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Future directions and emerging trends of sustainable energy harvesting: innovations in photovoltaic and thermoelectric systems

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This review seeks to present a comprehensive overview of recent advancements in sustainable energy harvesting technologies, with a focus on photovoltaic (PV), and thermoelectric (TE) systems. It examines the evolution of next-generation PV technologies, such as perovskite and tandem solar cells, which demonstrate remarkable potential for high-efficiency, low-cost energy conversion. In parallel, it explores progress in TE materials, including nanostructured and organic compounds, that have led to enhanced thermoelectric performance and broadened application prospects. The review discusses key challenges related to the scalability, stability, and integration of these systems. Furthermore, it highlights the synergies of combining PV and TE technologies to enhance overall energy-harvesting efficiency. The review concludes by identifying emerging trends and proposing strategic directions for future research to accelerate the development and commercialization of sustainable energy harvesting solutions.

1. Introduction

The escalating environmental challenges and the limited availability of fossil fuels have made the advancement of sustainable energy-harvesting technologies a critical priority for researchers and engineers worldwide.[1] Sustainable energy harvesting involves capturing and converting renewable energy sources into usable electrical power in an environmentally responsible manner. Among the various technologies developed for this purpose, photovoltaic (PV) and thermoelectric (TE) systems stand out due to their potential to provide clean, renewable energy.[2–5] Growing environmental pressures and the limited availability of natural resources have intensified research into renewable energy technologies. Among these technologies, solar PV systems, which directly convert sunlight into electricity, have emerged as a leading solution and sustainable power generation.

Recent advances in PV technology, particularly in perovskite solar cells (PSCs), have led to notable improvements in efficiency while simultaneously lowering manufacture costs compared to conservative silicon based cells.[6] These advances have influenced renewable energy policies by encouraging investment and accelerating adoption due to easier manufacturing and higher performance. However, issues such as long-term stability and degradation from moisture, heat, and UV exposure remain unresolved. Additionally, concerns remain about the environmental footprint of PV production, particularly due to reliance on toxic or scarce materials (*e.g.*, lead, silver) and challenges with panel disposal and recycling.[7] TE systems offer complementary benefits by converting industrial waste heat into electricity. Recent improvements in TE materials with higher figures of merit (ZT) have enhanced energy conversion potential.[8] Nevertheless, TE systems still face limitations due to relatively low efficiencies and high material costs, which hinder large-scale deployment. The continued development of PV and TE technologies relies on ongoing advancements in materials and scalable manufacturing techniques to enhance both performance and cost-effectiveness.[9]

Compare the energy conversion efficiencies of PV and TE systems. For example, (PV) systems can achieve power conversion efficiencies of up to 20–25%,[10] TE systems typically exhibit relatively low conversion efficiencies of approximately 5–10% when operating with a hot-side temperature of ~500–800 K and a near-room-temperature cold side.[11] Assess the power density of both systems, considering factors like the area required to generate a given amount of power. Compare the optimal operating conditions for each system. PV systems require sunlight, while TE systems rely on a temperature gradient.[12] The wide range of applications for PV, from small-scale residential

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installations to large-scale solar farms. The applications of TE systems, such as in automotive exhaust heat recovery and remote power generation for sensors. The need for materials with higher efficiency and stability in both PV and TE systems.[13]

This review aims to systematically examine recent advancements in PV and TE technologies, with a particular emphasis on material innovations, performance optimization, and integration strategies.[14] A key novelty of this work lies in its dual focus, it not only provides a comparative analysis of progress in both PV and TE systems but also explores their potential synergy in hybrid configurations for enhanced energy harvesting. By bridging insights from both domains, this review provides a comprehensive perspective that can inform future research and guide the advancement of more efficient and scalable sustainable energy technologies.[15] Fig. 1 illustrates the progression of conventional and emerging PV and TE systems, PV system (*e.g.*, silicon based, perovskite and tandem solar cells) and TE materials (*e.g.*, nanostructured and inorganic) for energy harvesting technology. It also highlights the hybrid of PV and TE systems for enhanced energy conversion efficiency, along with key challenges and advantages for advanced applications.

1.1 Overview of sustainable energy harvesting technologies

Sustainable energy harvesting is the capture, conversion, and utilization of green energy in an environmentally friendly mode while ensuring a sustainable energy supply.[16,17] With global energy demands on the rise, the advancement of high-performance, cost-effective, and the sustainable energy technologies has become increasingly essential.[18–20] Consequently, a large portion of the incident energy is lost as heat. The performance of PV devices declines as temperature increases. Therefore, utilizing this generated and unexploited heat enhances the performance of PV cells.[21–23] Sustainable energy harvesting using PV and TE systems represents a crucial pillar in the global transition toward renewable energy.[24,25] With continuous innovations, these technologies are poised to play an increasingly vital role in meeting future energy demands while minimizing environmental impacts. Numerous research conducted in recent years has demonstrated that energy can be extracted from the sun and high temperatures,[26] adding value to alternative energy sources, enhancing the urban environment, and lowering the frequency of pollutants. Energy harvesting technologies provide a promising approach to decrease or eliminate the power requirements of electronic devices. However, their full environmental benefits can only be achieved if the materials and manufacturing processes employed are also sustainable. Material selection is critical to influencing the efficiency, longevity, and ecological footprint of energy-harvesting devices. Conventional energy harvesting systems often use materials that are non-renewable, toxic, or difficult to recycle, raising long-term environmental concerns. To overcome these challenges, researchers are investigating alternative materials that maintain energy-harvesting performance while minimizing environmental impact, as shown in Fig. 2a. Energy harvesting in roadways and vehicles is considered through various sources. For roadways, the main types are solar, piezoelectric, and geothermal energy, all of which can be converted into electrical power. Solar energy, in particular, can be harnessed using photovoltaic cells, solar collectors, and thermoelectric generators. In vehicles, the primary sources are electromagnetic, triboelectric, and piezoelectric energy, which

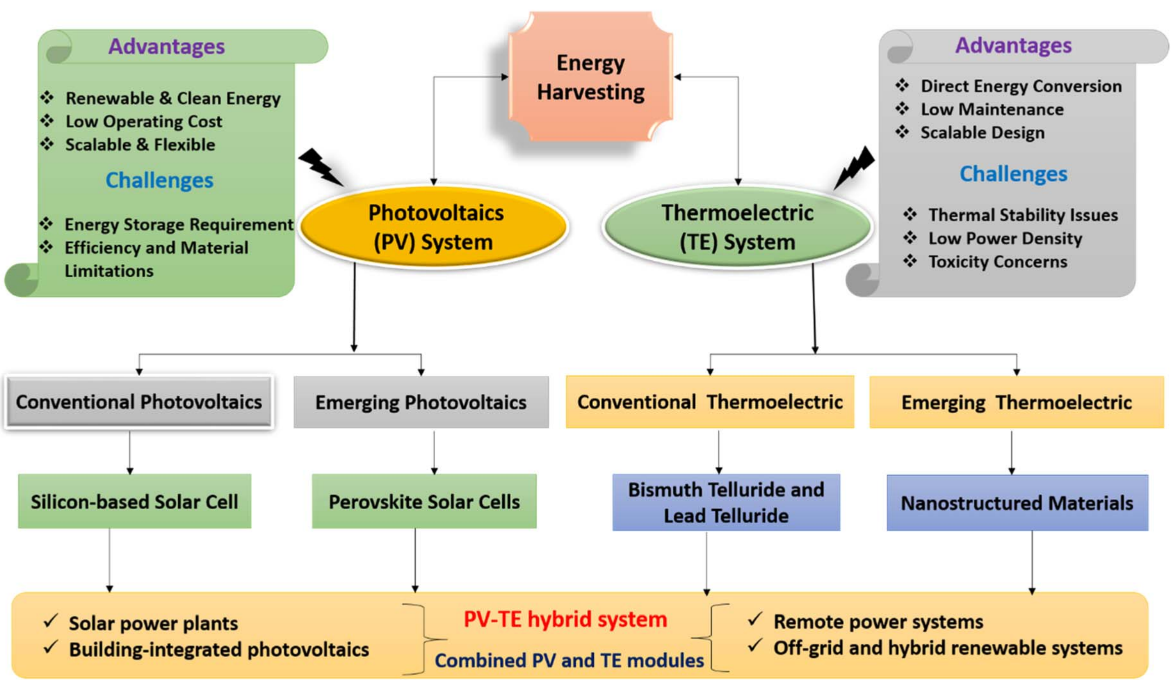

Fig. 1 Schematic representation of advancements and integration strategies in sustainable energy harvesting systems.

