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Review

Contributions of Green Energy Materials to Sustainable Development Goals

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Abstract: The global shift toward renewable and green energy highlights the critical role of green energy materials in achieving sustainability goals. This paper focuses on how these materials contribute to the three pillars of sustainability: environmental, economic, and social, in alignment with the United Nations Sustainable Development Goals (SDGs). Green energy materials, including photovoltaic materials, thermoelectric materials, electrochemical storage materials, and other materials appear to play a vital role in meeting these pillars. It is found that using these materials, green and renewable energy is projected to contribute up to 55% of global electricity use by 2030. Green energy materials have achieved the three pillars of sustainability. Environmentally, they help to mitigate climate change, reduce greenhouse gas emissions, and protect ecosystems. Economically, these materials foster innovation, create jobs and opportunities, and stimulate economic growth within the green energy sector. Socially, they improve the living standards by providing access to clean energy, reducing health risks, while supporting the development of sustainable cities and communities. By aligning with sustainable development goals, such as clean water, climate action, economic growth, and affordable energy, green energy materials are necessary for achieving a sustainable future. Despite these advances, widespread adoption remains hindered by economic, policy, and technological barriers. Therefore, there is a need for integrative policies, improved lifecycle analysis, and inclusive access to green energy technologies to ensure equitable transition and global sustainability.

Keywords: energy materials; green energy materials; green materials; sustainability; Sustainable Development Goals (SDGs)

1. Introduction

Carbon dioxide (CO_2) is the most abundant greenhouse gas (GHG) contributing to global warming and climate change [1], and it represents 55% of the total greenhouse gas emissions [2]. The energy sector is a major cause of this negative environmental impact, as illustrated in Figure 1 [3]. This impact will lead to rising global temperatures, melting ice sheets, elevating sea levels, and the loss of biodiversity [4]. For instance, the atmosphere's concentration of greenhouse gases is projected to increase the average global temperature by approximately 1.5 °C by 2030 and this would be one of the most serious crises facing humanity if nothing is done to solve it [5]. In addition to that, climate change has several other negative effects such as increased flooding and drought, which may lead to increased poverty, hunger, and limited economic growth in the region [6]. As a result, it is estimated that drought alone will displace nearly 700 million people by 2030.

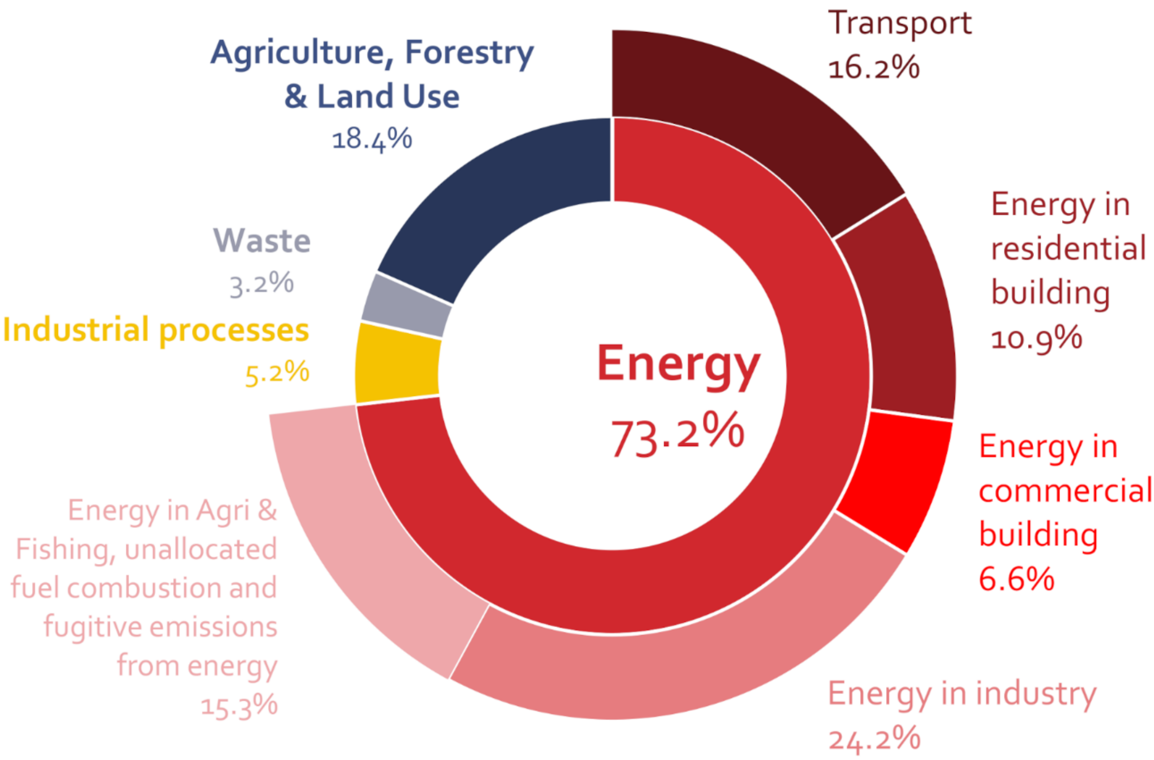

Figure 1. Global greenhouse gas emissions by sector [3].

The rapid growth in global energy use and CO_2 emissions levels highlights the need of sustainable energy practices [7]. Sustainability is defined as the ability to meet the needs of both present and future generations, which is the basic principle of sustainable development [8]. Sustainable development combines the three pillars of sustainability which are environmental, economic, and social in order to build a sustainable and resilient system. Furthermore, it aims to secure reliable and affordable energy supplies for all generations while reducing the effect of the energy field on climate change [9,10]. This has encouraged the decision-makers to focus on the sustainable development goals (SDGs) proposed by the United Nations (UN), which integrate economic development with environmental and social sustainability. Achieving the SDGs in the energy sector requires a shift from fossil fuels to sustainable, carbon-free solutions [11]. The replacement of conventional fossil fuel power plants with clean and affordable energy sources that are carbon free alternatives is highly beneficial. Therefore, recently clean energy has emerged as a practical long-term approach to meet the energy challenge and to avoid its negative climate and environmental impacts. All these factors allowed the SDGs to serve as a platform to boost global and international collaboration across all industries towards sustainability. For example, by 2030, the European Union aims to increase the share of renewable energy sources to 55% and reduce greenhouse gas emissions by at least 55% to achieve carbon neutrality by 2050 [7,12].

Green energy derived from clean and natural sources with minimal environmental impact, is considered as a strategic element in shaping sustainable energy. Although it is not a new concept, it has recently gained huge attention because of its ability to meet and achieve SDGs. The large-scale implementation of green energy practices contributes to sustainable development by ensuring energy security and mitigating climate change [4]. Besides, green energy offers reliability and availability while reducing greenhouse gas emissions, expanding energy supply options, and reducing reliance on fossil fuels [7]. The transition to green energy systems addresses concerns about the limited availability of fossil fuels [13]. This shift has led to a global movement towards green energy technologies and materials to meet energy demands while mitigating environmental damage.

Energy materials are designed or optimized specifically for use in applications that are related to energy. These materials are fundamental for various renewable energy technologies, such as solar cells, fuel cells, batteries, and supercapacitors [14]. They are important for efficient energy generation, conversion, and storage to create a clean, sustainable, low-carbon energy system [15]. Materials used in energy harvesting, conversion, and storage are essential for the sustainability of the energy sector [16]. For instance, highly recyclable materials have low emissions and cause minimal pollution. By designing and optimizing energy materials, scientists and engineers can create more efficient and sustainable energy solutions for the future. Governments should encourage investment in green energy to secure a more sustainable future [17]. Thus, International efforts aim to decrease pollution rates, lower reliance on fossil fuels, and limit climate change impacts.

This work aims to critically review the main contributions of green energy materials to the pillars of sustainability and the SDGs. A particular focus is given to several energy materials such as photovoltaic materials, thermoelectric materials, electrochemical storage systems, etc. In addition, it investigates the potential of these materials to improve environmental performance, economic stability, and social equity through energy advancement. Basically, it mainly focuses on the potential of developing alternative non-toxic components using green materials to improve energy materials in terms of sustainability. The paper also identifies emerging materials and discusses how these materials directly align with SDG implementation, as well as the interconnection between green energy materials and some SDGs. This review addresses the gap that lies in its integration of material science with sustainability goals.

This review is structured as follows: Section 2 details the research methodology applied in this research paper. Section 3 discusses the different types of green energy materials, introduces SDGs, and explains how they align with material science. Section 4 highlights the SDGs and the role of green energy materials in achieving a more sustainable future in terms of the three pillars of sustainability. In addition, this section presents the pillars of sustainability and their direct connection to green energy. Section 5 summarizes key challenges to real-world applications and outlines the limitations of current research. Section 6 provides concluding remarks, and future recommendations and work.

2. Research Methodology

This review explores the sustainability impact of green energy materials. It examines how these materials contribute to renewable and green energy technologies that also support the environmental, economic, and social pillars of sustainability. To conduct this review paper, the focus was placed on materials used in energy harvesting, conversion, and storage, such as photovoltaic, thermoelectric, batteries, hydrogen fuel cells, thermal energy storage materials, etc. The objective of the review was guided by four main research questions: (1) What are the current trends in green energy materials? (2) How do green energy materials compare to conventional ones in terms of sustainability? (3) How do these materials align with the three sustainability pillars and SDGs? And (4) what challenges limit the real-world adoption of these materials? In order to address these questions, a detailed literature search was carried out using major academic databases, including Scopus, ScienceDirect, IEEE Xplore, SpringerLink, and MDPI. Google Scholar was also utilized to access the most recent open-access papers. The literature search was limited to publications between 2019 and 2025. Scopus served as the primary search platform; however, access to some articles was limited by institutional restrictions, and some articles were excluded for being out of the scope of the topic. For this literature review, several keywords were selected to search for the topic. The keywords selected were energy materials, green energy, green materials, green energy materials, and sustainable development goals. Articles were screened and selected based on clearly defined inclusion and exclusion criteria. Ethical considerations were strictly observed. All data and studies referenced in this paper were sourced from publicly accessible academic journals. Proper credit is given to all authors and institutions through detailed citation. No proprietary datasets or unpublished materials were used in the preparation of this manuscript.

3. Green and Advanced Materials for Clean Energy Applications

3.1. Green Energy Materials

Green energy materials contribute to the global transition towards sustainable energy systems. As shown in Figure 2, these materials operate differently including harvesting, converting, or storing green energy [14]. Energy harvesting materials capture ambient energy from sources such as sunlight, heat, or mechanical load and convert it into usable electrical energy [14]. Similarly, energy conversion materials transform energy from one form to another to optimize the effectiveness of renewable energy systems [16]. Energy storage materials are essential elements in renewable energy technologies, as they store energy to address the temporal mismatch of energy supply and demand [11].

