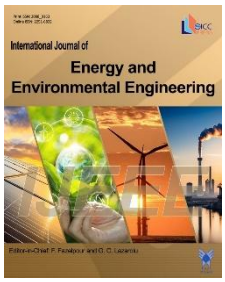

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Green Energy Materials: Pathway to the Green Future

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Abstract

The increases in power costs and environmental pollution are major contributors to global warming worldwide. Modern power generating systems therefore require green technologies that focus on improving energy harvesting-based power generation. Green energy materials are essential for converting other types of energy into electrical energy. Among the major energy storage technologies, heat energy storage has maximum efficiency and can be converted into electrical energy by thermoelectric devices. Thermoelectric materials play a dual role: they convert thermal energy into electricity via the Seebeck effect and provide heating or cooling when electrical energy is applied through the Peltier effect. This review highlights the role of thermoelectric devices in converting heat to electricity and in the reverse process for effective thermal management. The review also encompasses the utilization of renewable energy sources, such as photovoltaics, for hydrogen generation to mitigate the intermittency of solar energy.

Keywords: Conductive polymer; Hydrogen storage; Photovoltaics Pollution; Seebeck effect; Peltier effect; Thermoelectric generators

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1. Introduction

On March 15, 2021, the PV magazine published that the world has installed 1Tw solar power to meet the world energy crisis and reduce carbon emissions into the atmosphere. Approximately 580×10^{18} joules (1.84×10^{13} watts) of energy are consumed globally each year, and the demand for energy is increasing daily. The PV module makes very little contribution (1:1840) to energy production globally [1]. To increase energy production for global energy needs due to population growth, global industrialization and life comfort, the production rate of renewable energy plays a vital role. Most of the available global energy originates from the burning of fossil fuels, which poses a serious threat to human civilization because of the increase in the Earth's temperature (global

warming). The scientific advisory committee for global climate change of the United Nations reported that the environmental temperature might range from 1.6°F to 6.3°F by the year 2100 [2]. CO2 emissions are responsible for global warming, and an almost 50% increase in CO_2 emissions has been recorded since 1750 [3, 4]. This annual global CO_2 emission from fossil fuels is depicted in Fig. 1. Renewable energy refers to energy that is derived from sources that are naturally replenished, such as sunlight, wind, rain, tides, and geothermal heat. Global warming, on the other hand, is the long-term heating of Earth's climate system, primarily due to human activities, such as the burning of fossil fuels such as coal, oil, and natural gas, which release greenhouse gases into the atmosphere, trapping heat and causing the Earth's average temperature to rise. Renewable energy plays a crucial role in addressing global warming because it has a significantly lower carbon footprint than fossil fuels do. Burning fossil fuels releases large amounts of carbon dioxide and other greenhouse gases into the atmosphere, trapping heat and contributing to global warming. In contrast, most renewable energy sources do not produce greenhouse gas emissions during their operation. For example, solar power generates electricity by harnessing energy from the sun, whereas wind power uses turbines to generate electricity from the wind. Both solar and wind power do not produce greenhouse gases during operation. Investing in renewable energy can help mitigate global warming by reducing greenhouse gas emissions, which are the main drivers of climate change. By transitioning to renewable energy sources, we can reduce our reliance on fossil fuels, which will result in lower greenhouse gas emissions and help to limit the increase in global temperatures. Additionally, renewable energy sources are often localized and do not require the transportation of fuels, reducing the emissions associated with fuel extraction, transportation, and combustion. Renewable energy also offers other environmental and social benefits beyond addressing global warming. It can help improve air and water quality, reduce the risk of oil spills and other environmental disasters, create jobs, stimulate economic growth, and increase energy access in remote and underserved areas. To address global warming effectively, it is crucial to adopt and promote renewable energy sources as cleaner and more sustainable alternatives to fossil fuels. This requires implementing supportive policies, investing in renewable energy infrastructure, promoting research and development in renewable energy technologies, and raising awareness about the importance of renewable energy in mitigating climate change.

These hostile changes, especially greenhouse gas (GHG) emissions, have lethal consequences for deteriorating a healthy atmosphere. The artificially increased GHG concentration leads to unexpected heavy rainfall, unstable sea water levels, changing weather patterns, ice melting, and alarming floods and droughts. Overall, manmade activities contribute approximately 86% of GHG emissions, of which power plants and other power generation contribute 36%, whereas 40% is contributed by coal [5]. In the present-day scenario, Earth and its inhabitants are facing major problems in which energy crises, limited energy resources, daily increases in global warming and air pollution are at the top of the list [6]. In many countries, energy is commonly produced by burning coal or natural gas, while other countries meet their electricity needs through nuclear power or hydropower [7]. These sources of energy are hazardous to the Earth's atmosphere because of the emission of harmful gases and heat, leading to fuel waste and posing environmental threats. It is assumed that approximately 30% of this heat is wasted in the form of hot exhaust gases. Thus, not only is useful energy wasted into the surrounding environment, but it also causes various types of pollution.

In such a situation, clean and sustainable energy sources that can convert waste heat into useful energy while being environmentally friendly are needed, thereby addressing the abovementioned problems [8, 9]. There are many conversion technologies available for mitigating greenhouse gases. However, in this review, we target thermoelectric and photovoltaic technologies for the mitigation of greenhouse gases.

2. Thermoelectric materials

Thermoelectric materials (TEs) use thermoelectric technological principles, e.g., the Seebeck and Peltier effects, where heat energy is converted into electrical energy, and are called converting devices [10]. Natural energy resources are limited, and it is estimated that we have depleted 80% of available resources and 50% of oil reserves thus far. If we continue to consume oil at the current rate, it is not unreasonable to predict that our oil resources could be completely exhausted within the next 32 years, which is alarming [11]. Keeping in mind the above threats, researchers have developed TE materials, which are semiconductor devices that exploit the Seebeck effect by generating a voltage signal upon exposure to a temperature gradient or exploit the Peltier effect by producing a temperature gradient upon application of electricity [12]. TE devices are very useful because they not only have direct power generation methods from waste but also provide cheap and green energy without producing environmentally harmful waste. However, for the optimum performance of TE modules, several factors, such as material choice, business strategy, and the operational environment, are necessary [13]. TE materials have many applications, such as in electricity generators, thermal sensors, military uses, aerospace technology and power plants and in transport industries for the emission

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of hot gases. TE materials also have applications in enhancing the ability of solar cells to generate electricity [14]. The conversion efficiency of thermoelectric materials, which is called the "Figure of merit" of thermoelectric materials and is denoted by ZT, is a metric of their performance. Those materials that have high figures of merit (e.g., ZT= 3-4) have 40% conversion capability of waste into electrical energy. Optimizing the thermoelectric properties, such as the Seebeck coefficient, electrical conductivity and thermal conductivity, can increase the value of the figure of merit. The figure of merit of conductivity can be calculated via the relation $ZT = S^2\sigma T/k$, where "S" is the Seebeck coefficient, "σ" is the electrical conductivity and "k" is the thermal conductivity of that material [15]. It is crucial to increase the ZT of thermoelectric materials at the microstructural (bulk grain) level because their electrical and thermal properties are mutually interdependent. This can be achieved by controlling the microstructure and dopant concentration. An increase in the figure of merit values compared with those of bulk materials may result from nanostructuring, which reduces the thermal conductivity through phonon scattering, or from an increased power factor due to quantum confinement effects [16]. Nanostructuring plays a key role in enhancing the figure of merit value because of its unique characteristics at the nanoscale [17, 18]. At the nanoscale, the thermoelectric properties of materials can be modified without badly affecting their figure of merit. Researchers have developed various methods to achieve this, including preparing nanocomposites by incorporating nano-inclusions into thermoelectric materials, controlling crystallographic grains, and reducing grain sizes to the nanoscale [19, 20].