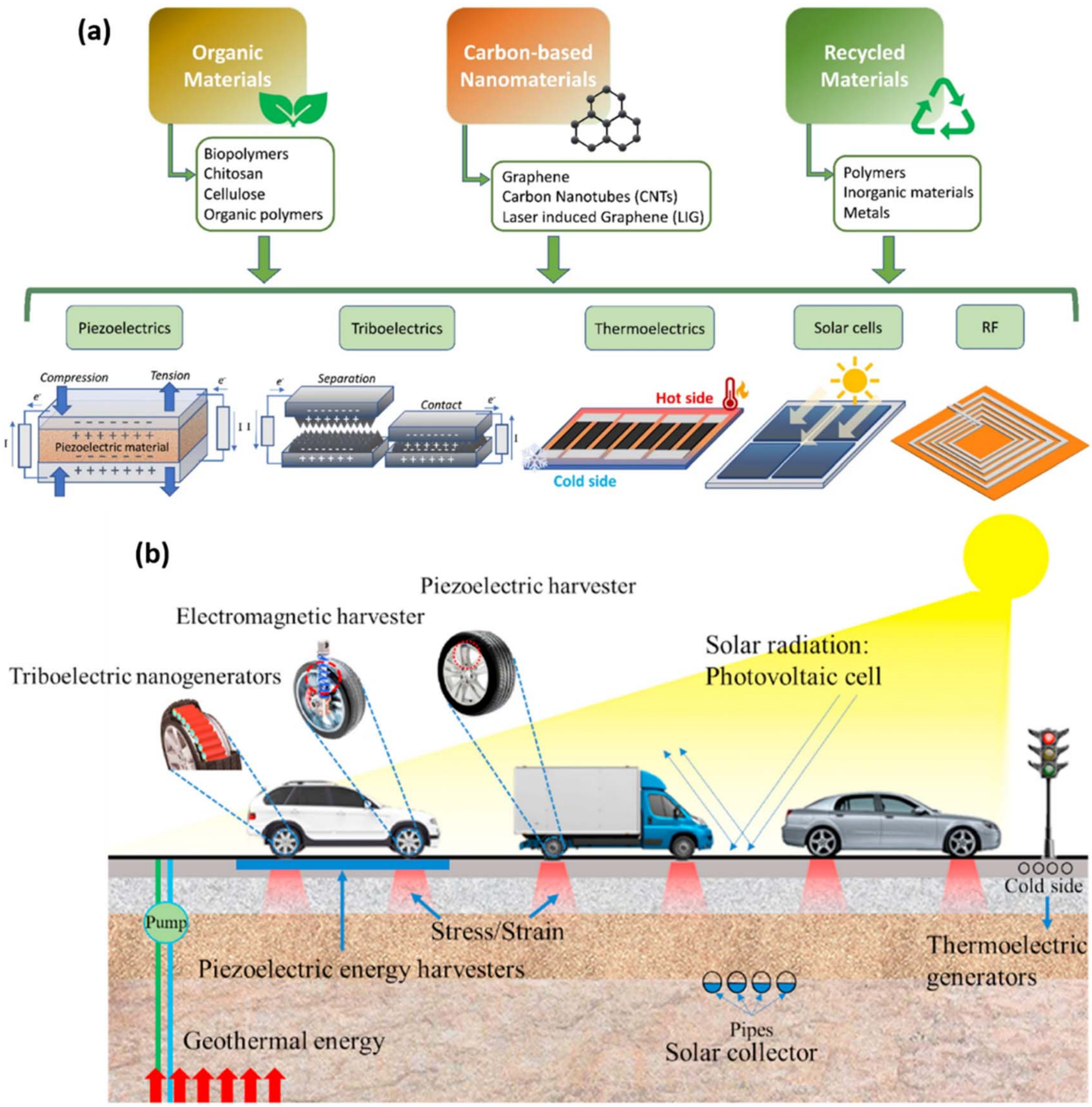

Fig. 2 (a) Sustainable materials for energy harvesting and their application on devices, this figure has been reproduced from ref. 27 with permission from Springer, Copyright 2025. (b) Energy harvesting technologies, this figure has been reproduced from ref. 28 with permission from Elsevier, Copyright 2021.

can also be transformed into electricity. An overview of these energy harvesting approaches is shown in Fig. 2b.

1.2 Importance of photovoltaics and thermoelectric energy harvesting systems

PV and TE systems are essential components of the sustainable energy landscape.[29] PV systems harness the power of the sun, providing a clean, renewable source of electricity, while TE systems offer innovative solutions for waste heat recovery and energy efficiency.[30,31] The synergistic interaction between PV and TE systems arises from their complementary mechanisms of energy harvesting, enabling hybrid systems to utilize both the photon and thermal components of solar energy for higher overall efficiency.[32] PV cells convert sunlight into electricity, while TE modules leverage the heat generated by PV systems to produce additional power through the Seebeck effect. This dual approach not only enhances energy conversion but also provides thermal management, maintaining PV cells at optimal operating temperatures and mitigating heat-induced efficiency losses. TE components further influence charge carrier dynamics within PV cells, reducing recombination losses and improving open-circuit voltage.[33]

The incorporation of solar selective absorbers (SSA) enhances thermal capture for the TE modules while ensuring sufficient light transmission to the PV cells, improving overall efficiency.[34] Nanostructured composites and bismuth telluride are key to enhancing TE performance through a high Seebeck coefficient combine with low thermal-conductivity, whereas higher temperature resistant PV materials, such as perovskites, enable long-term and stable operation.[35] Effective system design, including techniques like phase-change materials and heat spreaders, optimizes temperature gradients and enhances thermal management. Compact, modular configurations allow for scalability and easy customization, enabling applications from residential installations to large solar farms.[36]

1.3 Techno-economic feasibility analysis

The techno-economic feasibility of sustainable energy harvesting systems, particularly hybrid PV and TE systems, has been significant development. Recent studies have shown that hybrid systems may offer cost effective and efficient solutions for various applications. For example, a hybrid solar-hydrogen systems (HSHSs) have demonstrated their potential to contribute to be cleaner and more buoyant energy prospect by optimizing system performance and lowering costs.[37] The hybrid energy system for rural electrification in Somalia found that integrating PV.[38,39] These results highlight the economic viability of hybrid systems in providing sustainable energy solutions.

1.4 Life cycle impacts and environmental assessment

The life-cycle impacts of sustainable energy-harvesting systems are also crucial for assessing their overall environmental sustainability. A comprehensive life cycle assessment (LCA) of hybrid systems demonstrates substantial reductions in atmospheric emissions of greenhouse gases and other environmental influences relative towards conventional energy sources.[39] Moreover, the use of environmentally benign materials combined with energy-efficient components strengthens the sustainability of these systems throughout their entire life cycle.

1.5 Industrial adoption trends and applications

The adoption of sustainable energy-harvesting technologies is gaining momentum across industries. The growth includes the proliferation of IoT devices, promoting green energy, and advancements in low-power electronics. Industries such as smart infrastructure, medical and wearable technology, and industrial automation are leading the adoption of energy harvesting solutions.[40] For instance, smart infrastructure is increasingly harnessing ambient energy to power lighting, HVAC systems, and traffic management networks, while wearable medical devices are leveraging body heat to provide continuous operation without recharging.[41]

2. Overview of photovoltaic systems

PV technology uses semiconductors, such as silicon, to absorb sunlight and generate electricity *via* the photovoltaic effect. Advances include thin-film, perovskite, and tandem solar cells, which improve efficiency and reduce costs. PV technology is key to sustainable energy, powering applications from rooftops to large solar farms.

2.1 Thin-film solar cell

CdTe is a vastly efficient thin film photovoltaic material with large optical absorption coefficient, allowing for thin layers to be used while still capturing a significant amount of sunlight.[42] CdTe photovoltaics' relatively simple manufacturing process compared to other thin-film technologies and its lower manufacturing cost are advantages. Cadmium's toxicity, however, is a very serious problem and thus proper handling and disposal must be ensured to minimize environmental and health effects. The CdTe PV cell efficiency can also be controlled extensively by defects and impurities within the material.[43]

The CIGS has a high absorption coefficient and can be deposited on flexible substrates, this enables applicability across a broad spectrum of uses, particularly for applications including BIPV and portable electronics.[44] Its bandgap can be tuned by varying the composition, allowing for optimization of performance in different light conditions.[45] The complexity of the deposition process and the need for high vacuum conditions can increase manufacturing costs. The scarcity and expense of critical raw materials, including indium and gallium, can restrict scalability and increase production costs. Organic photovoltaics are lightweight and can be made flexible, which opens opportunities for integration into various products and structures. They can be fabricated using low-cost solution processing techniques, potentially reducing production costs.[46] Additionally, the bandgap of organic materials can be tuned through chemical synthesis to optimize performance for specific applications. The efficiency of OPVs is generally lower than that of inorganic PV technologies. They also tend to have shorter lifetimes due to degradation of the organic materials under prolonged exposure to sunlight and environmental conditions.[47]

2.2 Perovskite solar cell

PSCs are a category of photovoltaic devices that utilize a perovskite-structured material, commonly a hybrid organic–inorganic lead or tin halide, as light-absorbing active layer,[48] They have been of great interest in PV technology due to the fact that they exhibit high efficiency and low cost of production.[49,50] Astonishingly, PSCs have attained power conversion efficiencies (PCEs) over 25%, rivalling traditional silicon-based solar cells. Low-cost production, the materials and processes used to manufacture PSCs are generally less expensive than those for conventional silicon solar cells.[51] Flexibility, PSCs can be fabricated on flexible substrates, allowing for a variety of applications beyond traditional rigid panels.[52,53]

The bandgap of perovskite materials can be tuned by modifying their composition, making them well-suited for tandem solar cells and other applications that require specific absorption properties.[54,55] Stability, PSCs are disposed to degradation from moisture, heat, and ultraviolet light, which affects their long-term stability. The usage of lead in many high-efficiency perovskite materials poses environmental and health risks. While laboratory-scale efficiencies are high, scaling up the production process to industrial levels while maintaining performance remains a challenge.[56] PSCs have emerged as prominent candidates for third-generation PV technologies, garnering considerable research attention owing to their exceptional optoelectronic characteristics and cost-effective solution-based fabrication.[57] Over the past decade,

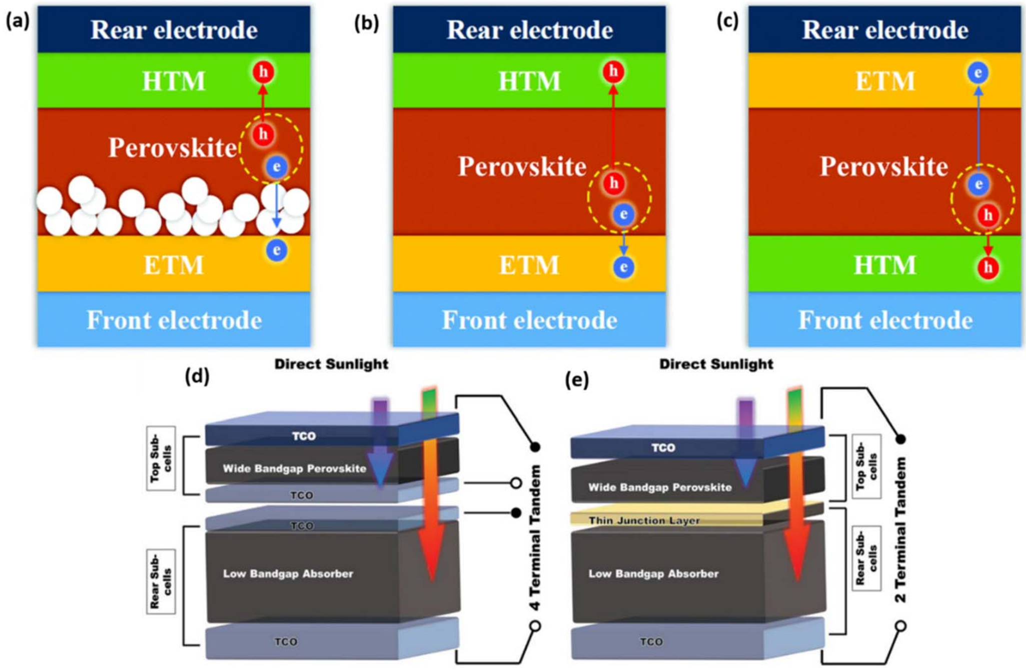

Fig. 3 The standard perovskite solar cell comes in three different device configurations: (a) mesoporous regular PSC structure, (b) planar regular PSC structure, and (c) planar inverted PSC structure. This figure has been reproduced from ref. 65 with permission from Royal Society of Chemistry, Copyright 2020. (d and e) A schematic illustration of 2T (two-terminal) and 4T (four-terminal) tandem solar cells typically highlights the structural differences between the two configurations. This figure has been reproduced from ref. 66 with permission from Wiley, Copyright 2020.

collaborative efforts have elevated the certified power conversion efficiency (PCE) of PSCs to 25.2%. PSCs are generally categorized into regular (n–i–p) and inverted (p–i–n) architectures. Regular PSCs can be further divided into mesoporous in Fig. 3a and planar in Fig. 3b configurations, depending on whether a mesoporous scaffold is employed. In these devices, n-type and p-type semiconductors serve as the front and rear charge transport materials (CTMs), respectively. In contrast, inverted PSCs (IPSCs) show a reversed device structure and charge transportation, as shown in Fig. 3c.