The performance of many of these technologies depends on the materials used in their manufacture [16]. Therefore, developing highly efficient and green energy materials is necessary for advancing sustainable and renewable energy technologies. The term "green" often refers to materials that are less toxic or non-toxic [18]. They typically meet key criteria such as abundance, recyclability, non-toxicity, and non-hazardous [19–21]. These materials can be divided into two categories: environmentally-based materials and biomass-based materials [22]. The basic requirements for energy material technologies are illustrated in Figure 3 [16]. The main benefits of green energy materials include reducing greenhouse gas emissions, providing clean energy, enhancing economic growth, and improving the quality of life. This approach aligns with the SDGs and ensures that these materials contribute to a reliable and sustainable energy for the future. Table 1 compares green materials with conventional materials within green energy technologies in terms of several categories.

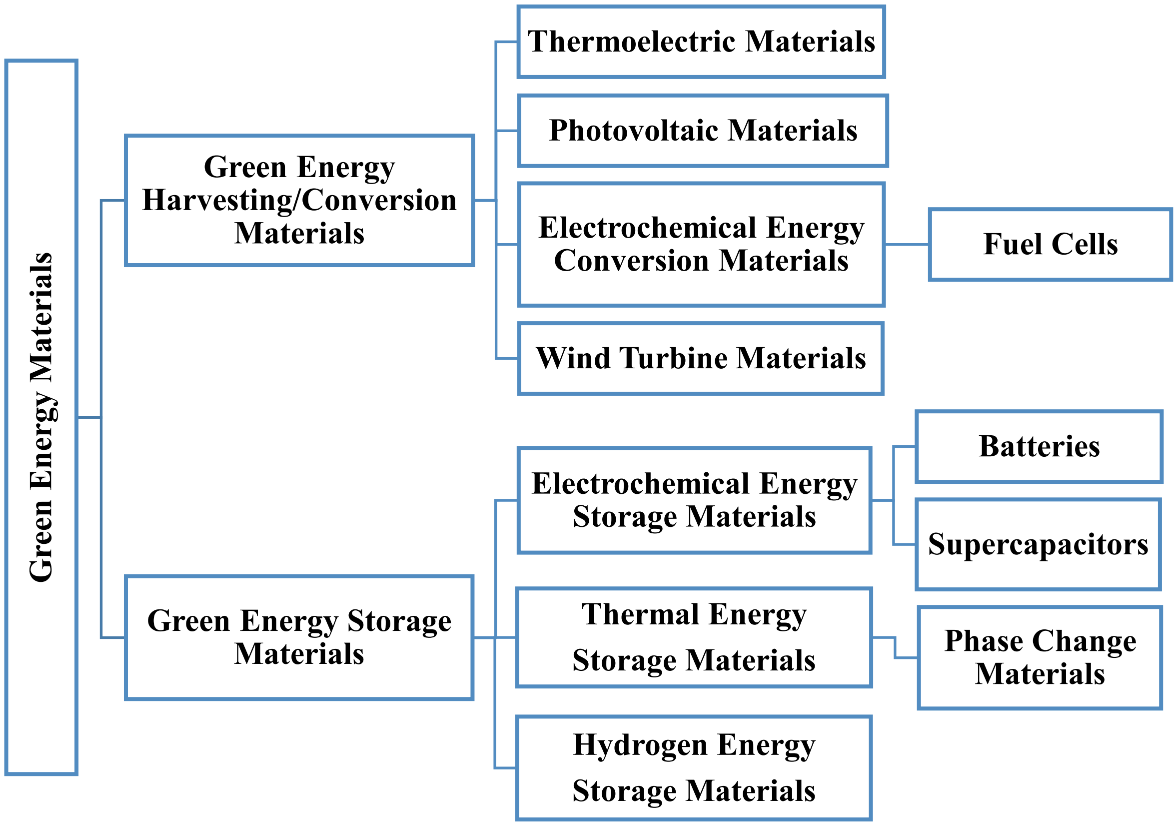

Figure 2. Green energy materials.

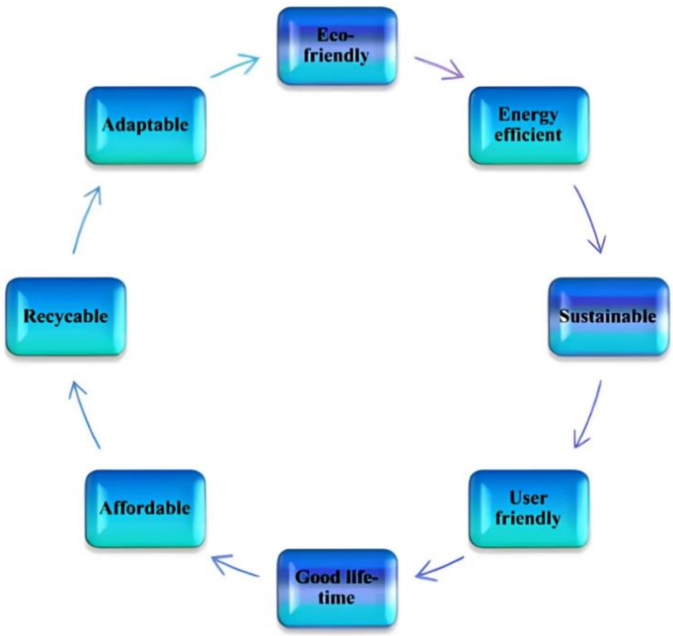

Figure 3. Basic requirements for green energy material technologies [16].

Table 1. Comparison Between Conventional and Green Energy Materials.

Categories	Conventional Materials	Green Materials	Ref.
Availability	Finite and Limited Depleted Resources	Renewable and Sustauible Widely available	[23]
Environmental Impact	High CO_2 Emissions Toxic Waste	Zero/Low CO_2 Emissions Recyclable Biodegradable Lower toxic	[24]
Cost	Cheaper upfront but higher long-term due to fuel costs.	Higher upfront but significantly lower over the lifecycle.	[25,26]

3.1.1. Green Energy Harvesting & Conversion Materials

Photovoltaic Materials

Photovoltaic (PV) cells often referred to as solar cells, convert sunlight into electrical energy directly through the photovoltaic effect process [13,27]. Basically, this process involves converting photons from sunlight into electrons to generate electricity [28], thus this type of energy source is sustainable and cost-effective [7]. Typical solar PV panels have an energy efficiency of 16% to 22% [13], and an operational lifespan of about 25 years [29]. Despite their numerous benefits, the improper disposal at the end of their lifecycle can pose serious hazards to the environment [29,30]. By 2050, PV energy sector waste is expected to increase by millions of tonnes [31], as indicated in Figure 4 [32]. To mitigate these concerns, researchers are developing eco-friendly PV materials that balance toxicity, efficiency, cost, and durability [33–35]. Silicon photovoltaics (SPV), perovskite photovoltaics (PPV), dye-sensitized photovoltaics (DSPV), and organic photovoltaics (OPV) are among the most promising options to address the world's energy demands [35,36]. The highest conversion efficiencies achieved by these cells are 27.6% for silicon, 25.2% for perovskite, 12.3% for dye-sensitized, and 13.76% for organic solar cells [35].

The majority of photovoltaic cells are silicon-based, with crystalline silicon (C-Si) solar cells being the most dominant on the market due to the abundance and non-toxicity of silicon [36]. They offer high efficiency rates often exceeding 20% [13,36], along with good durability and a long lifespan so they are suitable for a wide variety of applications [13]. Nevertheless, their production is associated with high material costs because they require high-purity silicon and energy-intensive processes [36,37]. Studies have found that using advanced materials or recycled silicon could potentially decrease greenhouse gas emissions by up to 50% [38].

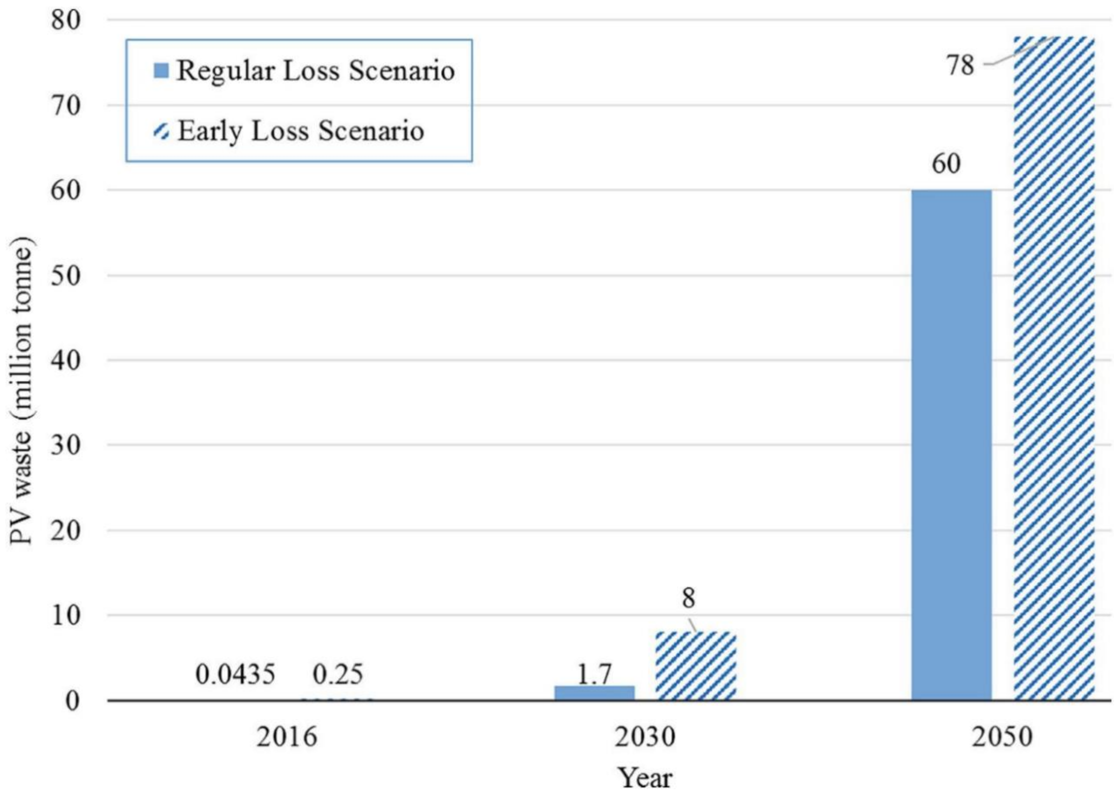

Figure 4. Estimated cumulative End-of-Life PV waste [32].

