmental sustainability, energy supply security, economic stability, and social aspects. A global carbon tax is the most promising instrument to accelerate the decarbonization process. However, this process will be very challenging for humanity due to high capital requirements, competition between energy sectors for decarbonization options, inconsistent environmental policies, and public acceptance of changes in energy consumption. An additional challenge is the need to establish global standards and mechanisms to support international cooperation in emission reduction. The lack of consistency between legal regulations in different countries may hinder the harmonious achievement of climate goals. Ensuring a just transition is also a critical element, so that changes in the energy sector do not exacerbate social inequalities, especially in regions dependent on fossil fuels. At the same time, developing innovative technologies that enable the efficient use of renewable energy sources and their integration with existing energy systems will be essential. The growth of green jobs and appropriate public education are indispensable to ensure social acceptance and support for the energy transition [17].

Table 1. *Cont.*

Title of the Scientific Paper	The Most Important Issues Presented in the Paper
Economic effects of sustainable energy technology progress under carbon reduction targets: An analysis based on a dynamic multi-regional CGE model.	The implementation of sustainable energy technologies (SET) reduces electricity costs for residents, optimizes industrial structures, decreases fossil fuel consumption, improves energy use patterns, and lowers carbon emission taxes. The cumulative impact of renewable energy sources surpasses the effect of individual sources, with newer renewable energy options such as wind and solar energy outperforming traditional ones like hydropower and nuclear energy. Advances in alternative energy technologies have had varied effects on the global energy environment and economic development. The development of such technologies also contributes to increasing the energy independence of individual nations, which is particularly crucial in the context of global geopolitical challenges and the volatility of fossil fuel markets. Additionally, the implementation of SET supports the diversification of energy sources, enhancing the stability of power systems and minimizing the risk of energy supply disruptions. The impact of these technologies on improving residents' quality of life through reduced pollution emissions and better air quality cannot be overlooked, as it directly affects public health. In the long term, sustainable energy technologies provide a solid foundation for a green energy-based economy, fostering the growth of new industries and job opportunities in the green technology sector [18].
The impact of regional policy implementation on the decoupling of carbon emissions and economic development.	The study suggests that different cities should adopt measures tailored to their natural conditions and economic characteristics in order to transition to a low-emission economy. Utilizing the potential of regional cooperation is crucial for decoupling economic development from carbon dioxide emissions, thereby promoting sustainable economic growth and environmental protection in a way that benefits both sides. Additionally, it is essential to implement energy-saving technologies and develop infrastructure that allows for more efficient management of natural resources. Cities can collaborate on investing in modern public transport systems that reduce emissions, as well as in solutions based on renewable energy sources, such as joint wind or solar farms. An important component of the strategy is also the exchange of knowledge and experiences between regions, which allows for better adaptation of actions to local conditions. Adopting an integrated approach to spatial planning and developing public–private partnerships can further strengthen the effectiveness of efforts towards a transition to a low-emission economy [19].
The effects of environmental innovations and international technology spillovers on industrial and energy sector emissions–Evidence from small open economies.	Most technological investments are made in large countries with a leading technological position. Thus, emission reductions in small open economies, such as the Nordic countries, depend not only on domestic technological development but also on the spread of technology from foreign countries. The transfer of technological knowledge, innovation exchange, and international cooperation are key to the rapid implementation of zero-emission solutions in these regions. Moreover, the development of international markets for clean energy technologies can provide smaller economies with access to modern technologies, accelerating their energy transition. Cooperation with larger countries can also help reduce the costs associated with the implementation of new technologies, making them more accessible and attractive in the markets of smaller economies [20].

Table 1. *Cont.*

Title of the Scientific Paper	The Most Important Issues Presented in the Paper
Towards a low-carbon and beautiful world: assessing the impact of digital technology on the common benefits of pollution reduction and carbon reduction.	Achieving peak carbon neutrality requires more innovative solutions. Joint emission reduction programs can lower environmental management costs more effectively than individual emission reductions, enabling more efficient deployment of technologies on a larger scale. Digital technologies, such as artificial intelligence, data analytics, and the Internet of Things (IoT), can indirectly improve synergies by creating new opportunities for monitoring, optimizing, and managing energy consumption. Through intermediary channels, such as digital collaboration platforms, these technologies can support the promotion of innovations in green technologies, reduce energy intensity, and improve the energy structure. Furthermore, the development of digital solutions can contribute to better energy demand forecasting and increase the efficiency of entire energy systems, which is crucial for achieving carbon neutrality goals [21].
Digital finance, regional innovation environment and renewable energy technology innovation: Threshold effects.	The correlation between technological innovation in renewable energy and carbon neutrality has been extensively studied. Meanwhile, an efficient digital financial system that incorporates digital solutions in the financial sector, along with an environment conducive to innovation, is essential for promoting renewable energy. Digital finance can provide innovative funding mechanisms, such as green bonds and renewable energy investments, which can significantly accelerate the transition to cleaner energy sources. Additionally, leveraging blockchain technology and smart contracts can enhance transparency, efficiency, and traceability in the energy sector, thereby fostering greater investment in renewable energy projects. A strong synergy between digital finance and innovation in the renewable energy sector is crucial for scaling up sustainable energy solutions and achieving carbon neutrality [22].
Assessing the Impact of Fiscal Decentralization and Green Technology Innovation on Renewable Energy Use in European Union Countries: What is the Moderating Role of Political Risks?	Significant efforts must be made to develop the renewable energy sector and ensure affordable, clean, and reliable energy in order to achieve sustainable goals. Only by investing in renewable technologies and creating effective policies to support the green transition will it be possible to meet the growing demand for energy while simultaneously reducing greenhouse gas emissions. Despite this ambitious goal, fossil fuels still play a crucial role in the energy balances of EU member states. This is due to their availability, price stability, and existing infrastructure, which makes their complete elimination in the short term a challenge, especially in coal-dependent regions. Therefore, it is essential to simultaneously implement decarbonization measures and gradually replace fossil fuels with renewable energy sources, taking into account the specific needs and capabilities of individual countries [23].

