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Renewable vs Non-Renewable Energy: A Comparative Study of Environmental, Economic, and Social Implications for Sustainable Development

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Abstract

The global energy landscape is undergoing a fundamental transformation as societies grapple with the environmental consequences of fossil fuel dependence and seek sustainable alternatives to meet growing energy demands. This comprehensive study examines the comparative advantages and disadvantages of renewable and non-renewable energy sources across multiple dimensions including environmental impact, economic viability, technological maturity, and social implications. Through systematic analysis of current literature and empirical data, this research evaluates the potential of renewable energy technologies to replace conventional fossil fuels while addressing climate change mitigation and energy security concerns. The study reveals that while renewable energy sources offer significant environmental benefits and declining costs, challenges remain in terms of intermittency, storage requirements, and infrastructure transformation needs. Non-renewable sources continue to dominate global energy supply due to established infrastructure, energy density advantages, and reliability factors, despite their substantial environmental costs. The findings indicate that a successful energy transition requires integrated approaches combining technological innovation, policy support, economic incentives, and social acceptance to overcome existing barriers and achieve sustainable energy systems.

Keywords: Renewable energy, Non-renewable energy, Energy transition, Climate change, Sustainability, Energy economics, Environmental impact

1. Introduction

Energy consumption patterns have become critical determinants of environmental sustainability, economic development, and social well-being in the contemporary world. Global primary energy consumption reached 595.15 exajoules in 2021, with fossil fuels accounting for approximately 82% of total energy supply despite growing renewable energy deployments (1). The continued reliance on non-renewable energy sources contributes significantly to greenhouse gas emissions, air pollution, and climate change impacts that threaten global ecosystems and human societies.

The Intergovernmental Panel on Climate Change emphasizes the urgent need for rapid decarbonization of energy systems to limit global warming to 1.5°C above pre-industrial levels (2). This objective necessitates fundamental transformations in energy production, distribution, and consumption patterns that favor low-carbon alternatives to conventional fossil fuels. Renewable energy technologies have experienced remarkable cost reductions and performance improvements, with solar photovoltaic costs declining by 90% since 2009 and wind energy costs falling by 70% over the same period (3).

However, the transition from non-renewable to renewable energy systems involves complex technical, economic, and social challenges that require comprehensive analysis to inform policy decisions and investment strategies. Understanding the comparative characteristics of different energy sources across multiple dimensions provides essential insights for designing effective energy transition pathways that balance environmental objectives with economic viability and social acceptance.

Non-Renewable Energy Sources: Characteristics and Implications

Fossil Fuel Energy Systems

Coal, oil, and natural gas constitute the primary non-renewable energy sources that have powered industrial development and economic growth for over two centuries. These fossil fuels offer several advantages including high energy density, established extraction and processing infrastructure, reliable supply characteristics, and mature technologies for energy conversion (4). Coal provides approximately 27% of global primary energy, oil accounts for 31%, and natural gas contributes 25%, demonstrating their continued dominance in global energy systems.

The energy density advantage of fossil fuels enables efficient transportation and storage, making them particularly suitable for applications requiring high power outputs and continuous availability. A single kilogram of coal contains approximately 24-35 megajoules of energy, while gasoline provides about 44 megajoules per kilogram, significantly higher than most renewable alternatives (5).

However, fossil fuel combustion generates substantial environmental impacts including greenhouse gas emissions, air pollutants, and ecosystem degradation. Coal combustion produces approximately 820 kilograms of CO₂ per megawatt-hour of electricity generation, while natural gas generates about 490 kilograms of CO₂ per megawatt-hour (6). These emissions contribute directly to climate change and represent the largest single source of anthropogenic greenhouse gases.

Nuclear Energy Systems

Nuclear energy represents a unique category of non-renewable energy that provides low-carbon electricity generation through uranium fission reactions. Nuclear power plants contribute approximately 10% of global electricity generation and play significant roles in national energy security strategies (7). Nuclear energy offers several advantages including minimal greenhouse gas emissions during operation, high capacity factors exceeding 90%, and substantial electricity generation from relatively small fuel quantities.

The energy density of nuclear fuel exceeds that of any other energy source, with one kilogram of uranium-235 containing approximately 80 terajoules of energy, equivalent to 2,700 tons of coal (8). This extraordinary energy density enables nuclear plants to operate continuously for 18-24 months between refueling cycles while occupying relatively small land areas compared to renewable alternatives.

