

Polymer Advancements in Renewable Energy Technologies: Bridging Sustainability and Practicality

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ABSTRACT

Renewable energy technologies have seen substantial progress in recent years, with solar, wind, and water becoming key sustainable energy sources. Solar photovoltaic technology, in particular, has advanced significantly, driving down costs and making renewable energy more economically viable across many regions. Despite these advancements, challenges such as technological maturity, high costs, and inefficiencies in energy storage and transmission continue to hinder widespread adoption. Conductive polymers have emerged as promising materials to address these challenges, particularly in enhancing organic solar cell efficiency. Their lightweight and flexible properties make them ideal for portable and adaptable energy applications. Structural modifications, including adjustments to conjugation lengths, side chains, and the incorporation of nanomaterials, have improved light absorption, charge transport, and overall energy conversion efficiency. This review explores the critical role of polymers in renewable energy technologies, focusing on their application in solar cells, energy storage, and sustainable material design. It highlights innovative approaches to polymer development, such as nanocomposite integration and chemical modifications, which have enabled significant advancements in energy efficiency and sustainability. By addressing current challenges and uncovering future potential, this study emphasizes the importance of polymers in driving the transition to renewable energy systems.

KEYWORDS

Renewable Energy; Solar energy; Wind power; Bioenergy; Hydropower; Sustainability

1. INTRODUCTION

Renewable energy, derived from natural sources such as solar, wind, tidal, and geothermal energy, offers an environmentally sustainable alternative to non-renewable resources. Unlike fossil fuels, which are finite and contribute significantly to environmental degradation, renewable energy sources have minimal environmental impact and are widely distributed, making them suitable for local development and utilization. The growing global energy demand, coupled with the urgent need to address environmental challenges like climate change, has prompted major economies to implement policies and measures aimed at accelerating the transition to renewable energy systems [1].

Recent advancements in renewable energy technologies have marked a transformative era. Solar, wind, and water energy have emerged as key contributors to the global energy mix. Solar photovoltaic technology, in particular, has transitioned from laboratory research to mainstream adoption in households worldwide. According to the International Renewable Energy Agency (IRENA), the declining costs of renewable energy technologies have positioned them as the most economically

viable energy solutions in many countries [2]. However, significant challenges persist, including varying levels of technological maturity, high implementation costs, and critical issues related to energy storage and transmission. As illustrated in Figure 1 (left), renewable energy sources such as wind, solar, biomass, and geothermal energy demonstrate the highest sustainability potential compared to conventional power sources like coal, nuclear, and natural gas.

Addressing these challenges requires innovative approaches, including the sustainable development and application of polymer materials. Polymers play a pivotal role in renewable energy technologies, particularly in the production of bio-based materials, solar cells, and energy storage solutions. Research has focused on designing and synthesizing polymers that minimize environmental burdens, extend service life, and optimize energy efficiency. Additionally, advancements in recycling, reuse, and material conversion techniques aim to mitigate the environmental impact of polymer usage in energy systems, further enhancing their sustainability [3].