Source: own elaboration.

The materials presented in Table 1 also highlight the significant role of strategies related to green energy, which can be further explored through the different approaches. According to Sulich and Grudziński [24], energy companies adopt three primary strategies to achieve green energy: isolation, market response, and adaptation. These strategies reflect the approaches firms take to align with environmental goals, market demands, and regulatory requirements in the transition to sustainable energy sources. It is also valuable to discuss and analyze these strategies in the context of the data presented, as they provide insight into the broader landscape of green energy adoption. The first is the isolation strategy, in which the company avoids or minimizes the impact of external factors, focusing on internal development. The next strategy is the market response strategy, where companies respond to the growing demand for renewable energy and to pressure from consumers and market regulations. Finally, the third strategy is the adaptation strategy, which includes active adjustment to changing market and environmental conditions by implementing new technologies and innovative solutions that enable the efficient use of green energy. Similarly, Borowski [4] distinguishes two approaches within the adaptation strategy: passive adaptation and active adaptation. Passive adaptation involves adapting to changes in a passive manner, reacting to them as they occur, often by implementing

regulatory requirements without major changes in previous practices. Active adaptation, on the other hand, means a proactive approach, where companies initiate changes themselves, investing in modern technologies, developing innovative solutions and implementing strategies that anticipate market and regulatory requirements, focusing on sustainable development and striving for zero emissions. Both concepts, those of Sulich and Grudziński, as well as Borowski, point to the key role of adaptation and flexibility in making strategic decisions by energy companies, which must face the growing requirements for green energy and the constant development of technology and regulations.

The papers presented in Table 1 demonstrate that achieving sustainable goals requires significant efforts to develop the renewable energy sector and ensure the provision of affordable, clean, and reliable energy. This can be achieved by investing in renewable technologies and supporting policies for the green transition. However, despite these goals, fossil fuels remain crucial in the EU energy balance due to their availability, price stability and infrastructure. Therefore, decarbonization measures must be implemented in conjunction with a gradual transition from fossil fuels to renewable energy, taking into account the specific needs and possibilities of each country.

3. Materials and Methods

The research methods applied in the study aimed at providing a comprehensive analysis of investments in renewable energy sources, particularly in the context of actions taken by energy companies and prosumers. The research was based on two main approaches: primary and secondary research, which together allowed for a complete understanding of the phenomenon under discussion. Figure 1 shows the concept of the desk research method, outlining the key steps involved in its application. These steps include defining and identifying scientific resources, as well as collecting, analyzing, and interpreting existing data to derive meaningful and valuable insights.

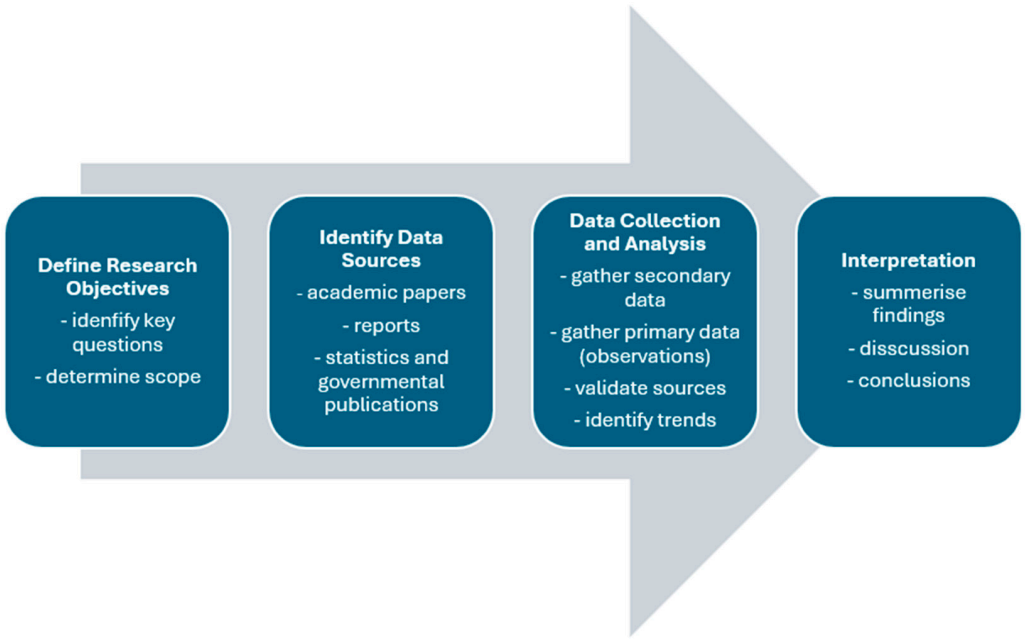


Figure 1. Stages of desk research implementation.

Primary research involved direct observations regarding investments in renewable energy sources, with a focus on photovoltaic and wind farms, as well as PV installations and wind turbines used by prosumers. Data were collected on the current status of these investments, including their size, efficiency, initial costs, and long-term results. The observations were conducted in various locations, enabling a comparison of the effectiveness

of solutions under different conditions. The use of primary research methods allowed for the collection of reliable and detailed data that directly addressed the research questions concerning the implementation of renewable energy sources in the context of the energy sector and prosumer activities.

