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## **Renewable Energy and Sustainability: Emerging Trends and Technology**

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## ABSTRACT

The quest for sustainable energy is growing at an alarming rate due to the need to mitigate climate change and the fact that our energy systems' sustainability holds a critical role in achieving a net zero economy. This study examines renewable energy and sustainability: emerging trends and technology. The study is guided by five objectives and five corresponding research questions. This paper explores the advancement made on each renewable energy source and their associated sustainability concerns. It is discovered that many landmark advancements have been made regarding solar, Wind, biofuel, and geothermal energy. However, despite the various advancements, many obstacles and sustainability concerns still exist. Furthermore, the paper shows that solar and wind energy technology offer the most promising options and has witnessed huge investment in the past decades, bringing their installed capacity far above other renewable sources. The study found out that: solar and wind energy are the most preferred for energy transition. While the study established that, hydrological energy is the largest renewable energy source though it requires huge financial involvement in the construction of dams in generating electricity. Based on the findings of the study, the recommended that, researchers should consider including artificial intelligence and machine learning in advancing renewable energy technology to address sustainability concerns.

**Keywords:** Sustainability, development, energy, renewable energy, solar, geothermal, biofuel, hydrological, wind.

## INTRODUCTION

Almost every day, sunlight shines, wind blows, and water flows, but inherent in these natural resources lies an enormous alternative energy, the so-called renewable energy. Renewable energy sources are clean energy that emanate from constantly replenished sources like the sun, water, wind, etc. Renewable energy is often thought of as a new technology, even though it has existed for as long as humanity. For more than 500 years, wind power has been used to sail boats and power mills while the sun has been used for various heating applications (*Renewable Energy: The Clean Facts*, 2025). Renewables have only become a more critical power source these days due to the innovation of more affordable and advanced ways of exploiting and capturing these resources. Renewables have been so prominent in today's energy mix. It accounts for 29% of the global electricity generation in 2024 (Enerdata, 2024). Renewable energy includes solar, wind, hydropower, biofuels, geothermal, bioenergy, etc. Although renewable energy is crucial in the global transition to a net zero economy, a more important issue is what researchers referred to as 'sustainability'.

This paradigm is now seen as crucial in the quest to mitigate the impact of climate change. By the sustainability of renewable energy, we refer to the ability to ensure that while pursuing advancement in renewable energies, we also address climate change, reduce environmental pollution and ensure long term energy security. This is why renewable energy and sustainability are widely discussed, in fact, two inseparable topics and the issue of global warming is linked to energy and sustainability (Ray, 2019).

The strong advocacy on renewable energy is birthed out of the need for sustainability. Major opinions are that the earlier path of the industrial revolution era will lead to a great disaster for future generations. Hence, the concept of 'Sustainability' and resultantly, the desire for Renewable energy (Ray, 2019). The ability to meet the current energy demand without compromising the ability of future generations to do the same, while relying on eco-friendly sources that can be replenished.

Studies have shown that energy is at the cornerstone of climate change, as it is the primary source of the blanket greenhouse gas that envelopes our earth. Fossil fuel alone accounts for over 75% of global greenhouse gas emission and nearly 90% of carbon dioxide emission. Science has established that to prevent the worst impact of climate change, we need to halve emissions by 2030 through investment in advanced alternative energy sources that are eco-friendly (United Nations (2022)).

### **Statement of the Problem**

The increasing global demand for energy, coupled with the need to mitigate climate change and ensure sustainable development, requires the development and deployment of advanced renewable energy systems. Despite the growth of renewable energy technologies, there are still significant challenges to be addressed, including energy storage, grid integration, and cost competitiveness. This study aims to investigate emerging trends and technologies in advanced renewable energy systems, with a focus on identifying opportunities and solutions to these challenges.

### **Aim and Objectives of the Study**

The main of this paper is to explore the advancements in various renewable energy technologies, and their associated sustainability issues. Specifically the study seeks to:

1. Explore the sustainability of wind energy.
2. Examine the efficiency of solar energy.
3. Examine the source of hydrological energy.
4. Investigate generations of biofuels as alternative to non-renewable energy fuels.
5. Explore the advancement of geothermal energy.