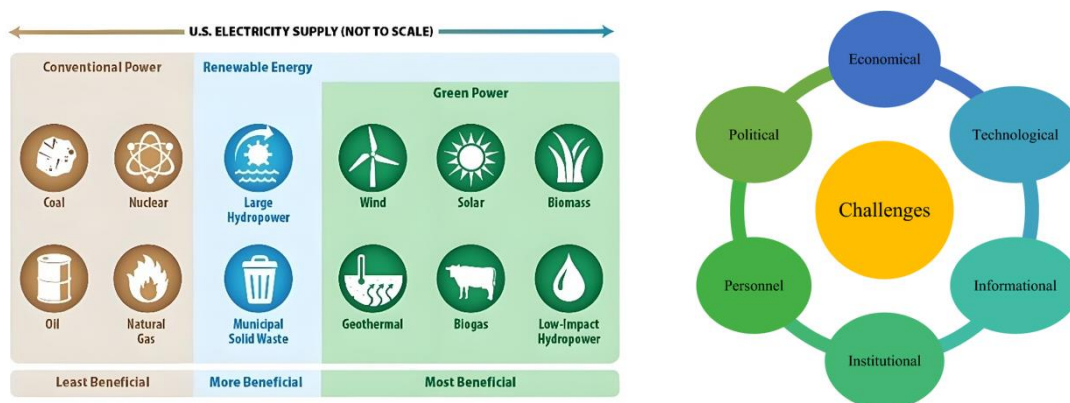


Figure 1. Comparative Overview of Energy Sources and Challenges in Renewable Energy Adoption.

2. ROLE OF RENEWABLE ENERGY AND POLYMERS IN SUSTAINABLE ENERGY SYSTEMS

2.1. Contribution of Renewable Energy to Global Energy Supply

Renewable energy sources have become essential

in addressing the growing global energy demand and mitigating environmental degradation. As of 2001, renewable energy accounted for 13.5% of the global primary energy supply, with biomass contributing 80% of that share [4]. Historically, renewable energy sources dominated the global energy landscape three centuries ago, and research suggests that with continued innovation, this level of reliance on renewables could be achieved once again. Looking forward, solar and wind power are expected to play a pivotal role in shaping sustainable energy systems.

2.2. The Significance of Solar Energy

Among all renewable energy sources, solar energy is the most abundant and versatile. It can be directly utilized through solar thermal systems or photovoltaic technologies. Furthermore, wind power and hydroelectricity are considered indirect forms of solar energy, as they are driven by the sun's influence on atmospheric and hydrological processes. The sun's ability to heat air masses, combined with the Earth's spherical shape, rotation, and fluctuations in solar irradiance, creates the air pressure differentials necessary for generating wind and water cycles [5]. These inherent advantages make solar energy a cornerstone of future renewable energy systems.

2.3. Polymers in Renewable Energy Systems

Polymers have emerged as a key material in advancing renewable energy technologies, contributing to efficiency improvements and sustainability across various applications. Their role extends beyond enhancing energy sources to promoting circular material lifecycles through innovative recycling techniques.

2.3.1. Conductive Polymers in Solar Cells

Conductive polymers have revolutionized the efficiency of organic solar cells due to their lightweight and flexible properties. These characteristics make them particularly suitable for flexible and portable solar panels. Researchers have further enhanced their functionality by modifying the polymer structure—such as adjusting conjugation lengths, optimizing side chains, and incorporating nanomaterials. These modifications improve light absorption, charge transport, and reduce resistance, resulting in more efficient solar energy conversion systems [6].

2.3.2. Polymers in Battery Technologies

Polymers are also transforming the design and functionality of modern batteries. As electrolytes, they provide lightweight and flexible alternatives to traditional liquid electrolytes, thereby improving energy density and reducing safety risks [7]. In their solid or gel forms, polymers are more stable, minimizing issues like leakage or flammability. In electrode applications, polymers serve as binders that help form stable and cohesive structures. Their lightweight nature enables higher active material loading, increasing energy density. Moreover, their flexibility accommodates the expansion and contraction of electrodes during operation. When conductive additives are incorporated, these polymers also demonstrate enhanced electrical conductivity, ensuring improved battery performance and durability.

2.3.3. Recycling and Reuse of Polymers

In addition to their functional roles, polymers contribute to sustainability through advanced recycling and reuse techniques. One of the most promising methods is chemical recycling, which breaks down polymers into their base monomers or chemicals [1]. These components are then reconstructed into new polymers with equivalent or enhanced properties. Unlike mechanical recycling, which can degrade material quality over time, chemical recycling preserves the performance of polymers, making them ideal for high-quality applications in renewable energy systems. These processes not only enhance the material lifecycle but also reduce the environmental burden associated with polymer use.