Secondary research involved the analysis of available materials and information sources, such as industry reports, statistical data, and scientific articles from prestigious international journals, which are recognized for their rigorous peer-review process and high academic standards. In particular, reports published by the International Energy Agency (IEA), the European Environment Agency (EEA), as well as national reports prepared by the Polish Renewable Energy Association (PSEW) and Polish Power Grid (PSE), were utilized. Statistical data were sourced from databases such as Eurostat, the Central Statistical Office (GUS), and REN21's Renewable Global Status Report. Based on secondary research, it was possible to determine the costs associated with investments in renewable energy sources.

Secondary research relied on reputable publications recognized by the academic community to ensure that the analysis was based on reliable and credible sources. Additionally, numerous scientific articles published in leading international journals such as Energies, Renewable Energy, Energy Policy, Sustainability, as well as Journal of Cleaner Production were analyzed. These articles provided valuable insights into the theoretical and practical aspects of implementing renewable energy sources, including detailed financial analyses, environmental impacts, and strategies applied in different regions of the world. The recognition of these journals in the academic community, along with their high citation rates, confirms that the content they contain provides a solid foundation for formulating conclusions and conducting further research. Such a selection of sources helped establish strong theoretical and practical foundations for studying phenomena related to investments in renewable energy sources, further enhancing the credibility and substantive value of the analyses.

The materials used provided detailed information on current market trends, policies supporting the development of renewable energy sources, statistics on renewable energy production and consumption, as well as forecasts for sector growth. This enabled the comparison of primary research findings with a broad range of publicly available data, enriching the analysis with both global and national perspectives and allowing for the identification of key challenges and opportunities in this area. Analyzing these materials, including renowned scientific publications, also facilitated the verification of the results obtained from the primary research and provided solid theoretical foundations for drawing conclusions regarding the directions of investment in renewable energy sources.

The combination of both research methods allowed for a more comprehensive picture of the development of the renewable energy market and enabled more precise conclusions about the future of this sector, both in the context of large energy companies and individual investors—prosumers [25].

4. Results and Discussion

The pursuit of zero emissions presents not only technological challenges for energy companies but also organizational and structural ones. To implement ambitious emission reduction plans aimed at achieving net zero emissions by 2050, companies—particularly in the energy sector—must not only adopt policies promoting clean energy production but also make significant financial investments and adopt advanced technologies. Estimates of the global costs to achieve net-zero emissions by 2050 range from around $3.5 trillion to as much as $9 trillion per year. The figures given above vary depending on estimates published in different reports (e.g., Energy Transitions Commission, McKinsey & Company,

International Energy Agency (IEA)) [26–28]. These figures underline the significant financial commitment required for a global low-carbon transition.

A crucial aspect of this process is the development of long-term strategies that facilitate a smooth transition to renewable energy-based production while minimizing financial risks. Special emphasis should be placed on creating synergies between environmental and economic goals, which requires integrating sustainable technologies and fostering collaboration with diverse stakeholders, including prosumers and financial institutions.

Flexibility in implementing these strategies is essential, enabling companies to adapt to rapidly changing market, regulatory, and technological conditions. To address climate, environmental, and societal challenges, companies are adopting various approaches. These include adaptation strategies, which focus on aligning operations with external environmental, regulatory, and market requirements; prosumer strategies, which emphasize partnerships with consumers who produce energy for their own use and actively influence the energy sector; and sustainable technology integration strategies, which prioritize implementing modern technological solutions to enhance energy efficiency and reduce emissions.

Each of these strategies requires an appropriate financing model that ensures efficient resource utilization while achieving both environmental and business objectives. Analyzing financing mechanisms and available sources of capital is critical for understanding how companies can effectively pursue their energy transformation goals.

4.1. The Economic Aspect of Energy Transformation

The costs of investing in low-emission energy are significantly higher than those associated with fossil fuels. It is estimated that for every dollar spent on fossil fuels, an average of three dollars is invested in low-emission technologies. The total cost of fully decarbonizing the global energy system by 2050 could amount to $215 trillion, representing a 19% increase compared to a transition that does not account for climate goals. These estimates are based on analyses conducted by the International Renewable Energy Agency (IRENA) [29,30] and the International Energy Agency (IEA) [31,32].

Despite these high costs, the necessity of reducing greenhouse gas emissions compels action to finance various investments aimed at achieving net-zero emissions [33]. These investments include renewable energy sources (RES), such as wind farms, photovoltaic installations, and green hydrogen production [34,35], as well as technologies enabling the production of clean energy from coal, such as advanced carbon capture and storage (CCS) systems and low-emission coal-fired boilers [36,37]. These latter solutions can serve as critical transitional elements in energy transformation, particularly in regions heavily dependent on fossil fuels.

Investments in low-emission energy also yield measurable economic benefits. Long-term savings stem from reduced fuel expenditures, lower healthcare costs associated with environmental pollution [38], and the avoidance of potential carbon emission penalties. Increased investment in environmentally and socially friendly energy development delivers multidimensional benefits, not only in the context of climate protection but also in improving quality of life and reducing public health expenditures. Energy companies can reduce social inequality during the transition to renewable energy systems by offering financial support programs, equitable access to energy, and targeted investments in communities that are energy poverty. Collaborative efforts with local governments and NGOs can also help create inclusive policies and infrastructure to promote energy affordability and resilience.

Fossil fuel-based energy production generates significant amounts of air pollutants, such as particulate matter (PM2.5, PM10), sulfur dioxide (SO_2), and nitrogen oxides (NO_x).