Thin-film photovoltaic cells made from materials like gallium arsenide (GaAs), cadmium telluride (CdTe), and copper indium diselenide ($CuInSe_2$) [36], offer a cheaper, lighter, and more flexible alternative to conventional silicon PV cells [13,39]. These cells are easier to manufacture because they require less material [13]. Currently, cadmium telluride (CdTe) is the most widely used thin-film technology in the photovoltaic market [40,41]. It has an efficiency of 17.3% due to its excellent light absorption properties [42,43]. However, cadmium is known to be a highly toxic substance with limited natural abundance [34]. This has led to replace it with copper zinc tin sulfide (CZTS) solar cells that are made from non-toxic and abundant materials, also it is considered a promising alternative with a lab-scale efficiency of about 11.4% [44,45].

Recently, novel and emerging photovoltaic technologies such as perovskite, dye-sensitized, and organic photovoltaic cells have gained a huge attention because of their promising efficiency and potential to reduce the negative environmental impact [36]. Perovskite PV cells, in particular, have the potential to reach higher efficiency than C-Si solar cells [34]. Although they have reached efficiencies above 25%, they still face challenges regarding operational stability, reliability, and environmental concerns due to the presence of toxic lead [35,46]. While dye-sensitized PV cells are designed to mimic the photosynthesis process [36], they are a high-quality, cost-effective and environmentally friendly alternative [43]. Even they have a huge potential, their efficiency and long-term stability require further improvement [36]. For instance, Bahutair et al. [47] examined the potential of MXenes in enhancing the performance of dye-sensitized solar cells. It has been found that this material exhibits excellent electron conductivity. While being environmentally friendly, they offer potentially lower-cost solutions compared to conventional materials. Furthermore, organic PV cells use organic semiconductors such as organic polymers as a light-absorbing layer to convert light into electricity [13,48]. They have low-cost and flexible production, and they do not contain hazardous materials like cadmium [36,49]. Similar to dye-sensitized PV cells, organic PV cells face issues related to efficiency and stability [36]. Further research aims to overcome these challenges and develop photovoltaics cells made with green materials that are more efficient, sustainable, and environmentally friendly. This effort is important for optimizing the use of photovoltaic cells while minimizing their environmental impact.

Thermoelectric Materials

A significant portion of primary energy is lost as waste heat across various sectors, estimated to be over 60% [50], as shown in Figure 5 [51]. Most conventional energy production and conversion technologies heavily rely on thermal processes that generate large amounts of waste heat released into the environment. This waste heat contributes to energy loss and global warming [50]. Hence, it is very important to harness and recycle this waste heat into useful forms of energy via efficient, eco-friendly, and sustainable technologies for better energy management. Thermoelectric materials provide a green, effective solution for directly converting thermal energy into electricity when exposed to temperature gradients [52,53]. As shown in Figure 6 [51], a temperature difference (ΔT) between the two ends of a thermoelectric material causes charge carriers to travel and flow from the hot end to the cold end, which generates electricity [54–56]. By using waste heat to produce electricity, the efficiency of thermal processes can be significantly improved [52]. These materials are valuable for both energy harvesting and local cooling applications [57].

Compared to other different energy conversion materials, thermoelectric materials have several advantages, including the absence of moving parts or working fluids, minimal pollution, long lifespan, noise-free operation, and low maintenance [58,59]. Their performance is typically evaluated using a dimensionless figure of merit called the ZT value. This is a key parameter that determines efficiency. It describes the involved different parameters in terms of the Seebeck coefficient (S), electrical conductivity (σ), absolute temperature (T), and thermal conductivity (κ) [53]. Current research in this field mainly focuses on developing materials with high electrical conductivity and Seebeck coefficient while maintaining low thermal conductivity [60]. Hence, a work by Caballero-Calero et al. [61] highlighted several eco-friendly, non-toxic, and earth-abundant alternative thermoelectric materials that provide high ZT values and cost-effective thermoelectric materials with high performance.

Inorganic crystalline semiconductors, such as bismuth telluride (Bi_2Te_3) [61,62],have dominated the field of thermoelectric materials because of their high performance [50,59]. They have been limited by their high toxicity, fragility, and high price [59]. Consequently, these have led to the development of green, abundant, and cost-effective organic thermoelectric materials. These materials feature low thermal conductivity, low cost, non-toxicity, and flexibility [59]. Due to their limited efficiency, organic thermoelectric materials are not widely adopted for commercial applications. They can be categorized into two primary types of materials: carbon nanomaterials (CNMs) and organic conducting polymers [63].

Carbon materials and conducting polymers have been widely used in the fabrication of thermoelectric materials. These materials are naturally excellent electrical conductors, so they have good thermoelectric efficiency. For instance, carbon nanotubes (CNTs) and graphene are characterized by their high electrical conductivity, non-toxicity, and lightweight [64–66]. Similarly, conducting polymers, such as polyaniline (PANI), poly(3,4-ethylenedioxythiophene) (PEDOT), and polypyrrole (PPy) [53], exhibit high electrical conductivity, good flexibility, excellent environmental stability, and non-toxicity [53,59]. However, the high thermal conductivity of carbon materials remains a major challenge for thermoelectric applications [67]. Because of this, a hybrid approach is often used in advanced thermoelectric materials, combining the strengths of carbon nanomaterials with organic conducting polymers [53]. This combination takes advantage of the high electrical conductivity of carbon nanomaterials and the low thermal conductivity of organic conducting polymers. As a result, materials with improved thermoelectric performance are produced, although they are not yet comparable to conventional thermoelectric materials [61]. Their green and sustainable properties make them attractive for certain applications, such as waste heat recovery.

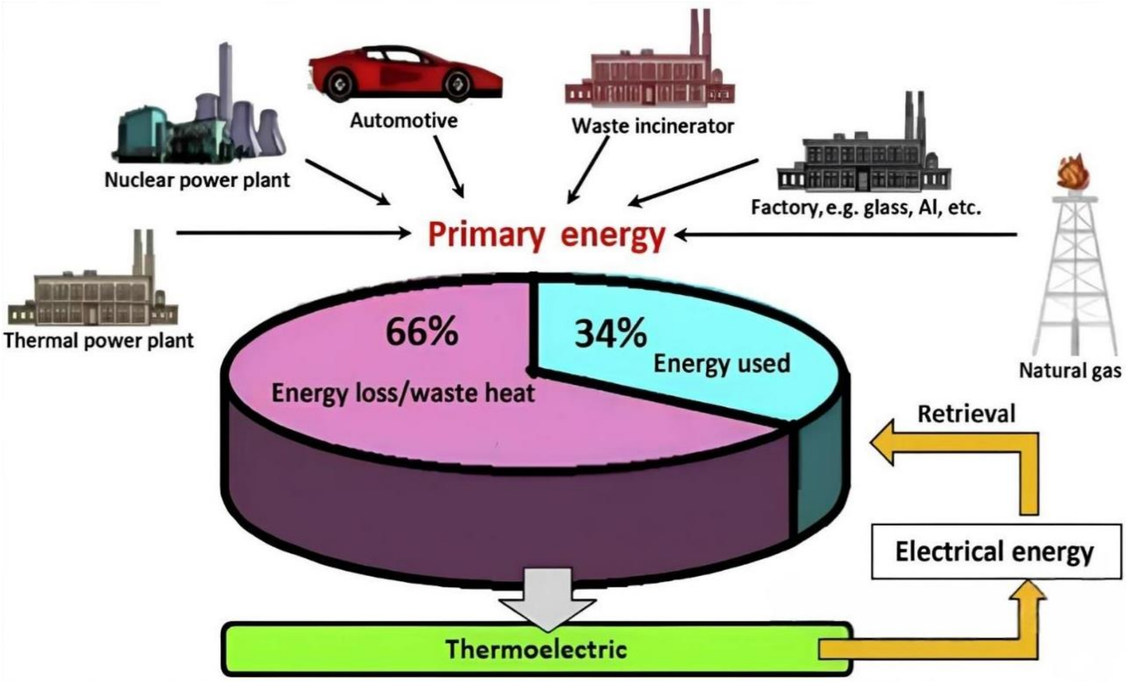

Figure 5. Waste heat energy from various sectors [51].

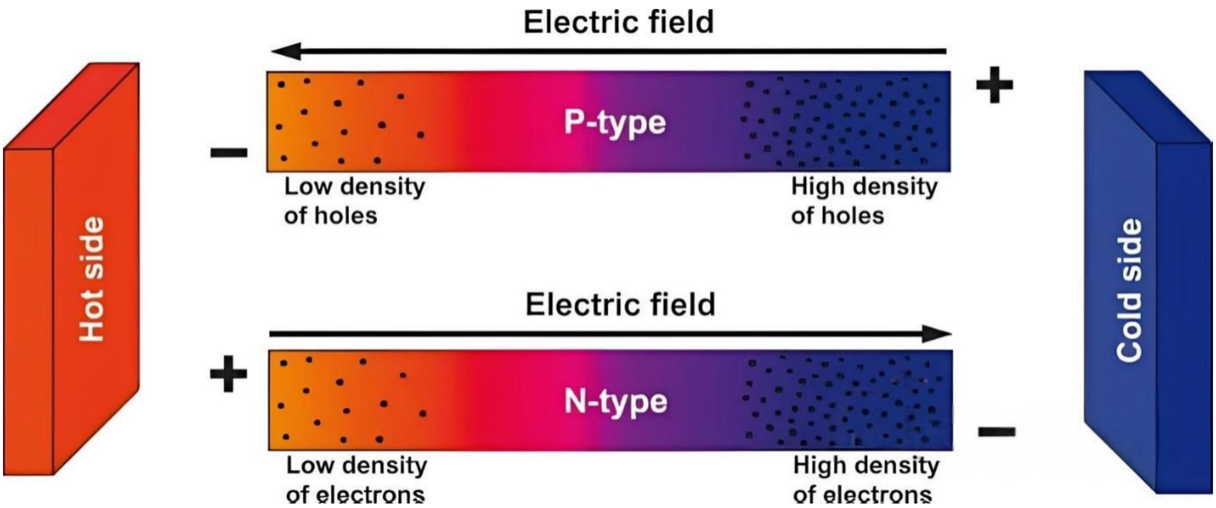

Figure 6. Schematic representation of the thermoelectric effect [51].

Electrochemical Energy Conversion Materials

Fuel cells (FCs) are advanced electrochemical conversion devices that convert chemical energy into electrical energy through redox reactions with high efficiency and without CO_2 emissions [68,69]. Thay are one of the most cleanest energy conversion systems available, also they are known for their high energy density, superior energy conversion efficiency, and environmental safety [70]. Among the various types of FCs, the polymer electrolyte membrane or proton exchange membrane fuel cell (PEMFCs) stands out as the most common and promising technology for both portable and stationary applications, including transportation [68,71]. This is due to its high power density, high energy conversion efficiency of 40–70%, low operating temperature below 80 °C, rapid start-up, and minimal emissions [69,72,73]. Consequently, these cells generally have a longer lifespan compared to other fuel cells.

