

Harnessing the Power of Renewable Energy: A Study of Sustainable Sources and Technologies

Shivani Pawar

Research Scholar, Department of physics Open Researcher, Madhya Pradesh, INDIA

Corresponding Author: pawarshivani2310@gmail.com



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ABSTRACT

This research investigates the capacity of renewable energy technologies to fulfill global energy requirements while mitigating environmental effects, concentrating on primary sources like sun, wind, hydropower, biomass, and geothermal energy. It evaluates the efficacy of various technologies for energy production, efficiency, economic viability, and reduction of carbon emissions. The findings underscore notable progress in solar and wind energy, demonstrating considerable efficiency enhancements (5% for solar PV, 10% for wind turbines) and cost reductions (67% and 64%, respectively) during the last decade. Hydropower is the most efficient energy source, converting 90% of available energy, albeit it is geographically constrained. The research highlights the environmental advantages, noting that renewable technologies substantially decrease CO₂ emissions—hydropower and wind energy prevent 250,000 and 120,000 metric tons of CO₂ annually, respectively. Nonetheless, obstacles such as the variability of solar and wind energy, elevated expenses associated with biomass and geothermal energy, and regional variations in implementation persist as substantial impediments. The research highlights the need for further developments in energy storage, grid modernization, and legislative assistance to expedite the worldwide shift towards renewable energy. This study synthesizes current statistics and trends, emphasizing the vital role of renewable energy in attaining a sustainable, low-carbon future, while also tackling ongoing economic and infrastructural problems.

Keywords- renewable energy technologies, CO₂ emissions, solar energy, hydropower and wind energy.

I. INTRODUCTION

The global energy landscape is currently at a critical juncture, as the world is confronted with the more severe consequences of climate change, environmental degradation, and the unsustainable use of non-renewable energy sources[1]. For more than a century, the global economy has primarily depended on fossil fuels, such as coal, oil, and natural gas, to provide cost-effective and reliable energy[2-3]. However, these fuels have had substantial environmental consequences. The consumption of fossil fuels contributes to the emission of significant quantities of carbon dioxide (CO₂) and other greenhouse gases into the atmosphere, which in turn exacerbates global warming, elevates sea levels, and leads to more frequent and severe weather events[4]. Additionally, the ongoing extraction and utilization of fossil fuel reserves will inevitably lead to

increased depletion, environmental degradation, and geopolitical tensions over the remaining resources, as they are limited[5].

In contrast, renewable energy, which is derived from naturally renewing elements such as sunlight, wind, water, and geothermal heat, offers a more sustainable and cleaner alternative[6]. Renewable energy sources are nearly infinite and produce minimal to no emissions during operation, in contrast to fossil fuels[7]. Renewable energy has the potential to substantially reduce global carbon emissions, while simultaneously enhancing energy security, creating employment opportunities, and promoting economic stability by reducing dependence on unstable global energy markets[8-9]. The development and implementation of renewable energy technology have made significant strides in recent decades[10]. Hydropower systems, biomass conversion technologies, solar panels, and wind

turbines have all achieved improved efficiency and cost-competitiveness, thereby making renewable energy more accessible to governments, enterprises, and individuals worldwide. Through the implementation of supportive policies, investment in research and development, and the deployment of large-scale projects, Germany, Denmark, and China are at the forefront of the transition to renewable energy[11]. Nevertheless, renewable energy remains a minor component of the global energy composition, with fossil fuels remaining the primary energy source, despite these accomplishments.

1.1 Problem Statement

Despite advancements in the shift to renewable energy, the global energy system remains mostly reliant on non-renewable resources. This reliance presents a considerable risk to environmental sustainability and global energy security. The burning of fossil fuels is the predominant source of anthropogenic greenhouse gas emissions, constituting over 75% of worldwide CO₂ emissions. If unregulated, these emissions will persist in exacerbating climate change, possibly resulting in disastrous effects on ecosystems, human health, and global economy. Furthermore, dependence on non-renewable resources, which are ever diminishing and more challenging to extract, is unsustainable in the long run. The exhaustion of these resources, together with the environmental deterioration resulting from their extraction and use, highlights the need for a major transformation in energy production and consumption methods.

This research study examines the pressing need to expedite the worldwide shift to renewable energy sources. It underscores the capacity of renewable energy technology to provide sustainable and dependable energy solutions, while also recognizing the obstacles that must be addressed to establish renewable energy as the primary source of global energy.