These pollutants are direct causes of numerous respiratory, cardiovascular, and cancer-related illnesses [39]. According to studies by the World Health Organization (WHO), air pollution is one of the leading health risk factors, causing millions of premature deaths annually worldwide [40,41]. By replacing fossil fuels with clean energy sources, the overall air quality improves, leading to fewer illnesses and lower healthcare costs.

Investments in renewable energy sources, such as solar, wind, and geothermal energy, significantly reduce emissions of these harmful substances, leading to improved air quality. As a result, direct healthcare costs for treating pollution-related diseases decrease, as do indirect costs related to lost worker productivity, sick leave, and long-term health consequences [42].

From an economic perspective, initial increased spending on clean energy pays off over the long term through significant reductions in costs associated with maintaining societal well-being. Numerous economic models indicate that reduced healthcare expenses and improved economic productivity resulting from better environmental quality can yield benefits far exceeding the initial investment [43,44]. Consequently, the development of environmentally friendly energy should be viewed not as an expense but as a strategic investment in public health, social stability, and long-term economic sustainability.

Economically, this phenomenon of incurring additional upfront costs to achieve long-term savings is often referred to as "initial costs for long-term benefits" or the "costs and benefits shift" [45]. It is also frequently linked to the concept of "sustainable investment", which involves expenditures aimed at long-term improvements in public health, environmental protection, and quality of life in the context of sustainable development [46].

In a broader context, this phenomenon is also associated with the theory of "hidden costs" or "externalities", where the costs of negative environmental and health impacts are often overlooked in traditional cost–benefit analyses. Within the framework of sustainable investments, these "hidden costs" are accounted for, and investments in clean energy or improved energy efficiency become long-term solutions for reducing expenses related to diseases, pollution, and environmental degradation [47].

In economic terms, a related concept is "ecological capital", referring to the value of natural and ecological resources that must be preserved or invested in to reduce long-term external costs [48]. In public health, the term "preventive cost-effectiveness" emphasizes the benefits of early investments in preventing health or environmental issues before they become more expensive to address [49].

In short, this can be considered "strategic investments in long-term prevention" in the context of sustainable development and minimizing external costs, leading to a better balance of costs and benefits over the long term.

Energy transformation supports the creation of healthier and more sustainable communities. It encompasses not only the development of renewable energy technologies but also comprehensive adaptation of energy companies to new challenges. These companies must transform their business models, invest in infrastructure modernization, and develop employee competencies in environmentally friendly technologies [3,50].

This process can also help reduce social inequalities by creating new jobs in the green energy sector and in companies integrating renewable energy sources with existing systems [51]. Adapting energy companies also means improving energy access in developing regions through investments in local solutions, such as micro solar installations or small wind farms, which not only meet energy needs but also support local economic development.

Moreover, by adapting to the new reality, energy companies can implement solutions that minimize health burdens on the poorest social groups, who are most vulnerable to the adverse effects of environmental pollution. For example, phasing out coal-fired power

plants and replacing them with renewable sources can significantly reduce air pollution, providing direct health benefits to local communities [52].

Energy transformation is, therefore, not just a technological change but also a strategic adjustment by enterprises, enabling the achievement of sustainable development goals and the construction of a more equitable energy system [53]. Additionally, the development of new economic sectors, such as green hydrogen production, wind farm construction, and CO_2 capture and storage infrastructure, creates thousands of new jobs and stimulates technological innovation. These benefits demonstrate that financing energy transformation not only supports climate goals but also serves as a catalyst for sustainable economic development [54].

4.2. Technologies Supporting Zero Emissions

Achieving zero-emission goals requires investment in advanced technologies that will allow replacing traditional energy sources with more ecological solutions [55]. Renewable energy sources, such as wind, solar, geothermal energy and energy storage technologies, which enable stabilization of supply even in conditions of variable production, play a key role here. The development of lithium-ion batteries, flow batteries and other innovative solutions in the field of energy storage is the foundation for the efficient use of renewable energy [56].

Another important element of zero-emission technologies is the development of supporting infrastructure, such as smart energy networks, which allow for more efficient management of energy flows, minimizing losses and optimizing its consumption. Another important aspect is technologies related to carbon capture, storage, and utilization (CCUS), which allow for reduced emissions from heavy industry and fossil fuel-based power plants [57].

In addition, transport plays a significant role in achieving emission neutrality. The introduction of electric vehicles and the development of infrastructure for charging them, as well as research into the use of hydrogen as the fuel of the future, are key directions of transformation in this sector. Hydrogen, especially when produced using green energy, has the potential to replace fossil fuels in trucking, shipping, and aviation. The economic implications of transitioning industrial facilities to green hydrogen fuel include high initial costs for production, infrastructure, and technology integration. Green hydrogen, produced via electrolysis using renewable energy, is currently the most expensive type of hydrogen. In comparison, gray hydrogen, produced from natural gas, is cheaper but emits significant CO_2. However, green hydrogen offers long-term savings through lower operational costs, especially as renewable energy becomes more affordable, and plays a crucial role in reducing emissions in hard-to-abate sectors like steel and chemical production, where decarbonization is particularly challenging.

Advanced digital technologies such as artificial intelligence, data analytics and the Internet of Things (IoT) can support the achievement of zero-emission goals by improving process efficiency, better monitoring energy consumption and optimizing energy systems. Digitalization also enables better forecasting of energy demand and identification of areas requiring modernization [58,59]. Digital technologies like AI and IoT contribute to optimizing energy systems for zero-emission goals by improving efficiency through real-time monitoring, predictive maintenance, and optimizing energy distribution and usage. AI can analyze large datasets to predict demand fluctuations, while IoT devices enable better integration of renewable sources, enhancing grid flexibility. These technologies also support the management of energy storage systems, ensuring a consistent supply even with intermittent renewable energy sources.