The operation of PEMFCs relies on two key chemical reactions: hydrogen oxidation (HOR) at the anode and oxygen reduction (ORR) at the cathode [74]. At the anode, hydrogen gas undergoes an oxidation reaction that releases protons (hydrogen ions) and electrons. The protons travel through the polymer electrolyte membrane (PEM) to the cathode, while the electrons flow through an external circuit to the cathode. At the cathode, oxygen from the air undergoes a reduction reaction and combines with the hydrogen ions to form water. They are considered environmentally friendly because this process generates electricity directly with only water and heat as by-products [75] as shown in Figure 7 [76]. The PEMFCs face serious barriers related to the cost and environmental footprint of their materials, especially platinum in the electrodes and Nafion in the membranes. While both platinum and Nafion are widely used materials in PEMFCs, these two materials are expensive and not eco-friendly [68,77]. Additionally, platinum is a precious and scarce catalyst electrode [77]. These issues have prompted research into green and eco-friendly alternatives. Green material can be applied to various components in fuel cells mainly for membranes and catalysts [78].

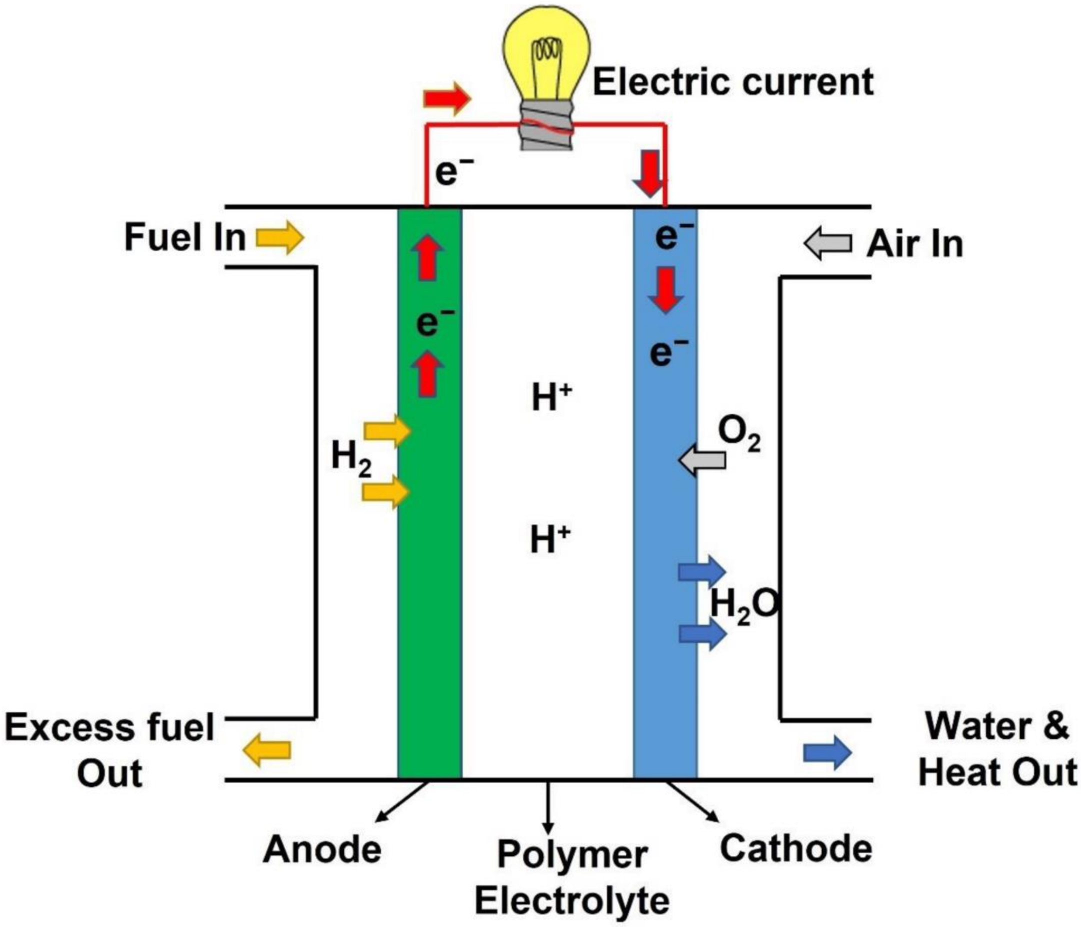

Figure 7. Fuel cell operation [76].

In recent times, graphene and graphene-based materials along with non-precious catalyst electrodes made of recyclable carbon nanostructures such as reduced graphene oxide have been considered affordable and sustainable alternatives to platinum-based catalysts in fuel cell [71]. Their large specific surface area, mechanical flexibility, excellent electrical conductivity, and low cost present the possibility to produce cleaner and more affordable fuel cells that could lead to the widespread commercialization of fuel cells [71]. Furthermore, natural polymers or biopolymers are excellent for developing non-toxic and biodegradable materials [68]. As an example, biopolymers such as chitosan and cellulose are abundant, cost-effective, biodegradable, and exhibit good proton conductivity [68,78]. These properties make them potential substitutes for conventional Nafion membranes in PEMFCs [68]. Several Studies have explored their potential, for instance, Ali et al. [79] reviewed different modification techniques to improve the proton conductivity, stability, and overall performance of these natural polymers. The results showed that while they are promising, they still face problems like water swelling and limited durability.

Wind Turbine Materials

Wind energy has emerged as a major sustainable and eco-friendly source of electricity [80], which uses wind turbines that produce net-zero emissions. Recently, this form of energy generation has expanded rapidly worldwide. The blades of wind turbines are one of the main components of wind energy turbines, with an estimated lifespan of around 20–25 years [81]. They harness the wind's kinetic energy and convert it into rotational motion to generate electricity [82]. Most components of wind turbines can be easily recycled. However, blades which are typically made from composite materials like glass fiber-reinforced polymer (GFRP) or carbon fiber-reinforced polymer (CFRP) are difficult to recycle [83]. Since they often end up in landfills, they represent an important source of the huge amounts of hazardous composite waste. To meet the need for greener and more eco-friendly materials in manufacturing these blades, the wind energy sector is seeking to develop such alternative materials-based approaches to improve the performance and recyclability of the blades while minimizing their environmental impact.

The composite materials commonly used in wind turbine blades have unique advantages including excellent mechanical properties and lightweight construction [84]. Researchers are now focusing more on alternative composites that possess a specific set of properties: (i) high performance, (ii) high specific strength, (iii) eco-friendliness, (iv) recyclability, (v) biodegradability, (vi) cost-effectiveness, and (vii) long lifespan [85]. One promising category of green materials for constructing wind blades is bio-based composites. They combine natural fibers such as flax, hemp, or bamboo with biodegradable resins [86]. Especially, bamboo-derived composites can be an environmentally friendly and long-lasting composite to fabricate wind turbine blades [86]. So, these natural fibers are becoming popular because of their affordability, good mechanical properties, impressive specific strength, non-abrasiveness, biodegradability, and eco-friendliness [87]. Nonetheless, their performance can be negatively affected by increased moisture absorption, flexibility, and lower thermal stability [88].

Recycling the blades of wind turbines can ensure the sustainability of wind turbines [89]. This involves producing blades from recyclable materials, such as thermoplastic composites, natural fiber composites, and thermoset composites [90]. Rathore et al. [91] examined various approaches for the end-of-life (EOL) management of wind turbine blades, such as thermal and chemical treatments to recover carbon and glass fibers, which highlighted the need for more efficient recycling solutions. Thermoplastic composites, like Elium thermoplastic resin [89], are excellent options due to their good impact resistance, lightweight nature, cost-effectiveness, and recyclability [90,91]. The structural characteristics of Elium indicate its potential as a viable alternative to traditional epoxy [86]. In addition, unlike thermoset composites, thermoplastic composites are easier to recycle [91].

3.1.2. Green Energy Storage Materials

Electrochemical Energy Storage Materials

Electrochemical energy storage (EES) materials efficiently and sustainably store energy, especially for electricity generated from renewable sources to provide a constant energy supply [92,93]. Among the various renewable energy storage technologies, EES materials are notable for their high efficiency, versatility, and flexibility [94]. Secondary batteries and supercapacitors, in particular electrical double-layer capacitors (EDLCs) [95], are among the most effective methods for storing electricity via electrochemical processes [96], as illustrated in Figure 8 [97]. These processes involve the charge and discharge of electrons and electrolyte ions across the electrode-electrolyte interface [94]. They convert electrical energy into chemical energy during charging and release it back as electrical energy during discharge. Since electrode materials are a main component of batteries and supercapacitors, their activity and stability are critical to the efficiency of these devices [92]. Key properties of electrode materials that should be taking into account when selecting the materials include high specific surface area, high electronic conductivity, porosity, and electrochemical stability.

To overcome the limitations related to conventional materials such as cost, complexity, and toxicity issues in the fabrication of electrodes for EES devices, there is a need for sustainable approaches to develop green, naturally abundant, and non-toxic materials for EES devices [98]. Carbon-based materials such as graphene, carbon nanotubes, and activated carbon have been proven to have excellent electrochemical properties and can be extracted from biomass or waste materials [99] to reduce the reliance on limited resources. Besides carbon-based materials, natural fibers are also gaining importance in sustainable EES. For example, natural fibers like flax, which are abundant, easily recyclable, and biodegradable, have proven to be affordable and excellent biomass materials for EES device fabrication [100–103].

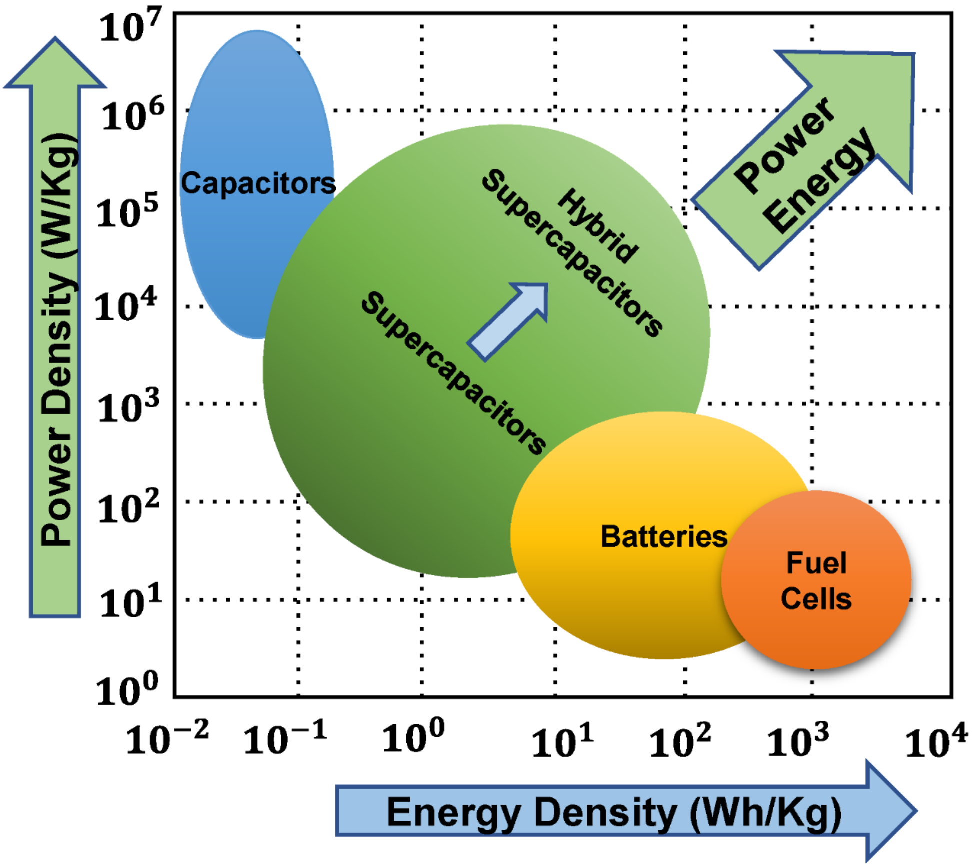

Figure 8. Ragone plot of various electrochemical energy storage devices [97].