2.3 Tandem solar cells

Tandem solar cells (TSCs) are advanced PV cells engineered to outperform conventional single-junction solar cells by layering (or stacking) junctions of different semiconductor materials.[58–60] The layers trap a larger portion of the solar spectrum, making the entire system more efficient. Single-junction solar cells have a theoretical efficiency ceiling of about 33%, as described by the Shockley–Queisser limit.[61] TSCs aim to exceed this limit by using multiple junctions. Monolithic 2T TSCs, these are tandem solar cells with two terminals.[62] The cells are stacked in a single structure, sharing the same substrate, which leads to a more compact design but can be challenging to fabricate due to the need for precise matching of current through each layer. Mechanically Stacked 4T TSCs, these TSCs have four terminals and are made by stacking two separate solar cells mechanically. Each cell operates independently, which allows for more flexibility in material selection and optimization but can result in a bulkier and more complex assembly.[63] While TSCs have demonstrated the potential to break the SQ limit, the primary challenge remains in cost-effectively constructing these cells.[63,64] The development are focused on improving fabrication techniques, material stability, and overall efficiency to make TSCs viable for widespread commercial use. Despite the potential for tandem devices to surpass the Shockley–Queisser (SQ) limit, a significant challenge lies in developing a cost-effective tandem configuration. Fig. 3d and e illustrates the two primary tandem configurations: monolithic 2-terminal (2T) TSCs and mechanically stacked 4-terminal (4T) TSCs.

2.4 Development in technology

The development of novel hole and electron transport materials (HTMs and ETMs) has improved charge extraction and reduced recombination losses.[67] Passivation techniques have been applied to minimize surface defects and improve the performance of perovskite films. Innovations in stacking different semiconductor materials, such as perovskite-silicon tandems, have led to significant efficiency gains by enabling the use of a broader spectrum of sunlight. Techniques for passivating the surface of quantum dots have reduced non-radiative recombination and improved efficiency. Integrating quantum dots with perovskites has led to hybrid solar cells with superior light absorption and charge separation.[68–70] Combining quantum dots with organic semiconductors has resulted in flexible and lightweight solar cells with good efficiency.[71–73]

On TiO_2-coated FTO glass, layers of ZrO_2, nanoporous TiO_2, and a carbon black/graphite electrode were sequentially

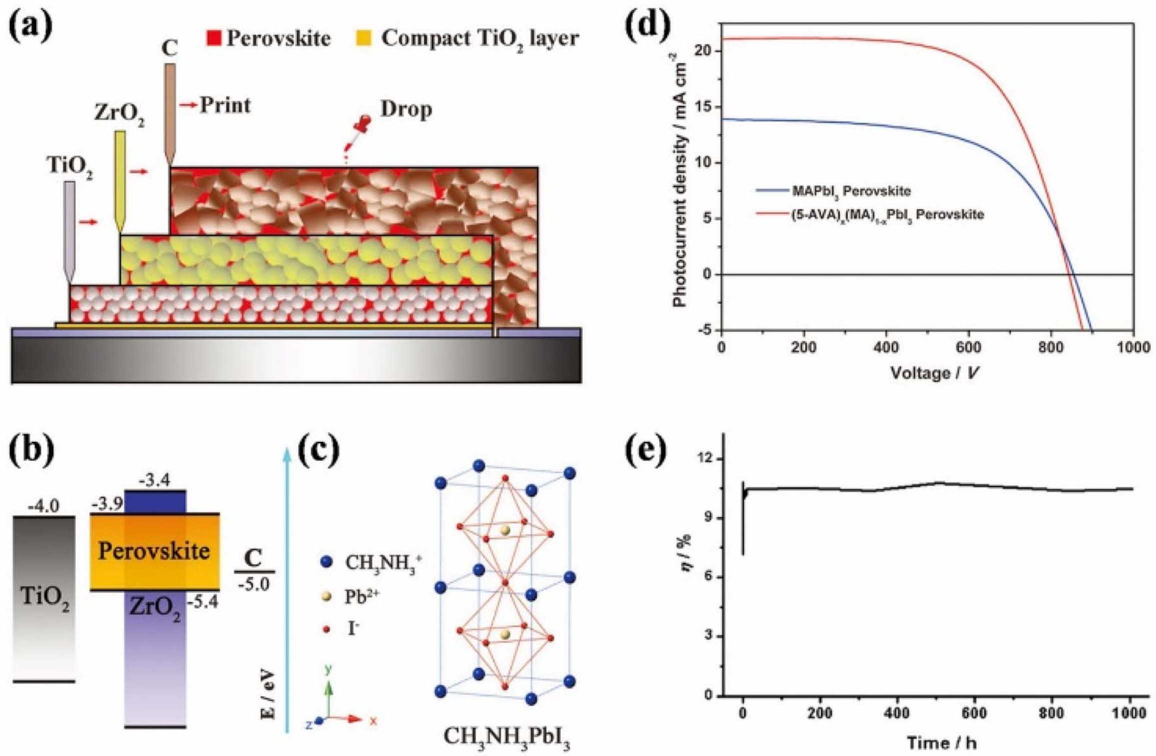

Fig. 4 (a) Fully printable mesoscopic perovskite solar cells, (b) schematic of the device's energy band structure, (c) crystal structure of $CH_3NH_3PbI_3$, (d) current–voltage (J–V) curves of the printable solar cells, and (e) stability assessment of a $(5\text{-}AVA)_x(MA)_{1-x}PbI_3$ solar cell. This figure has been reproduced from ref. 74 with permission from Willey, Copyright 2016.

deposited. The electrode was then treated with a perovskite precursor solution, which infiltrated the carbon layer and reached the underlying TiO_2 and ZrO_2 layers, as shown in Fig. 4a and b. The subsequent heat treatment completed the device fabrication. The ZrO_2 layer served as a spacer, preventing direct contact between the TiO_2 and the carbon electrode. $MAPbI_3$-based devices exhibited a power conversion efficiency (PCE) of 7.2%. By introducing 5-ammoniumvaleric acid (5-AVA) iodide into $MAPbI_3$ to form a mixed-cation perovskite, $(5\text{-}AVA)_x(MA)_{1-x}$ PbI_3, the PCE increased to 11.6%, with a certified value of 12.8% Fig. 4c and d. The NH_3^+ groups of 5-AVA act as nucleation sites, promoting charge transfer between TiO_2 and the perovskite, while the –COOH groups bind to the surfaces of the mesoporous TiO_2 and ZrO_2 layers. The cells demonstrated stable PCE after more than 1000 hours of air-based operation under 1-sun illumination in Fig. 4e. In addition, placing a self-assembled monolayer of silane between $CH_3NH_3PbI_3$ and TiO_2 improved interfacial properties and overall device performance. Device performance was improved through investigation of the size of TiO_2 nanoparticles as well as the composition of the carbon electrode.

3. Overview of thermoelectric systems

TE technology converts heat directly into electricity using the Seebeck effect, or uses electricity for cooling *via* the Peltier effect. It relies on materials with high electrical conductivity but low thermal conductivity, such as bismuth telluride (Bi_2Te_3) or skutterudites. TE devices are used for waste heat recovery, remote power generation, and solid-state cooling applications. TE energy conversion directly transforms heat into electrical energy through the TE effect. This effect leverages the properties of certain materials that produced an electrical voltage when subjected towards temperature gradient. TE devices are solid-state devices with no moving parts, making them reliable and maintenance-free for various applications, including waste heat recovery and cooling.[75] TE energy harvesting operates oppositely to TE refrigeration and has been the subject of extensive research in recent decades.[76,77]

Since the discovery of the Seebeck and Peltier effects, doped semiconductor materials have been used to get more electrical conductivity with less thermal conductivity, thereby in search of a larger figure of merit. Fig. 5a and b illustrate a generic two-terminal Seebeck TE energy harvester in folded and unfolded configurations, respectively. The arrangement in Fig. 5a resembles a p–n junction in solar cells; however, the central metallic contacts remove the junction barrier, allowing elastic TE transport. Fig. 5b emphasizes both the structural similarities and differences between a solar cell and a TE engine, though the reason for the substantial disparity in efficiency solar cells being far more efficient remains unclear. Recent studies indicate that, compared to conventional two-terminal TE devices made from the same material, a p–n junction TE engine that leverages hot-