Investments in green technologies not only contribute to reducing emissions, but also stimulate the development of new economic sectors, create jobs and support the development of an innovation-based economy. In this way, advanced technologies become not only a tool to combat the climate crisis but also a foundation for future sustainable development. Table 2 presents the key technologies and infrastructures supporting this transformation.

Table 2. Technological solution toward zero-emission.

Technological Solution	Key Aspects
Offshore Wind Farms	Offshore wind farms harness stronger and more stable winds at sea, enhancing energy production efficiency. However, they involve high investment costs and technical challenges, such as constructing structures resistant to extreme weather conditions. Development may impact marine ecosystems through noise, environmental changes, and disruptions to migratory routes. The construction and operation of turbines may affect local marine life, particularly seabirds and marine mammals, through habitat disturbance and collisions.
Onshore Wind Farms	Onshore wind farms are more cost-effective than offshore alternatives, making them accessible to many countries. While their efficiency may be limited by less stable winds, they remain a critical part of the energy mix, supporting renewable energy expansion and enabling local communities to benefit from affordable clean energy. They can pose a threat to bird migration.
Photovoltaic Farms	Solar energy, captured through photovoltaic farms, is a rapidly growing renewable energy source that significantly reduces greenhouse gas emissions. These installations require large land areas, which may lead to land-use conflicts, particularly in agricultural zones. Production of solar panels also involves raw material use and waste generation, posing challenges for achieving full ecological neutrality.
Gas Power Plants with CCS	Modernizing gas power plants with Carbon Capture and Storage (CCS) technology reduces CO_2 emissions by capturing and securely storing carbon underground. These plants serve as a transitional solution, ensuring stable energy supplies while renewable sources scale up. However, CCS technology requires substantial investments and further improvements to increase efficiency and reduce costs.
Fuel Switching to Green Hydrogen	Retrofitting energy facilities, such as power plants and industrial units, to use green hydrogen as a fuel is crucial for decarbonizing energy and industrial sectors. This transition addresses significant greenhouse gas emissions from these high-impact industries.
Nuclear	Nuclear energy is a reliable, stable, and greenhouse gas-free energy source. Investments in small modular reactors (SMRs) offer cost-effective, flexible, and quicker-to-deploy solutions compared to traditional nuclear plants. SMRs are especially suited for remote or infrastructure-limited areas.
Battery Energy Storage Systems Power Plants	Batteries store surplus energy for later use, ensuring grid stability amidst fluctuating renewable energy generation. Modern battery technologies, such as lithium-ion, provide high efficiency and long lifespans but require further advancements to address raw material availability and recycling issues. Battery systems are critical for integrating renewable sources like wind and solar into a reliable energy network.
Pumped-Storage Hydropower	Pumped-storage plants store excess energy by using it to pump water to higher altitudes, releasing it to generate electricity when demand peaks. This enhances the reliability of renewable energy systems, minimizes waste, and offers low operational costs. Challenges include environmental factors like water ecosystem protection and hydrological conditions.

Source: own elaboration based on [60–62].

The descriptions presented in Table 2 indicate that the implementation of modern technologies that support emission reduction and environmental protection includes various approaches that together create a comprehensive system of actions for sustainable development. Investments in renewable energy sources, such as onshore and offshore wind

farms, photovoltaics, and hydropower, are of key importance, which allow for a reduction in greenhouse gas emissions and the stabilization of energy systems. The modernization of gas power plants by implementing CCS technology and the transition to green hydrogen enable a more ecological use of existing infrastructure [63].

Energy storage, including the development of advanced batteries, is crucial for the stability of the energy system based on renewable sources, which are characterized by production variability. Hydropower additionally supports the balancing of the system, enabling efficient storage of energy in the form of water pumped to a higher level.

At the same time, the implementation of technologies requires solving the challenges related to them, such as the impact on the environment or the high cost of initial investments, which should be included in energy transformation strategies. The joint action of these solutions creates a solid foundation for achieving climate goals and environmental protection in a global perspective.

Companies investing in zero-emission technologies play a key role in the global energy transformation. Although the costs associated with decarbonization are high, the ecological, economic, and social benefits outweigh the potential financial burden. However, achieving climate goals requires international cooperation, political support, and the involvement of the private sector in the development and implementation of innovative technologies [64]. Only integrated actions will allow us to achieve climate neutrality by 2050. International cooperation fosters knowledge sharing, resource pooling, and coordinated policies in global forums such as COPs that drive clean energy adoption. By adopting common actions and coordinating them, countries can accelerate innovation, reduce costs, and implement sustainable solutions more effectively, ensuring a faster transformation towards a low-carbon future.

4.3. Economic Aspects of Building Wind Farms and Nuclear Power Plants

In this economic research section of the paper, a detailed comparison of the costs associated with different energy technologies will be presented. This will include examining the costs associated with building wind farms, both onshore and offshore, as well as the costs of building large nuclear power plants and small modular reactors (SMRs). By breaking down these costs, a clearer understanding of the economic feasibility of each technology and their potential contribution to a sustainable energy mix will be provided. The comparison will also highlight differences in scalability, operational efficiency, and the long-term financial implications of investing in each of these energy sources.