(1) Lithium-Ion Batteries Materials

Batteries are EES devices used in stationary and mobile applications. During the charge-discharge process, they operate through a reversible Faradaic redox reaction at the two electrodes [94]. This process converts the chemical energy that is stored in the electrode materials into electrical energy or the reverse via electrochemical redox reactions. The electrolyte facilitates ion transfer from one electrode to the other and it acts as a charge transfer medium [92].

Lithium-ion batteries (LIBs) have attracted attention as electrochemical energy storage materials due to their rechargeable nature, minimal environmental impact, long lifespan, high energy density, and low self-discharge rates compared to other traditional rechargeable batteries [92,104]. Basically, the energy density, activity, and performance of LIBs depend largely on the chemical and physical characteristics of the cathode and anode materials [92]. Despite certain advantages, LIBs still face some sustainability challenges related to the high costs of raw materials that are used, the use of toxic materials, safety concerns, and end-of-life disposal issues [104]. Figure 9 [104] indicates that when developing batteries, it is important to consider sustainability along with improving technical characteristics [105].

One approach to enhancing the sustainability of LIBs is to utilize green alternatives to traditional materials such as cobalt [106]. Lithium iron phosphate (LFP) cathodes that are made of abundant and non-toxic elements reduce the need for toxic cobalt. Besides excellent long-term recyclability and thermal stability, they are associated with reduced environmental impact, enhanced safety, and lower cost in comparison to lithium cobalt oxide ($LiCoO_2$) cathodes [104]. On the other hand, there are efforts to develop anodes using sustainable materials like graphene-based composites and carbon nanotubes. These materials have large specific surface area, and high conductivity, leading to better electrode performance and remarkable mechanical stability [92].

The lack of critical metal materials, especially cobalt and lithium, has raised concerns in the LIB industry [107]. Therefore, battery recycling is a key factor in achieving a sustainable storage system [104]. Wu et al. [107] evaluated the environmental impact and GHG reduction potential of different LIB recovery strategies. The results show that the direct recycling process has the lowest environmental impact compared to other processes. Reusing important materials like lithium, cobalt, and nickel from spent batteries can reduce the demand for raw material extraction and minimize environmental pollution [108]. The green footprint of lithium batteries can be improved by designing recyclable, less toxic, and more abundant components.

Figure 9. Sustainable battery [104].

(2) Supercapacitors Materials

Supercapacitors (SCs) are electrochemical devices that store energy through electrochemical conversions [109]. They consider a cleaner and more sustainable way of energy storage. Basically, they work by adsorbing/desorbing charged ions from the electrolyte onto the surface of a highly porous electrode by applying a potential differences [110]. The primary goal of SCs is to increase energy density without sacrificing high power density [109]. Therefore, SCs are expected to have a major role in future energy storage due to their high power density around 10^3–10^4 W/kg, excellent cycle life equal to 10^4 cycles, low pollution, low maintenance costs, rapid energy storage, stability, and enhanced safety compared to batteries [92,94]. They are classified based on their energy storage mechanisms and electrode materials.

Electrode materials are responsible for optimizing the electrochemical properties of SCs, including low toxicity, safe disposal, and enhanced electrochemical activity [109]. Most conventional electrode materials are toxic and harmful to the environment, which has led to the use of green, eco-friendly, biodegradable and bio-waste materials for SCs. Green supercapacitors should be fabricated using eco-friendly, low-cost, and non-toxic materials to generate less harmful waste and consume less energy during production [109]. Sustainable materials like activated carbon, graphene, and carbon nanotubes are important in the development of environmentally friendly supercapacitors. For instance, activated carbon is cheap, easy to manufacture, and an excellent alternative due to its high surface area, porosity, and high electrical conductivity [109]. It can be obtained from bio-waste sources such as animal products, minerals, plants, and vegetables [111–113]. Additionally, graphene is a preferred electrode material for its chemical stability and unique electrical, thermal, and mechanical properties [114–116]. Similar to activated carbon, it has a high surface area that enhances its performance.

Metal oxides/hydroxides, conducting polymers, and hybrid composites are alternative electrode materials in SCs [92,117], since they reduce the need for scarce or toxic elements. Therefore, Meena et al. [118] presented the latest advancements in plant-based materials used for designing and constructing green supercapacitors. It found that metal oxide-based nanostructures synthesized through green methods exhibit high specific capacitance, low cost, increased energy density, and low environmental impact. However, challenges such as low electrical conductivity, power density, and surface area need to be improved [118]. On the other hand, conducting polymers, such as polypyrrole and polyaniline, are being extensively researched as promising alternatives for SC applications [117]. This is due to their excellent charge storage capacity, low cost, flexibility, and simple synthesis process [118]. Thus, the move towards green supercapacitors involves using non-toxic and eco-friendly materials in their construction to minimize the environmental damage.

Thermal Energy Storage Materials (Phase Change Materials)

Thermal energy storage (TES) is essential in modern energy systems, as over half of the global final energy demand is thermal [119]. Their technology stores thermal energy for later use in heating, cooling, and power generation [120]. Effective thermal energy storage systems require specific designs for charging and discharging heat at the desired times, utilizing materials with suitable thermal properties [11]. They are particularly beneficial in buildings and industrial processes, where energy can be stored during low-demand periods and released when demand is high [121]. The advantages of these materials include reduced waste heat, increased efficiency, improved reliability, and decreased environmental pollution especially CO_2 emissions. Thermal energy can be stored as sensible heat, latent heat, thermochemical heat, or a combination of these methods [122]. Figure 10 shows the number of publications for thermal energy storage, which is rising rapidly and is projected to continue rising in the coming years reflects its evolution [123]. Latent heat storage (LHS) offers a higher energy storage density than sensible heat storage (SHS) [124,125].

During latent heat storage, significant amounts of energy are stored through the absorption or release of latent heat during a material's phase change [121]. The materials used for this purpose are known as phase change materials (PCMs) [126,127]. They are valued for energy conservation and thermal control due to their properties: high heat capacity, high density, low cost, reliability, thermal stability, non-corrosiveness, non-segregation, low toxicity, and minimal supercooling [128]. However, they also have disadvantages including low thermal conductivity, leakage, volume changes, and flammability [128].

Phase change materials are categorized into organic, inorganic, and eutectic mixtures based on their chemical nature [128,127]. High latent heat and high energy density are key factors when selecting a phase change material [129]. Inorganic PCMs generally offer higher energy density and thermal conductivity compared to organic materials [129]. They are also inexpensive and non-flammable [128], but they are more corrosive and prone to supercooling [129]. In contrast, organic PCMs exhibit greater chemical stability and undergo congruent melting, which helps reduce supercooling [130]. One drawback of organic PCMs is their low thermal conductivity, which slows the rates of heat storage and release [131,132]. Moreover, these materials can be either paraffin or non-paraffin types [133].

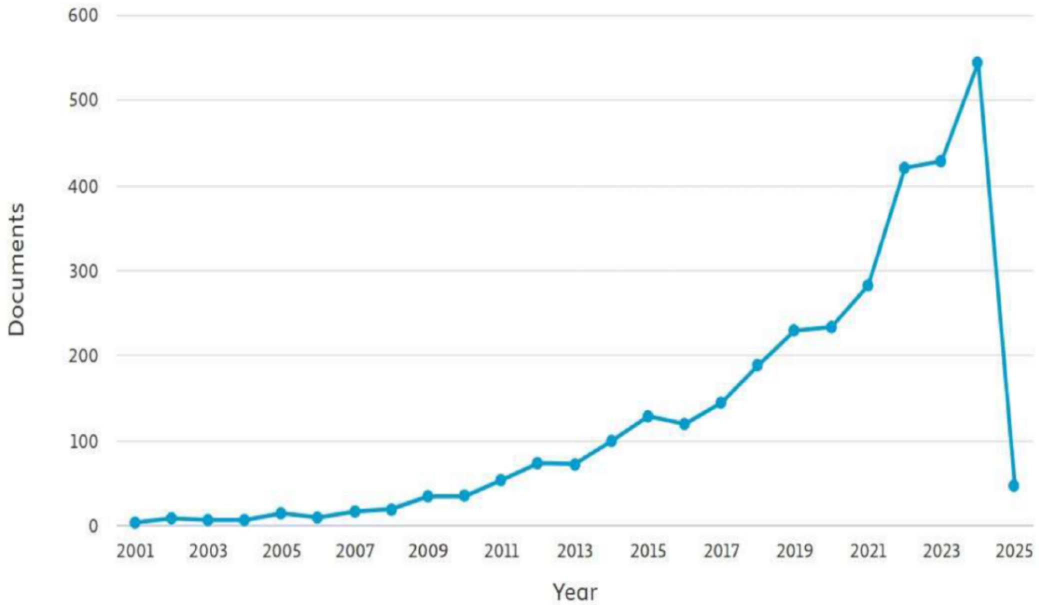

Figure 10. The annual scientific production for thermal energy storage [123].

Paraffin PCMs are widely used in thermal energy storage applications [134]. However, as petroleum-based materials, they indirectly consume fossil fuels contributing to global warming [135]. Even though they have high latent heat energy, wide melting temperature range, limited supercooling, and stable performance [136], their reliance on crude oil makes them less environmentally friendly [121]. Thus, there is a need for sustainable bio-based PCMs as green alternatives to paraffin-based materials.

Among non-paraffin organic PCMs, fatty acids and fatty acid esters are particularly promising bio-based options due to their essential properties [137,138]. They are derived from bio-sources such as animal fat, tropical oils, waste cooking oil, and natural waxes [139,140]. These materials offer high latent heat, stable chemical composition, thermal stability, and abundance [135,141,142]. Furthermore, they are non-toxic, biodegradable, and less flammable, making them well-suited for construction and building materials [143]. However, these non-paraffin PCMs are approximately three times more expensive than paraffin PCMs [130].