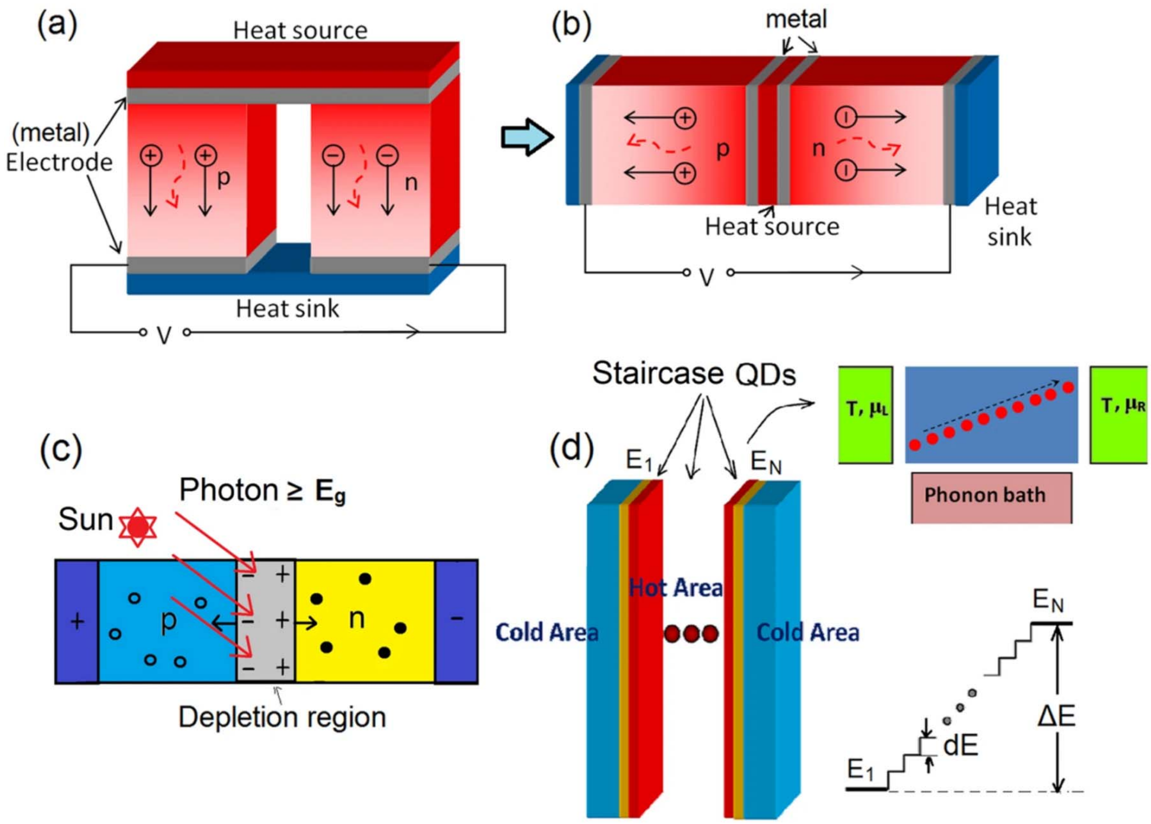

Fig. 5 (a) Illustration showing how a traditional TE energy harvester produces heat-generated electricity, (b) the TE energy harvester's unfolded shape, (c) the operation of a solar cell can be described as a three-terminal apparatus that mimics inelastic processes, specifically those involving photon absorption, (d) a schematic of a TE harvester employing quantum dots in a staircases configuration. Here, electron hopping between a chain of quantum dots with a staircase of energy levels is assisted by phonons. Electricity is produced using the heat of a hot phonon bath. This figure has been adapted from ref. 78 with permission from Nature, Copyright 2016.

phonon-assisted interband transitions can achieve significantly higher efficiency and greater output power. Moreover, the underlying mechanism that accounts for the differences in efficiency and power between solar cells and TE engines has been shown to resemble inelastic transport processes in a three-terminal configuration in Fig. 5c. Two specific structures are considered in this context: (1) each nano-engine contains a single pair of quantum dots (QDs), and (2) each nano-engine incorporates a staircase energy arrangement consisting of NQDs in Fig. 5d.

Ionic thermoelectric (iTE) and thermocells (TECs) are gaining attention as promising alternatives to conventional electronic TE for energy conversion, relying on ionic transport driven by temperature gradients, similar to the Seebeck effect.[79] These systems exploit the Soret effect, where temperature differences cause ions to migrate within ion-conducting materials, generating an electrochemical potential. This principle has been observed in ionic liquids and solid electrolytes, enhancing thermoelectric energy harvesting. TECs convert heat into electricity through electrochemical reactions in ion-conducting materials, offering an efficient, self-powered solution without moving parts.[80] Their efficiency can be improved by optimizing electrolyte properties and temperature gradients, with nanomaterials like quantum dots and nanosheets enhancing ionic transport and energy conversion. iTE and TEC systems hold significant potential for fire warning applications, offering faster, more accurate detection compared to traditional gas or smoke sensors.[81]

3.1 Development in technology

Recent advancements in the TE materials have emphasized the evolving interdependence and decoupling of key efficiency parameters. This is particularly evident in high-performance organic thermoelectric materials, which offer notable advantages such as low thermal conductivity and high mechanical flexibility, making them ideal candidates for applications in green energy harvesting and thermoelectric refrigeration. As a result, there is growing interest in developing organic thermoelectric materials as sustainable alternatives to traditional inorganic materials. These organic materials are seen as promising solutions for harvesting waste heat and solar thermal energy, contributing to greener energy solutions.[82] TE materials are key to enhancing energy conversion efficiency, which is crucial for waste heat recovery, power generation, and cooling applications.[83] The nanostructures in TE materials can reduce thermal conductivity while maintaining electrical conductivity.

The quantum dot inserting, nanowire fabrication, and superlattices are commonly used.[84,85]

Electrical power can be generated in a small part-free device by employing complementary n-type and p-type materials in Fig. 6a. Nano-structuring offers solutions to many limitations of conventional TE materials. This approach encompasses the development of novel materials designed to provide favorable TE properties while avoiding the drawbacks associated with traditional tellurides, such as brittleness, high cost, scarcity of constituent elements, and toxicity nano structuring to enhance TE performance by using conventional TE materials, like Bi_2Te_3 and PbTe in Fig. 6b. Moreover, accurately measuring thermal conductivity in small samples remains challenging, and some TE studies report only the power factor. A key difficulty in developing TE materials lies in the interdependence of parameters, particularly through carrier concentration as shown in Fig. 6c, regardless of which performance metric is prioritized. Nano structuring offers a solution by effectively decoupling the relationships among σ, S, and k through phenomenon occurring at short-length scale. By exploiting inconsistencies in phonon and charge carrier scattering lengths, thermal conductivity can be reduced more efficiently than electrical conductivity and thereby augment the power factor with respect to bulk materials through quantum confinement effects in nanostructures. Because of this, nanostructured materials such as the $Si_{0.80}Ge_{0.20}B_{0.16}$ alloy, Fig. 6d and e, these nanostructured materials have demonstrated both higher power factors and lower thermal conductivity compared to their bulk counterparts with the same chemical composition. These combine nanostructured materials with bulk materials to achieve a balance between low thermal conductivity and high electrical conductivity.[86,87]

4. Quantitative analysis photovoltaic and thermoelectric materials

PV and TE materials represent two distinct yet complementary approaches to energy conversion, operating on fundamentally different physical principles. Photovoltaic materials convert solar radiation directly into electricity *via* the photovoltaic effect,[89] in which photons generate electron–hole pairs across a semiconductor bandgap. Their performance is typically evaluated using parameters such as power conversion efficiency (η), open-circuit voltage (V_{oc}), short-circuit current density (J_{sc}), fill factor (FF), and bandgap energy (E_g). In contrast, thermoelectric materials generate electricity from a temperature gradient *via* the Seebeck effect, and their efficiency is quantified by the dimensionless figure of merit ($ZT = S^2\sigma T/k$), where S is the Seebeck coefficient, σ is electrical conductivity, T is absolute temperature, and k is thermal conductivity.[90]

While high-efficiency PV materials, such as crystalline silicon and emerging perovskites, can achieve power conversion efficiencies of 20–25% under standard illumination, state-of-the-art thermoelectric materials typically exhibit ZT values of 1–3, corresponding to lower overall energy conversion efficiencies. Quantitatively, PV systems are primarily limited by radiative recombination and thermodynamic losses (*e.g.*, the Shockley–Queisser limit), whereas TE materials face intrinsic trade-offs between electrical and thermal conductivities.[91] A

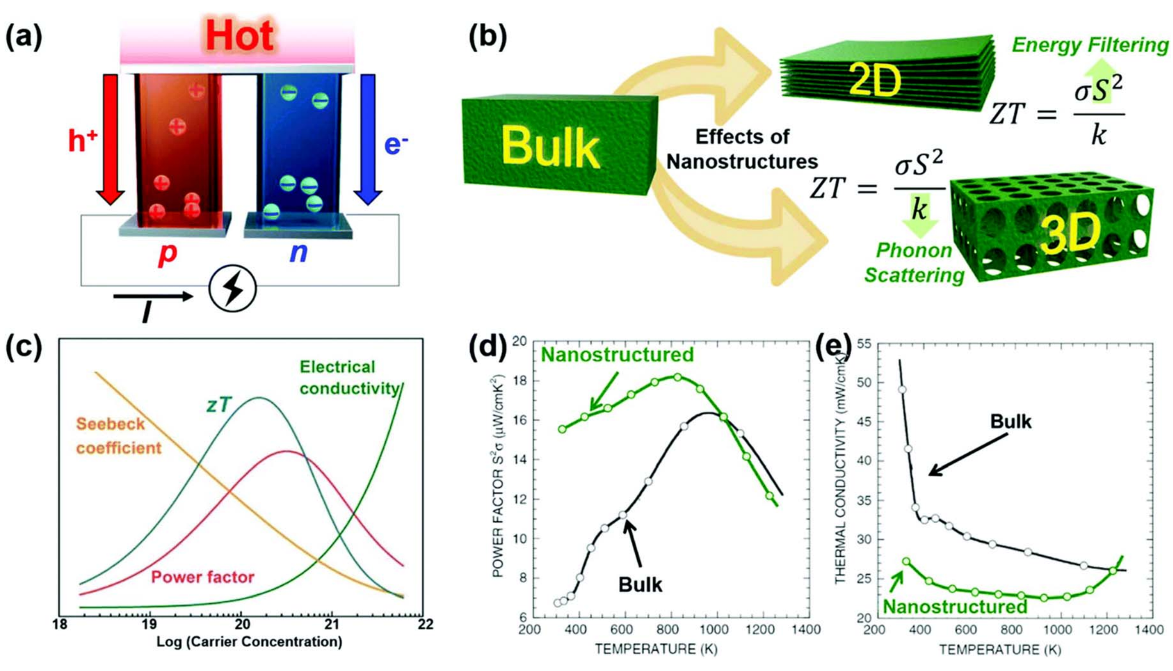

Fig. 6 (a) The illustration of a TE generator's fundamental operation. (b) Schematic of 2D and 3D nanostructures showing how phonon scattering and energy filtering can improve the thermoelectric figure of merit (ZT). (c) Trends in the power factor based on the general relationship between the Seebeck coefficient and electrical conductivity as a function of carrier concentration. (d) Comparison of the power factor in a nanostructured alloy. (e) Comparison of the thermal conductivity of the nanostructured alloy with that of a bulk material of the same composition. This figure has been adapted from ref. 88 with permission from the Royal Society of Chemistry, Copyright 2019.

