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Review Article

Environmental, Financial and Energy Implications of Renewable Energy Systems

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Abstract

This paper explored various sustainability measures to evaluate renewable electricity generation systems, drawing from a comprehensive literature review. The metrics examined included energy payback time, greenhouse gas emissions, and electricity production costs. We found notable differences among the technologies in these areas. To enhance the assessment process, we introduced a novel figure of merit that combines greenhouse gas emissions, energy payback duration, and production costs into a single framework for ranking renewable energy sources. This approach not only facilitates clearer comparisons between technologies but also highlights the trade-offs inherent in sustainability evaluations. Our findings indicated that small hydro and wind power emerged as the most environmentally friendly electricity generation methods, reinforcing the need for a holistic evaluation in renewable energy research.

Keywords: Greenhouse gas; renewable energy systems; energy payback time; wind energy; electricity production costs.

Introduction

Energy is crucial for modern society, and ensuring its sustainability is becoming increasingly important. As global energy demand continues to rise, the need for safe, abundant, and accessible energy sources is more critical than ever. Recent data indicates that renewables now contribute approximately 13.5% of the world's energy needs, marking a significant increase compared to earlier decades as the renewable energy sector grows faster than the overall market [1].

Historically, energy generation has been dominated by fossil fuels due to their availability and low cost. However, growing concerns about greenhouse gas emissions and environmental impacts are driving a shift toward cleaner alternatives [2]. Renewable resources—such as solar, wind, hydro, and geothermal—are becoming more accessible and diverse. With appropriate policies, technological advancements, and societal commitment, renewables could potentially meet up to 50% of global energy consumption by the mid-21st century [3].

Despite this potential, coal-fired power plants remain prevalent, particularly in emerging economies, due to their low generation costs and the availability of raw materials. Without significant initiatives to reduce emissions, the number of coal plants is likely to increase, contributing substantially to global greenhouse gas emissions. The energy sector continues to be a major source of emissions, driven by manufacturing, transportation, and electricity generation, with countries like India experiencing substantial rises in energy demand fueled by population growth and economic development [4].

Life cycle assessments (LCAs) have thoroughly examined the environmental impacts of various electricity generation technologies [5]. While technologies such as nuclear and solar are often labeled as "carbon-free," it is important to recognize that emissions can occur throughout their life cycles [6]. Transitioning to renewable energy for electricity generation offers notable environmental and economic advantages, especially as many renewable technologies become more cost-competitive [7].

This article aims to evaluate the performance of renewable energy technologies using a comprehensive figure of merit (FM) that incorporates three critical indicators: greenhouse gas emissions, energy payback duration, and electricity generation cost. By analyzing these metrics, we provide a holistic evaluation of renewable energy technologies, enhancing the understanding of their sustainability and potential within the current energy landscape.

Technologies for Renewable Energy Sustainability Indicators

Energy Payback Time (EPBT)

The term "energy payback time" (EPBT) refers to the number of years a renewable energy system needs to generate enough energy to offset the primary energy consumed throughout its entire life cycle. This concept is essential for evaluating the sustainability of renewable energy systems, as it directly reflects their efficiency and environmental impact. To calculate EPBT, we first determine the primary energy required for electricity generation based on annual energy output and total energy needs. This involves converting yearly power generation (measured in kWh) to primary energy, which requires knowing the average efficiency of power generation projects in the region being studied.

Recent research has made significant strides in life cycle analysis (LCA) methodologies, which now incorporate various sustainability indicators such as greenhouse gas emissions, energy payback time, and resource consumption [8]. It's also crucial to consider contemporary factors that influence renewable energy systems, including social impacts, land use, and water consumption. These elements are key for a comprehensive assessment of sustainability and should be included to accurately represent current challenges and opportunities in renewable energy deployment [9].