Nuclear energy faces significant challenges including high capital costs, long construction times, radioactive waste disposal concerns, and public acceptance issues related to safety perceptions. The average construction cost of nuclear plants has increased significantly, reaching \$6,000-\$12,000 per kilowatt in many developed countries (9).

Renewable Energy Sources: Technologies and Potential

Solar Energy Systems

Solar photovoltaic and thermal technologies harness abundant solar radiation to generate electricity and provide heating applications. Global solar capacity reached 942 gigawatts by 2021, representing the fastest-growing renewable energy technology with annual deployment rates exceeding 20% (10). Solar energy offers several advantages including zero fuel costs, minimal maintenance requirements,

modular deployment options, and universal availability of the primary energy resource.

Photovoltaic technology has achieved remarkable efficiency improvements and cost reductions through technological innovation and manufacturing scale economies. Commercial silicon solar panels now achieve efficiencies of 20-22%, while advanced technologies including perovskite tandem cells demonstrate potential efficiencies exceeding 30% (11). However, solar energy faces challenges related to intermittency, weather dependence, and diurnal variations that affect electricity generation patterns. Solar capacity factors typically range from 15-25% depending on geographic location and system design, requiring energy storage or backup systems to ensure reliable electricity supply (12).

Wind Energy Systems

Wind power utilizes atmospheric air movements to generate electricity through aerodynamic turbines installed onshore and offshore locations. Global wind capacity exceeded 837 gigawatts in 2021, with offshore wind representing the fastest-growing segment due to superior wind resources and reduced visual impact concerns (13).

Modern wind turbines achieve capacity factors of 35-45% onshore and 50-60% offshore, demonstrating improved performance compared to earlier technologies. Technological advances including larger rotor diameters, higher hub heights, and advanced control systems have enhanced energy capture and reduced costs significantly.

Wind energy challenges include intermittency variations, noise concerns, visual impacts, and potential effects on bird and bat populations. Geographic concentration of optimal wind resources may require substantial transmission infrastructure investments to connect remote generation sites with electricity demand centers (14).

Hydroelectric Power Systems

Hydroelectric power represents the oldest and most established renewable energy technology, contributing approximately 16% of global electricity generation. Large-scale hydroelectric projects provide multiple benefits including electricity generation, flood control, irrigation support, and recreational opportunities (15).

Pumped-storage hydroelectric systems offer valuable grid services including load balancing, frequency regulation, and energy storage capabilities that support integration of variable renewable sources. These systems can respond to electricity demand changes within seconds and provide essential grid stability services.

However, large hydroelectric projects can generate significant environmental and social impacts including ecosystem disruption, fish migration barriers, sediment trapping, and community displacement. Climate change affects hydroelectric generation through altered precipitation patterns and water availability (16).

Other Renewable Technologies

Biomass energy utilizes organic materials including wood, agricultural residues, and energy crops to provide heating, electricity, and transportation fuels. Geothermal energy harnesses underground heat sources to generate electricity and provide heating applications in suitable geological locations. Ocean energy technologies including tidal and wave power systems are emerging as additional renewable

options with significant long-term potential (17).

Economic Comparison and Cost Analysis **Capital and Operating Cost Considerations**

Renewable energy technologies typically require higher upfront capital investments but minimal ongoing fuel and operating costs compared to fossil fuel systems. Solar and wind installations have experienced dramatic cost reductions, with levelized costs of electricity falling below fossil fuel alternatives in many markets (18).

The levelized cost of electricity from utility-scale solar photovoltaic systems declined from \$359 per megawatt-hour in 2009 to \$57 per megawatt-hour in 2021, while onshore wind costs decreased from \$135 to \$38 per megawatt-hour over the same period (19). These cost reductions reflect technological improvements, manufacturing scale economies, and competitive market development.

Non-renewable energy costs face increasing volatility due to fuel price fluctuations, carbon pricing policies, and environmental regulation compliance requirements. Coal and natural gas plants also require ongoing fuel purchases that represent 60-80% of total electricity generation costs, creating exposure to commodity price risks (20).

External Cost Considerations

Environmental and health externalities associated with energy systems represent significant but often unaccounted costs that affect societal welfare. Air pollution from fossil fuel combustion generates substantial health costs including respiratory diseases, cardiovascular problems, and premature mortality that affect vulnerable populations disproportionately.