Table 1 Analysis of photovoltaic material

Material	Fill factor (FF)	Bandgap energy (E_g, eV)	Open-circuit voltage (V_{OC}, V)	Short-circuit current density (J_{SC}, mA cm^{-2})	Power conversion efficiency (η) %	References
Silicon	0.81	1.12	0.7	42	24.7	92
Cadmium telluride	0.79	1.5	0.79	23.7	18.31	93
Copper indium gallium selenide	0.76	1.2	0.646	33.6	16.1	94
Perovskite	0.84	1.51	1.1948	24.16	24.2	95

quantitative analysis therefore highlights that PV materials are generally superior for direct solar-to-electric conversion, whereas TE materials are particularly advantageous for harvesting waste heat, making their integration in hybrid PV–TE systems a promising strategy for enhanced total energy utilization. Tables 1 and 2 analysis of PV and TE materials.

A sustainable energy source, solar cell technology is more expensive than fossil fuels.[99] The most widely used solar cells typically achieve efficiencies of 15–20%, while next-generation devices can reach up to 30%.[100] Conventional solar cells are inefficient due to heat-induced losses of about 50% of their efficiency; incorporating nanomaterials, including fullerenes, carbon nanotubes (CNTs), and quantum dots, as depicted in Fig. 7a and b, could boost their efficiency. In general, the application of nanotechnology techniques can be advantageous for developing higher-efficiency, low-cost solar cells. Due to their small particle size, nanomaterials can easily flow through plumbing and pumps without causing problems. The great direct energy absorption capacity of nanofluids enabled them to bypass intermediary heat transfer stages. Great absorption in the sun region and low emittance in the infrared range are examples of nanofluids great optical selectivity.[19] A reduction in material restrictions was correlated with a more consistent receiver temperature in the solar collector using nanomaterials. Receiver performance may be enhanced by increased heat transfer resulting from the addition of nanoparticles, driven by enhanced convection and thermal conductivity.

5. Hybrid photovoltaics and thermoelectric systems

Explore the potential for integrating PV and TE systems to create hybrid energy harvesting solutions. For example, using TE systems to recover waste heat from PV panels, which can improve overall system efficiency.[102] Analyse the synergistic benefits of combining these technologies, such as enhanced energy capture and reduced environmental impact.[103]

Recent advancements further underscore the practical benefits of hybrid PV–TE systems. The demonstrated a PV–TE hybrid generator consisting of PV array and a TE array, achieving a conversion efficiency of 18%.[104] Similarly, Zhang *et al.* reported hybrid systems where various solar cells were connected to a single TE array, with conversion efficiencies of up to 12.4%. Notably, the open circuit voltage and output power in these system was found to be equal to the algebraic sum of their PV and TE components, illustrating the additive benefits of integrating these technologies.[105] Hybrid PV–TE systems offer environmental as well as practical benefits through maximizing solar energy utilization and minimizing non-renewable resource utilization. By recovering waste heat, these systems not individual enhance energy output but also reduce emissions contributing to global warming, thus supporting the development of a sustainable energy landscape. These systems exemplify how synergistic integration and material innovation can maximize renewable energy potential.[106] The combination of PV and TE systems offers substantial advantages, including enhanced energy efficiency and sustainability. TE modules mitigate PV heat losses by converting waste heat into electricity, reducing thermal load and maintaining PV efficiency. Studies have shown that doping TE materials like Bi_2Te_3 into dye-sensitized solar cells (DSSCs) have achieved improved power conversion efficiency (PCE) by over 20%,[107] while transparent DSSCs combined with SSAs and TE arrays achieved efficiencies of up to 12.8%.[108]

In combination, these approaches are instrumental in lowering greenhouse gas emissions, improving energy reliability, and advancing sustainable development goals. The two fields of development will most likely continue to make processes more efficient, cheaper,[109,110] and applicable and thereby push the trend for an antiseptic and more sustainable future in energy. The proposed system is illustrated in Fig. 8a.

Table 2 Analysis of thermoelectric material

Material	Seebeck (S)	Electrical conductivity (σ)	Temperature (K)	Thermal conductivity (k)	figure of merit (ZT)	References
Bismuth telluride	200	150	300	300	1.64	96
Lead telluride	100	200	900	250	1.1	97
Skutterudites	200	300	900	200	2.2	98

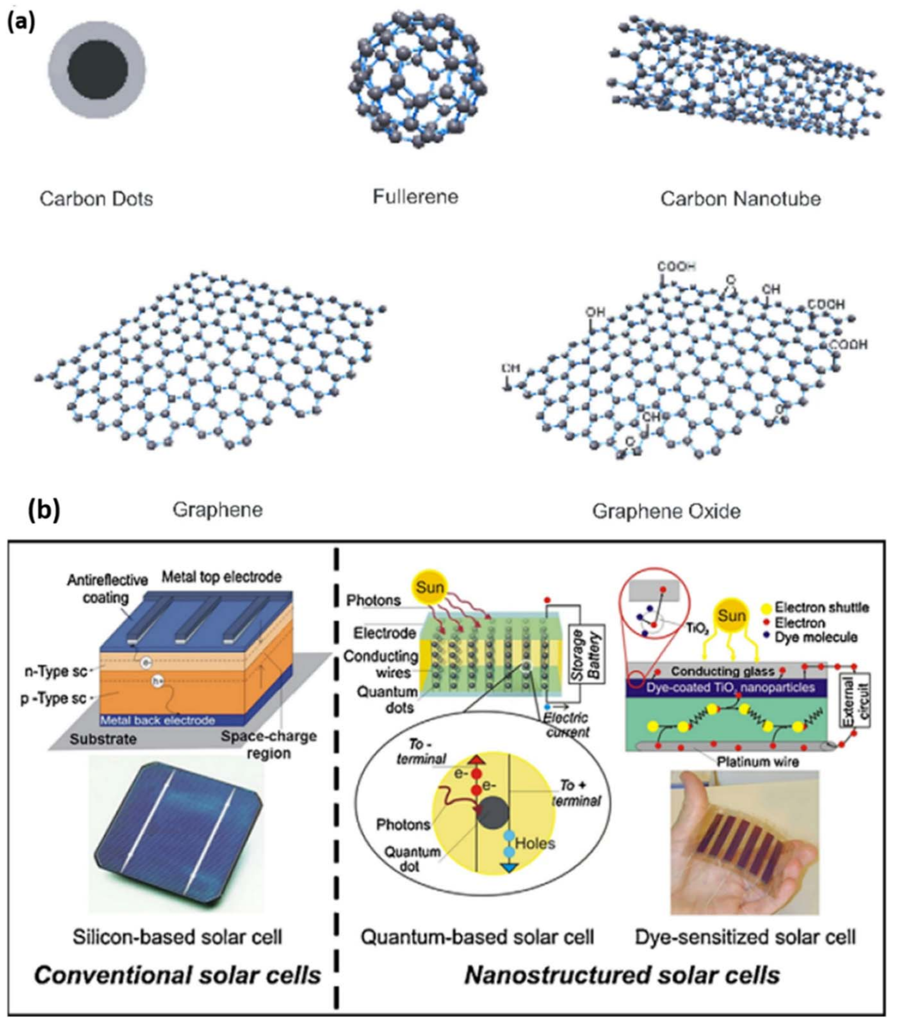

Fig. 7 (a) Carbon nanomaterials with zero dimensions, carbon dots, and fullerene. Carbon nanotubes are one-dimensional carbon nanomaterials. Carbon nanomaterial in two dimensions, graphene and graphene oxide, (b) transition from conventional silicon-based solar cells to nanostructured technologies, including quantum-dot and dye-sensitized solar cells, PV technology has evolved. This figure has been adapted from ref. 101 with permission from Springer, Copyright 2018.

To achieve optimal efficiency in a PV–TE hybrid system, the performance of the thermoelectric generator (TEG) must be improved. Achieving this requires a detailed assessment of the thermal flux and temperature-distribution within the TEG. Solar thermoelectric generator (STEG) subsystem is analyzed separately initially to project its maximum performance. The effectiveness of the overall system is both dependent on heat loss and on the pattern of heat flow and thus it is significant to assess energy transfer across each system boundary. As illustrated in Fig. 8b, the solar radiation of given insolation falls on heat absorbing layer, which is referred to as the selective solar absorb SSAs.