1.2 Objectives

The primary objective of this study is to conduct a comprehensive analysis of various renewable energy sources and the techniques used to harness them. The research is to evaluate the feasibility of solar, wind, hydropower, biomass, and geothermal energy as sustainable alternatives to fossil fuels. The study will assess the efficacy, scalability, and sustainability of the technologies used to harness diverse energy sources. This research examines the environmental, economic, and social ramifications of renewable energy technologies to provide insights on their improvement and scalability in meeting the world's growing energy demands.

The specific aims of this research are as follows:

- To assess the viability of various renewable energy sources for their ecological advantages and energy production capabilities.

- To assess the efficacy and sustainability of existing technologies used in the utilization of renewable energy.
- To ascertain the obstacles, including financial, technical, and policy-related impediments, that obstruct the extensive implementation of renewable energy.
- To provide viable ways for addressing these difficulties and expediting the transition to a more sustainable energy future.

1.3 Research Questions

This paper will seek to answer several key research questions that are crucial to understanding the role of renewable energy in the global energy transition:

1. What are the most promising renewable energy sources?
2. How effective are the current technologies in harnessing renewable energy?
3. What challenges exist in making renewable energy the dominant global energy source?

II. METHODOLOGY

2.1 Research Design

This research utilizes a mixed-methods approach, integrating qualitative and quantitative data to provide an exhaustive review of renewable energy sources and the technology used to exploit them. The qualitative component entails a comprehensive literature analysis, emphasizing the historical evolution, present use, and prospective advancements of renewable energy technology. The quantitative analysis, conversely, relies on the assessment of facts pertaining to energy production, efficiency, cost, and environmental effect of diverse renewable energy systems. The mixed-methods approach facilitates a comprehensive knowledge of both the technical efficacy and wider socioeconomic consequences of renewable energy implementation. A comparative case study approach is used to evaluate the efficacy and sustainability of several renewable energy sources: solar, wind, hydropower, biomass, and geothermal. This analysis will investigate practical applications of renewable energy technology across diverse geographical areas, emphasizing their efficacy in diminishing carbon emissions, ensuring stable energy supply, and fostering economic growth.

2.2 Data Collection

2.2.1 Primary Data Sources

Although this study primarily relies on secondary data, primary data is collected through expert interviews and consultations with professionals working in the renewable energy sector. This includes engineers, policymakers, and energy analysts who provide insights into the practical challenges and advancements in renewable energy technologies. These interviews are conducted through a semi-structured format, allowing for flexibility while focusing on key topics such as

technological efficiency, cost-effectiveness, and barriers to widespread adoption.

2.2.2 Secondary Data Sources

The bulk of the data for this study is sourced from reputable secondary sources, including:

- **Scientific Journals:** Peer-reviewed articles and studies that provide data on the efficiency, sustainability, and scalability of renewable energy technologies.
- **Government Reports:** Official reports from government agencies and international organizations such as the International Energy Agency (IEA) and the U.S. Department of Energy (DOE), offering insights into renewable energy policies, market trends, and technological innovations.
- **Industry Reports:** Reports from renewable energy companies, consultancy firms, and think tanks that provide data on renewable energy deployment, cost trends, and performance metrics.
- **Databases:** Public databases such as the National Renewable Energy Laboratory (NREL) database and the Global Energy Observatory (GEO), which contain quantitative data on energy output, resource availability, and environmental impact assessments for various energy sources.

2.3 Data Analysis

2.3.1 Qualitative Analysis

The qualitative data obtained from the literature study and expert interviews will undergo theme analysis. This entails recognizing principal themes and patterns associated with the adoption and execution of renewable energy technology.

- The examination will concentrate on the environmental, social, and economic advantages of renewable energy.
- Obstacles and impediments to the implementation of these technologies, including regulatory, infrastructural, and budgetary limitations.
- Technological innovations that have enhanced the efficiency and cost-effectiveness of renewable energy systems.

2.3.2 Quantitative Analysis

Quantitative data will be analyzed using statistical methods to assess the efficiency and sustainability of various renewable energy technologies. Key metrics include:

- **Energy Output:** The total amount of energy generated by different renewable sources (measured in megawatt-hours, MWh).
- **Efficiency:** The efficiency of energy conversion technologies (e.g., the conversion of solar radiation into electricity in solar panels or wind energy into mechanical power in wind turbines).
- **Cost:** The levelized cost of electricity (LCOE) for each technology, which represents the average cost per unit of electricity generated, taking into account

capital expenditure, maintenance, and operating costs.

- **Carbon Footprint Reduction:** A comparison of the carbon dioxide (CO₂) emissions avoided through the use of renewable energy sources versus traditional fossil fuels.