### **Research Questions**

The following research questions guided the study

1. How can wind energy be sustained?
2. How is solar energy efficient?
3. What is the source of Hydrological energy?
4. What are the generations of biofuels as alternative to non-renewable energy fuels?
5. In what ways does the advancement of geothermal energy influence energy sustainability?

### **Scope of the study**

This study will focus on:

1. Emerging trends and technologies: Investigating emerging trends and technologies in advanced renewable energy systems, including solar, wind, hydro, and geothermal energy.
2. Sustainability and environmental impact: Evaluating the sustainability and environmental impact of advanced renewable energy systems.
3. Cost competitiveness: Analyzing the cost competitiveness of advanced renewable energy systems and identifying opportunities for cost reduction.

### **Significance of the study**

This study is significant because it:

1. Supports sustainable energy transition: By identifying emerging trends and technologies in advanced renewable energy systems, this study can inform the development of sustainable energy solutions.
2. Informs policy and investment decisions: The findings of this study can inform policy and investment decisions in the renewable energy sector, supporting the development of sustainable energy systems.
3. Contributes to climate change mitigation: By advancing the development and deployment of renewable energy systems, this study can contribute to climate change mitigation efforts.

### **Literature Review**

#### **Theoretical Framework**

In this study, the theoretical perspective is based on advancement in renewable energy technologies and their sustainability, especially as it relates to renewable energies like Solar, Wind, Geothermal, Marine and Bioenergy. Although, Renewable energies are widely agreed and accepted as the alternatives to fossil fuel and the future energy to ensure net-zero economy; however their utility scale development comes with a multifaceted sustainability challenges. These challenges necessitate the need for a wholistic approach ensuring their sustainable development and deployment.

The sustainability concerns identified in most of the renewable energy technologies are very crucial in evaluating their feasibility and long-term viability. This term paper will look at the various advancement in various renewable energy technology and their sustainability concerns to determine the progresses made so far and future direction.

### Conceptual Framework

#### Wind Energy and its sustainability

Renewables, especially solar and wind are most preferred for energy transition. Wind energy costs have decreased by about 1/3 since 2009, and the installed capacity has grown to 645GW as of 2019 due to pressure on climate change, forcing huge investment in renewable energy. Investment in wind energy is as high as \$134.1 B.

Sustainability of wind energy is paramount for climate mitigation and energy security. Forecasted to reach a capacity of 2110 GW by 2030, it could create 2.4 million jobs and provide 20% of global electricity generation by 2050, and 5.8TW by 2050(Darwish & Al-Dabbagh, 2020).

In wind energy conversion, the wind is basically used to drive a wind turbine, which in turn drives a generator through some mechanical arrangement to generate electricity. The wind turbine blade captures the mechanical energy upstream and converts it to electrical energy (JOSHUA & Sthuthi, 2019).