By integrating these modern insights and expanding the literature review to cover recent studies, this research seeks to provide a more relevant and thorough evaluation of the sustainability of renewable energy technologies. To compute EPBT, we use the following equation:

$$EPBT = \frac{TOTAL\ PRIMARY\ ENERGYREQUIREMENTOF\ SYSTEM\ THROUGHOUT\ ITS\ LIFE\ CYCLE\ (G)}{ANNUAL\ PRIMARY\ ENERGY\ GENERATION\ BY\ THE\ SYSTEM\,(G/year)} \quad (1)$$

Green House Gas Emissions

Greenhouse gas emissions (measured in gCO2 eq/kWh) are typically assessed throughout the entire life cycle of each renewable energy source, from construction to decommissioning ("cradle to grave"). This comprehensive approach offers valuable insights into the environmental impacts of different technologies, as emissions can vary widely. For example, the majority of emissions from photovoltaic (PV) and wind energy systems arise during the manufacturing process, with estimates often based on the average energy mix used in that region [10], [12].

Recent advancements in life cycle analysis (LCA) methodologies have refined these estimations, allowing for a more detailed assessment of emissions across different phases: production, operation, and decommissioning [13]. Additionally, it's essential to consider factors that affect sustainability beyond emissions alone, such as social implications, land use, and water consumption, all of which can significantly influence the overall evaluation of renewable energy technologies [14], [15].

Equation (2) outlines the framework for calculating greenhouse gas emissions, providing a quantitative basis for evaluating the climate impact of renewable energy systems. By incorporating these modern insights, the analysis aims to offer a more holistic understanding of sustainability within renewable energy technologies.

The methodology includes various equations to calculate key sustainability indicators like energy payback time (EPBT), greenhouse gas (GHG) emissions, and costs. However, it's important to clarify these equations for better comprehension. For instance, in the EPBT equation, "G" represents the total energy generated by the system over its operational life, which is crucial for determining the time required to recoup the energy invested in construction and maintenance [12-18].

While focusing on GHG emissions, EPBT, and cost provides valuable insights, there is a need for a stronger justification for limiting the analysis to just these three metrics. While they are critical for understanding the environmental and economic performance of renewable energy technologies, expanding the framework to include additional sustainability dimensions—such as land use, water consumption, and social impacts—could significantly enhance the robustness of the analysis. Incorporating these factors would allow for a more comprehensive evaluation of renewable energy systems, better reflecting the complexities and interdependencies of sustainability challenges in today's energy landscape [15-21].

$$\text{GHG emission} = \frac{\text{Total CO2 emission throughout its life cycle (gCO2eq)}}{\text{Annual power generation }(\frac{\text{KWHe}}{\text{year}}) * \text{lifetime (year)}} \quad (2)$$

Generation Cost of Electricity

The average cost of electricity production for each generation technology encompasses the full life cycle, including construction, installation, operation, maintenance, dismantling, and recycling. However, costs associated with backup systems, which are often necessary for intermittent renewable sources like wind and photovoltaics, are typically excluded from these estimates. This exclusion can have a significant impact on the overall economic assessment, as reliance on backup systems introduces additional financial implications [22].

Electricity production costs can vary widely across different systems. Photovoltaic (PV) systems, in particular, show considerable cost variability due to factors such as the type of solar cells used, location-specific conditions (like solar radiation intensity), and variations in manufacturing costs [23], [24]. Furthermore, social and environmental costs—such as land use and water consumption—are increasingly acknowledged as essential components of the overall cost assessment [25].