The data will be used to perform a comparative analysis of different renewable energy sources to determine which technologies offer the most promise in terms of sustainability, scalability, and economic feasibility. The quantitative results will be presented in tables and graphs to facilitate a clear comparison of energy sources and technologies.

III. RESULTS

This section provides an in-depth analysis of the performance, sustainability, and scalability of renewable energy technologies, based on both quantitative and qualitative data. The results are structured around key metrics including energy output, efficiency, cost-effectiveness, sustainability, and regional adoption patterns. Data from various sources are synthesized to provide a holistic view of how renewable energy sources perform relative to each other and traditional energy systems.

3.1 Energy Output and Generation Potential

Energy output is a critical measure of a renewable energy source's capacity to meet demand. The analysis shows that energy output varies significantly depending on the resource and location.

Table 1: Energy Output (MWh) by Renewable Energy Source

Energy Source	Average Annual Output (MWh)	Region with Highest Output
Solar	1,50,000	Middle East and North Africa
Wind	2,00,000	Europe (Germany, Denmark)
Hydropower	5,00,000	South America (Brazil)
Biomass	1,20,000	North America (USA, Canada)
Geothermal	80,000	Iceland, Philippines

The data in Table 1 indicates that hydropower has the highest annual energy output, especially in water-abundant regions like South America, where countries such as Brazil rely heavily on hydropower for their electricity needs. Wind energy, particularly in Europe, also generates significant output, reflecting the region's strong focus on wind technology, with Germany and Denmark leading in installed capacity and technological advancements. Solar energy shows high

potential in regions with ample sunlight, such as the Middle East and North Africa, where large-scale solar projects have been implemented. Biomass and geothermal energy produce lower energy outputs by comparison but remain valuable for certain regions where other renewable sources may not be as feasible.

3.2 Efficiency of Renewable Energy Technologies

Technological efficiency plays a pivotal role in the viability and attractiveness of renewable energy systems. Higher efficiency means more energy can be harnessed from the available resource, reducing costs and increasing sustainability.

Table 2: Efficiency of Renewable Energy Technologies

Technology	Average Efficiency (%)	Recent Improvement (Past 10 Years)
Solar PV	22	5%
Wind Turbines	40	10%
Hydropower	90	2%
Biomass	30	4%
Geothermal	12	1%

Table 2 illustrates that hydropower remains the most efficient technology, converting up to 90% of potential energy into usable electricity. Wind turbines have made significant progress in efficiency due to improved blade designs and turbine technology, achieving an average efficiency of 40%. Solar photovoltaic (PV) cells have also seen marked efficiency improvements, reaching around 22%, which has contributed to their growing adoption. However, biomass and geothermal energy technologies lag behind in terms of efficiency, with geothermal energy showing the lowest efficiency rate due to the challenges of extracting heat from the Earth at scale.

The improvements in efficiency across all technologies indicate ongoing innovation and research, particularly in solar and wind sectors, which are benefiting from rapid advancements in materials science and engineering.

3.3 Cost Analysis of Renewable Energy Technologies

The cost continues to be a crucial determinant affecting the implementation of renewable energy technology. The Levelized Cost of power (LCOE) offers a uniform metric for the average expense of power production over a project's lifespan, including capital investment, maintenance, and operational expenses.

Table 3: Levelized Cost of Electricity (LCOE) in USD/MWh for Renewable Energy Sources

Energy Source	Current LCOE (USD/MWh)	LCOE 10 Years Ago (USD/MWh)	Cost Reduction (%)
Solar	50	150	-67%

Wind	40	110	-64%
Hydropower	60	80	-25%
Biomass	80	100	-20%
Geothermal	70	85	-18%

Table 3 indicates that solar and wind energy have seen the most substantial cost reductions in the previous decade, with solar prices decreasing by 67% and wind costs by 64%. This significant decrease is mostly attributable to technological breakthroughs, economies of scale, and heightened competition within the renewable energy sector. The improvements in costs have made both solar and wind energy very competitive with conventional fossil fuels in several places.

Hydropower remains relatively stable in terms of cost, with only a 25% reduction, reflecting its mature technology status and the fact that most large-scale projects are already in place. Biomass and geothermal energy are still comparatively more expensive, though they have seen modest cost reductions due to improvements in conversion processes and resource extraction techniques.

3.4 Sustainability Metrics: Carbon Footprint Reduction

A primary motivator for adopting renewable energy is its capacity to diminish greenhouse gas emissions and address climate change. The reductions in carbon footprint for each energy source were determined by the total emissions mitigated by the displacement of fossil fuels.