Bismuth telluride (Bi_2Te_3) and skutterudite have very high figures of merit, which is why they are currently used in the manufacturing of thermoelectric generators (TEGs). However, these materials have several disadvantages, including high weight, environmental toxicity, and high cost [21].

Additionally, they are not suitable for moderate-temperature applications (250°C--650°C) [22]. Lightweight materials with a ZT value of 1 or higher are ideal for TEGs, as they not only increase the efficiency but also reduce the overall weight of the device. Additionally, the materials used should be inexpensive for large-scale deployment. However, commonly used thermoelectric materials such as bismuth telluride (Bi_2Te_3) and skutterudite compounds are both heavy and toxic, causing environmental and health concerns. To address these issues, magnesium-based composites and their alloys have emerged as promising alternatives because of their low weight, reduced toxicity, and potential for effective thermoelectric performance.

TE materials operate in three different temperature ranges, depending on the application.

- Low-temperature range (< 177°C), i.e., alloys based on bismuth.
- Intermediate temperature range (177°C--577°C), i.e., alloys based on lead.
- High-temperature range (> 1027°C), i.e., alloys based on SiGe.

Almost all metallic materials, including semiconductors, have thermoelectric properties. However, semiconductors have more appropriate thermoelectric materials because of their effective ZT value during optimization.

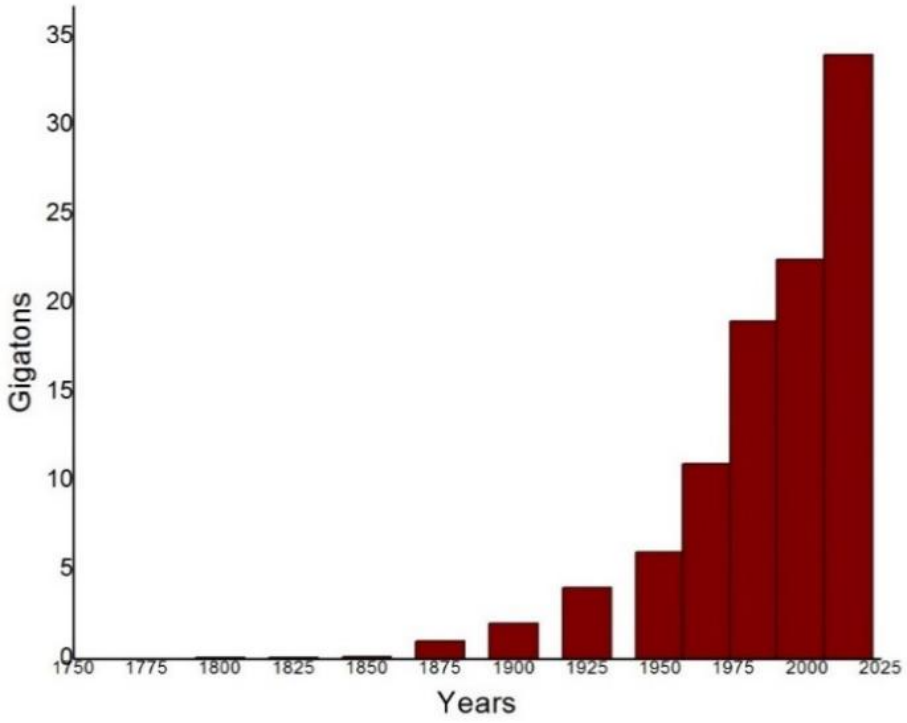

Figure 1. Annual global CO2 emissions

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The ZT value of semiconductor thermoelectric materials is high *because of their* exceptional properties, e.g., high carrier mobility, medium carrier concentration, and *low* electron *count*. Metals, on the other hand, have high carrier *concentrations* that *overlap with* the valence conduction bands and cause the valence conductivity to coincide [23]. The increase in temperature may lead to an *increase* in the thermal conductivity of the electrons due to saturation of the electron support concentration (*the* maximum support concentration (n) *is approximately* 1025 per cm). An increase in temperature creates a concentration gradient in metallic conductors and is therefore unsuitable *for* use as a thermoelectric material [23, 24]. The two main approaches to optimize thermoelectric materials are as follows: (i) mass production techniques, which include alloy formation, doping, nanostructuring by reducing the particle size, and the preparation of nanocomposites; and (ii) the fabrication of thin films. Therefore, nanotechnology, with its ability to manipulate materials at the nanometric scale, plays a vital role in advancing thermoelectric material development [25-27].

2.1. Seebeck effect

In 1821, Seebeck discovered that a temperature gradient caused voltage generation in thermoelectric materials. According to Seebeck observations, the combination of two dissimilar materials with different junction temperatures (T and T_+, T.) leads to a difference in voltage (_V) that is proportional to the difference in temperature. To explain this effect, an experiment was conducted in which two thermocouples of dissimilar materials labelled “A” and “B” were electrically coupled in series while being thermally coupled in parallel and arranged in combination as open circuits. By applying two different temperatures (T_1>T_2) at points A and B, an electromotive force (emf) is generated at both different points, as the materials have charge differences, as shown in Fig. 2. The ratio of the voltage generated to the difference in temperature represented as (V/T) is associated with the intrinsic properties of the material, which can be expressed as the Seebeck coefficient or thermostability denoted by α. The Seebeck effect can be expressed via the following equation:

$$V= \alpha\Delta T$$

where α = Seebeck coefficient or between the thermocouples A and B, V = thermoelectric voltage and $\Delta T= T_1-T_2$ temperature difference. The direction of the flow of charges in a circuit is obtained from the sign of the Seebeck coefficient. If electrons generate electricity, then the sign of the Seebeck coefficient will be negative or otherwise positive. This voltage is known as the Seebeck voltage[28-31].

2.2. Peltier effect

The Peltier effect, which is the reverse of the Seebeck effect, was first described by Peltier in 1834 [32]. The current begins to flow inside the material if a potential difference is introduced to two separate places C and D of the same material, as shown in Fig. 3. The temperatures at the other two junctions, A and B, which are made of identical materials, differ. The temperature at one connection is high, whereas the temperature at the other junction is low (which is similar to heating and cooling at these points). This causes the rate of cooling -q across the other junction and the rate of heating q at one junction. For various types of materials, these phenomena vary [33]. Mathematically, the Peltier effect is represented by the following equation:

$$\Pi= I/q$$

where Π represents the “Peltier coefficient”, q represents heat flow, and I represent electric current.