In the United States and the European Union, the cost of power production is typically reported in cents per kWh. Given the similarities in development levels in these regions, calculations often interchangeably utilize both the US dollar and the euro. Equation (3) presents the estimated cost of generating power, providing a quantitative framework for comparing the economic viability of various renewable energy technologies. By integrating contemporary insights and broader cost considerations, this analysis seeks to offer a more comprehensive understanding of the economic sustainability of renewable energy systems.

$$\text{Cost of electricity generation} = \frac{Annualised\ expensesof\ the\ system\ \ (cent\ /year)}{Annual\ electricity\ generation\ by\ the\ system(KWHe/year)} \quad (3)$$

Sources of renewable energy for power production

System of wind energy

Wind energy is a promising source of clean electricity, utilizing the wind's kinetic energy to generate power without emitting pollutants. Although it's a relatively new player in the energy sector, wind energy currently makes up about 0.3% of global installed power capacity. However, it only contributes around 0.1% to the overall electricity supply, largely due to its intermittent nature [7].Recently, we've seen rapid growth in wind power installations, driven by technological innovations and favorable policies that encourage renewable energy adoption [22-25]. This aligns with a broader global shift towards cleaner energy sources, though the variability of wind can create challenges for reliable power generation.

It’s also vital to consider the social and environmental implications of wind energy. Issues like land use, impacts on local wildlife, and community acceptance are crucial for the sustainable development of wind projects. Addressing these concerns will help maximize wind energy's potential contribution to the energy landscape [25-30].

Looking more closely at specific challenges, we find that greenhouse gas (GHG) emissions linked to wind energy vary significantly by region. This variation is influenced by factors like the energy mix used to manufacture wind turbine components and the local emissions from the grid. For example, if a region relies heavily on fossil fuels for electricity during manufacturing, it can raise the overall emissions associated with wind energy systems [30-35].

Cost is another important factor. The price of generating electricity from photovoltaic (PV) systems can differ widely, based on factors like the type of solar cells used, local solar radiation, and economies of scale in production. In sunnier regions, PV systems often yield lower costs per kilowatt-hour due to their enhanced efficiency and reduced energy losses.

Energy payback time (EPBT) is another critical metric, showing how long it takes for a technology to produce the energy required for its own construction and maintenance. In Denmark, for instance, the EPBT for wind energy is significantly shorter compared to other regions, reflecting the advanced technology and efficiency of their wind farms. In contrast, some PV systems have longer EPBTs, indicating a need for improvements in manufacturing and technology.

The performance of renewable technologies also varies by location and type. Offshore wind farms typically offer higher power ratings and lower emissions than their onshore counterparts. Similarly, PV systems perform better in regions with abundant sunlight.

As renewable technologies evolve, improvements in efficiency, manufacturing methods, and supportive policies will continue to influence these metrics. It's important to keep these trends in mind as we collectively move towards a cleaner energy future.[35-40].

In recent years, there has been an exponential increase in the development of wind farms, especially in nations like Denmark, Germany, and Spain. The total wind power capacity in the European Union increased dramatically from 439 MW in 1990 to 34,205 MW by the end of 2004 [18]. According to World Energy Council projections, by 2020, new worldwide wind capacity might range from 180 GW to 476 GW [19].The price of wind-generated power in large-scale systems decreased dramatically from 20 to 3.7-euro cents per kWh between 1980 and 2005 [20–21]. There is fewer life cycle analysis (LCA) research on high-capacity wind turbine power generation, despite the fact that many studies concentrate on the environmental effects of renewable energy. As more capacity is deployed, wind turbine costs keep falling. At three to five cents per kWh, wind power is already competitive with other electricity producing methods in windy locations. The global average cost was predicted to drop even further to about 2.7–3 cents per kWh by 2020 as a result of improved turbine designs and economies of scale from mass manufacture. Sustainability indicators for wind energy systems are shown in Table 1.

Table 1. Wind energy systems' sustainability indicators are included

S. no.	Year	Power rating (kW)	GHG emissions (gCO2eq/kWhe)	Cost (US cent/kWhe)	Location	EPBT (years)	Life (years)
1	1997 [22]	30	16.5	NA	Denmark	0.39	20
2	1996 [23]	100	123.7	NA	Japan	NA	20
3	1999 [24]	1500	19	NA	India*	1.0	20
4	1996 [25]	6600	25	NA	UK	NA	20
5	2001 [26]	100	39.4	NA	Japan	1.4	25
6	2005 [6]	300	29.5	NA	Japan	NA	NA
7	2007 [27]	22.5	20.5	5.74	Turkey	1.4	25

Table 2. PV system sustainability indicators.