2.4. Challenges and Future Potential

Despite their significant contributions, polymers face challenges in scaling and optimization for renewable energy systems [4]. Enhancing polymer stability, recyclability, and cost-efficiency are ongoing research priorities. By integrating polymers into renewable energy applications, the energy sector can overcome performance and sustainability challenges, paving the way for more advanced, durable, and efficient energy systems.

3. INNOVATIONS IN POLYMERIC NANOCOMPOSITES FOR CLEAN ENERGY APPLICATIONS

3.1. Ferrocene-Based Nanoporous Organic Polymers and Carbon Dots (CDs) in Energy Systems

Ferrocene-based nanoporous organic polymers represent a groundbreaking advancement in the development of clean energy solutions. These materials leverage the unique properties of ferrocene,

a metallocene compound with excellent thermal and chemical stability, to create high-performance energy systems. Ferrocene-based polymers are particularly well-suited for applications such as energy storage, solar cells, and catalytic processes due to their porous structure, which allows for efficient mass and electron transport.

Carbon dots (CDs), a cutting-edge family of multifunctional carbon nanomaterials, are revolutionizing several fields, particularly clean energy applications, by supporting the transition toward a sustainable bioeconomy. With remarkable properties such as tunable optoelectronic behavior, fluorescence, low toxicity, and superior biocompatibility, CDs are rapidly gaining traction in various energy-related applications. Figure 2 illustrates two primary methods for synthesizing CDs:

(1) **Top-Down Strategy (Left):** This approach involves reducing larger carbon structures, such as carbon nanotubes, graphene, and fullerene, into nanoscale carbon dots. Techniques such as laser ablation, electrochemical reduction, arc discharge, and chemical exfoliation are commonly used. These processes are advantageous for creating uniform nanostructures while utilizing bulk carbon precursors.

(2) **Bottom-Up Strategy (Right):** In this method, smaller precursors such as polymers and small molecules are assembled into carbon dots through microwave synthesis, hydrothermal treatment, and pyrolysis. This strategy allows precise control over the size, structure, and functional properties of the resulting CDs, enabling their use in specialized applications.

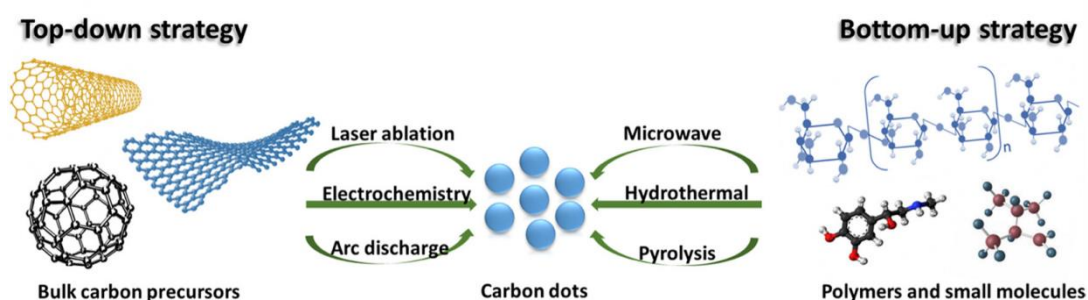


Figure 2. Schematic Representation of Top-Down and Bottom-Up Strategies for Carbon Dot Synthesis.

The scalable production of CDs using Green Chemistry principles is an active area of research. Adopting eco-friendly synthesis routes not only reduces environmental impact but also aligns production methods with sustainable industrial standards. Moreover, incorporating CDs into polymer matrices is emerging as a transformative strategy, enhancing their application potential in energy systems, such as energy storage and conversion, while improving handling and recyclability. CDs exhibit a combination of amorphous and nanocrystalline cores, often containing sp^2 carbon clusters and oxygen-functional groups such as carboxyl, hydroxyl, and aldehyde groups. These structural features make them highly versatile for various applications:

(1) **Energy Applications:** CDs have shown exceptional potential in the energy field due to their high electron charge transfer efficiency and ionic conductivity. These properties make them ideal for electrode materials in batteries and fuel cells. When combined with polymer nanocomposites, CDs enhance energy density and stability while maintaining environmental friendliness through their non-toxic nature.