Hydrogen Energy Storage Materials

Green hydrogen (H_2) is an ideal method for storing energy safely and cleanly since not all energy storage technologies are considered devices [144]. H_2 is one of the universe's simplest, lightest, and most abundant elements [68]. Moreover, it has the highest specific energy density of 120–142 MJ/kg, which is 2.75 times the energy density of hydrocarbons [23]. Although hydrogen is relatively rare in its natural state on Earth, it can be efficiently produced through water electrolysis [13]. This process involves breaking down water into hydrogen and oxygen using electricity produced from renewable sources, thereby producing green hydrogen [145,146]. Hydrogen fuel is more than twice as efficient as gasoline [147,148], making it an environmentally friendly alternative to traditional fuels. As a non-toxic and clean energy carrier with zero-net emissions, it can store chemical energy for future use. However, storing hydrogen is still a challenge due to its low volumetric energy density [149].

A primary difficulty in utilizing hydrogen as an energy source is developing safe, reliable, and effective storage methods. Materials-based hydrogen storage is a promising approach [150], utilizing materials that absorb or adsorb hydrogen and release it through thermal or catalytic decomposition [149]. These materials either physically bond hydrogen molecules to internal surfaces, such as in porous carbons (PCs) and metal-organic frameworks (MOFs) or chemically bond hydrogen molecules to the base material, as seen in simple metal hydrides [151].

Metal hydrides, which consist of metals and hydrogen have attracted significant interest because of their high hydrogen storage capacities, large energy density, cost-effectiveness, and eco-friendliness [149]. These advantages make them promising materials for H_2 energy storage. However, finding materials that combine high H_2 capacity with stability and safety factors, remains a major limitation [152]. For instance, magnesium hydride (MgH_2) is known for its potential for efficient hydrogen storage due to its high hydrogen capacity, low cost, lightweight nature, and chemical stability [153]. In addition to metal hydrides, various carbon materials, including activated carbon, carbon nanotubes, and graphene have been extensively studied for hydrogen storage applications. These materials can be obtained from synthetic carbon or from natural sources such as biomass [149]. They offer a high specific surface area, excellent mechanical strength, and superior thermal conductivity [149,154]. Among these, activated carbon attracts the interest of hydrogen storage researchers because of its widespread availability, low cost, and high specific surface area [149]. Metal-organic frameworks are another class of materials with significant potential for hydrogen storage. They are porous materials with large surface areas and adjustable pore sizes, which are effective features for hydrogen adsorption and desorption through physisorption. However, the slow kinetics of adsorption/desorption affect the practical applicability of metal-organic frameworks in hydrogen storage [149].

3.2. Integrating Green Energy Materials into Sustainable Development

According to the 1987 report from the Brundtland Commission, sustainable development is defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [8]. This definition gained huge attention at the Rio Conference in 1992, when the Earth Summit officially approved the concept of sustainable development [155]. In order to ensure a sustainable environment and future, the UN took the initiative to set the SDGs. Thus, they were developed during the UN Conference on Sustainable Development held in 2012 and were endorsed by all UN Member States in 2015 as part of the 2030 Agenda [156].

This agenda consists of 17 key goals and 169 targets, as illustrated in Figure 11 [157]. These global goals represent a key step towards achieving sustainable development that includes all aspects of sustainability and every sector and part of society. They explore the interactions between nature and humans to provide a sustainable life for all generations. In addition, they serve as a global call to address serious issues and take action by 2030. They call upon all countries both developed or developing to work together and collaborate to solve many issues such as ending poverty and hunger, improving public health, fostering economic growth, mitigating climate change, and protecting the environment [158]. SDGs are structured to balance the incorporation of all the three pillars of sustainability: environmental, economic, and social [159].

The transition to green energy is essential for sustainable development since it can mitigate global environmental, economic, and social conflicts. For this reason, supporting the production of green energy materials is needed in this shift as it provides clean energy that is free of contamination for an eco-friendly environment. They may directly or indirectly contribute to the achievement of numerous goals related to SDGs. Also, they can extend the role of specific materials towards a sustainable future. These energy materials support the widespread adoption of sustainable and green materials, develop clean environments free of toxic emissions, promote a sustainable economy, and enhance the quality of life for the people within the region.

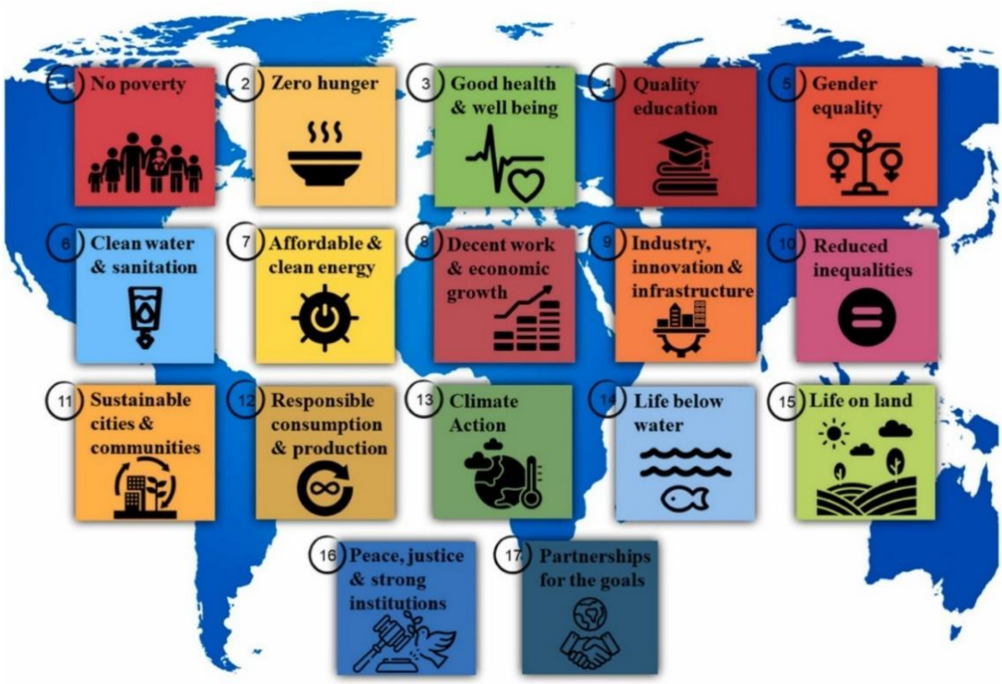

Figure 11. The 17 Sustainable development goals [157].

4. The Role of Green Energy Materials in Sustainability

4.1. Contribution of Green Energy Materials to the Pillars of Sustainability

Sustainability is most commonly viewed through three pillars: environmental, economic, and social sustainability. These pillars form the basis of sustainable development, which seeks to fulfill the needs of both current and future generations [8]. Green energy materials are important for harvesting, converting, and storing green energy. These materials play a major role in supporting the three pillars of sustainability. They contribute directly or indirectly by providing solutions to mitigate environmental harm, stimulate economic growth, and ensure social equity. Hence, the development of these materials could align with several SDGs, which are illustrated in Figure 12. Table 2 summarizes the contributions of green energy materials to achieving these goals.

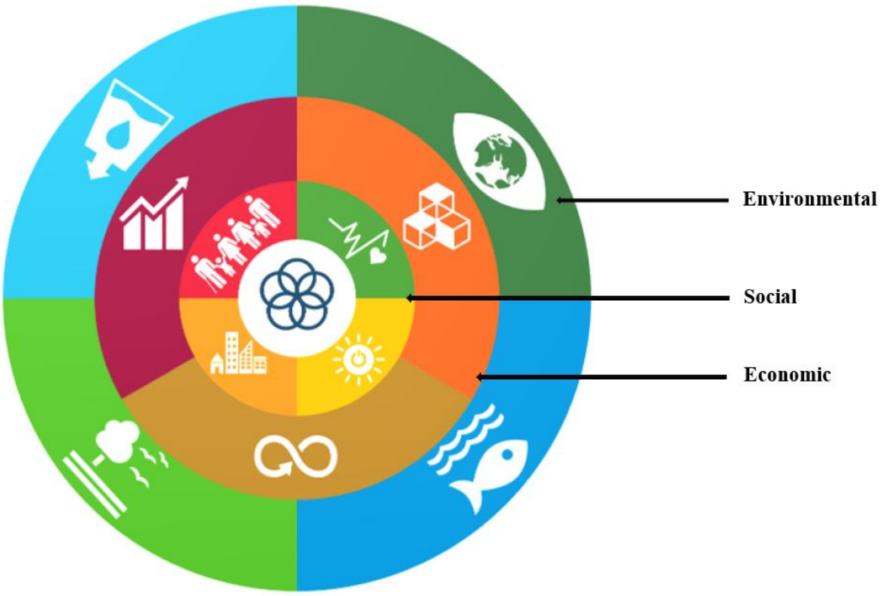

Figure 12. Pillars of Sustainability.

4.1.1. Environmental Contribution

Environmental sustainability ensures that natural resources and ecosystems are preserved and protected over the long term [160]. Several green energy strategies have been proposed to achieve global climate goals along with maintaining economic growth and well-being [7]. Green energy materials are critical to this transition, as they enable and facilitate the development of green energy technologies that can significantly reduce many of the negative impacts of the energy sector. These technologies will have the potential to mitigate the effects of climate change through the reduced emissions of greenhouse gases, clean water availability, and preservation of marine and terrestrial ecosystems [161].

SDG 6: Clean Water and Sanitation

Most of the recent advances in energy materials have introduced innovative solutions to address water contamination and disinfection challenges [162], offering substantial potential to meet the global demand for clean water [163]. Green energy materials highly contribute to achieving SDG 6, through the sustainable operation of water purification, treatment, and distribution systems [158]. They facilitate access to clean water via renewable and sustainable energy technologies. Preserving unpolluted water and air requires sustainable technologies, which depend heavily on the substances involved in their manufacture [23]. The use of eco-friendly and recyclable materials in these systems will decrease pollution and promote sustainability.

Photovoltaic materials enable solar-powered water pumps and desalination units to provide sustainable access to water in remote, isolated and neglected regions [13]. These systems operate independently of traditional power grids, and this will allow communities to have access to clean water. In addition, thermoelectric materials enhance the efficiency of water heating and cooling systems for sustainable operations. They maintain a reliable power source for water treatment plants and sanitation facilities. Besides, electrochemical energy storage materials can provide a stable supply of green energy for sanitation infrastructure. This is achieved through the storage of excess energy gained from renewable energy resources to be used during low energy production periods. Through the mitigation of fossil fuel dependency and reduction of greenhouse gas emissions, these green energy materials will establish a sustainable sanitation infrastructure and ensure access to clean water worldwide [163].