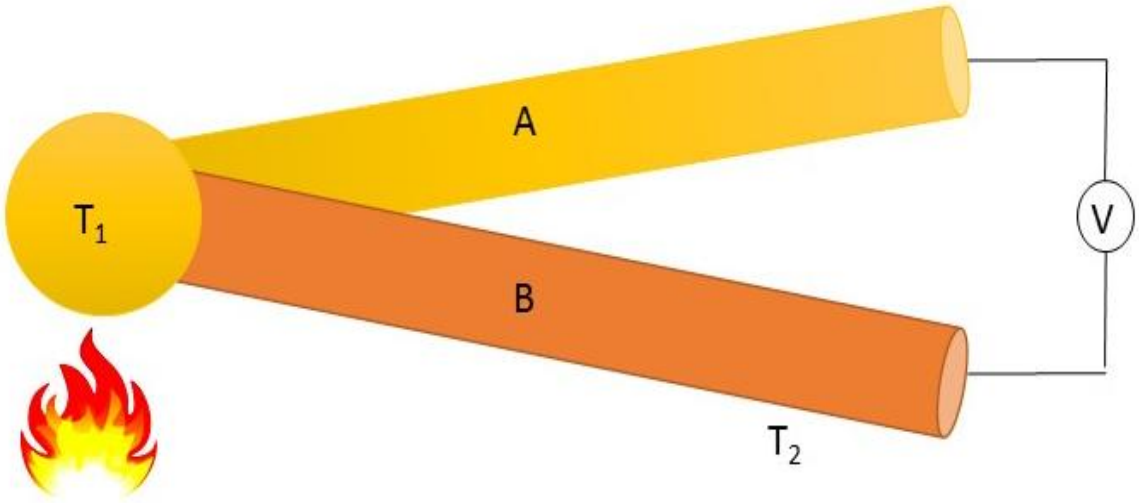

Figure 2. The thermocouple function connects two dissimilar metals to yield a measurable voltage with a temperature gradient

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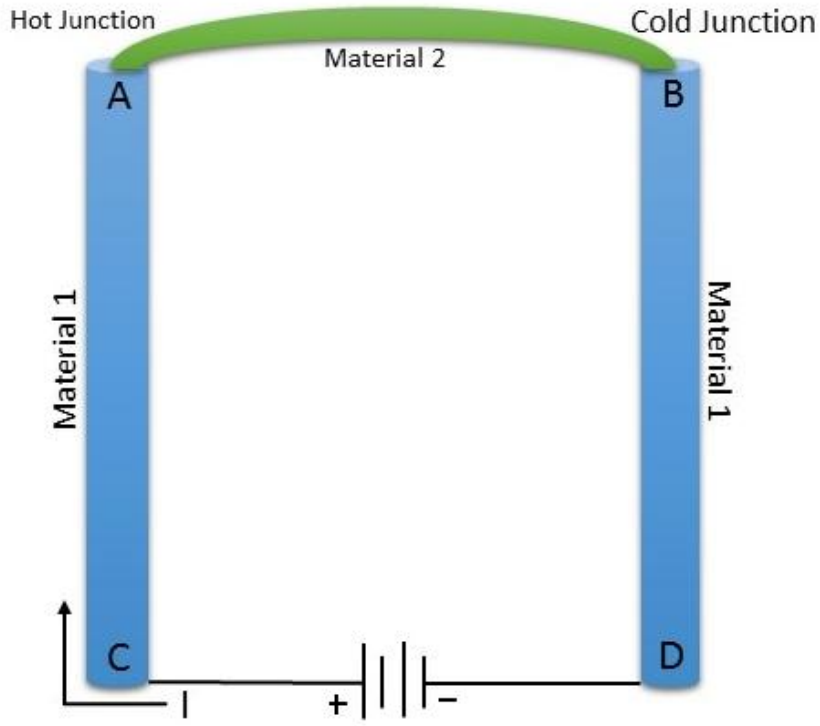

Figure 3. Schematic diagram of the Peltier effect

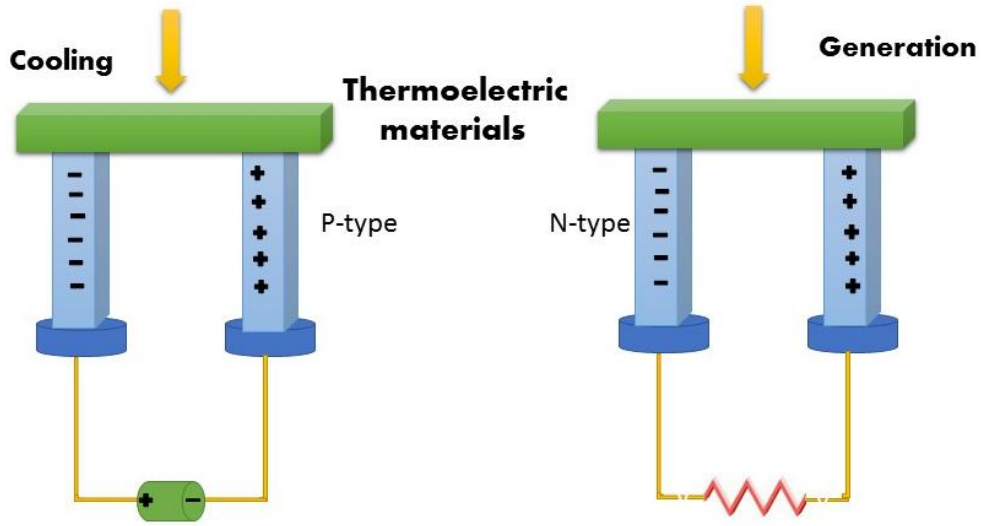

Figure 4. Schematics of the thermoelectric materials (generation and cooling)

3. Thermoelectric devices

The solid-based thermoelectric (TE) energy transformation technique is of great interest because of its electrical output and temperature-controlled devices. The prospect of transforming heat energy into an electrical current or electric current into heat is realized by a thermoelectric generator (TEG) or thermoelectric cooler (TEC), which is based on the principle of coupling the transport between phonons and electrons. Modern TE refrigeration is also based on the principle of the Peltier effect, whereas TE power-generated devices work on the principle of the Seebeck effect. The versatile TE material is composed of n-type and p-type semiconductor materials coupled through electrical metallic contact. Refrigeration and power generation are accomplished collectively by using the same module. A TE module or device is coupled electrically in series and thermally in parallel and comprises an array of pads. TE energy conversion employs the Seebeck effect, where changes in the temperature gradient result in voltage generation that can be used to drive a current through a load resistance or device. Heat is converted into electricity in this process. In contrast, the heat in the Peltier effect is produced with the passage of electric current in a TE material to create a temperature gradient. The passage of current gives rise to charge carriers in the TE materials and rejects heat versus refrigeration. A TE power production device may

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transform waste heat, which has 0% efficiency, into usable electrical energy, with an efficiency of 7–8% or more.

Fig. 4 displays the schematics of the thermoelectric materials (generation and cooling). The most effective TE materials currently in use have a ZT value of 1, which is a realistic upper limit for more than 30 years after the mid-1990s.