S. no.	Type of cell	Year/References	Power rating (kW)	GHG emissions (gCO2eq/kWhe)	Cost (US cent/kWhe)	Location	EPBT (years)	Life (years)
1	mc-si	2006 [29]	14.4	44	NA	UK	8	NA
2	c-si	2000 [30]	0.035	300	NA	India	NA	20
3	c-si	2000 [31]	3300	60	NA	Italy	3.2	30
4	a-si	2000 [31]	3300	50	NA	Italy	2.7	30
5	c-si	1997 [6]	3	91	NA	Japan	15.5	20
6	c-si	2008 [15]	100000	12.1	19–20	China	1.9	30
7	c-si	2006 [16]	2.7	165	57	Singapore	4.5	25
8	c-si	2008 [15]	100000	9.5	19–20	China	1.5	30
9	a-si	2008 [15]	100000	15.6	19–20	China	2.5	30
10	c-si	1995 [32]	35 $kWhe/m^2$	NA	NA	India	3.95	NA

Photovoltaic (PV) system in the sun

Solar photovoltaic (PV) technology uses semiconductors called solar cells to directly convert sunlight into electricity. Photovoltaic modules are made up of these solar cells that are linked and hermetically sealed. The modules are assembled into solar PV systems and power plants along with additional parts like storage batteries. PV systems are modular and incredibly dependable. Although many places of the Earth experience significant sun radiation, the market potential for solar energy is still constrained by the comparatively high cost of solar panels. PV system installation costs are now about $5,000 USD/kW;however, they are steadily declining as a result of mass production and manufacturing scale-up. A 100 MW large-scale solar power plant established in Ita et al.'s study [15] was compared tofive different PV module types were used in the Gobi Desert: amorphous silicon with 6.9% efficiency, cadmium telluride (CdTe) with 9%, multi-crystalline kinds a and b with 12.8% and 15.8% efficiency, and copper indium CIS of selenium with 11% efficiency. The PV business has expanded quickly on a global scale; in 2005, an estimated 1.5 GW were installed [28]. Grid-connected systems have accounted for the majority of this development, although the off-grid sector has also been growing. The primary current drawback of PV is the high cost of PV cells and the corresponding BOS (balance of system). The sustainability indicators for solar PV systems are displayed in Table 2.

Table 3. Sustainability metrics for solar thermal energy systems.

S.no.	Location	EPBT (years)	GHG emissions (gCO2eq/kWhe)	Cost (US cent/kWhe)	Power rating (MW)	Type	Year of study/References	Lifetime (years)
1	Australia	NA	36.2	NA	100	Central receiver	1999[34]	NA
2	Spain	NA	202	NA	17	Central tower	2008[35]	25
3	USA	NA	43	NA	100	Central receiver	1990[36]	30
4	Spain	NA	196	NA	50	Parabolic trough	2008[35]	25

Table 4. Sustainability metrics for tiny hydro systems.

S.no.	Location	EPBT (years)	GHG emissions (gCO2eq/kWhe)	Cost (US cent/kWhe)	Power rating (MW)	Type	Year of study/References	Lifetime (years)
1	Japan	NA	18	NA	10000	Run-of River	1996[39]	30
2	India	2.71	74.88	NA	50	Run-of River	2008[40]	30
3	India	1.99	55.42	NA	100	Run-of River	2008[40]	30
4	India	1.28	35.29	NA	3000	Run-of River	2008[41]	30
5	India	1.31	35.35	NA	250	Canal-based	2008[41]	30
6	India	1.58	42.98	NA	1000	Canal-based	2008[41]	30
7	India	1.26	33.87	NA	400	Canal-based	2008[41]	30
8	India	1.1	31.2	NA	2000	Dam-toe	2008[41]	30
9	India	2.25	62.4	NA	1000	Dam-toe	2008[41]	30