An inclusive overview of the latest innovations in TE and PV systems, examining the technological breakthroughs, material developments, and system integration strategies that are shaping the future of sustainable energy harvesting. By examining the synergies between these two domains, the potential of combined PV–TE systems and hybrid energy harvesting approaches can be highlighted, offering pathways towards further enhancing the efficiency and sustainability of renewable energy solutions.[112]

In recent years, numerous hybrid systems integrating TE and PV components have been investigated, with the goal of maximizing the utilization of both heat and light. As shown in Fig. 9a, PV cells primarily absorb the visible light (200–800 nm) and ultraviolet (UV) regions of the solar spectrum, whereas a TE uses the infrared (IR) area (800–3000 nm). The schematic of the hybrid PV–TE system is shown in Fig. 9b. Experimentally, a hybrid photovoltaic-thermal (PVT) system was constructed using thin-film TE modules, a heated mirror, and a near-infrared focusing lens, achieving a maximum power output of 0.19 μW and an open-circuit voltage of 78 mV. In a similar setup, thermoelectric generators (TEGs) contributed approximately 10% of the hybrid system's total output power. Another hybrid solar system, depicted in Fig. 9c, integrated water circulation with TEGs placed between the PV module and a heat extractor. In this system, the temperature difference across the TEG junctions was found to correlate linearly with the

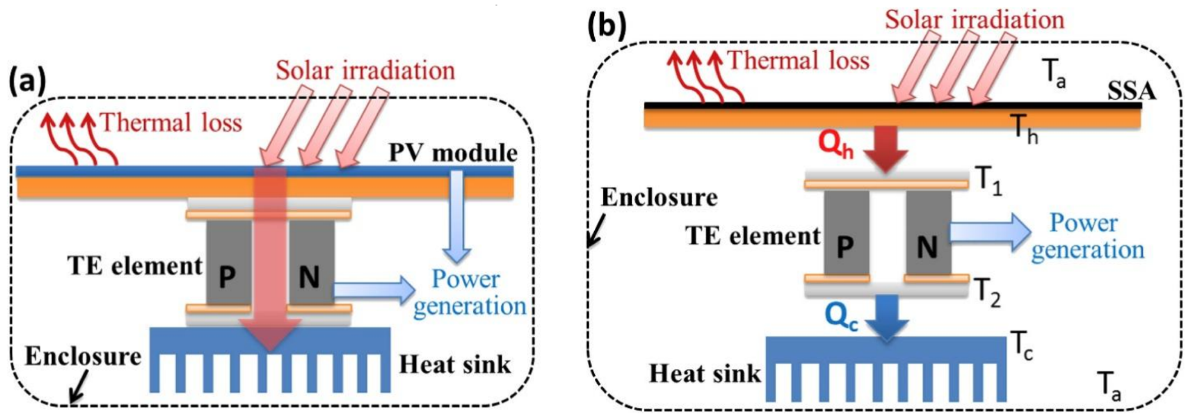

Fig. 8 (a) Diagram of the PV–TE hybrid scheme, (b) thermal flux, and temperature distribution within the solar thermoelectric generator (STEG). This figure has been adapted from ref. 111 with permission from Elsevier, Copyright 2016.

generated current, voltage, and overall efficiency, creating a hybrid system that combined a heat engine, concentrator, TEG, and PV cell. Both theoretical and experimental energy and exergy analyses were conducted for this TE heating and cooling system powered by a PVT heat pipe under summer and winter operating conditions.

Other developments include hybrid systems combining a heat engine, concentrator, TEG, and PV cell, with studies reporting the PVT panel achieving thermal and electrical efficiencies of 23.5% and 16.7%, respectively. Concentrated hybrid PV–TE systems have been compared across various PV technologies including silicon thin-film, polymer, copper indium gallium selenide (CIGS), and crystalline silicon to evaluate combined PVT–TE performance under different irradiation levels. Optimization of load matching and overall system performance has also been investigated using thermodynamic approaches. Additionally, in central-southern China, the performance of an integrated PV-air source heat pump (ASHP) system was experimentally assessed. Beyond conventional PV–TE architectures, hybrid devices that integrate dye-sensitized solar cells (DSSCs) with ZnO-based TE nano-generators, as shown in Fig. 9d, have demonstrated the ability to simultaneously convert light and mechanical energy into electricity.

To enhance solar absorption of the nano-pillar surface in Fig. 10a, the short-circuit current of a nano-pillar PV cell exceeds that of a nano-hole PV cell, while the nanostructure has

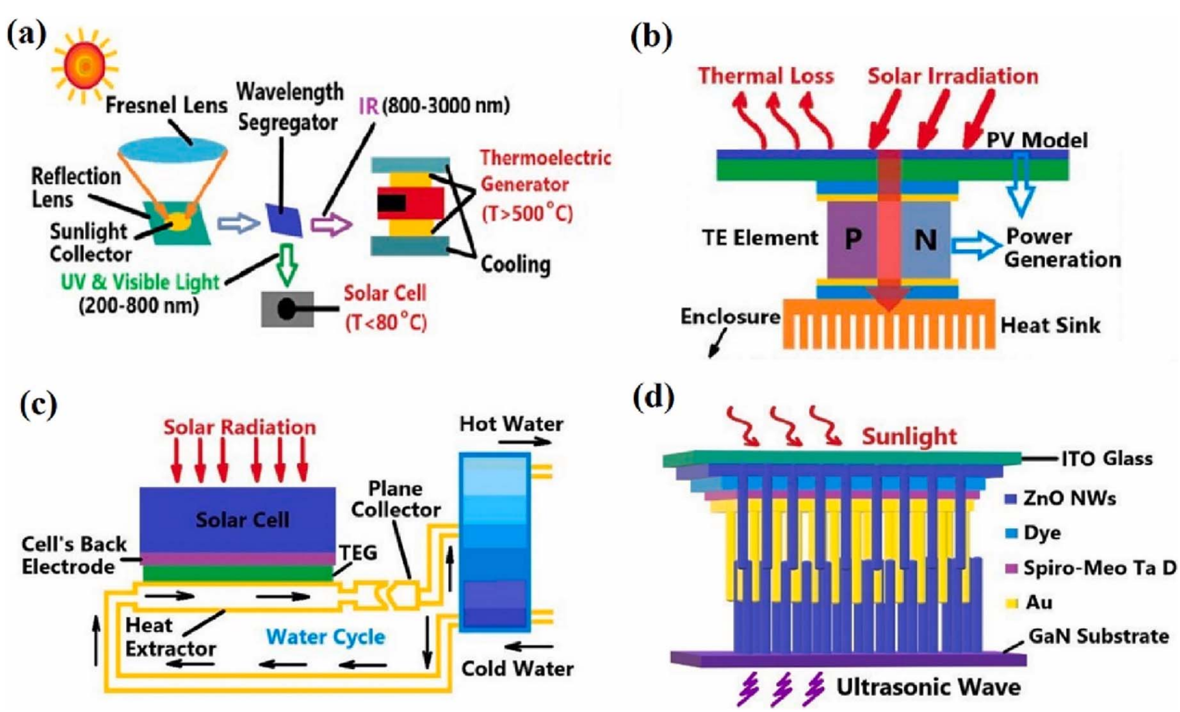

Fig. 9 (a) Solar energy concentration, (b) a hybrid PV–TE system schematic, (c) a PVT system schematic with TEGs and non-concentrated radiation, (d) and the structure of a compact hybrid cell. This figure has been adapted from ref. 113 with permission from Elsevier, Copyright 2023.

minimal effect on the open-circuit voltage. Fig. 10b illustrates the operation of the PV–TE system under AM1.5 solar illuminations. The system's power output is determined by the TE module's electrical resistance and reaches its maximum only when the TE resistance is near the optimal value.[114] Additionally, the optimal TE resistance for a series-connected configuration is significantly lower than that for a parallel-connected configuration, due to the reduced number of TE legs and consequently lower overall resistance. According to this, series-connected PV–TE systems are easier to construct than parallel-connected systems. Further, the PV–TE system with nano-pillars also possesses higher output power than the hybrid system with nano-holes. This is mainly due to the reason that the PV cell with nano-pillars possesses more capability for generating power than with nano-holes. Secondly, the nano-pillars exhibit decreased solar radiation reflectance compared to the nano-holes. A decreased reflectance of solar radiation indicates that more solar energy may be used by the TE module. Consequently, the TE module's performance may be enhanced by the nano-pillars. The adoption of the PV cell with nano-pillars is due to its high output power. As shown in Fig. 10c, the PV, PV–TE, and PV–EC top-surface temperatures and efficiencies are calculated and plotted as functions of the concentration ratio. The PV–EC system has a considerably lower surface temperature than PV and PV–TE. For the PV–TE system, an increase in PV surface temperature is due to the added thermal resistance of the TE unit. On the contrary, direct evaporative cooling in the PV–EC system actively reduces the working temperature, resulting in efficiency far greater than that of PV and PV–TE under the same conditions. When PV is assisted by TE in the PV–TE module, hardly much progress is observed because TE's intrinsic efficiency is quite low, often between 1 and 5%. It is evident from Fig. 10d that EC positively affects PV in terms of efficiency. To observe its impact on the total efficiency of the module, EC is also tried with PV–TE. The temperature gradient, which is based on the intrinsic qualities of the TE material, directly affects the TE efficiency. The Table 3 is the Comparison of PV or TE technologies.

5.1 Hybrid systems: engineering considerations

The hybrid photovoltaic and thermoelectric systems hold great promise for sustainable energy harvesting, a thorough engineering analysis. To critical aspects of system-level performance, thermal management, integration challenges, and device-level limitations.[116]

5.1.1 System-level performance. To maximize the efficiency of hybrid PV–TE systems, simulations by means of tools like MATLAB and COMSOL Multi-physics can help optimize design parameters for maximum energy yield.[117] For instance, a well-designed hybrid system can achieve an overall efficiency increase of up to 20% compared to standalone PV systems. Real-world applications, such as hybrid systems installed in remote off-grid locations, demonstrate the practical benefits of combining these technologies.[118]