(2) **Environmental Applications:** CDs integrated with polymer matrices play a significant role in environmental sustainability. Their reusability, combined with low toxicity, makes them suitable for applications such as water purification and pollutant removal. The ability to chemically recycle CD-based composites ensures minimal waste generation, further aligning with green energy goals.

(3) **Biomedical Applications:** In biomedical research, CDs are valued for their hydrophilicity, biocompatibility, and biodegradability. These properties enable their use in drug delivery systems, imaging, and biosensors, highlighting their potential beyond energy systems.

The integration of CDs into ferrocene-based polymer matrices enhances their properties, such as electron charge transfer and ionic conductivity, which are critical for applications in batteries and fuel cells. Moreover, the porous structure of these polymers allows for effective adsorption and desorption of reactants, making them suitable for catalytic processes like water splitting and CO₂ reduction. By aligning the synthesis of ferrocene-based polymers and CDs with green chemistry principles, researchers are developing scalable, eco-friendly production methods that reduce the environmental impact of these advanced materials. These efforts not only contribute to the sustainability of energy systems but also pave the way for the next generation of high-performance renewable energy technologies.

3.2. Polymeric Nanocomposites for Solar Fuel Applications

The depletion of traditional energy sources and the urgent need to address rising CO₂ emissions have intensified research into alternative, sustainable fuels. One promising approach involves water splitting and CO₂ reduction using photocatalytic systems to generate eco-friendly energy sources. Among the various materials explored, conducting polymers (CPs) have emerged as efficient and cost-effective photocatalysts, distinguished by their high light absorption efficiency, tunable electronic properties, and structural stability.

Prominent conducting polymers such as polyaniline, polythiophene, and polypyrrole have been integrated with semiconducting nanomaterials to develop highly efficient photocatalytic composites. These polymeric nanocomposites exhibit synergistic effects due to the interplay between the polymer and the inorganic semiconducting materials, enhancing their overall photocatalytic performance. The unique electronic configurations of the composites allow for improved exciton separation, extended light absorption ranges, and enhanced substrate adsorption. These properties collectively boost photocatalytic activity under visible light. Furthermore, these nanocomposites demonstrate significant resistance to photocorrosion, a common limitation in traditional photocatalytic materials.

The inclusion of conducting polymers into these composites has also been shown to alter band structures, reducing electron-hole recombination and improving charge transfer. For example, in CO₂ photoreduction, the band configurations of the composite materials enhance catalytic activity by promoting the reduction of CO₂ into useful hydrocarbons or fuels. Similarly, in water splitting, CPs paired with semiconductors effectively catalyze the generation of hydrogen, a clean and sustainable energy carrier. This catalytic synergy underscores the potential of conducting polymeric nanocomposites in addressing critical energy challenges. Future research is focused on optimizing the structural, electronic, and optical properties of these materials to further enhance their efficiency. These innovations are anticipated to play a vital role in the global shift toward renewable energy solutions.

3.3. Carbon Nanotubes and Graphene Derivatives in Conducting Polymer Composites

The integration of conducting polymers (CPs) with carbon-based nanomaterials such as carbon nanotubes (CNTs) and graphene derivatives (GDs) has led to the development of high-performance composites with remarkable electrical and mechanical properties. The combination of CPs with CNTs and graphene derivatives creates a robust and interconnected network, enabling faster and more efficient charge transfer, which is critical for energy applications such as supercapacitors, batteries, and fuel cells.

In these composites, the functional groups of CPs and carbon-based nanomaterials interact through covalent or non-covalent bonding, resulting in a synergistic effect that enhances the material's overall performance. For instance, in CP/CNT composites, CNTs act as templates for the polymer structure, providing mechanical stability and facilitating π - π interactions. These interactions improve electrical conductivity and charge mobility, making the composites suitable for energy storage applications. Similarly, in CP/GD composites, graphene derivatives enhance the surface area and provide weakly bound electrons, which are instrumental in processes like regenerating the redox couple (I^-/I_3^-) in dye-sensitized solar cells.