SDG 13: Climate Action

Climate change has become a critical global issue, resulting in massive environmental degradation primarily due to the heavy dependence on fossil fuels [13]. The energy field is a major contributor to this issue, responsible for approximately 75% of global GHG releases [30]. The increase in atmospheric greenhouse gas concentrations has contributed to global warming and climate change. This highlights the requirement of green energy systems to limit the increase in global temperatures by an average of 2 °C by 2030 [164]. Hence, governments all over the world are urged to establish targets, policies, and action to combat climate change and its consequences [158]. Green energy has proven to be a key solution for achieving SDG 13 by reducing emissions and mitigating negative environmental impacts [165–167]. As green energy systems help lower the greenhouse gas emissions, including carbon dioxide (CO_2) nitrogen oxides (NO_x), and sulfur dioxide (SO_2) [168]. This will be useful to resolve climate issues and protect the environment.

Green energy materials have a tremendous impact on the reduction of greenhouse gas emissions and contribute towards ending the climate crisis since they provide clean, sustainable, and zero-emission energy. They provide clean and sustainable energy supplies for renewable energy systems that emit zero emissions and minimize the consumption of fossil fuels. Furthermore, these materials support sustainable development by ensuring a reliable energy supply and promoting environmental conservation for a more sustainable future. The utilization of natural and green resources, such as recyclable, non-toxic, and bio-based materials in these energy technologies, can reduce resource depletion and minimize hazardous waste, as they pose a critical threat to the environment. For these reasons, using sustainable, inexpensive techniques to produce affordable, environmentally friendly, and sustainably extracted materials can facilitate the achievement of this goal without compromising others [169].

SDG 14: Life Below Water

The oceans are home to millions of living organisms and serve as a primary protein source for billions of people [163]. They are currently threatened by increasing pollution caused by climate change. Higher concentrations of greenhouse gas emissions, especially CO_2 emissions cause ocean acidification. This occurs because seawater absorbs carbon dioxide, which lowers its potential of hydrogen (pH). This acidification poses a great threat to marine ecosystems. SDG 14 seeks to manage and protect these marine environments by mitigating marine pollution and combating ocean acidification [6]. These goals can be encouraged and achieved through the use of green energy materials.

Green energy materials generate and store clean energy that is free from the harmful emissions of fossil fuels. By keeping ocean acidity levels stable, these materials support aquatic life protection from the harmful and negative effects of acidification [170]. In addition, the utilization of eco-friendly, recyclable and biodegradable materials significantly reduces the discharge of pollutants released into water bodies, thereby decreasing the overall environmental footprint and enhancing marine conservation efforts. For instance, green fuel cells can provide clean energy for marine transportation, such as hydrogen-fueled ships. These will substantially reduce pollution compared to conventional marine fuels and promote cleaner marine operations. Green energy materials support sustainable and low-impact energy solutions that contribute to the preservation of marine ecosystems and the reduction of toxic emissions [6].

SDG 15: Life on Land

Climate change negatively affects billions of people worldwide and poses a serious threat to ecosystems, biodiversity, and various environmental challenges [6,28]. To combat these impacts, global initiatives are focused on achieving long-term positive outcomes for biodiversity and ecosystems through the adoption of green energy. SDG 15 calls for immediate action to protect natural ecosystems, reduce their degradation, and conserve biodiversity [158]. This goal includes efforts to mitigate climate change by adopting renewable and green energy technologies that produce zero emissions. Therefore, green energy materials facilitate the development of these technologies, which help lower greenhouse gas emissions. This reduction is vital for alleviating climate change and its harmful effects on terrestrial ecosystems while promoting sustainable land use practices.

It is essential to adopt sustainable methods for producing and disposing of energy materials to prevent environmental degradation and reduce solid waste. Involving green, eco-friendly and recyclable materials in energy technologies helps preserve terrestrial ecosystems, reduce air and soil pollution, enhance biodiversity, and decrease the need for mining and deforestation [6]. Moreover, transitioning to sustainable energy systems that incorporate green materials minimizes the environmental footprint and improves public health by reducing pollution. Integrating green energy materials into the energy sector can highly contribute to the conservation of terrestrial life and ensure a healthier planet for future generations. Therefore, advancing green energy materials is crucial not only for mitigating climate change but also for promoting sustainable development that benefits both the environment and human health [163].

4.1.2. Economic Contribution

Economic sustainability focuses on promoting economic growth that ensures long-term stability [160]. Green energy is expected to become a major economic factor for reducing net CO_2 emissions during the shift towards a carbon-neutral economy. Green energy materials will encourage innovation, develop new eco-friendly technologies, and create job opportunities within the green energy sector. Additionally, the development and production of advanced energy materials from sustainable sources can boost the sustainable economy by opening new markets and attracting investment [26].

SDG 8: Decent Work and Economic Growth

Global demand for energy is increasing, primarily driven by economic growth, which presents opportunities for further economic development. However, shortages in energy supply can hinder this growth, making the transition to clean and efficient green energy essential for ongoing progress [4]. Studies show that renewable energy technologies stimulate new economic activities while also contributing to a cleaner environment. As a result, green energy materials align with SDG 8 by promoting sustainable economic development and providing decent job opportunities within the green energy sector. One of the key benefits of transitioning to green energy and utilizing these materials is job creation, which is vital for both developed and developing nations [171]. For example, these materials are produced sustainably using green, non-toxic, and recyclable resources, opening up numerous opportunities in research, development, and manufacturing. This shift in turn contributes to economic development by enhancing productivity. Furthermore, the implantation and integration of green energy materials across various industries and systems generates numerous green energy projects that promote sustainable industrial growth. Emerging businesses in the green energy sector offer opportunities for entrepreneurial investment and clean energy generation. It is estimated that improving the performance and availability of clean energy will require annual investments of approximately $950 billion by 2030 [30].

SDG 9: Industry, Innovation, and Infrastructure

Sustainable Development Goal 9 emphasizes the importance of advancing sustainable industrialization, along with encouraging innovation and developing resilient infrastructure as key components of economic development [158]. Establishing a sustainable energy infrastructure requires the advancement of effective energy harvesting, conversion, and storage technologies [1]. Green energy materials, including photovoltaic, thermoelectric, phase change, and electrochemical materials, are vital for generating and storing reliable and clean energy while lowering reliance on fossil fuels and improving energy security. Scientists and engineers are concentrated on enhancing the performance and durability of clean energy technologies. Hence, materials science and engineering are fundamental to achieving the technological advancements desired in the energy sector [163].

Establishing a carbon-neutral energy infrastructure based on renewable sources requires the development of advanced and affordable energy materials [172]. For long-term sustainability, they must be manufactured using abundant, non-toxic, recyclable, and chemically stable materials [1]. These green materials not only reduce their environmental footprint, but they also stimulate innovation, which promotes industrial growth, sustainable manufacturing, and technological progress. The United Nations Agenda promotes sustainable innovation through green materials and technologies to mitigate the production of toxic residue. Moreover, the widespread use of these materials across various industries, especially the energy sector, highlights the importance of research related to materials and nanotechnology [163]. Thus, innovation and research are key to developing these materials and attracting entrepreneurs to invest in sustainable and profitable projects.

SDG 12: Responsible Consumption and Production

Production and consumption are fundamental aspects of the global economy, yet they pose serious threats to the environment and climate due to unsustainable resource use, hazardous combustion systems, and increased waste [30]. To foster sustainable practices, these challenges must be addressed. SDG 12 ensures that consumption and production practices are sustainable [158]. It seeks to lower the use of conventional energy sources in the production and consumption stages of economic activities, minimize their negative impacts, as well as improve waste management of the activities that produce waste [158]. Thus, it contributes towards responsible resource management by restricting the use of energy to sustainable practices and alternatives such as using green energy materials. The application of green, eco-friendly, and recyclable materials in these systems aids in supporting sustainable consumption and production [1]. Additionally, it reduces waste, mitigates negative environmental impacts and promotes a circular economy. It found that recycling and reusing waste materials are key strategies for responsible consumption and production. These waste management procedures must be easy to implement and affordable. It is important to enhance recycling and waste reduction efforts by companies to implement more sustainable consumption and production models by 2030 [173].

4.1.3. Social Contribution

Social sustainability aims to enhance the living standards of a community along with ensure equitable access to resources and opportunities to all individuals [160]. Green energy materials have a very important role in promoting social sustainability through maintaining the accessibility of clean energy, improving living standards, and developing sustainable cities and communities. Moreover, these materials help to mitigate health risks associated with fossil fuel emissions for better public health. This approach not only increases access to green energy for poor communities but also supports the SDGs that focus on reducing disease, pollution, and poverty [174,175].

SDG 1: No Poverty

Climate change is also one of the key cause of poverty since it results in natural disasters like flooding and drought, which are expected to displace millions by 2030 [6]. In response, green energy has been considered as a critical factor in enhancing global wealth and well-being, especially in developing countries [163]. Besides that, green energy materials contribute significantly towards achieving SDG 1 by providing sustainable, affordable energy that can lift communities out of poverty [158]. These materials facilitate the generation and storage of low-cost electricity in remote regions. Therefore, they reduce the consumption of expensive and polluting fuels while improving the living standards. Further, manufacturing and development projects for these materials with the use of green, non-toxic, and recycled sources create job opportunities and increase the demand for skilled personnel [176]. This job creation increases economic prospects within communities and significantly helps in lowering unemployment and poverty rates. Thus, through providing different types of jobs and economic opportunities within the clean energy sector, green energy materials indirectly contribute to poverty reduction.

SDG 3: Good Health and Well-Being

Global warming and climate change creates a lot of issues, including health problems and environmental concerns. All of these issues are associated with the high concentrations of greenhouse gases and many other waste by-products [4]. The extensive use of poisonous and hazardous energy materials has led to serious and harmful environmental problems like air contamination, which has a negative impact on human health. This air pollution is linked to various diseases, such as cancer, cardiovascular disease, and respiratory issues like asthma [177]. In 2016, the urban air quality standards failed to meet the World Health Organization standards, as residents being exposed to an air that was 2.5 times more contaminated than recommended levels [30]. This drop in air quality caused the deaths of approximately 4 million people alone that year [30]. Therefore, there is need to reduce the negative climate change impacts in order to protect and save lives. As stated by the United Nations Development Programme (UNDP), green energy is more reliable energy that can be used to improve the health and human well-being [178].

Green energy materials help achieve SDG 3 by preventing air pollution and improving public health. They significantly enhance air quality, mitigate the effects of climate change, and minimize the public health and environmental threats posed by hazardous and toxic materials. Additionally, these materials made from eco-friendly and sustainable sources can provide clean energy, hence decreasing the spread of diseases caused by pollution [4]. For instance, they can ensure a reliable and stable power supply for hospitals, clinics, and healthcare facilities located in the remote areas. This helps in having access to electricity needed for life-saving medical equipment and services without posing much danger to the environment. The use of green energy materials assists in obtaining healthier environments, better health outcomes, and improved living standards for individuals [178].