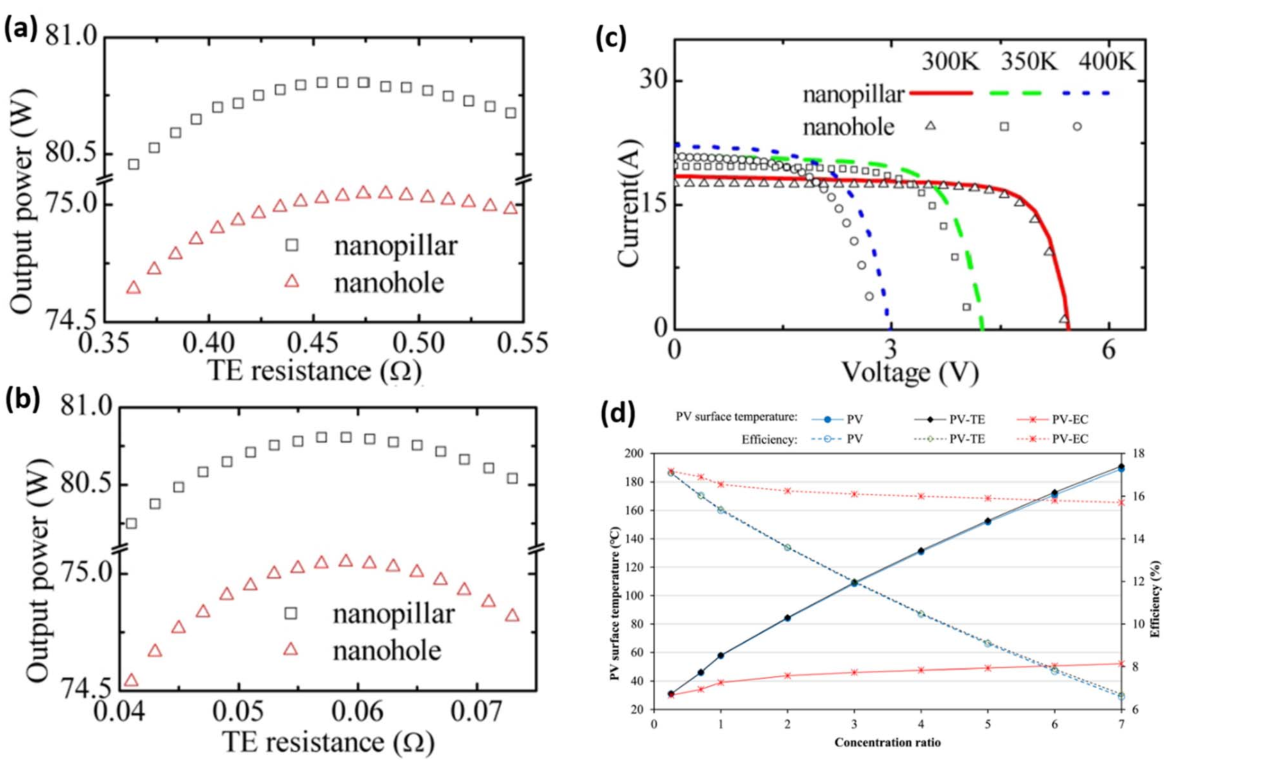

Fig. 10 The impact of the output power on the TE resistance. Parallel connections (a) and serial connections (b). G is 1000 W m^{-2}, and the temperature is 55 °C. (c) The PV cell I–V curves with various nanostructures. This figure has been adapted from ref. 115 with permission from Elsevier, Copyright 2019. (d) PV module efficiency, PV–TE, and PV–EC top surface temperatures. This figure has been adapted from ref. 32 with permission from Elsevier, Copyright 2022.

Table 3 Key research gaps and future directions for sustainable PV–TE systems

Area	Identified gap	Current limitation	Emerging solution	Future research direction	References
PV materials	Stability of emerging absorbers	Degradation under humidity and heat	Interface passivation	Long-term outdoor stability studies	157
TE materials	Use of rare/toxic elements	Limited sustainability	Earth-abundant compounds	Green thermoelectric materials	158
Hybrid interfaces	Thermal mismatch	Efficiency loss	Advanced thermal interface materials	Multi-physics modeling of interfaces	159
System-level	Lack of LCA analysis	Unknown environmental impact	Life-cycle assessment tools	Standardized sustainability metrics	160
Materials discovery	Slow experimental screening	Time & cost intensive	Machine learning	AI-integrated material design	161

5.1.2 Thermal impedance. Effective thermal management is a cornerstone of hybrid system design. Materials with low thermal impedance are essential for efficient heat transfer between PV cells and TE devices.[119] Thermal interface materials (TIMs) play a vital role in enhancing thermal conductivity. For example, using a high-performance TIM can reduce thermal resistance by up to 30%, ensuring that both PV and TE components operate within their optimal temperature ranges.[120]

5.1.3 Integration challenges. Integrating PV and TE components presents both mechanical and electrical challenges. Mechanically, robust design is necessary to withstand environmental stresses.[121] Electrically, voltage and current matching are critical for optimal performance. Advanced control systems can dynamically adjust the operation of each component, ensuring maximum energy harvesting under varying conditions.[122]

5.1.4 Device-level limitations. Both PV cells and TE modules have inherent limitations. PV cells face challenges, including MPPT efficiency and temperature-induced performance degradation.[123] TE modules are constrained by low efficiency and the need for significant temperature gradients.

5.2 Real-world deployment

The real-world deployment of PV and TE systems has gained considerable momentum in recent years, driven by advancements in materials science, policy incentives, and growing demand for clean energy solutions. PV systems have used commercial, and utility-scale sectors,[124] with countries integrating solar farms and rooftop solar panels into their energy infrastructure. The emergence of high-efficiency technologies such as perovskite and tandem solar cells has further enhanced the viability of solar power by reducing leveled costs and increasing energy yields under diverse environmental conditions.[125] TE systems, though comparatively less commercialized, have found practical applications in position markets. They are increasingly used for waste heat recovery in automotive exhaust systems, industrial manufacturing processes, and remote power generation, where reliability and maintenance-free operation are critical. Wearable TE generators have also emerged for powering low-energy biomedical devices and consumer electronics by harvesting body heat.[126]

5.2.1 Monitoring and optimization. The deployment of these systems often includes monitoring mechanisms to ensure reliability and sustainability. The PV modules are connected to microcontrollers for real-time data monitoring, which helps in analysing performance metrics such as voltage, current, power, and efficiency.[127]

5.2.2 Large-scale applications. The potential for large-scale distribution of energy harvesting systems is significant, especially in the context of the IoT.[128] Compact energy harvesters are essential for powering the growing ecosystem of smart devices in smart homes, cities, manufacturing, and healthcare. The advancement of sustainable and high-performance materials is essential for the broader adoption of these technologies.[129]

6. Challenges in sustainable energy harvesting

Challenges in sustainable energy harvesting encompass a variety of technical, economic, and environmental issues. Enhancing the efficiency of energy conversion in technologies such as PV, TE, and bioenergy systems is of critical importance.[130] For example, while some PV systems have reached efficiencies of over 20%, many still struggle with efficiency losses due to factors like recombination and thermalization. The development of sustainable energy systems often depends on materials that are either scarce or expensive. For instance, rare earth elements are crucial for some high-performance energy systems but are limited in availability, leading to supply chain concerns. Scaling up lab-scale technologies to commercial production levels remains a significant challenge.[131] This is particularly true for emerging technologies like perovskite solar cells and novel TE materials, where maintaining performance while reducing costs at scale is difficult. Intermittent energy sources, such as solar and wind, necessitate effective energy storage solutions and seamless grid integration to maintain a stable power supply. Current battery technologies, however, are limited by challenges related to energy density, cycle life, and environmental impact. While sustainable energy harvesting aims to reduce carbon emissions, some technologies can have unintended environmental impacts.[132,133]

For instance, OPVs and certain thin-film technologies are prone to degradation from UV exposure and moisture.[134] The economic factors often hinder the adoption of sustainable energy technologies. Subsidies for fossil fuels, lack of carbon pricing, and inadequate support for research and development can slow the transition to sustainable energy.[135] As energy consumption in buildings rises, integrating thermoelectric materials presents a promising solution to enhance energy utilization. These materials, especially low-dimensional nanomaterials, find applications in energy harvesting, building cooling, temperature sensing, and corrosion mitigation. However, several challenges hinder their widespread adoption. Improving material efficiency is a major concern, as current TE often lack the performance needed for cost-effective large-scale use. Manufacturing costs are also high due to complex production processes and expensive materials.

Additionally, the long-term durability and stability of TE materials in real-world environments, especially under fluctuating temperature conditions, remain uncertain. Integrating these materials into building systems like roofs, walls, and HVAC requires addressing compatibility with existing infrastructure and ensuring reliable operation in diverse environments.[136] IoT is integrating an ever-growing number of things that are connected to the Internet. As new technologies are included and connected, such as smart grids, smart cities, and smart transportation, this ecosystem keeps growing and expanding Fig. 11a. IoT is beginning to have an impact on several application domains, and there will be a lot more developments that will significantly improve our daily lives in terms of increased convenience and ubiquitous access to a variety of services from any device, anywhere, at any time.

As a result, wireless communication device batteries get depleted soon and need to be replaced frequently. In military networks under constant scrutiny, replacement of batteries in deployed networks can be potentially hazardous, laborious, and costly. As a result, energy harvesting is the most practical solution to power such low-power IoT devices with continuous energy. Another advantage of energy harvesting is that it needs minimal setup for a lengthy duration. Solar cells, or PV cells, consist of two layers of semiconductor material, most often silicon doped separately with P-type and N-type material. The N-type is designed to interact with light; when photons strike the material, they are absorbed and allow electrons to move through the PN junction and create electrical current. This closes gaps in the P-type substance, unused electrons are discharged in the direction of the N layer. As illustrated in Fig. 11b, light energy is thus converted into electric energy. Harvesting light energy is seen to have enormous promise for

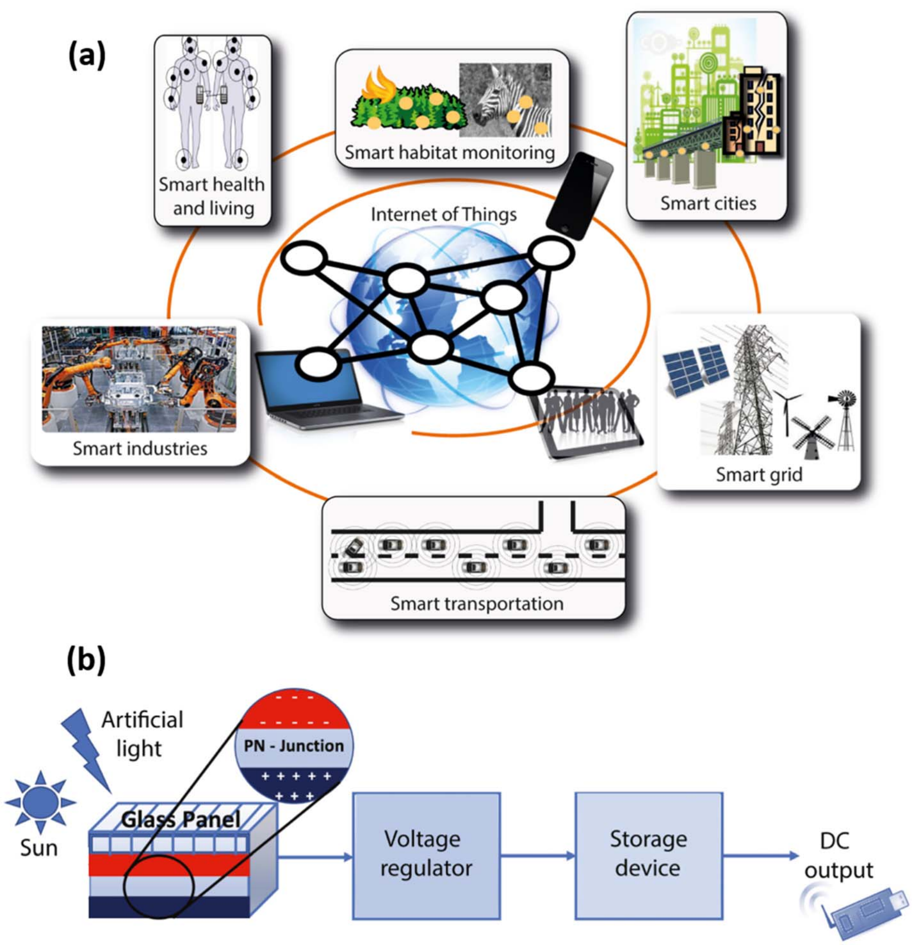

Fig. 11 (a) IoT applications. (b) A standard solar energy harvesting device. This figure has been adapted from ref. 137 with permission from Elsevier, Copyright 2020.