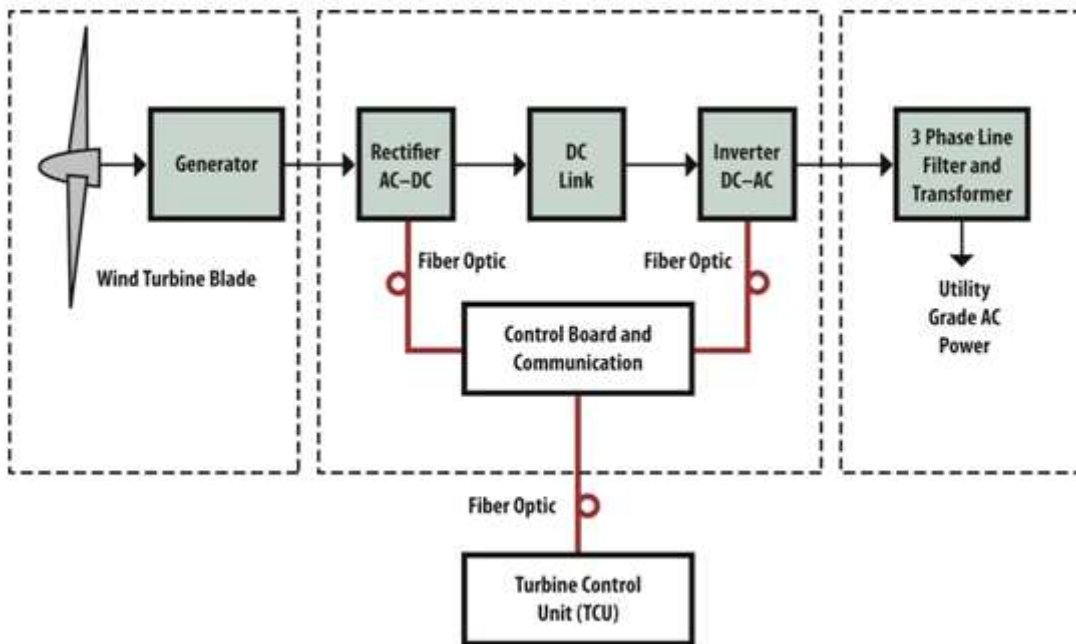


Figure 1: Block diagram of a wind energy conversion system (S. Sawalha, 2024)

As far as wind energy is concerned, onshore wind energy and offshore wind energy conversion are available energy conversion technologies. Both methods of wind energy conversion employ the same working principle, but differ in terms of location. Progress has been made in the wind energy sector, mainly due to technological advancements. Innovations such as larger turbine designs, floating wind turbines, and the use of advanced materials have enhanced efficiency and reliability. These developments have led to more energy capture and reduced costs, making wind energy more competitive in the global energy market. (Nwankwo Charles Uzundu & Dominic Dummene Lele, 2024).

While advancements in wind energy technology have led to economic benefits, Important issues such as wildlife impacts and noise pollution from wind turbines need to be effectively managed. These environmental impacts, coupled with poor community engagement, often lead to low social acceptance

and poor public perception. It is important to address this environmental impact to make advancement in wind energy more sustainable.

According to the work of Nwankwo & Dummene Lele., (2024)Hybrid systems that combine wind energy with other renewable sources can provide a more stable energy supply in the future. For instance, combines hybrid offshore wind and floating photovoltaic systems. Additionally, international cooperation and knowledge transfer are extremely important for the future development of global standards for wind energy.

### Advancement in Solar Energy

Solar power, particularly Solar Photovoltaic (PV), is the most promising option of all renewable energy. The great Alexandre Edmond derived the photovoltaic effect, which allows sunlight to generate electricity by using semiconductor material to absorb sunlight (photons) and convert it to electrical energy. The essential components of a solar cell are as shown in Figure 1. A single PV cell generates between 1-2W and a typical solar panel can contain up to 72 cells or more. Solar technology has since experienced many transformations, from the early discoveries to today's high efficiency and various high-end applications. Amongst them are mobile device applications, heating applications, electricity generation, and cooling, to mention but a few.

The milestone recorded in solar technology is owed to the various advancements in material science, manufacturing technology, and increased global demand for renewable energy. (Sanuja et al. 2023).