4.3.1. The Costs of Building Onshore and Offshore Wind Farms

The construction of wind farms, both onshore and offshore, plays a key role in the energy transformation and increases the share of renewable energy in the global energy mix. However, both types of installations differ significantly in terms of costs related to implementation, maintenance and the technology used, which has a direct impact on their economic profitability and the pace of implementation. Onshore wind farms are characterized by relatively lower investment costs, which results from easier access to construction sites, lower technical requirements, and lower costs of transporting components. Additionally, their operation and maintenance are also cheaper compared to offshore installations. However, restrictions related to the availability of suitable locations and often lower wind speeds can affect efficiency and energy production [65]. Offshore wind farms, despite higher construction costs, offer greater possibilities in terms of energy generation thanks to stronger and more stable winds in the open sea. These costs result from the need to build more advanced foundations, specialist installation vessels, and the expansion of the transmission infrastructure that must transport energy to the mainland. In addition, operating

offshore wind farms is more expensive due to the harsher environmental conditions that result in more frequent maintenance and more expensive repairs [66].

Despite these differences, both onshore and offshore wind farms contribute to the decarbonization of energy systems. However, their economic viability depends on factors such as support policies, access to cheap financing, technological development, and local geographical and climatic conditions. The key challenge remains to optimize the costs and improve the efficiency of both types of installations so that they can play an even greater role in the global energy transformation. Tables 3 and 4 provide a detailed analysis of the costs associated with the construction of wind farms [67].

Table 3. Costs per 1 MW generated energy related to the construction of onshore wind farms.

Cost Category	Cost Range [USD]	Description
Wind Turbines	800,000–1,400,000	Cost of a single turbine with a capacity of 1 MW, including manufacturing, transportation, and installation. Prices vary based on the manufacturer, technical specifications, and market conditions.
Foundations	150,000–250,000	Costs related to the preparation and construction of turbine foundations, including geotechnical surveys and earthworks.
Electrical Infrastructure	200,000–300,000	Covers installation of cables, transformers, and connection of the wind farm to the power grid.
Access Roads and Logistics	50,000–100,000	Costs for constructing access roads, transporting components, and logistics during the construction phase.
Permits and Consultations	20,000–50,000	Expenses for obtaining necessary permits, conducting environmental impact assessments, and organizing community consultations.
Operational and Maintenance (O&M) Costs	20,000–30,000 annually	Annual operation and maintenance costs for 1 MW, including servicing, repairs, and monitoring turbine performance.

Source: own elaboration based on [68–70].

From Table 3, it can be observed that the total cost of building 1 MW of an onshore wind farm ranges between 1,300,000 and 2,100,000 USD, influenced by factors such as location, turbine size, and logistical complexities. These costs encompass various components, including the purchase of turbines, construction, grid connection, land acquisition, and operational infrastructure. Although onshore wind farms generally require lower initial investments compared to offshore alternatives, the cost variability is significant, driven by terrain characteristics, permitting processes, and regional market conditions. Over time, continuous advancements in turbine technology and the achievement of economies of scale are expected to drive these costs down further, enhancing the feasibility and attractiveness of onshore wind as a leading source of clean energy.

From Table 4, it can be observed that the total cost of building 1 MW of an off-shore wind farm ranges from approximately 3,000,000 to 5,500,000 USD, significantly higher than onshore wind farms. These costs include specialized turbines, foundation structures, grid connections, and increased logistical challenges due to marine conditions. Despite higher

initial investments, offshore wind farms benefit from stronger, more consistent winds, leading to greater energy output and efficiency over time.

Table 4. Costs of Building Offshore Wind Farms per 1 MW generated energy.

Cost Category	Cost Range (USD)	Description
Wind Turbines	1,500,000–2,500,000	Cost of a single 1 MW turbine, including manufacturing, transportation, and offshore installation
Foundations	800,000–1,200,000	Costs for constructing offshore foundations such as monopiles, jackets, or gravity-based structures, depending on depth and seabed conditions
Electrical Infrastructure	400,000–600,000	Costs for installing subsea cables, offshore substations, and connecting the wind farm to the onshore power grid.
Installation and Transportation	500,000–1,000,000	Expenses for transporting turbines, foundations, and cables to the site and their installation using specialized vessels and equipment
Permits and Consultations	50,000–150,000	Expenses for obtaining environmental permits, ecological studies, and conducting public consultations
Operation and Maintenance (O&M)	40,000–60,000 annually	Annual operational and maintenance costs, including turbine servicing, inspections, and monitoring the farm's performance.

Source: own elaboration based on [68–70].

The costs and considerations associated with wind farm development are influenced by a range of factors, including geographic location, seabed characteristics, the distance to grid connections, and prevailing market dynamics. Offshore wind farms, situated in marine environments, face unique challenges such as higher construction costs, more complex logistics, and greater exposure to harsh weather conditions. Onshore wind farms, while typically more cost-effective, may contend with land-use conflicts, variable wind conditions, and local regulatory requirements. These differences underscore the nuanced trade-offs involved in selecting between onshore and offshore wind energy solutions. Table 5 provides a detailed comparison of the most significant elements that distinguish onshore and offshore wind farms.

Table 5 clearly illustrates the differences between onshore and offshore wind farms in terms of cost and operational complexity. Offshore wind farms, although significantly more expensive to build due to the complex requirements of marine environments, offer the advantage of utilizing stronger and more stable wind resources. Onshore wind farms, on the other hand, are a more cost-effective and logistically straightforward option, but they are often hampered by challenges such as land-use conflicts and inconsistent wind conditions. These differences highlight the trade-offs between the two approaches, emphasizing the critical role of tailored site planning and technological innovation in promoting sustainable energy solutions. Ultimately, this comparison highlights the clear balance between cost-efficiency, scalability, and environmental impact that defines any type of wind energy project.

Table 5. Comparison between onshore and offshore installations.

Category	Onshore Wind Farms	Offshore Wind Farms
Capital Costs per MW (USD)	$1,300,000–$2,100,000	$3,000,000–$5,500,000
Operational Costs (USD/MWh)	$30–$50	$100–$150
Efficiency Factor	25–40%	35–55%
Construction Time	1–2 years	2–5 years
Land/Space Requirements	Requires land permits	Requires sea permits, often farther offshore
Environmental Impact	Noise and visual impact on land	Potential marine ecosystem disruption

Source: own elaboration based on [71,72].