For device fabrication, thermoelectric generators are constructed by joining multiple n-type and p-type TE materials, as shown in Fig. 4 and in Fig. 5. The temperature difference between these two junctions will generate an electric current, which will be allowed to flow in a series of TE materials for cooling purposes via the Peltier effect [34]. In such devices, the charge carriers carry heat directionally, disturbing the electron balance in both materials, which results in a temperature gradient at the two junctions. These TE generators are coupled with the building materials to cool the interior of the building with less power. The coefficient of performance (COP) of the cooling phenomenon depends on the figure of merit (ZT) of the material. The maximum values of the COP at given Th and Tc values are strongly ZT dependent [35].

$$\text{COP} = \frac{T_c}{T_h - T_c} \frac{\sqrt{1+ZT} - T_{h/T_c}}{\sqrt{1+ZT}+1}$$

Jinkai Chen et al. reported the integration of TEGs into transparent glazing for windows and roofs to promote sustainable development in residential applications. They used transparent TE materials to align with transparency protocols and acquire additional energy from the environment [36]. The optical properties of transparent TE-coupled glasses can be characterized by the transparency and absorbance given in equation (44). T_{tran} characterized the ability of transparent light, whereas A_{abs} characterized the ability of materials to absorb light.

$$T_{tran} = \frac{I_t}{I_o}, \qquad A_{abs} = -\log_{10}\frac{I_t}{I_o} \qquad 44$$

Here, I_t is the transmitted light intensity, and I_o is the incident light intensity.

3.1. Polymer thermoelectric

Thermal energy has the ability to transform heat energy into electrical energy and may be the best choice for power generation. The entire potential of thermoelectricity has not yet been achieved because of various factors, including cost, productivity, abundance, and physical performance. Despite significant advances made in the past decade, mainly attributed to their lower thermal conductivity, thermoelectric materials can be greatly improved.

A comparison of the thermoelectric and inorganic thermoelectric properties of the polymers is shown in Table 1. Conductive polymers have the ability to use thermoelectric materials, with the best polymer separation properties, and compete with conventional inorganic thermoelectric materials. Polymer-based materials are distinguished primarily by their low natural heat conductivity and low production costs. This makes it possible to create novel device architectures for less than a dollar/watt than conventional thermals. Moreover, optimal polymer materials tend to have less thermal energy than their regular inorganic counterparts do.

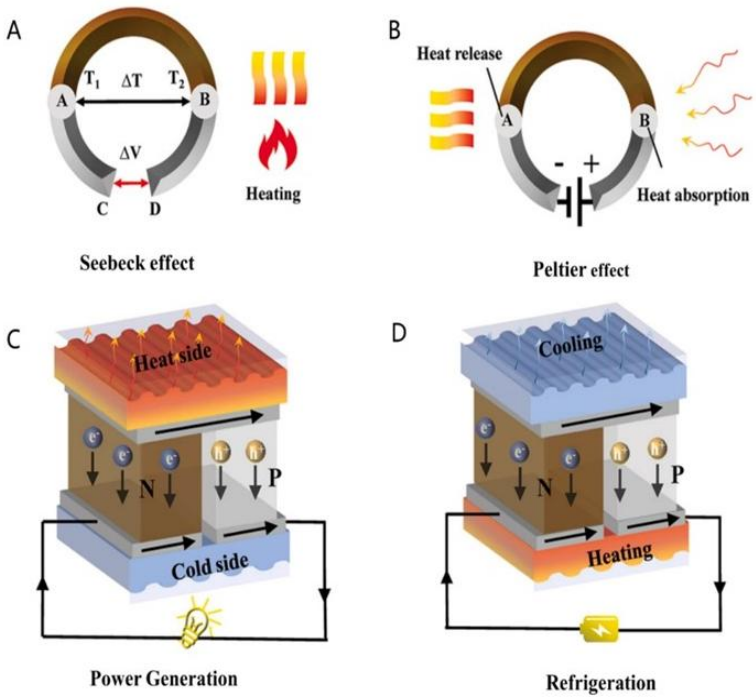

Figure 5. Schematic illustration of the TE effect and the TE module, including the (A) Seebeck effect, (B) Peltier effect, (C) power generation, and (D) refrigeration. Reprinted with permission from Copyright 2022, Wiley

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Table 1. Comparison of an industry-leading polymer (PEDOT:PSS) with an inorganic substance (Bi2Te3)

Polymers TEs	Features	Inorganic TEs
$\sigma \approx 900$ s/cm		$\sigma \approx 1000$ S/cm
S ≈75μV/K	2-3x more couples	S≈200μV/K
K ≈0.25 W/m-K	HX considerations	K ≈ 1.3 W/m-K
$s^2\sigma \approx 500$ μW/m-k^2		$s^2\sigma \approx 4000$ μW/m-k^2
ZT≈ 0.4	$\eta \leq \frac{ZT}{4}\frac{\Delta T}{T_H}$	ZT≈ 0.8
T_{MAX}≈ 200 ℃		T_{MAX}≈ 250 ℃
Costs Material: S0.34/kg Manufacturing: S4.76/m^2	Low Cost	Costs Material: S125/kg Manufacturing: S165/m^2

As a result, polymer-based devices require additional pairings to improve their performance, as the conductivity of the polymer is a critical factor [37]. PEDOT is one of the most effective and widely used polymers because of its high electrical conductivity when properly treated. It also possesses advantages such as low density, good environmental stability, and ease of fabrication [32]. One of the main challenges limiting the widespread use of PEDOT is its insolubility in water and most common solvents. To address this, the PEDOT:PSS solution typically contains 7% dimethyl sulfoxide (DMSO), which enhances its conductivity, along with 0.25% w/w Triton X-100, which is added as a surfactant to improve film formation and stability [38]. There are three main methods used to improve the PD performance of lead polymers: substance abuse and drug treatment, posttreatment and crystallization. The dopants and dopant concentration play a major role in improving the overall properties of the thermoelectric materials. It has a major effect on the Seebeck coefficient of conductive polymers [39-41]. Many substances can be used as dopants, such as dimethyl sulfoxide (DMSO) [42], tetrahydrofuran (THF) [43] and KOH[44] . Electrical conductivity is established after substance abuse with the appropriate drug. Doping not only improves the electronic properties of thermoelectric materials but also enhances the flexibility of conductive polymers several times, generally because the drug is used for refurbishment. Bubnova et al. [45] used a ZT value of 0.25 with PEDOT-Tosylate. The conductivity of PEDOT:PSS increases to 1000 S/cm or more as various organic solvents are used [44]. The primary issue limiting the performance of TEs is the conductivity of the n-type polymer, which is significantly lower than that of the p-type polymer [46, 47]. Mathematically, the conductivity is defined as σ=qnμ (where n is the density and μ is the mobility of charge carriers), and n doping can be used to increase the electron density and improve the conductivity of conductive polymers. The use of dopants is an effective way to increase the charge carrier density in the majority of semiconductors. Unlike classical inorganic doped semiconductors, the doping of conjugated polymers by intermolecular charge transfer involves a redox chemical reaction between the polymer and dopant. Effective n-doping in TE polymers is achieved via electron transfer to the lowest unoccupied molecular orbital (LUMO) inside the polymer semiconductor. Along with electron transfer in n-type polymers, a hydride (H^-) or an anion may also be transferred to apprehend the doping [47]. The n-doping process in conducting polymers gives rise to two kinds of charge carriers, polarons and bipolarons. Polarons (radical anions) and bipolarons (dianions) are both quasiparticles and have charges associated with lattice distortion. Lattice distortion is a chemical process and can be understood as an emerging quinoid structure richer in a planar structure. Lattice distortion results in downwards and upwards shifts in the lowest occupied molecular orbital (LUMO) level and highest occupied molecular orbital (HOMO) level, respectively. This localized orbital shifting results in a variation in the band gap of the material through doping with a change in the localized electronic states (polaron states). The few bipolar states are fully occupied states and lie farther than the valance-conduction band edges rather than the polaron states because of substantial phonon–electron coupling. All these phenomena are shown in Fig. 6.