SDG 7: Affordable and Clean Energy

According to the International Energy Agency (IEA) statistics in 2022, only 91% of the world's population had access to electricity, while 685 million people lived without it [179]. Limited access to energy can negatively affects human and economic development, especially in less developed countries [28]. As a result, there is an urgent need to transform the world's energy generation and storage systems into greener alternatives that provide clean, zero-carbon-emission energy [4,28]. Green energy materials are contributing towards this shift by facilitating the availability of clean energy at lower costs. This approach is in line with SDG 7, which ensures that all individuals have access to affordable, sustainable, reliable, and modern energy [158]. For the achievement of this goal, the materials used in innovative energy conversion, harvesting, and storage technologies should be non-toxic, plentiful, easily accessible, and affordable [1]. Moreover, access to clean, green, and sustainable energy supports the attainment of other SDGs.

SDG 11: Sustainable Cities and Communities

Green energy materials are the key resources for accomplishing SDG 11, which involves building inclusive, safe, resilient, and sustainable cities and communities [158]. Implementing green energy infrastructure in urban areas and cities can lower greenhouse gas emissions significantly. The advancement of these green, non-toxic, recyclable, and lightweight materials holds substantial potential to help humanity construct and build sustainable cities [163]. For instance, the energy efficiency of buildings and transportation in a city can be improved by using green thermoelectric materials to enhance the environmental performance and support urban sustainability. Incorporating phase change materials in concrete can enable buildings to reach net-zero emissions and enhance the thermal comfort for heating, cooling, and air conditioning [180]. Thus, they reduce the reliance on fossil fuels that increases the future sustainable energy usage [180,181]. Besides, fuel cells made from green materials provide clean fuel for green hydrogen-powered vehicles in order to accomplish sustainable public transportation and mobility. In contrast, electrochemical energy storage materials ensure a reliable power supply for urban infrastructure. These materials minimize the negative impacts on the environment and facilitate an effective shift towards a clean and sustainable future. In this regard, the adoption of green energy materials encourages eco-friendly practices within communities and cities which satisfy the social needs [163].

Table 2. Contributions of Green Energy Materials to SDGs.

SDGs	Contributions of Green Energy Materials	Interconnectedness (Direct or Indirect)	Ref.
SDG 1	• Create jobs and opportunities • Mitigate poverty rates • Empower communities	Indirect	[163,174–176]
SDG 3	• Improve air quality • Lower the rates of respiratory diseases • Enhance public health	Indirect	[4,178]
SDG 6	• Reduce water pollution • Access to clean water • Preserve natural resources	Indirect	[13,23,162]
SDG 7	• Reduce reliance on fossil fuels • Access to affordable energy sources • Access to sustainable and clean energy	Direct	[1,4,28]
SDG 8	• Create job opportunities • Promote Green energy investments • Foster economic growth	Indirect	[4,30,171]
SDG 9	• Encourage sustainable innovations • Develop new green materials and technologies • Promote sustainable industrial practices • Improve energy infrastructure	Direct	[1,163,172]
SDG 11	• Minimize urban pollution • Enhance energy efficiency of buildings • Sustainable buildings and infrastructure	Direct & Indirect	[163,180,181]
SDG 12	• Support the adoption of renewable and green resources • Promote sustainable production and consumption patterns • Reduce the negative environmental impact of energy production and consumption (Recycling)	Direct & Indirect	[1,30,173]
SDG 13	• Mitigate climate change • Decrease reliance on fossil fuels • Lower Greenhouse Gas emissions • Adopt zero or low-carbon energy alternatives	Direct	[164–168]
SDG 14	• Minimize marine pollution caused by fossil fuel usage. • Reduce ocean acidification • Protect marine ecosystems • Protect water quality	Indirect	[6,170]
SDG 15	• Reduce terrestrial pollution • Preserve terrestrial ecosystems and biodiversity • Promote sustainable land use practices • Decrease deforestation	Indirect	[6,28,176]

4.2. Green Energy and Sustainability Pillars

The adoption of green energy technologies is not only about technological development but fundamentally about implementing the core principles of sustainable development. The three pillars of sustainability are central to the purpose and outputs of green energy systems [6]. Recent studies emphasize that aligning these three pillars with renewable energy solutions will be critical to achieving SDGs, especially the goals related to affordable and clean energy, climate action, and economic growth. From an environmental perspective, the most direct alignment between sustainability and green energy is observed in emissions reduction, ecological conservation, and resource circularity. Shifting from fossil energy perspectives to renewable energy production from sources like solar, wind, hydrogen, and geothermal significantly reduces greenhouse gas emissions, lowers air and water pollution, and minimizes the ecological footprint compared to fossil-based energy production [182]. According to recent findings, countries that use green energy technologies have achieved up to 55% reduction in net greenhouse gas emissions, as well as contributed up to 55% of electricity use by 2030 [7]. Furthermore, innovations in recycling and waste-to-energy systems are enabling circular economies where energy production is harmonized with environmental protection [183]. In terms of economic sustainability, green energy presents multiple benefits. It enables job creation and promotes industrial and technological advancement. Investment in renewable energy infrastructure has been shown to yield more employment opportunities. This contributes to long-term economic resilience, especially in rural or underserved regions [184]. While socially, green energy supports equity by increasing access to clean energy, reducing energy poverty, and improving public health [185]. The relationship between the three sustainability pillars and the green energy illustrates that the energy transition is not just a technical effort but a strongly ethical and developmental one as well. This integrated pathway assures that energy transformation benefits are both equitable and long-lasting across generations [186].

5. Challenges and Limitations

Although advanced and green materials for green energy technologies have progressed quickly and are being developed rapidly for the environment and energy systems, the large-scale industrial and commercial use of these materials is still constrained by many technical, economic, environmental, and social barriers [187]. These materials, ranging from perovskites and metal-organic frameworks (MOFs) to bio-derived polymers and 2D materials like MXenes and graphene, have the potential to make huge changes in different technologies. However, a deeper analysis of their limitations reveals critical gaps that must be addressed before these innovations can be implemented or used in real-world energy sector applications.

One of the major challenges lies in the stability, long-term reliability, and operational lifetime of many of these emerging materials. While most green energy materials have shown remarkable performance and efficiencies under laboratory conditions, they often fail to maintain those results under variable real-world conditions. Indeed, laboratory testing often does not capture the full range of environmental stresses that energy materials encounter during operation. As these conditions can lead to rapid degradation and poor functional durability over time, this will make them unreliable for actual long-term use in these green energy technologies. Consequently, their market competitiveness remains questionable [188]. Economic viability is another major challenge. The production of these materials, while being a clean alternative, is still more expensive than conventional materials. As these materials require sophisticated and cost-intensive synthesis methods that are not only costly but also hard to scale consistently while maintaining quality [189]. This makes large-scale manufacturing difficult and prevents easy integration into existing supply chains. Many advanced materials also depend on rare or difficult-to-source components, further complicating their commercial potential.

Material availability is also a critical concern. Many advanced energy technologies rely on critical raw materials for their development. These materials are often concentrated in geopolitically sensitive regions and are associated with ethically questionable mining practices, raising issues of sustainability of extraction, availability, toxicity, and price fluctuations [190]. While some green alternatives are under development, they often do not yet match the performance of more established technologies. In addition, environmental impacts associated with the entire material lifecycle are increasingly scrutinized. Although green in application, many advanced materials have hidden footprints in their production and disposal phases. Besides, some materials are toxic, non-biodegradable, or difficult to recycle, raising concerns about long-term sustainability and waste management [191].

Integration with existing manufacturing ecosystems and energy infrastructures presents additional challenges. Advanced materials may require new design standards or operate under conditions incompatible with conventional technologies, leading to higher costs and adoption resistance. Therefore, the successful integration of green materials into energy technologies needs not only material optimization but also an understanding of engineering compatibility, environmental policy, lifecycle cost analysis, and user acceptance, a combination that is still rare in current industrial practice [192]. This review relies on the available published literature rather than experimental data or lifecycle assessments of specific materials. This review summarizes a strong portion of the literature on the most widely studied energy materials; however, it does not cover all emerging alternatives, particularly those in early-stage development or ongoing experimental studies, as the focus was placed on SDGs alignment.

6. Conclusions

Green energy materials are important in promoting sustainability from an environmental, economic, and social perspective. The energy produced using these materials is expected to contribute up to 55% of total electricity generation by 2030. They reduce pollution, protect marine and terrestrial ecosystems, and ensure access to clean water. In addition, these materials foster growth via innovation, job creation, and the advancement of new sustainable technologies. Moreover, these materials provide clean and affordable energy, improve public health, and assist in building resilient and sustainable cities. This will not only contribute to achieving many of the sustainable development goals but will also provide an effective approach to sustainability. It is evident that as the world approaches these materials from a global perspective, more efforts need to be directed towards the greener alternatives in order to attain the SDGs.

To enhance the potential of green energy materials in achieving the SDGs, several recommendations are presented in this context. Policymakers should provide supportive policies and programs to encourage the application of sustainable materials in renewable energy technologies in line with SDGs 7 and 9. For instance, designing supportive policies for recycling and reusing materials will further reduce waste and contribute to SDG 12. In addition, leaders of industry are encouraged to invest in the development of more efficient and environmentally friendly materials for more cleaner manufacturing processes to reduce environmental impacts towards SDGs 8, 9, 13, 14, and 15. Innovation by green materials researchers should aim at the enhancement of efficiency in renewable energy, and collaboration efforts across fields are necessary to deal with specific challenges in developing materials contributing to SDGs 7, 12, and 13. Accelerating the adoption of green energy technologies by supporting research in developing countries is consistent with SDGs 6, 7, 11, and 13. Furthermore, international organizations should encourage sustainable materials to have global standards and promote the exchange of knowledge, thus enabling further support for both the developed and developing world in attaining SDGs 1 and 3.

For future work, the successful deployment of green energy materials requires public understanding, awareness, acceptance, and behavioral change, all of which are difficult to achieve without comprehensive education. Also, researchers, engineers, policymakers, and economists must collaborate more closely to develop technologies that are not only efficient but also socially acceptable, affordable, and eco-environmental.

Author Contributions

B.N.: methodology, investigation, data curation, formal analysis, writing—reviewing and editing; M.T.: conceptualization, project administration, supervision, investigation, methodology, data curation, formal analysis, writing—reviewing and editing; A.A.-O.: conceptualization, project administration, investigation, methodology, formal analysis, writing—reviewing and editing; M.Y.: methodology, investigation, formal analysis, writing—reviewing and editing. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

The data that support the findings of this study are available on request.

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Conflicts of Interest

The authors declare no conflict of interest.

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