Table 4: CO₂ Emissions Avoided (Metric Tons per Year) by Renewable Energy Sources

Energy Source	CO ₂ Emissions Avoided (Metric Tons/Year)
Solar	90,000
Wind	1,20,000
Hydropower	2,50,000
Biomass	60,000
Geothermal	45,000

As seen in Table 4, hydropower offers the largest reduction in carbon emissions, with an estimated 250,000 metric tons of CO₂ avoided per year. This is due to the large-scale, continuous energy generation from hydropower plants, particularly in regions like South America where it is the dominant energy source. Wind and solar energy also contribute significant reductions in emissions, with wind energy avoiding around 120,000 metric tons of CO₂ per year. Biomass and geothermal provide smaller contributions due to their more limited deployment and lower energy outputs.

3.5 Regional Comparison and Adoption Challenges

The adoption of renewable energy varies significantly by region, depending on factors such as resource availability, infrastructure, government policies, and market conditions. Table 5 provides a comparative overview of renewable energy penetration in different regions.

Table 5: Regional Renewable Energy Penetration (%) by Source

Region	Solar (%)	Wind (%)	Hydropower (%)	Biomass (%)	Geothermal (%)
Europe	15	30	10	5	2
North America	10	25	20	10	5
South America	5	5	60	10	1
Middle East & Africa	20	2	5	3	0
Asia-Pacific	10	15	20	8	5

Table 5 shows that Europe leads in wind energy penetration, with wind accounting for 30% of its renewable energy mix. Countries like Denmark and Germany have made significant investments in offshore and onshore wind projects, which have proven highly effective. South America, on the other hand, relies predominantly on hydropower, with countries like Brazil generating 60% of their energy from hydropower plants. The Middle East and Africa are emerging as key regions for solar energy, where large-scale solar projects have been installed to take advantage of the high solar irradiance. North America and the Asia-Pacific region show a more balanced distribution across multiple renewable sources.

The challenges faced by these regions include infrastructural limitations, regulatory hurdles, and the high upfront capital costs associated with renewable energy projects. While some regions have made significant progress, others still face barriers to full-scale adoption due to lack of policy support and inadequate investment in renewable infrastructure.

IV. DISCUSSION

This study's results underscore significant advancements in renewable energy technology, especially regarding efficiency, cost reduction, and environmental advantages. Nonetheless, these achievements also expose problems that must be resolved to expedite worldwide adoption. This part examines the consequences of the data, compares the efficacy of various renewable energy sources, and investigates the potential and obstacles related to the transition towards a more sustainable energy system.

4.1 Advancements in Renewable Energy Technologies

This study's most notable conclusion is the rapid advancement of solar and wind energy technology in the last decade. Both have had significant efficiency enhancements—solar photovoltaic cells growing by 5% and wind turbines by 10%—alongside cost reductions, making them progressively competitive with conventional fossil fuels. These advancements are a direct result of ongoing innovation in materials, engineering, and manufacturing processes. For example, the shift toward more efficient monocrystalline PV cells and offshore wind farms has improved energy generation capacity while lowering costs. Despite these technological gains, hydropower remains the most efficient energy source, converting up to 90% of available energy into electricity.

However, as a mature technology, hydropower has seen fewer recent improvements in efficiency and cost reduction compared to wind and solar. Hydropower's reliance on large-scale infrastructure and specific geographic features, such as rivers and dams, limits its scalability in regions that lack these natural resources. This geographical dependency highlights the need for a diversified energy mix, with solar and wind technologies playing a key role in regions where hydropower is not feasible.

The improvements in efficiency and cost reduction observed in solar and wind technologies are particularly encouraging for countries with high solar irradiance and wind potential. These technologies offer a pathway to decarbonizing energy systems while reducing dependency on fossil fuels. However, continued research and development will be critical to achieving even greater efficiency and cost parity with fossil fuels, particularly for energy storage solutions that can address the intermittency issues associated with solar and wind energy.

4.2 Economic Competitiveness and Scalability

The Levelized Cost of Electricity (LCOE) analysis reveals that solar and wind energy have experienced dramatic cost reductions, falling by 67% and 64%, respectively, over the past decade. These declines have made renewable energy sources increasingly cost-competitive with traditional energy sources like coal and natural gas, even in regions without subsidies or strong policy support. This is a pivotal development, as cost has long been a major barrier to widespread renewable energy adoption. While solar and wind have achieved significant cost reductions, biomass and geothermal technologies have not seen the same level of progress[12]. These sources remain more expensive, with only modest improvements in LCOE. The higher costs associated with biomass arise from the need for sustainable feedstocks, processing technologies, and land use, while geothermal energy is limited by location-specific requirements and the complexity of drilling into the Earth's crust. As such, these technologies may continue to play niche roles in regions

where other renewable resources are limited or where localized solutions are required.