4. Microscopic view of the thermoelectric effect

The study of the Seebeck coefficient (α) at the microscopic level provides the basis for understanding the thermal transport phenomena in thermoelectric devices in a nonequilibrium state. Electron diffusive transport, such as energy-dependent charge mobility in nanomaterials, may produce a large Seebeck effect, which is suppressed by the electronic specific heat and Seebeck coefficient in many thermoelectric materials at the low-temperature limit. The spin-dependent Seebeck effect (SdSE) results from the spin-dependent scattering of conduction electrons or spin fluctuations [48].

In many elementary models for homogeneous thermoelectric materials, the Seebeck coefficient is defined as “the average entropy per charge carrier weighted by the contribution of the carrier to conduction” and therefore relates conduction to the Seebeck coefficient. Notably, many d-electron-based magnetic materials exhibit strong SdSE capabilities throughout a wide range of temperatures, ranging from slightly below to considerably well above the ordering temperature, and exhibit ferromagnetic, weakly ferromagnetic, or antiferromagnetic transitions.

The thermal spin oscillations of delocalized d-electrons give rise to an extra Seebeck effect, denoted as αm, which is based on the thermodynamic spin degrees of

freedom, through the thermal spin oscillations of delocalized d-electrons.

Effective solid-state cooling is caused by the magneto-caloric effect, which is a thermodynamic property of the material where a change in field-induced spin entropy is achievable [49].

It has also been reported that the Seebeck coefficient strongly influences the order of microstructures. The main contribution is provided by the secondary Seebeck coefficients of phonons (S_{ph}), electrons (S_{el}) and electron–phonon interactions ($S_{el\text{-}ph}$) [50]. In metals or inorganic semiconductors, S_{ph} is superior to other secondary Seebeck coefficients in contributing S because of the mean free path [51].

In the majority of conjugated polymers, S_{ph} and $S_{el\text{-}ph}$ are ignored because of their perfect crystal structure and coupling of phonons with electrons. Thus, the Seebeck coefficient of the conjugated polymer is affected mainly by S_{el}.

5. TE materials in building applications

The Peltier effect has important implications for the cooling process required in household applications. The integration of such materials necessitates their importance in high-temperature regions worldwide. TE materials offer a promising solution for cooling by converting potential differences into temperature differences. Therefore, TE materials and solar panels can be coupled with buildings to convert external heat and solar energy (electric energy) to cool the interior of the building. This technology has additional benefits of inert cooling, as no gas will be utilized in the cooling process, in addition to reducing energy consumption [52]. TE materials are functional materials that facilitate the charge flow mechanism between the temperature gradient and reduce the degree of thermal collision between the carriers; the temperature decreases, and thus, a cooling mechanism is achieved.

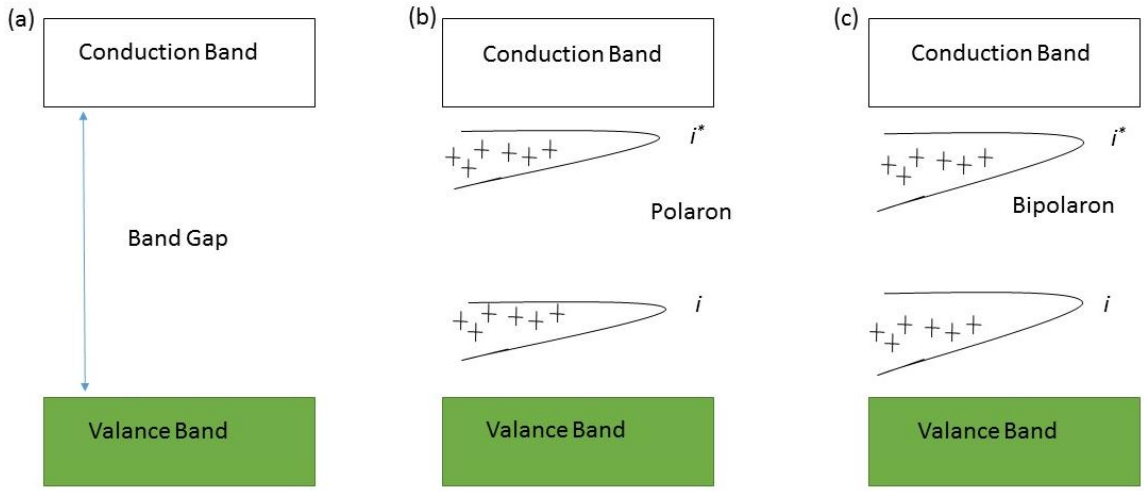

Figure 6. N-type doping of polymers: (a) neutral polymer; (b) polymer with polaronic states; (c) polymer with bipolaron states

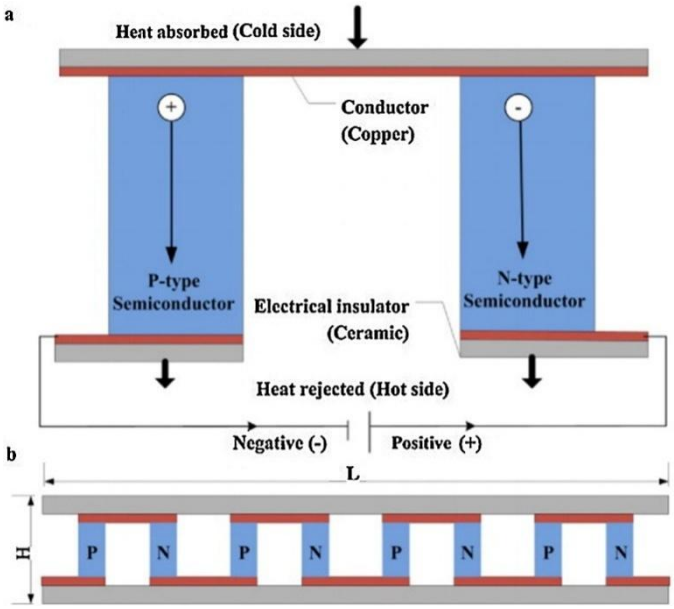

Figure 7. Schematic design of the TE modules. (a) Temperature and current gradient scheme (b) Integrated pn-junctions for a TE device. (Reprinted with the permission of Elsevier 2015)

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Table 2. Major bioenergy resources

Type	Availability	Management	References
Agriculture residues	Straw husk bagasse	Heat, syngas, biofuel, and electricity production	[57]
Forestry residues	Wood chips Sawdust leaves	Heat, biochar, syngas, and electricity production	[57]
Animal manure		Biochemical conversion	[58]
Household residues		Biofuel, heat	[59]
Energy crops		Biofuel, heat, syngas	[57]