The structural flexibility of CPs also complements the rigidity and conductivity of carbon nanomaterials, allowing the composites to accommodate expansion and contraction during charge-discharge cycles in batteries and supercapacitors. This property ensures long-term stability and durability. Furthermore, the incorporation of graphene derivatives into CP matrices significantly enhances the composites' ability to conduct electricity and facilitates the transport of ions, making them ideal for next-generation energy storage systems.

Recent advancements have also focused on fine-tuning the functionalization of these composites. For example, the covalent attachment of CPs to CNTs or GDs allows for precise control over the electronic and mechanical properties of the material. Additionally, non-covalent interactions such as π - π stacking and hydrogen bonding provide a means to improve conductivity without compromising flexibility or structural integrity. These carbon-based CP composites hold immense potential for revolutionizing renewable energy technologies. Their applications range from energy harvesting systems like solar cells to energy storage devices like batteries and supercapacitors. Ongoing research aims to explore the scalability of these composites and their integration into commercial renewable energy systems.

4. PRACTICAL APPLICATIONS AND SYSTEM-LEVEL INNOVATIONS OF POLYMER-BASED RENEWABLE ENERGY SYSTEMS

4.1. Introduction to System-Level Challenges

The global push for renewable energy adoption has highlighted key challenges in system implementation, including durability, scalability, and cost efficiency. Polymers, with their versatile properties, have emerged as a transformative solution for addressing these challenges. Unlike traditional materials, polymers offer lightweight structures, flexibility, and adaptability, which make them ideal for renewable energy systems. This chapter explores the application of polymers in solar energy, energy storage, and hydrogen systems, emphasizing their role in overcoming technical and operational barriers in real-world energy systems.

While Chapter 3 focused on the material science behind polymers and nanocomposites, this chapter shifts attention to their practical deployment in engineered systems. It examines how polymers enhance energy system design, optimize performance, and contribute to sustainable energy solutions.

4.2. Polymers in Solar Energy Applications

4.2.1. Deployable Solar Panels with Shape Memory Polymers

Shape memory polymers (SMPs) have opened new frontiers in solar energy applications by enabling dynamic and adaptive systems. SMPs can undergo reversible shape transformations in response to environmental stimuli, such as heat or light, making them particularly valuable for deployable solar panels. A significant advancement in this area was achieved by Professor Jinsong Leng's research team at Harbin Institute of Technology, which developed a flexible solar cell system using SMP-based composites [12]. These panels address critical challenges in aerospace, where compact storage, controlled deployment, and structural stiffness are essential. The system, successfully demonstrated

aboard the Shijian-20 satellite, represents a breakthrough in solar technology. Beyond aerospace, terrestrial applications of SMP-based solar panels include portable systems for disaster response, military operations, and off-grid power generation. By enabling efficient deployment and durability under harsh conditions, SMPs significantly enhance the adaptability of solar energy systems.

4.2.2. Integration of Polymers in Photovoltaics

Polymers are playing a critical role in the evolution of photovoltaic (PV) systems, particularly in the development of perovskite solar cells. As encapsulation materials, polymers protect sensitive perovskite films from moisture and UV degradation, thereby improving their operational lifespan and stability [13]. Additionally, polymers are incorporated into active PV layers to enhance light absorption and charge transport, addressing limitations in conventional silicon-based cells.

Recent breakthroughs in polymer-perovskite hybrid systems have achieved record-breaking efficiency rates, positioning these materials as the next-generation solution for solar energy. By reducing material costs and enabling flexible panel designs, polymer-based photovoltaics are expanding the reach of renewable energy technologies to residential, commercial, and industrial sectors.