4.3.2. The Costs of Building Large-Scale Nuclear Power Plants and Small Modular Reactors

Nuclear power plays a key role in reducing greenhouse gas emissions by offering a stable and reliable source of energy that does not emit carbon dioxide during operation. Nuclear energy can be produced in two main types of reactors: large-scale nuclear reactors and small modular reactors (SMRs). Both solutions have their unique advantages and disadvantages, which concern both technical and economic aspects [73].

Large-scale reactors are capable of producing large amounts of energy, which makes them effective in meeting energy demands on an industrial scale. However, the construction of such units is associated with high capital costs and long lead times, which makes them less flexible in response to changing energy needs. In addition, due to their size, they require extensive infrastructure and access to large areas.

Small modular reactors (SMRs) are a modern solution that offers greater flexibility due to the possibility of building in modules, which allows for a gradual increase in production capacity. SMR construction costs are usually lower per unit project, and their design allows for location in places inaccessible to large reactors. The disadvantage, however, is their lower efficiency on a global scale and the still developing technology market, which can affect availability and operating costs [74].

Key factors related to the choice between these solutions, such as construction costs, implementation time, efficiency, or location possibilities, are presented in the table below, which allows for a comprehensive comparison of both technologies. This allows for a better understanding of their potential and limitations in the context of the global energy transformation and the fight against greenhouse gas emissions. The basic differences between these two types of energy production are presented in Table 6.

Table 6 highlights the efficiency and low-emission benefits of nuclear reactors, both traditional large-scale designs and small modular reactors (SMRs), while underscoring the significant differences in their construction and operational characteristics.

The disparity in construction timelines between these two reactor types arises from differences in scale, complexity, and construction methodologies. Traditional nuclear reactors are large-scale projects requiring extensive on-site construction, advanced systems, and lengthy regulatory and licensing processes. The on-site nature of their construction increases logistical challenges and the potential for delays caused by weather, supply chain disruptions, or unforeseen issues.

Table 6. Main differences between large scale and small modular reactors.

Type of Reactor	Total Cost [USD]	Cost per 1 MW [USD]	Construction Time	Comments
Traditional Nuclear	25 billion–35 billion	3 million–5 million	10–15 years	The range is consistent with international costs for large-scale nuclear power plants, depending on location and design. Nuclear power plants require extensive transmission infrastructure adapted to their high power and continuous operation. High-voltage lines (400–750 kV) are key, which minimize losses during energy transport over long distances, and transformer stations, which adjust the voltage to the grid.
Small Modular Reactor	50 million–3 billion	5 million–10 million	3–5 years	Smaller installed capacities result in higher unit costs per MW. However, SMRs offer the benefits of shorter construction times, modularity, and potentially lower operating costs. Costs may decrease with mass production and experience in their construction.

Source: own elaboration based on [75,76].

In contrast, SMRs leverage modular and standardized designs, enabling the majority of components to be prefabricated in controlled factory environments. This approach reduces on-site construction efforts, accelerates assembly, and minimizes delays. SMRs also benefit from simplified regulatory requirements in some regions due to their smaller size and inherent safety features. Their incremental deployment and reduced infrastructure demands further shorten construction timelines, making them well-suited for locations with limited resources or variable energy needs [77].

Large-scale reactors are characterized by high initial costs, long lead times, and economic efficiency primarily in large industrial applications. SMRs, while having higher per-unit energy operating costs, offer shorter construction timelines, lower upfront investments, and greater flexibility in site selection. This flexibility allows SMRs to be tailored to specific local conditions, making them an appealing solution for areas with limited infrastructure or fluctuating energy demands.

Both reactor types play a vital role in the transition to sustainable energy. The decision between them should consider local economic, technical, and environmental conditions to optimize their integration into energy systems.

The importance of the renewable energy sector in mitigating climate change has been in the spotlight for years, constituting a key element of the greenhouse gas emission reduction strategy. However, it is equally important to take into account climate threats that can affect the stability and efficiency of renewable energy systems. Extreme weather events, variability of atmospheric conditions, or limited availability of raw materials can pose challenges for the sector. Therefore, it is necessary for energy companies to adapt by implementing modern technologies and investing in infrastructures resistant to climate change and flexible management models that will allow for long-term energy transformation goals to be achieved [78].

5. Recommendation

Based on the conducted research, key recommendations can be formulated regarding the development of renewable energy, taking into account various technologies and

the specifics of location, region, and climate. In addition, optimizing project locations, modernizing infrastructure, and integrating digital technologies such as AI and IoT in the energy sector further improve operational efficiency and cost effectiveness. Economic and technological analysis serves as the foundation for these recommendations, helping to identify the most effective strategies and technologies that can be implemented in different parts of the world, considering specific geographical and infrastructural conditions.

1. Onshore Wind Farms

Economic Analysis—The construction of onshore wind farms involves investment costs that include the purchase of turbines, the construction of transmission infrastructure, and the modernization of local energy networks. The cost of installing wind turbines varies depending on the region, but the average construction cost is approximately $1.3–2.1 million per MW of capacity. On the other hand, operational costs for wind farms are relatively low, as the energy source (wind) is free.

Technological Analysis—Modern wind turbine technologies offer high efficiency and increased durability (the lifespan of wind turbines is usually around 25–30 years). However, wind quality and land availability can be limiting factors in some regions.