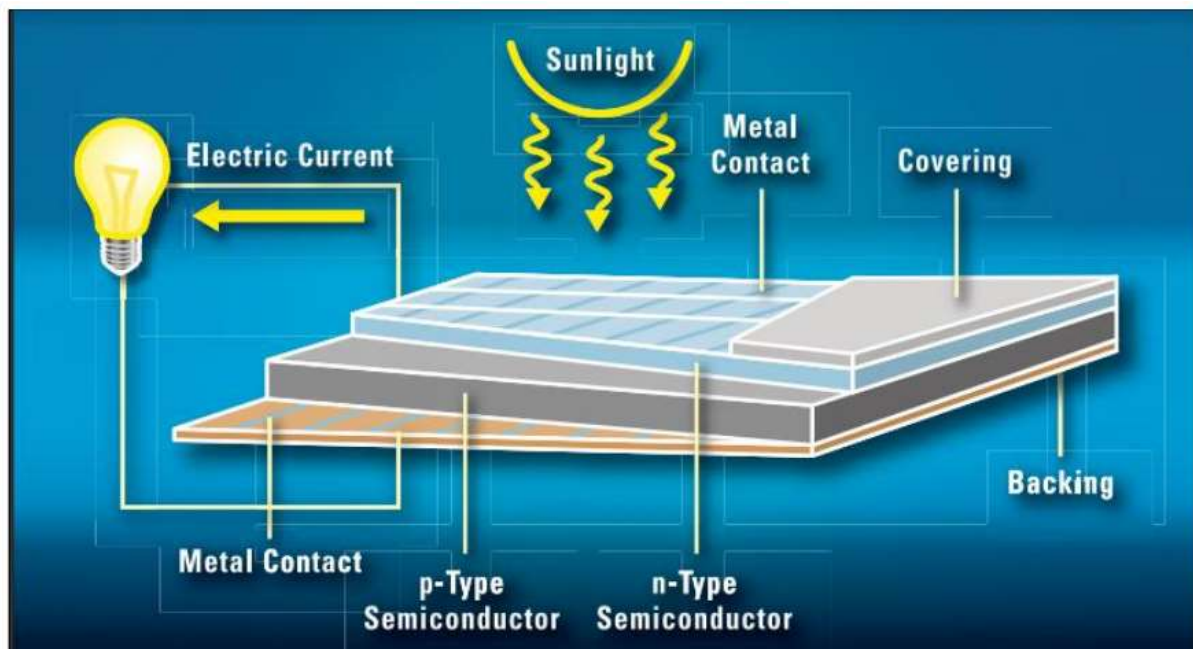


Figure 2: Component of a solar cell (Sanuja et al., 2023)

The first generation of solar cell is characterized by the silicon-based cell with less regard for cost and more application in satellite technologies. (*Advancement in Solar Technology: Evolution, Generation, Future Prospective, and Challenges - A Review[v1] | Preprints.Org, n.d.*)

With even more contemporary innovations in the field of solar technologies including silicon photovoltaic cells, thin-film solar cells, perovskite solar cells, bifacial panels, concentrated solar power, and building-integrated Photovoltaic, the issue of efficiency is still a central point of research.

Much advancement has been made in solar technology. The key areas of advancement are in terms of efficiency improvements. Advancements in solar efficiency have led to enhanced performance and drastic cost reductions in technology.

New materials like the perovskite cell have been explored, showing high potential for high efficiency and low cost. However, much research is ongoing regarding the stability and efficiency. From heterojunction solar cells, Light-trapping structure, Quantum efficiency improvements, to manufacturing techniques like the diamond wire method, anti-reflective coating, self-cleaning coating, Roll-to-Roll Manufacturing, and advanced encapsulation techniques.

As far as application of solar technology is concerned, some of the advancements made include Integration of energy storage with PV system to enhance reliability and accessibility, Intelligent charge controllers, life cycle analysis, Solar Tracking system, Concentrated Solar Thermal applications, Feed-in-Tariff, Net metering, (Sanuja et al., 2023)

Despite all these improvements and advancements, many dissenters are still very concerned about the sustainability of technology. Some of the sustainability issues with solar technology are the fact that PV production can lead to greenhouse gas emission and environmental degradation, Big installations can disrupt ecosystems, and it requires a huge expanse of land. Other sustainability issues include end-of-life disposal, intermittency, material sourcing, and energy-intensive manufacturing, requiring careful consideration and more innovative solutions.

Many efforts are ongoing to address the sustainability concerns through environmental impact assessment, sustainable manufacturing process, Net metering policy, investment in tax credit, etc. It is clear that even though technological innovations in solar technology are enormous, challenges still abound.

### **Source of Hydrological Energy**

Hydropower's energy is another very promising and currently the largest renewable energy source. It is derived from water moving from higher to lower elevations, mainly from rivers and reservoirs. When it relies on water stored in the reservoir, it is called a reservoir hydropower plant, while the one that harnesses energy flow from the river is a river power plant. (Raj & Andrew, 2023).

Hydroelectric power plants need a huge amount of construction work and expenses. Most of the suitable locations for Hydropower are already occupied. Sedimentation and flooding are the biggest drawbacks of large hydropower projects. Typically, people are forced to migrate, and interference with natural habitats is very common. Hence, a serious concern for sustainability.