Solar Thermal System

The technology used to generate solar thermal electricity can be broadly divided into five categories: solar chimney, solar pond, central receiver, paraboloidal dish, and parabolic trough. The power output of these systems typically ranges from 30 to 150 MW [33]. The solar receiver in a parabolic trough solar system is made up of a number of parabolic reflectors that concentrate light onto a black absorber tube that is situated along the focal line. A heat transfer fluid cools the absorber tube by absorbing heat and pumping it to a heat exchanger in a steam Rankine cycle, which produces electricity. A huge array of two-axis tracking mirrors, or heliostats, in the central receiver system focuses sun energy onto a centrally located receiver fixed a top a tower. This concentrated heat is used to produce electricity. A flat surface covered with glass in a solar chimney system exposes the earth and air beneath it to sunlight, raising their temperature by about 35°C over the surrounding air temperature (greenhouse effect). The roof is angled in the direction of a central, tall chimney, where hot air rises and creates a stream of air that wind turbines can use to produce power. A paraboloidal dish reflector in the dish-Stirling system directs sunlight onto a heat absorber, usually a tube or heat-pipe, that is positioned near the dish's focal point.

Table 5. Figure of merit for renewable based electricity sources.

S.no.	Location	EPBT (years)	source	FM	Power rating (MW)	Type	Year of study	Lifetime (years)
1	Denmark	NA	Wind	900	30	Offshore	1997	20
2	India	2.71	Wind	900	1500	NA	1999	20
3	Japan	1.99	Wind	729	100	Offshore	2001	25
4	Turkey	1.28	Wind	729	22.5	Urban area	2007	25
5	UK	1.31	Solar PV	48	14.4	mc-si	2006	NA
6	India	1.58	Solar PV	30	0.035	c-si	2000	20
7	Italy	1.26	Solar PV	168	3300	c-si	2000	30
8	Italy	1.1	Solar PV	192	3300	a-si	2000	30
9	Japan	2.25	Solar PV	18	3	c-si	1997	20
10	China		Solar PV	360	100000	c-si	2008	30
11	Singapore		Solar PV	12	2.7	c-si	2006	25
12	China		Solar PV	360	100000	c-si	2008	30
13	China		Solar PV	320	100000	a-si	2008	30
14	Australia		Solar thermal	360	100	Central receiver	1999	NA
15	Spain		Solar thermal	36	17	Central tower	2006	25
16	USA		Solar thermal	288	100	Central receiver	1990	30
17	Spain		Solar thermal	40	50	Parabolic trough	2006	25
18	India		Small hydro	560	50	Run-of River	2008	30
19	India		Small hydro	720	100	Run-of River	2008	30
20	India		Small hydro	810	3000	Run-of River	2008	30
21	India		Small hydro	810	250	Canal-based	2008	30
22	India		Small hydro	720	1000	Canal-based	2008	30
23	India		Small hydro	810	400	Canal-based	2008	30
24	India		Small hydro	810	2000	Dam-toe	2008	30
25	India		Small hydro	560	1000	Dam-toe	2008	30

A Stirling engine is powered by the heat it absorbs to produce energy.An expanse of water with a dark bottom that absorbs both light and salt is called a salt gradient solar pondSunlight is reflected and diffused, and it is transformed into thermal energy that is stored as hot water and can be utilized to generate electricity. Both solar thermal and photovoltaic (PV) systems may run in Southern Europe for less than 20 cents per kWh. In Southern Europe and North Africa, solar thermal power plants continue to be the most economical option due to their ability to generate electricity at rates as low as 10 cents per kWh. The sustainability metrics for solar thermal systems are shown in Table 3.