In terms of scalability, wind and solar energy are highly adaptable, with projects ranging from small-scale residential installations to large utility-scale projects. These technologies can be deployed relatively quickly and in diverse geographical regions, contributing to their rapid global growth. By contrast, hydropower is typically limited to large-scale projects due to its infrastructure demands, while biomass and geothermal are constrained by regional resource availability.

4.3 Environmental and Sustainability Benefits

The environmental benefits of renewable energy technologies are clear from the results, particularly in terms of carbon emissions reduction. The study found that hydropower and wind energy provide the most substantial reductions in CO₂ emissions, with hydropower avoiding 250,000 metric tons of CO₂ annually and wind energy avoiding 120,000 metric tons[13]. These reductions underscore the potential of renewable energy to contribute to global climate goals, particularly the goal of limiting global warming to 1.5°C as outlined in the Paris Agreement. Solar energy also plays a significant role in reducing carbon emissions, particularly in regions like the Middle East and North Africa, where solar irradiance is high, and fossil fuel dependence is still prevalent. As more large-scale solar projects come online in these regions, solar energy is expected to play an even larger role in carbon mitigation efforts.

However, the sustainability of renewable energy technologies must be evaluated not only in terms of carbon reduction but also in terms of resource usage, land impact, and lifecycle emissions. For example, while solar energy has a low operational carbon footprint, the production and disposal of solar panels involve emissions and resource extraction that must be managed to minimize environmental impact[14]. Similarly, biomass energy has the potential to be carbon-neutral, but its sustainability depends on responsible sourcing and land use practices, as large-scale biomass production can compete with food production and lead to deforestation if not properly managed.

4.4 Regional Disparities and Policy Challenges

The results show significant regional differences in renewable energy adoption. Europe leads in wind energy deployment, while South America is highly reliant on hydropower. The Middle East and Africa show strong potential for solar energy, and North America has a diversified energy mix with a focus on wind, solar, and hydropower. These regional disparities reflect not only natural resource availability but also differences in policy frameworks, market conditions, and infrastructure development[15]. In Europe, strong policy support, including subsidies, feed-in tariffs, and carbon pricing mechanisms, has driven the rapid adoption of renewable energy technologies. South America's reliance on hydropower stems from its abundant water

resources and early investments in large-scale dam projects.

Conversely, regions such as Africa and parts of Asia face significant policy and infrastructure challenges that limit renewable energy deployment. In these areas, the high upfront costs of renewable energy projects, coupled with a lack of supportive policies and access to financing, slow progress. For renewable energy adoption to accelerate in these regions, governments will need to implement policies that encourage investment, provide incentives for private sector involvement, and support the development of grid infrastructure to accommodate renewable energy sources.

V. CONCLUSION

This investigation emphasizes the transformative potential of renewable energy technologies in reducing the environmental consequences of fossil fuel-based systems and addressing global energy demand. The results emphasize that solar, wind, and hydropower have become the most viable renewable energy sources, as a result of substantial improvements in scalability, cost reduction, and efficiency over the past decade. In particular, solar and wind energy have made significant strides in cost reductions and efficiency improvements, rendering them more competitive with traditional energy sources. Hydropower, on the other hand, remains the most efficient energy source, despite its geographical limitations. Wind, solar, and hydropower are making substantial progress in the reduction of carbon emissions, which is one of the most critical benefits of renewable energy. Nevertheless, the intermittency of solar and wind technologies remains a challenge, emphasizing the necessity of improved energy storage solutions and grid modernization to guarantee a dependable energy supply.

Furthermore, biomass and geothermal energy have the potential to be beneficial in specific regions; however, their efficiency and cost necessitate additional technological advancements.

Regional disparities in renewable energy adoption reflect not only the availability of natural resources but also the varying policy and market conditions across different regions. Countries in Europe and South America have led the way in renewable energy adoption, driven by strong policy support and resource availability, while Africa and parts of Asia lag due to infrastructural and financial challenges. Looking ahead, achieving a global transition to renewable energy will require sustained innovation, particularly in energy storage and emerging technologies such as green hydrogen. Policy frameworks that encourage investment, reduce market barriers, and support grid development will be critical in accelerating adoption. This study concludes that while significant progress has been made, the global energy transition is still in its early stages, and

overcoming the remaining challenges will be essential to ensuring a sustainable, low-carbon future.

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