TE modules consist of p-type and N-type semiconductor materials, as shown in Fig. 7(a) [53]. The flow of direct current in modules enhances thermoelectric cooling when integrated into buildings. Space cooling is accelerated by lowering the cold-side temperature, which facilitates heat absorption and rejection to the hot side, thereby increasing the temperature gradient. In this way, the temperature difference is effectively utilized for cooling purposes by maintaining the proper direction of current flow. An array of such PN junctions, as shown in Fig. 7(b), integrated into a device fully leverages the temperature gradient to achieve the desired space cooling performance. In solar thermoelectric cooling, electron gas is utilized for cooling purposes, exhibiting inert characteristics that minimize environmental and health risks. There is growing consideration that conventional domestic refrigeration systems could be replaced with solar thermoelectric cooling, which would not only reduce manufacturing costs but also lower the health hazards necessary for food storage. Although the efficiency of solar thermoelectric cooling is currently much lower than that of conventional refrigeration systems, ongoing research aims to optimize the technology for more effective and practical utilization [54]. Practical devices based on the principles of TE materials are called thermoelectric generators (TEGs). TEGs are multiple p-type and n-type materials interconnected electrically in series and thermally in parallel. For a particular temperature gradient between the two electrodes of the TEGs, a voltage signal is generated and produces electricity to drive a load. Thus, TEGs are very useful for harnessing the temperature gradient, thereby enabling heat collection from the environment [34].

5.1. Bioenergy systems

Biowaste production is increasing due to population growth, and biomass disposal has become a global environmental threat. Converting this biomass into a useful energy source represents a viable strategy that not only addresses disposal challenges but also makes a significant contribution to the circular economy. Bioenergy production has been recognized as a valuable alternative to conventional renewable energy sources because of its renewable nature and ability to reduce greenhouse gas emissions [55].

The feedstocks for bioenergy are waste products, lignocellulosic materials, and agricultural residues, including wood, crop waste, animal dung, animal fats, and grains, which can be used to create biofuels, including biodiesel, bioethanol, and biogas [56]. The appealing characteristic of bioenergy technology lies in its ability to manage waste via conversion to valuable products such as heat, electricity, and biofuels. This will enhance energy security, support rural economies, reduce dependence on fossil fuels and significantly reduce greenhouse gases. Table 2 summarizes the resource availability and benefits of bioenergy. The challenging task is conversion technologies with higher yields and low inputs. There are three broad conversion technologies, namely, thermochemical, biochemical, and physicochemical processes. In thermochemical technology, heat is utilized to activate combustion, producing heat and electricity to power the system. During combustion, gasification converts biomass into combustible synthesis under a limited oxygen supply to produce bio-oil, biochar and syngas as liquid fuel [60]. In biomedical conversion, anaerobic digestion converts biomass into biogas as biomethane for transport applications.

It uses fermentation processes that convert sugar and starches into bioethanol and other bioproducts. Selective and suitable feedstocks with low input energy requirements are of paramount importance in the transesterification process [61]. In physicochemical processes, physical separation is used for pure chemical transformation for the extraction of energy-rich components from biomass. This method of transformation is commonly used for pretreatment of the upgradation steps [62].

Despite their significant potential, bioenergy supply chains have complex environmental implications, including feedstock logistics, high initial costs, and public acceptance, requiring a holistic approach to sustainability. Given that climate challenges are high priority, greenhouse gas emission assessments across feed stock cultivation and processing are carried out on the basis of carbon neutrality demands.

Land evolution, including deforestation and agricultural displacement, poses risks to biodiversity loss and land degradation, and the depletion of water resources necessitates mitigation strategies to prevent ecosystem harm. Overall, bioenergy systems represent a versatile and mature renewable energy option that can play a key role in achieving sustainable energy and climate goals when

appropriately integrated into broader energy systems [57, 63].

5.2. Photovoltaic systems

Solar energy is an important renewable source, and photovoltaic (PV) technology is the only promising approach for converting sunlight into electricity. Scientists are aiming to increase solar cell efficiency while reducing fabrication costs to meet growing energy demands.

Over the past decade, photovoltaic research has shifted toward more advanced hybrid configurations with novel material systems, including quantum dot-based photovoltaics and tandem and perovskite-based materials. These advanced PV technologies not only exhibit relatively high-power conversion efficiencies (PCEs) but also have the potential for low manufacturing costs. Despite recent advancements in the PV market, commercial silicon solar cells continue to play a leading role because of their excellent stability and long life. However, the efficiency of solar cells is constrained by the Shockley–Queisser limit, and to exceed this limit, multijunction or tandem solar cells are employed, but they are still in the experimental stage [64]. In parallel, significant efforts are ongoing to increase the efficiency of solar cells in ongoing single-junction conventional solar cells. In this context, perovskite solar cells have emerged as very promising candidates, exhibiting outstanding output characteristics.

Perovskite solar cell technology is an emerging technology with exceptional power conversion efficiencies ranging from 3.8% to 26.8% from 2009--2025. This exceptional growth in efficiency holds promise for perovskite as a next-generation solar cell technology. In addition to their rapid improvement in efficiency, perovskite solar cells exhibit strong light absorption, high charge–carrier mobility, low fabrication cost and ease of fabrication, and improved operational lifetimes, making them highly efficient for converting sunlight into electricity. Typically, low-cost, one-step, nonvacuum fabrication techniques are employed, where perovskite precursor solutions are deposited via spin-coating followed by low-temperature annealing (100–250°C) to achieve phase-pure perovskite thin films. Extensive research has been conducted over the past decade toward achieving stable perovskite solar cells aligned with the United Nations Sustainable Development Goals (UN SDGs). In particular, UN SDG-7 emphasizes ensuring affordable, reliable, clean, renewable, and sustainable energy access for all. Continued advancements in perovskite solar cell research are expected to promote renewable energy culture by providing green energy for human needs and technological development, thereby mitigating climate change and reducing greenhouse gas emissions. Research on perovskites is just a decade old, and they have become competitive partners with already established technologies. They consume very low-cost materials; therefore, perovskite solar cells will be very competitive in the near future [64]. Owing to their high absorption, tunable bandgaps, and low cost of synthesis via solutions, perovskites have emerged as milestones in solar-cell research. The efficiency of single-junction perovskite cells has improved by ~3.5% to ~25% in only a decade. The perovskite materials have many benefits, including high electron mobility (~800 cm^2/Vs), high carrier diffusion length (>1 μm), and high absorption coefficient (~10^5 cm^{-1}). These characteristics enable light to be captured efficiently while producing significant current densities [64]. Perovskite sources have a versatile structure so that various elements can be incorporated without affecting performance. The energy bandgap of these materials is easily tuned by this flexibility. Stability over a long period of time and resistance to moisture or heat are still problems. Researchers are focusing on passivation and additive engineering to increase the stability of perovskite solar cells [65, 66]. Perovskites are highly competitive materials that have emerged only within the last decade; however, they have exceptional properties. The rapid development of perovskite research led scientists to make early commercialization of these devices. However, their degradation and long-term stability have hindered their commercialization. The key solar cell parameters of perovskites are compared with those of other solar cell technologies in Table 3. When the full radiation spectrum is converted to electrical energy, an efficient device that has the ability to withstand high temperatures is needed. The development of such devices has been long and steady, and the advent of perovskite materials has paved the way for the development of efficient devices for energy conversion. However, the long-term stability of perovskite materials remains one of the most critical challenges limiting their commercialization, despite their outstanding photovoltaic performance. Perovskite materials are inherently sensitive to moisture, oxygen, continuous light exposure, and harsh environmental conditions; thus, these materials can be used to stop perovskite absorbers from functioning commercially.