Mini hydro power plant

The foundation of hydropower is a simple method that uses the kinetic energy that falling water releases. The water's motion powers a turbine in every hydroelectric power plant, converting it first into mechanical and subsequently electrical energy [37]. Although the term "small hydropower" (SHP) has no universally accepted definition, it is typically categorized based on electricity output. Various nations have different upperboundaries, which span from 5 MW to 50 MW. For instance, the Central Electricity Authority (CEA) of India categorizes SHP programs according to their output [38]. Three main categories of SHP projects exist: run-of-river, canal-based, and dam-toe schemes. The sustainability metrics for small hydro systems are shown in Table 4.

The merit figure

Comparing various energy systems according to their performance, net energy requirements, or other important metrics is frequently done using the figure of merit.Previous studies [42–43] have examined these systems' gross carbon emissions in great detail. This research proposes a figure of merit (FM) to equally weight and assess different sustainability indicators on a single platform. As demonstrated in Table 5, each technology is scored from 1 to 10 in accordance with its related indicator using FM for the chosen indicators. For each indicator, the technology with the highest value is ranked 1, the technology with the lowest value is ranked 10, and the remaining technologies are ranked in between. Higher ranks are given to lower values for energy pay-back time (EPBT), greenhouse gas emissions, and the cost of producing power. For greater numbers, the relative rank is 1, and for lower ones, it is 10(for lower numbers) in relation to these three metrics. Equation (4) is used to calculate the figure of merit:

$$\mathbf{FM = Relative\ rank_{cost} \times Relative\ rank_{GHG\ emission} \times Relative\ rank_{EPBT}} \quad \mathbf{(4)}$$

Every piece of information about the various renewable energy sources came from published works. A small number of research examine all three sustainability indices (energy intensity, GHG emissions, and EPBT). The majority of the literature looks at energy intensity or GHG emissions, and occasionally both are looked at in addition to EPBT. Knowing the lifespan of the power plant and the average electricity generating efficiency for the nation where the plant is located can be used to determine EPBT using energy intensity. The average electricity generation efficiency is taken to be 0.40 for the sake of this computation. The plant's energy intensity (ei) when itthe ratio of the energy required (E) for building, operation, and decommissioning to the total electricity production of the plant over its lifetime (t) is known as the power rating (P) and

load factor (l), as seen in Eq. (5) [7]:

$$ei = \frac{E}{P \times 8760 \times \lambda \times t} \quad (5)$$

Results and discussion

Four renewable energy sources—wind, photovoltaic, solar thermal, and small hydro—were examined based on the figure of merit. In order to evaluate GHG emissions and EPBT, Table 5 displays the FM values for these sources taking into account varying years of origin, capacity, and respective lifespan. Table 6 illustrates the FM values for wind, PV, solar thermal, and small hydro, which vary from 729 to 900, 12 to 360, 36 to 360, and 560 to 900, appropriately. These ranges represent differences in capacity, study periods, system lifespan, and geography. EPBT and GHG emissions significantly decline with system capacity. According to the findings, solar thermal and solar photovoltaic systems should come first when it comes to sustainable electricity generation, followed by wind and small hydro.

1. **Efficiency and Resource Availability**: Wind energy systems often outperform other technologies due to their ability to harness high and consistent wind speeds in optimal locations. The design and technology advancements in turbine efficiency have significantly reduced the cost of energy generation, allowing wind farms to achieve a lower cost per kilowatt-hour. In contrast, solar PV systems may face challenges related to intermittency and efficiency losses due to weather variability and less optimal site conditions.

2. **Environmental Impact**: Small hydro systems typically have a lower environmental footprint compared to large-scale hydroelectric plants, which can disrupt ecosystems and communities. The smaller scale and localized nature of small hydro projects often result in minimal land use and lower GHG emissions, contributing to a higher figure of merit. In addition, small hydro projects can often be integrated into existing water infrastructures, further minimizing environmental impacts.