4.2.3. Luminescent Solar Concentrators for Urban Energy Solutions

Polymers have also enabled the development of luminescent solar concentrators (LSCs), which offer a novel approach to urban energy generation. By integrating fluorescent dyes and high-refractive-index polymers, LSCs channel sunlight to smaller, highly efficient PV cells. Lusoco, a Dutch startup, has pioneered this technology by combining polymers with fluorescent inks to create dual-purpose systems that function as both energy generators and illuminated signage [14].

Applications of LSCs extend to architectural elements like windows and façades, where they transform buildings into active energy producers. This innovation is particularly valuable in urban environments, where space constraints limit the feasibility of traditional solar panels.

4.3. Polymers in Energy Storage Systems

4.3.1. Green Hydrogen-Lithium Hybrid Systems

Energy storage is a cornerstone of renewable energy adoption, and polymers are enabling significant advancements in hybrid systems that combine hydrogen fuel cells with lithium-ion batteries. Australian startup Lavo has developed an innovative hybrid system that uses polymer-based components to facilitate hydrogen storage and conversion [15]. These systems integrate lightweight polymer membranes for proton exchange, enhancing the efficiency of hydrogen fuel cells.

The hybrid approach addresses the intermittent nature of renewable energy sources like solar and wind, providing a stable and scalable solution for decentralized energy storage. Polymer-based systems also reduce safety risks and improve the operational lifespan of hybrid energy systems, making them suitable for both residential and commercial applications.

4.3.2. Polymer-Enhanced Hydrogen Production

Hydrogen production technologies have also benefited from advancements in polymer materials. Professor Weishan Li's team at South China Normal University developed a hydrogen production system integrating solar panels, rechargeable zinc-air batteries, and electrolyzers. The use of polymer membranes in electrolyzers ensures high efficiency and durability, achieving a solar-to-hydrogen conversion efficiency of 18.43% [15]. These membranes facilitate the separation of hydrogen and oxygen gases, ensuring high-purity outputs for industrial and energy applications. In addition to improving efficiency, polymers enable the miniaturization of hydrogen production systems, allowing for their deployment in off-grid locations. This scalability is critical for accelerating the adoption of hydrogen as a renewable energy carrier.

4.4. Optimization of Renewable Energy Systems

4.4.1. Polymer-Based Optimization of Solar Panel Design

The integration of polymers into solar panel designs has significantly improved their performance under diverse environmental conditions. Polymer encapsulation layers protect PV cells from moisture, UV radiation, and mechanical stress, extending the panels' operational lifespan. Additionally, polymers are used in anti-reflective coatings to maximize light absorption, further boosting energy output [15].

Advanced simulation techniques have also facilitated the design of flexible polymer-based panels that can withstand extreme weather conditions, such as high winds or heavy snow. These optimizations make polymer-enhanced solar panels a viable solution for both urban and rural applications.

4.4.2. Multifunctional Polymers for Integrated Energy Systems

Emerging research focuses on multifunctional polymers that integrate energy generation, storage, and thermal management capabilities. For instance, hybrid materials that combine photovoltaic functions with capacitive properties are being developed for applications in wearable electronics and autonomous devices. These multifunctional systems reduce the need for separate components, enhancing the overall efficiency and sustainability of renewable energy technologies.

5. FUTURE OUTLOOK

Sustainable polymers have emerged as a cornerstone in the evolution of renewable energy technologies, offering a pathway toward cleaner, more efficient energy systems. Their ability to combine adaptability, efficiency, and sustainability positions them as key enablers in addressing global energy and environmental challenges. This chapter explores the anticipated advancements in polymer technology, with an emphasis on innovation in material properties, manufacturing processes, and integration into broader industrial applications.

5.1. Enhancing Polymer Properties

Future research on sustainable polymers is expected to focus on improving their mechanical strength, thermal stability, and environmental adaptability. These improvements will expand their applicability across renewable energy systems, including solar cells, hydrogen storage systems, and energy storage devices. For instance, the development of polymers with enhanced thermal resistance and structural integrity will enable them to function reliably in harsh environmental conditions, such as extreme heat or fluctuating humidity. Moreover, advancements in nanocomposite technologies, such as the integration of carbon nanotubes or graphene derivatives, are anticipated to further enhance the conductivity, durability, and overall performance of polymers. These innovations will support the development of next-generation materials tailored for highly efficient energy systems.