2. Offshore Wind Farms

Economic Analysis—The construction of offshore wind farms comes with higher investment costs compared to onshore farms. The installation cost of offshore farms ranges from $3 to $5.5 million per MW of capacity. Additionally, the need to build subsea transmission infrastructure and adapt systems to challenging marine conditions increases costs. Nevertheless, in the long term, offshore wind farms can offer higher generation capacities and greater efficiency due to stronger and more stable winds.

Technological Analysis—Offshore technologies are more advanced but require specialized skills in the installation and maintenance of turbines in difficult maritime conditions. The increase in the efficiency of offshore turbines, particularly in terms of their unit power, makes investments in offshore wind farms increasingly cost-effective.

3. Large-Scale Nuclear Energy

Economic Analysis—Nuclear energy requires high initial investment costs, with the cost of constructing large nuclear power plants ranging from $6 to $9 billion per reactor. However, once construction is completed, nuclear plants offer a stable and high-capacity energy source, which is beneficial in countries with high energy demand. Operating costs are relatively low, but long-term costs associated with safety and radioactive waste management are significant. The investment cost for nuclear energy projects has been calculated, estimating that 1 MW ranges between $3 to $5 million USD, depending on the region and reactor type.

Technological Analysis—Modern nuclear reactor technologies offer higher efficiency and safety, but technological challenges, such as waste management and safety concerns, present substantial limitations. Additionally, the long construction period for large nuclear plants makes it difficult to respond quickly to changing energy needs.

4. Small Modular Reactors (SMR)

Economic Analysis—Small modular reactors (SMRs) offer lower initial costs, estimated at $1–3 billion per reactor, making them more accessible to developing countries and regions with lower energy demand. SMRs can be more flexible and faster to construct, which is a significant advantage. The investment required for 1 MW of SMR capacity is typically between $3 to $5 million, depending on the type and location. SMRs can be more flexible and faster to construct, which is a significant advantage.

Technological Analysis—SMRs are a technology that offers greater safety and flexibility, especially in smaller locations. Their modular design allows for faster installation and

adaptation to specific local conditions, which can be a significant advantage in regions with challenging infrastructure conditions.

Based on the conducted analyses, it is recommended to adjust strategies to the specific local geographic and climatic conditions to achieve optimal development of renewable energy. It is also essential to conduct detailed economic and technological analyses that will help select the most appropriate solutions for each region. Ultimately, implementing diverse technologies that consider specific needs and resources will contribute to an effective energy transition, supporting sustainable development goals.

6. Conclusions

The pursuit of carbon neutrality is one of the most significant challenges faced by modern energy companies. Key difficulties encompass both economic and technological aspects tied to transforming the energy sector. Implementing renewable energy solutions, such as onshore and offshore wind farms, nuclear energy, and energy storage, requires substantial financial investment and overcoming numerous technological barriers. The research results indicate that the costs associated with implementation vary depending on the strategy being adopted (e.g., wind or nuclear energy investment strategy). The costs also differ based on the type of renewable energy source.

Investment costs are among the most critical factors companies must consider when planning new projects. Examples presented in research highlight the high expenses associated with energy transformation. Building onshore wind farms is relatively less expensive, costing approximately $1.3–$2.1 million per MW, compared to offshore wind farms, which range from $3 to $5.5 million per MW. Offshore farms, however, are more energy efficient due to stronger and more stable winds but pose additional challenges related to infrastructure, such as undersea cables and transport systems.

Nuclear energy also plays a vital role in the transition to zero emissions, offering a stable energy source with minimal greenhouse gas emissions. Traditional nuclear power plants require massive financial outlays, ranging from $25 billion to $35 billion, and their construction takes 7 to 15 years. In contrast, small modular reactors (SMRs), although more expensive per MW ($5.2–$10.35 million), provide shorter construction times (3–5 years) and greater flexibility in integrating with local energy systems. However, SMRs are still in the early stages of development, facing technological limitations and requiring further investments in research and development.

Another crucial challenge is ensuring the stability of energy networks with the growing share of renewables, which are characterized by variable production. In this context, energy storage, particularly advanced battery systems, becomes an essential component of zero-emission strategies. However, battery costs remain high, and their longevity and efficiency demand further technological improvements.

The transition from fossil fuels to green energy also involves significant social and regulatory hurdles. Acquiring permits, integrating new technologies with existing infrastructure, and gaining public acceptance for new projects require strategic planning and collaboration with governmental and international institutions.

Shifting from fossil fuels to green energy is fraught with obstacles. Retrofitting existing energy systems, managing intermittent renewable energy production, and addressing the high costs of emerging technologies require innovative approaches and substantial capital. Additionally, balancing short-term economic pressures with long-term sustainability goals remains a delicate issue for energy companies navigating the complex landscape of carbon-neutral strategies. The adoption of the chosen strategy also carries environmental consequences. Wind farms, for example, can impact the landscape, alter local ecosystems, and contribute to higher noise levels. On the other hand, nuclear energy, while providing a

low-carbon energy source, may involve risks related to accidents or catastrophic events, such as radiation leaks or the long-term management of nuclear waste. These potential environmental impacts must be carefully considered alongside economic and technical factors when making strategic decisions in the energy sector. Additionally, the public perception and acceptance of these technologies can also influence their implementation and success.

In summary, achieving zero emissions requires a balanced approach to economic management, technological innovation, and adaptation to dynamic market and regulatory conditions. Hidden costs, such as environmental impacts and system upgrades, can affect the perceived affordability of energy transformation projects. During the transition to green energy, it is also important to remember that hidden costs, such as environmental impacts and system upgrades, can affect the perceived affordability of energy transition projects. Only through coordinated efforts can energy companies overcome these challenges and drive a sustainable transformation of the global energy system.

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