3. **Economic Viability**: The cost structures of wind and small hydro systems tend to be more favorable due to established technologies and competitive supply chains. In many regions, the capital costs for wind installations have decreased significantly over the years, making them economically attractive. Small hydro projects benefit from relatively low operational costs and high capacity factors, further enhancing their economic viability.

Inclusion of Policy Implications

The findings of this analysis have significant implications for energy policy, especially in developing countries like India and Nigeria, where there is a growing demand for sustainable energy solutions.

1. **Incentivizing Renewable Technologies**: Policymakers should consider implementing incentives and subsidies specifically aimed at promoting technologies with a higher figure of merit, such as wind and small hydro. This could involve financial support for project development, tax breaks for investors, and streamlined permitting processes. By focusing on the most effective technologies, countries can maximize the benefits of renewable energy investments.

2. **Investment in Infrastructure**: Developing countries need to invest in the necessary infrastructure to support renewable energy deployment. For instance, enhancing grid connectivity and storage solutions will be critical for managing the intermittent nature of renewables, particularly for solar and wind energy. This investment can help integrate a higher share of renewables into the energy mix.

3. **Capacity Building and Education**: Training programs and education on the benefits and implementation of renewable energy technologies are vital for fostering local expertise. By building local capacity, countries can create jobs and ensure that projects are developed and maintained sustainably.

4. **Regional Collaboration**: Encouraging regional cooperation in renewable energy projects can enhance energy security and optimize resource utilization. Collaborative initiatives can lead to shared infrastructure, which reduces costs and improves access to renewable technologies.

Table 6. Figure of quality range for dissimilar renewable electricity generation bases.

S. no	Figure of merit	System
1	36–360	Solar thermal
2	12–360	PV Solar
3	560–900	Small hydro
4	729–900	Wind

Conclusion

Three different sustainability indicators were used to assess the renewable energy technologies, and each was given equal weight in calculating the technologies' contribution to sustainable development. Based on their effects on the environment and the economy, these variables were used to rank the different renewable technologies. According to the analysis, wind and modest hydroelectric power are excellent sources of sustainable electricity. Where these solutions are not practical, attention can be directed on the advancement of solar thermal and photovoltaic systems. Greenhouse gas (GHG) emissions are an important component, but they are not the only environmental element to take into account; a more thorough assessment of sustainability should take land and water consumption into account as well. The cost of generation and greenhouse gas emissions are rising as new technologies are developed and mass production.

The findings of this study highlight significant variations in the performance of different renewable energy technologies, particularly in terms of greenhouse gas emissions, energy payback time, and costs. Technologies such as wind and small hydro demonstrate a higher figure of merit, driven by their efficiency, lower environmental impact, and economic viability. However, the implications of these results extend beyond mere performance metrics.

Broader Implications

In the context of global climate change targets, the advancement and adoption of renewable energy technologies are critical. As countries strive to meet their commitments under international agreements such as the Paris Agreement, transitioning to low-carbon energy sources will be essential for reducing greenhouse gas emissions. The insights gained from this analysis can guide policymakers in prioritizing investments in high-performing renewable technologies, thereby facilitating a more rapid transition to sustainable energy systems.

Moreover, promoting renewable energy development can lead to numerous co-benefits, including job creation, energy security, and reduced air pollution. By strategically focusing on technologies that offer the greatest environmental and economic advantages, nations can enhance their resilience against climate change while fostering sustainable economic growth.

Future Research

To further enrich the understanding of renewable energy systems, future research should explore several key areas. Firstly, investigating the social impacts of renewable energy projects—such as community acceptance, equity in access, and the implications for local livelihoods—will provide a more holistic view of sustainability. Understanding how these technologies affect communities is crucial for ensuring that renewable energy transitions are inclusive and just.Additionally, examining the ecological impacts of various renewable energy installations can help identify best practices for minimizing adverse effects on biodiversity and ecosystems. Studies that assess the life cycle impacts of renewable technologies, including land use changes and resource consumption, will contribute to more informed decision-making.

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