5.2. Optimizing Manufacturing Processes

The cost of polymer production remains a significant barrier to their widespread adoption in renewable energy technologies. Efforts to optimize manufacturing processes are likely to center around green chemistry principles, which aim to reduce energy consumption, minimize byproduct formation, and utilize renewable feedstocks. Technologies such as catalytic polymerization and chemical recycling are expected to play pivotal roles in achieving these goals. Scaling up production while maintaining cost efficiency will also be critical. The development of modular manufacturing systems, capable of producing high-performance polymers at scale without compromising quality, will be a key focus area. Such advancements will make sustainable polymers more competitive in the marketplace, encouraging their adoption in both energy systems and other industries.

5.3. Expanding Applications Beyond Energy Systems

While renewable energy technologies remain a primary focus, sustainable polymers are also poised to replace traditional petroleum-based plastics in a variety of industries. Applications in packaging materials, medical devices, and automotive manufacturing are particularly promising. For example, lightweight polymer composites could reduce vehicle weight, improving fuel efficiency and reducing carbon emissions in the transportation sector. Similarly, biocompatible polymers are being explored for use in medical implants and devices, where their biodegradability and low toxicity offer significant advantages.

5.4. Innovations in the Solar Energy Sector

The solar energy sector is likely to see continued advancements in polymer technology, particularly in the areas of photoelectric conversion efficiency, system stability, and cost reduction. Flexible and deployable solar panels, enabled by shape memory polymers and polymer-perovskite hybrids, are expected to gain traction in residential, commercial, and aerospace applications. Research efforts will also focus on enhancing the recyclability and biodegradability of these materials, aligning with global sustainability goals. Smart materials and structures represent another promising area of development. Polymers that dynamically adapt to environmental conditions, such as self-healing encapsulation layers or temperature-responsive coatings, could further enhance the efficiency and longevity of solar panels. These innovations will drive the adoption of polymer-based solar technologies in diverse markets, from urban infrastructure to remote energy systems.

5.5. Future Challenges and Research Directions

While the potential of sustainable polymers is immense, several challenges remain. Addressing the environmental impact of polymer production, ensuring scalability, and developing standardized methods for evaluating polymer performance are critical areas for future research. Additionally, the integration of polymers into complex energy systems will require interdisciplinary collaboration across materials science, engineering, and environmental science. Research into the neurocognitive effects of material innovation and the life-cycle analysis of polymer-based systems could provide valuable insights into their long-term sustainability and impact. Furthermore, policies and incentives that encourage investment in polymer research and development will be essential for accelerating progress in this field.

6. CONCLUSION

The rapid advancements in renewable energy technologies have redefined the global energy landscape, with solar, wind, and hydropower emerging as key contributors to a sustainable future. Solar photovoltaic technology, in particular, has significantly reduced energy costs, making renewable energy one of the most economically viable solutions worldwide. However, despite these advancements, persistent challenges remain, such as inconsistent technological maturity, high production costs, and the critical issues of energy storage and transmission. Addressing these challenges requires continuous innovation, particularly in the field of materials science.

Polymers have become a transformative element in renewable energy systems, offering unique properties such as flexibility, lightweight construction, and tunable characteristics. These attributes make polymers indispensable in applications ranging from organic solar cells to hydrogen storage systems. Advances in polymer science, including modifications to conjugation lengths, side chains, and nanomaterial integrations, have significantly enhanced light absorption, charge transport, and overall system efficiency. Furthermore, polymer-based nanocomposites, such as carbon dots and

conductive polymers, have opened new avenues for energy storage and conversion, with potential applications in both large-scale industrial systems and decentralized renewable energy setups.

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