New methods need to be adopted to tackle energy needs and climate change. Modern hydropower now explores marine movements, which has led to various advanced methods of extracting energy from water bodies. The modern methods include In-stream hydro-kinetic energy, wave energy, Tidal energy, and ocean thermal power. (Muratoglu & Yuce, 2016)

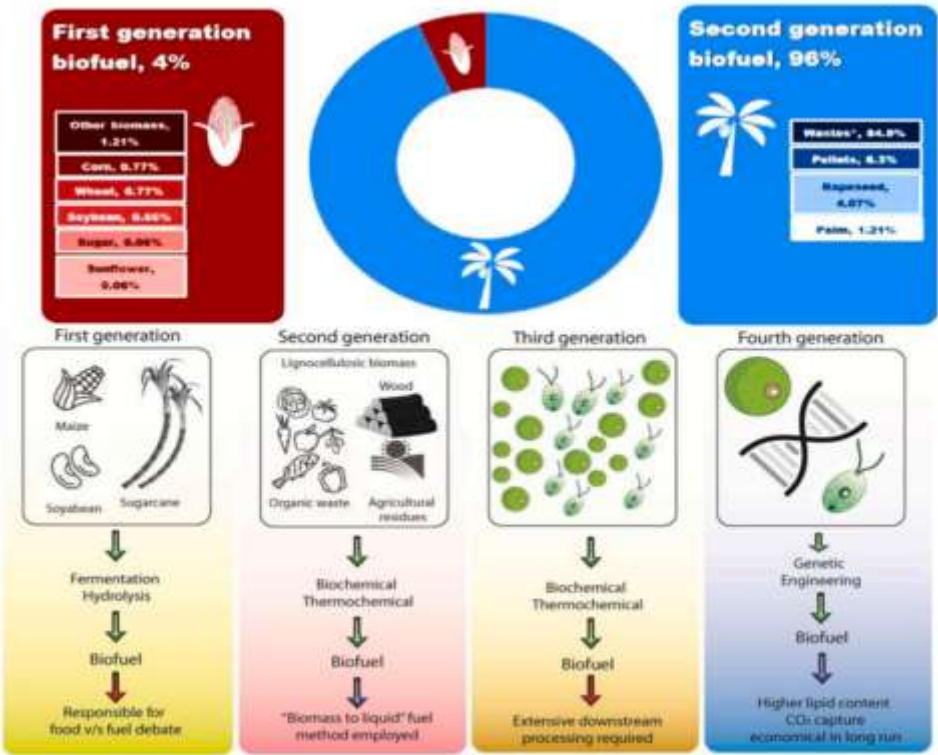
### **Generations of Biofuels as Alternative to Non-Renewable Energy Fuels**

Biofuels are derived from an organic source (biomass) created by living things that can be grown and harvested over and over again. For example, biofuels from *Jatropha* plants or bioethanol from sugar cane. As such, it is used as an alternative to non-renewable energy fuels. Biofuels can be in the form of Biodiesel (produced from vegetable oils), bioethanol (alcohol gotten from a fermentation process), or biogas. It is estimated that the world will fall short of petroleum oil by 2070-2080, necessitating the need for complementary power sources that are reliable, accessible, and renewable, and Biofuel is one of the renewables considered for such alternatives (Malode et al., 2021).

### **Generations of Biofuel**

Many years of research and advancement have culminated in biofuels being grouped into generations, as shown in Figure 3, depending on their feedstock.

- First generation consists of oil-based plants, starch yield, and sugar, but they contribute to nutrition and fuel conflict.
- Second generation, which has genetically transformed yields and is based on sustainable lignocellulosic. Second generation biofuels minimize food safety.
- Third generation biofuels produced by algae can be produced on a large scale, are relatively easy to refine, and have attracted a lot of recognition.
- Fourth generation of biofuels uses engineered cyanobacterial development, which is a new and rapidly evolving area in Biofuels development. (Malode et al., 2021).



Biodiesel’s environmental advantages come from its biomass production process, such as plant oils or animal fats, which capture carbon dioxide during growth. By Biodiesel sustainability, we refer to the economic, social, and environmental considerations linked to biofuel production such as biodiesel.

The aim is to minimize the environmental negative impact of biofuels and maximize their potential as a low-carbon energy source. The aspect of biodiesel sustainability that research and policy still need to address include feedstock selection, land use and resource management, deforestation and habitat conservation, waste utilization, and social impact. The choice of feedstock for biofuels production is important to sustainability.

It is important to note that Indonesia and Malaysia have advanced in the utilization of biodiesel to a higher level, even far above the United States, India, and China. (Ade et al., 2024)

**Advancement and Sustainability of Geothermal Renewable Energy**

Geothermal energy is a renewable energy source derived from the Earth's internal heat, used for heating, cooling, and electricity generation, by tapping into natural steam or hot water from the Earth's core (Rybach, 2007). The technology used in geothermal is divided into four classes, namely conventional

hydrothermal, low-temperature geothermal system, enhanced geothermal system (EGS), and direct use, including geothermal heat pumps (GHPs).