Table 3. Comparison of best results, PSC vs. other technologies

Solar cell	PSC ($MAPbI_3$) [67]	DSSC (HC/TiO_2) [68]	Si-PV (HBC) [69]
J_{sc}(mA/cm^2)	20.1	16.1	41.7
V_{oc} (V)	1.9	0.75	0.74
FF (%)	82.2	83	83.8
Efficiency (%)	30.9	30.2	26.6

Interfacial segregation further accelerates degradation and contributes to thermal and structural instability. To

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mitigate the degradation of perovskite absorbers, significant attention has been given to compositional engineering and interface modification. Although notable progress has been achieved through encapsulation of the absorber layer, this approach alone is insufficient for long-term stability. Therefore, in addition to efficiency enhancement, degradation remains a critical challenge, and without proper attention to stability issues, the commercialization of perovskite solar cells is unlikely.

Tandem solar cells employ multiple absorbers (each with a different bandgap) to absorb a broader spectrum of sunlight. As an example, a layer of perovskite together with silicon has the potential to absorb high-energy and low-energy photons, enabling efficiencies that are higher than those of single-junction cells [64]. All-perovskite tandems are also being developed. Recent applications have focused on defect passivation and accurate bandgap tuning. The efficiencies of these strategies are better than 25%, with high performance and enhanced long-term stability [65, 66].

Monolithic perovskite–silicon systems have laboratory-certified efficiencies$\sim 29-30\%$. The hybrid structure exploits the stability of silicon and the high absorption of perovskite, which results in outcomes that are greater than those of either of the other two technologies [64, 66]. Even new research is considering lead-free, triple-junction designs incorporating materials that are environmentally friendly, such as tin perovskites and kesterite absorbers. These designs are predicted to allow power conversion efficiencies to exceed 30% [70]. Table 4 compares different photovoltaic technologies in terms of their efficiency and key performance parameters.

Table 4. Comparison of different photovoltaic technologies

Technology	Materials/Structure	Recent Efficiency Record (%)	Key Advantages	Challenges	Reference
Silicon (c-Si) Single Junction	Crystalline silicon	$\sim 27-28\%$	Stable & established	Near efficiency limit	[64, 66]
Single-junction PSC	Metal halide Perovskite	~27.3%	Low cost & high absorption	Instability in moisture/heat	[64, 71]
Perovskite-Silicon Tandem	Perovskite + Silicon	$\sim 29-34.9\%$	Exceeds SQ limit	Interfacial recombination	[64, 66]
All-Perovskite Tandem	Dual Perovskite layers	$\geq 25.5\%$	Solution process-able	Material degradation	[65]
Lead-Free Triple Junction (Simulated)	Perovskite/kesterite	~30.7% (sim.)	Environmentally friendly	Requires optimization	[70]
Multijunction PV	III–V multijunction	>40%	Ultrahigh power conversion efficiency	Scalable fabrication complexity,	[72]

Table 5. Details about large-scale PSC modules produced by various firms or institute

Organization/Institute	Country	Achieved PCE (%)	Device Configuration & Fabrication Approach	Active/Module Area	Reference
Oxford Photovoltaics	UK	29.52	Bifacial perovskite–silicon tandem architecture	1 cm^2 (cell scale)	[64, 73]
Kaunas University of Technology	Lithuania	23.9	Spin-coated perovskite module	26 cm^2 (active area)	[74]
Saule Technologies	Poland	10.2	Flexible perovskite module via doctor-blade coating	15.7 cm^2	[73]
IMEC	Belgium	18.6	Large-area perovskite photovoltaic module	16 cm^2	[73]
NEDO & Panasonic	Japan	16.09	Inkjet-printed perovskite solar module	802 cm^2	[75]
Toshiba & NEDO	Japan	11.7	Crystal-growth-controlled perovskite module	703 cm^2	[64]
Solliance	Netherland	14.5	Slot-die coated perovskite cell	144 cm^2 (cell scale)	[76]
Chinese Academy of Sciences (CAS)	China	19.2	Slot-die processed perovskite module	16 cm^2	[77]
Microquanta Semiconductor	China	24.1	High-efficiency perovskite photovoltaic module	20 cm^2	[78]

Despite these benefits, several challenges still delay large-scale commercialization. Perovskite solar cells are stable only in darkness, are dry at room temperature, and in the absence of oxygen, their state-of-the-art laboratory-scale production techniques are not yet mass reproducible, as depicted in Table 5. Subsequent research should focus on enhancing long-term stability, developing scalable fabrication methods, investigating lead-free perovskites, and developing tandem and multijunction designs. The efficiencies of perovskite silicon tandem cells are already close to 30%, which highlights their high potential in next-generation, high-performance solar systems [64, 66].

6. Green hydrogen and energy integration strategies

The green energy sector is under tremendous stress to fulfil world energy requirements. This transition is needed as the world population is expanding exponentially with high energy demand[79]. Conventional energy resources are associated with high carbon emissions and significantly contribute to greenhouse gas emissions, resulting in negative impacts on the globe [80]. Most conventional energy resources are perfect with no intermittence and can be consumed in any application. However, the toxic effect of conventional resources is very high and therefore must be replaced with advanced renewable technology. The existing renewable energy technologies are abundant and cost effective but are intermittent. They need a specific storage mechanism that can store abundant renewable energy to avoid intermittence [81]. Hydrogen is an effective storage medium and is considered one of the most promising options among available storage technologies because of its high energy density and relative ease of energy conversion processes[82]. The energy in hydrogen is stored in its chemical bonds and is released as solar fuel when needed. During the consumption of hydrogen as a fuel, the only byproduct is water, which makes hydrogen very attractive for transportation and industrial processes because of its decarbonization potential. Among production technologies, the solar-driven hydrogen production method is highly effective because of its water splitting chemistry and low power consumption [83-86]. Additionally, hydrogen can be stored via different processes, including compression, liquification, or chemical bonding, and can be stored for a prolonged period of time, bridging the gap between intermittent renewable energies. Hydrogen storage materials are potentially viable solutions for standing at high pressure while offering high capacity, good cyclic stability, and cost effectiveness. However, hydrogen is highly flammable and must be stored under strict safety conditions [87] [88]. Table 6 provides a comparative overview of different storage methods in terms of capacity, energy density, consumption, safety, cost and difficulties, whereas Fig. 8 (a & b) present various hydrogen storage technologies, their densities, and their accessibility. The basic requirements for the use of hydrogen as renewable energy are its operating conditions, high gravimetric storage and efficient consumption. For balanced operating conditions, metal hydrides (MgH_2 [92], $LaNi_5H_6$ [93], and $TiFeH_2$ [94-96]), carbon-based materials, and MOFs [88] offer different balancing conditions, whereas complex hydrides such as $LiBH_4$, $NaBH_4$, and $NaAlH_4$ have high gravimetric storage, thereby requiring high temperatures and catalysts [97-99].