The International Monetary Fund estimates that global fossil fuel subsidies, including environmental externalities, reached \$5.9 trillion in 2020, equivalent to 6.8% of global GDP (21). These hidden costs highlight the economic advantages of renewable energy systems that generate minimal air pollution and environmental impacts during operation.

Environmental Impact Assessment **Climate Change Implications**

Lifecycle greenhouse gas emissions provide critical metrics for comparing environmental impacts of different energy technologies. Renewable energy sources demonstrate substantially lower carbon footprints compared to fossil fuel alternatives across all lifecycle stages including manufacturing, installation, operation, and decommissioning phases.

Solar photovoltaic systems generate 40-50 grams of CO₂ equivalent per kilowatt-hour over their operational lifetime, while wind energy produces 10-15 grams per kilowatt-hour. These emissions represent 95-98% reductions compared to coal-fired electricity generation and 90-95% reductions compared to natural gas systems.

Resource Depletion and Waste Generation

Non-renewable energy extraction depletes finite resource stocks and generates substantial waste products including mining overburden, processing residues, and combustion ash. Coal mining operations disturb approximately 2.4 million hectares annually and generate billions of tons of waste materials that require long-term management.

Renewable energy systems utilize inexhaustible energy flows but require material inputs for manufacturing solar panels,

wind turbines, and associated infrastructure. However, these materials can often be recycled at end-of-life, and the total material requirements per unit of energy generated are typically lower than fossil fuel alternatives.

Grid Integration and Reliability Challenges **Intermittency and Variability Management**

Variable renewable energy sources including solar and wind present challenges for electrical grid operations due to their dependence on weather conditions and natural cycles. Grid operators must maintain continuous balance between electricity supply and demand while accommodating fluctuating renewable generation patterns.

Advanced forecasting systems, demand response programs, and energy storage technologies provide solutions for managing renewable energy variability. Battery storage costs have declined by 90% since 2010, making grid-scale storage economically viable for supporting renewable integration.

Infrastructure Transformation Requirements

Transitioning to renewable energy systems requires substantial modifications to existing electrical infrastructure including transmission networks, distribution systems, and grid management technologies. Smart grid systems enable bidirectional power flows, real-time monitoring, and automated control capabilities that support distributed renewable generation.

The International Energy Agency estimates that achieving net-zero emissions by 2050 requires annual infrastructure investments of \$4 trillion globally, with substantial portions allocated to renewable energy deployment and grid modernization projects.

Policy Frameworks and Market Mechanisms

Renewable Energy Support Policies

Government policies play crucial roles in accelerating renewable energy deployment through feed-in tariffs, renewable portfolio standards, tax incentives, and auction mechanisms. These policies address market failures and provide economic incentives that account for environmental benefits not captured in energy market prices.

Carbon pricing mechanisms including carbon taxes and emissions trading systems create economic advantages for low-carbon technologies by internalizing climate change costs associated with fossil fuel combustion. Over 40 national and 30 subnational jurisdictions have implemented or scheduled carbon pricing initiatives.

Energy Transition Strategies

Successful energy transitions require comprehensive strategies that address technological, economic, and social dimensions simultaneously. Just transition policies ensure that communities dependent on fossil fuel industries receive support for economic diversification and workforce retraining programs.

International cooperation mechanisms including technology transfer, climate finance, and knowledge sharing initiatives accelerate global renewable energy deployment while supporting developing country energy access objectives.

Conclusion

The comparative analysis of renewable and non-renewable energy sources reveals fundamental trade-offs between environmental sustainability, economic considerations, and

system reliability requirements. Renewable energy technologies offer substantial advantages in terms of climate change mitigation, air quality improvement, and long-term cost competitiveness, while non-renewable sources provide established infrastructure, energy density benefits, and reliable supply characteristics.

The accelerating deployment of renewable energy systems, combined with declining costs and improving performance, demonstrates the feasibility of large-scale energy transitions that prioritize environmental sustainability. However, achieving complete decarbonization requires continued innovation in energy storage, grid integration, and system flexibility to address intermittency challenges effectively.

Future energy systems will likely feature hybrid approaches that combine multiple renewable technologies with advanced storage systems, demand response capabilities, and potentially some remaining role for low-carbon non-renewable sources during transition periods. The optimal energy mix depends on geographic resources, economic conditions, and policy priorities that vary across different regions and applications.

Successful energy transitions require coordinated efforts combining technological innovation, supportive policies, adequate financing, and social acceptance to overcome existing barriers and achieve sustainable energy systems that meet growing global energy demands while protecting environmental quality and climate stability.

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