The first three classifications produce energy, while the fourth is typically utilized to produce heat and cold water (Kumar et al., 2022). Many regions of the world are tapping into the vast geothermal resources available. For instance, as far back as 2013, over 11,700 megawatts (MW) of utility-scale geothermal capacity was in operation globally, with another 11,700 MW in planned capacity additions on the way (GEA, 2013).

Geothermal energy is commonly captured by tapping into naturally occurring hydrothermal convection systems, where cold water sent into earth's crust, is heated up, and then allowed to rise to the surface and is then used to drive electric generators.

Basically all the various designs of geothermal energy pull out water and steam from the ground, use it and return it as a warm water so as to prolong the source of the heat. The selection of the type of design to use is dependent on the geothermal resources available. Geothermal energy is often seen as a renewable energy source, but its development on a large scale poses a significant multi-dimensional set of sustainability implications. Hence, there is a need to develop it sustainably.

According to Shortall et al., (2015), the sustainability issues associated with geothermal energy include income poverty and inequality, Health risks, vulnerability to natural hazards, land use effects, and biodiversity. Another sustainability concern with geothermal is the emission of some air pollutants especially when it has to do with open systems like Geysars.

### **Key Findings of the Study**

The study finds out that:

1. Solar and wind energy are most preferred for energy transition. It equally established that wind energy it could create 2.4 million jobs and provide 20% of global electricity generation by 2050, and 5.8TW by 2050(Darwish & Al-Dabbagh, 2020).
2. Similarly, established that solar power, particularly Solar Photovoltaic (PV), is the most promising option of all renewable energy. It further established that, the advancement in solar energy include the Integration of energy storage with PV system to enhance reliability and accessibility, Intelligent charge controllers, life cycle analysis, Solar Tracking system, Concentrated Solar Thermal applications, Feed-in-Tariff, Net metering, (Sanuja et al., 2023).
3. Conversely, the study found out that hydrological energy is the largest renewable energy source though it requires huge financial involvement in the construction of dams in generating electricity.
4. Additionally, the study found out that, there are four generations of biofuel; which include: First generation which consists of oil-based plants, starch yield, and sugar, but they contribute to nutrition and fuel conflict. The second generation, which has genetically transformed yields and is based on sustainable lignocellulosic. Second generation biofuels minimize food safety. While the 3rd generation biofuels is produced by algae which can be produced on a large scale, they are relatively easy to refine, and have attracted a lot of recognition. The fourth generation of biofuels uses engineered cyanobacterial development, which is a new and rapidly evolving area in Biofuels development. (Malode et al., 2021).
5. Lastly, the study established that, the technology used in geothermal is divided into four classes, namely conventional hydrothermal, low-temperature geothermal system, enhanced geothermal system (EGS), and direct use, including geothermal heat pumps (GHPs).

### **METHODOLOGY**

This paper adopts qualitative research approach to review the advancement achieved so far in each renewable energy technology, their sustainability concerns and future directions. Secondary data, peer reviewed journal articles etc. were used.

The findings from the review will be used to develop recommendations for ensuring sustainable development of renewable energy technologies that can foster a balance between environment, social and economic considerations.

## CONCLUSION

Energy transition is a multifaceted problem that requires multiple approaches to address it. This paper has drawn and explored some of the latest advancements in renewable energy technologies. While acknowledging that there are lots of advancements and development in each technology- Solar, Wind, Biofuel, Marine energy, and Geothermal, there are also many sustainability concerns inhibiting the progress, wide adoption, and deployment of these technologies on a larger scale. There is a need for a strong and concerted effort in the integration of these technologies and investment to enable the achievement of the climate change target. Nevertheless, solar and wind remain the most promising solutions and widely utilized technologies in all renewables, irrespective of their technological advancement.

## RECOMMENDATIONS

Efforts put into the advancement of renewable energy are enormous and highly appreciated. However, it is hereby recommended that

1. Researchers should consider including artificial intelligence and machine learning in advancing renewable energy technology to address sustainability concerns.
2. Additionally, international cooperation and knowledge transfer are extremely important for the future development of global standards for renewable energy.

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