Table 6. Comparison of various hydrogen storage technologies

Technology	Storage capacity kg H_2/m^3	Energy density (kWh/kg)	Energy Consumption (kWh/kg)	Safety (pressure, temperature	Advantages	Challanges	Citation
Compressed gas	~ 20–40	~ 33	10 – 15	350–700 bar	Well established, technology	Low volumetric density, requires high pressure	[83]
Liquefied hydrogen	~ 71	~ 40	12 – 20 (liquefaction	–253°C storage	High storage density	High energy consumption for liquefaction	[85]
Metal hydrides	~ 100 – 150	~7 – 15	5 – 10 (Thermal cycling)	~10 bar, 300°C	High volumetric storage,	Heavy, slow release kinetics	[89]
MOFs	~ 30 – 60	~ 33	5 – 8 Adsorption/desorption	Low pressure operation	Tunable storage properties,	Expensive materials, low energy density	[90]
Chemical storage (Complex hydrides)	~ 85 – 150	~ 5 – 10	6 – 12 dehydrogenation	~1–10 bar, 100–200°C	High hydrogen content	Complex handling,	[91]

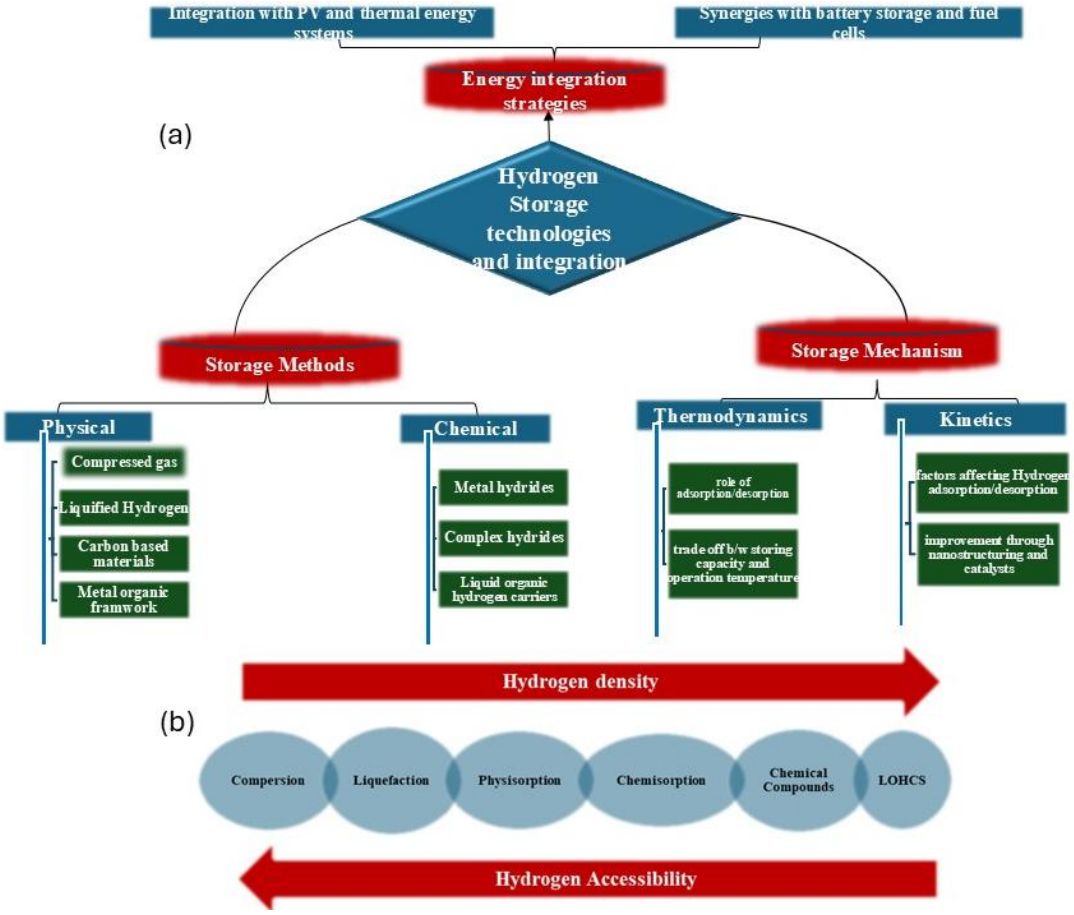

Figure 8. Schematic representation of **(a)** hydrogen storage and integration technologies and **(b)** the density and accessibility of stored hydrogen

Other hydrogen storage options, such as liquid organic hydrogen carriers (LOHCs) and synthetic fuels (e-fuels), offer alternative solutions in combination with nanostructuring and thermal management and support effective integration with hybrid photovoltaic systems for hydrogen generation [88].

However, there are various challenges to the widespread implementation of solar hydrogen, specifically, poor conversion efficiency, expensive production, issues with material durability, and the requirement for improved, earth-abundant catalytic systems [100]. Owing to the intermittency of solar energy, effective storage solutions are essential to ensure hydrogen generation through green methods. Continued efforts in catalyst design, reactor engineering, and combination with renewable infrastructure are rendering solar hydrogen systems increasingly feasible and scalable [101].

Hybrid solar–hydrogen systems that integrate highly efficient photovoltaic (PV) systems, solar thermal techniques, and advanced hydrogen storage materials for highly efficient renewable energy utilization and grid stability[102]. In such systems, the electricity generated by PVs is used to operate an electrolyzer for hydrogen generation, and the intermittent output of the sun is compensated by hydrogen storage[103]. The overall efficiency of the system depends on the PV conversion rate, performance of the electrolyzer and ability of the storage material to reversibly store hydrogen under practical conditions.

Highly efficient PV modules and advanced storage systems enable hydrogen generation, reduce energy losses and enhance the operational reliability of solar-driven hydrogen technologies. The integration of photovoltaic energy with solar-thermal hydrogen production, such as thermochemical cycles, requires energy optimization for commercialization.

Dual-use collectors, which generate electricity and thermal power at the same time, are a potentially promising solution. An emerging approach involves dual-use solar collectors capable of simultaneously producing electricity and thermal energy for hydrogen generation, necessitating advanced thermal management and heat storage solutions to maintain continuous operation during low solar periods [104, 105].

Electrical storage, such as batteries and supercapacitors, stores excess PV-generated electricity to sustain electrolysis under reduced solar input or at night [106], while stored hydrogen can be converted back to electricity during peak hours or in the absence of solar energy. These hybrid configurations enable effective energy shifting, enhance grid stability, and reduce dependence on fossil-fuel-based backup power systems [107].

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7. Conclusion

In this study, materials for green energy have been identified and reviewed. Two aspects of green energy materials were focused, namely, thermoelectric and photovoltaics. In thermoelectric, the operational principles of thermoelectric generators, the Seebeck and peltier effect, and microscopic thermoelectric materials were focused. In particular, the cooling features of thermoelectric materials coupled with buildings and integrated with the photovoltaic energy was highlighted. It is expected that TE based cooling will replace the existing environmentally hazard conventional refrigeration system and more research will be needed for the optimization of TE based materials. The 2nd part of the review is based on bioenergy generation, hydrogen, and integration of PV modules in advanced renewable energy technologies keeping in view the global transition toward a sustainable energy system. The emerging trends in PV energy systems are perovskites with exponential growth in the last decade. Besides remarkable efficiency growth, environmental stability challenges still existing which hinders them for commercialization. The intermittence of renewable energies can be enabled with hydrogen storage technologies through high gravimetric energy density which offers a low-carbon energy infrastructure.

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