Internet of Things applications. To collect light energy that can power all the specified IoT networks, PV cells are common in smart homes, business buildings, military systems, and environmental monitoring systems.

6.1 Scalability issues

Scalability issues in sustainable energy harvesting are a significant challenge as new technologies transition from research and development to widespread commercial use.[138] Many sustainable energy technologies rely on materials that are either difficult to produce in large quantities or have limited availability. For instance, the large-scale production of perovskite solar cells faces challenges in ensuring the consistent quality of the perovskite layers, which is critical for performance and longevity. Similarly, rare or expensive materials, such as indium or platinum, can become bottlenecks as demand increases. Moving from small-scale laboratory fabrication to industrial-scale production involves overcoming significant technical barriers.[139] For example, OPVs have shown promise in the lab, but scaling up production while maintaining efficiency and stability has been challenging. As production scales up, maintaining uniform quality across large batches becomes difficult. Variations in material properties, layer thickness, and processing conditions can lead to inconsistent performance. In technologies like TEs, where precise control over doping levels and nanostructures is crucial, even small inconsistencies can lead to significant drops in efficiency.[140]

Scaling up also requires corresponding infrastructure and integration into existing systems, for example, deploying large-scale solar farms or wind turbines requires significant land, transmission infrastructure, and grid integration.[141] Moreover, the intermittent character of renewable energy sources, including solar and wind, requires scalable energy storage solutions to ensure a stable and reliable power supply. The cost of scaling up sustainable energy technologies is often a major barrier. Even if technology is technically feasible on a scale, the economic cost of materials, manufacturing, and deployment must be competitive with existing energy sources. Economies of scale can help reduce costs, but only if there are sufficient market demand and investment to achieve those economies. As scaling increases, so do the potential environmental and social impacts. Large-scale mining for materials, land used for solar or wind farms, and the end-of-life disposal of energy systems have all become more significant concerns. Ensuring that scaling up does not lead to negative environmental or social outcomes is a key challenge. Supportive policies and regulations are crucial for scaling up sustainable energy technologies. However, the regulatory environment can be uncertain or inconsistent, creating barriers to investment and deployment. For example, changes in subsidies, tariffs, or environmental regulations can significantly impact the feasibility of large-scale projects.[142]

6.2 Environmental and economic considerations

Environmental and economic considerations are central to the challenges faced in sustainable energy harvesting.[143] Many sustainable energy technologies rely on materials that require extensive mining and processing, which can have significant environmental impacts. For example, mining practices for rare earth elements used in wind turbines and electric vehicles can lead to habitat destruction, water contamination, and toxic waste. Large-scale renewable energy projects, such as solar farms and wind turbines, require extensive land areas for installation. This can lead to habitat disruption, deforestation, and conflicts with agriculture or conservation areas.[144,145] Balancing the need for renewable energy with the preservation of natural ecosystems is a critical challenge. The production of sustainable energy technologies, such as solar panels and batteries, frequently involves energy-intensive processes that contribute to greenhouse gas emissions. While the phase of these technologies is carbon-neutral or low-carbon, the initial carbon footprint can be significant. For example, silicon production for PVs is energy-intensive, and the refining processes for battery materials often involve high emissions.

As the deployment of renewable energy technologies scales up, so does the issue of waste management. Solar panels, batteries, and wind turbine blades have finite lifespans and pose significant recycling challenges. Inadequate recycling infrastructure can lead to a build-up of e-waste, potentially offsetting the environmental benefits of these technologies. Some sustainable energy technologies, particularly bioenergy and geothermal systems, require significant water usage.[146,147] This can lead to water scarcity issues, particularly in arid regions, additionally, improper disposal of chemicals used in manufacturing processes can lead to water pollution, affecting both ecosystems and human health. For instance, the development of next-generation PVs, like perovskite solar cells, requires significant funding for research, pilot manufacturing, and scaling up production. The economic viability of these technologies depends on achieving cost reductions through technological advancements and economies of scale. Sustainable energy technologies must compete with established fossil fuel-based energy sources.[148]

In some regions, renewable energy still struggles to be cost-competitive without government support. The transition to sustainable energy can lead to economic disruption, particularly in regions dependent on fossil fuel industries. The losses in coal mining or oil extraction can create economic challenges, and retraining programs are necessary to help workers transition to new roles in the renewable energy sector.[149] While sustainable energy offers long-term benefits, the initial costs can be prohibitive for low-income communities or developing countries. Ensuring that the transition to sustainable energy does not exacerbate inequalities is essential. Economic models and policies that provide subsidies, financing, and support for decentralized energy systems are necessary to make sustainable energy accessible to all.[150]

7. Research gaps and future roadmap

Despite significant progress in PV and TE technologies, several critical research gaps remain to enable truly sustainable and scalable energy-harvesting systems. Current research largely prioritizes efficiency optimization, while long-term stability, material toxicity, recyclability, and life-cycle sustainability remain insufficiently explored. In PV systems, challenges include the degradation of emerging absorber materials, interfacial recombination losses, and limited circular-economy strategies. In TE materials, dependence on rare or toxic elements and performance trade-offs between electrical and thermal transport restrict practical deployment. Advancing hybrid PV–TE systems requires addressing several critical research gaps to enhance their real-world viability. First, a persistent challenge lies in balancing efficiency and long-term stability, as high-performing materials like perovskites often degrade over time, necessitating the development of robust materials and fabrication techniques.[151]

Second, effective thermal management remains essential, especially under fluctuating environmental conditions, highlighting the need for innovations such as phase change materials and advanced heat sinks.[152] Third, current optimization efforts tend to focus on individual components rather than the system as a whole, underscoring the importance of integrated frameworks that holistically optimize PV, TE, and energy storage components using advanced modeling tools.[153] Fourth, the limited translation of laboratory findings to practical applications calls for rigorous field testing and validation under diverse real-world conditions.[154] Finally, to facilitate widespread adoption, it is crucial to align technological progress with supportive policies and market mechanisms by actively engaging policymakers and industry stakeholders.[155] Addressing these interconnected challenges through interdisciplinary research and coordinated action will be pivotal to realizing the full potential of hybrid PV–TE energy-harvesting systems. The future of sustainable energy harvesting systems, particularly hybrid PV and TE systems, holds great promise but also presents significant challenges.[156] The key research gaps and future directions for sustainable PV–TE systems is shown on Table 3.

8. Summary, opportunities, and emerging trends

This review has highlighted the remarkable progress and emerging trends in the development of PV and TE systems, with a particular emphasis on their synergistic integration for sustainable energy harvesting. The complementary nature of these technologies where PV excels under high solar irradiance and TE scavenges waste heat offers a promising route to enhance overall energy conversion efficiency. Despite significant advancements in material design, device architecture, and system integration, several critical challenges remain. These include the need for high-performance and stable materials, cost-effective manufacturing processes, seamless integration strategies, and improved scalability. Addressing these barriers is essential for transitioning hybrid PV–TE systems from laboratory-scale prototypes to commercially viable solutions.

Continued research on stabilizing perovskites under environmental conditions is crucial. The focus is on lead-free perovskites, hybrid perovskite structures, and tandem architecture to achieve higher efficiency. Innovations in non-fullerene acceptors, which offer enhanced light absorption and flexibility, are driving efficiency improvements.[162] Integration of 2D materials like graphene and transition metal dichalcogenides in PV and TE systems promises tunable electronic and thermal properties. In nano-structuring and low-dimensional materials, it aims to increase the hybrid TE materials are emerging as promising solutions due to their flexibility, lightweight characteristics, and tunable properties. These materials can enhance the TE figure of merit (ZT) by reducing thermal conductivity while improving electrical conductivity.[163]

Hybrid systems combining PV and TE modules are increasingly being explored, as they enable the simultaneous capture of electrical and thermal energy, thereby enhancing overall energy conversion efficiency. Progress in grid integration and energy storage technologies, including advanced battery systems, is essential for effectively addressing the intermittency inherent to renewable energy sources.[164] The development of lightweight, flexible, and wearable energy harvesting devices is driven by advancements. Efforts to develop scalable and eco-friendly manufacturing processes, including the use of abundant materials and low-energy synthesis methods, are critical for widespread adoption.[165] In multi-junction and tandem cell configurations continues to push the efficiency limits of both PV and TE systems. The integration of artificial intelligence (AI) and the IoT with energy harvesting systems is gaining momentum, enabling real-time monitoring, operational optimization, and predictive maintenance.

Commercialization of sustainable energy harvesting, particularly for PV and TE systems,[166] is gaining momentum. With the growing global emphasis on reducing carbon emissions, the demand for renewable energy sources continues to rise. Sustainable energy harvesting technologies are finding applications in residential, commercial, industrial, and even remote and off-grid locations. Additionally, specialized applications in wearable electronics, IoT devices, and sensors are emerging. The ability of TE materials to convert waste heat into electricity also presents a significant opportunity, especially in industries with high thermal waste. For both PV and TE technologies, scaling up production is critical to reducing costs, advances in manufacturing processes, such as roll-to-roll printing for organic PVs or scalable synthesis methods for TE nanomaterials, are essential for commercialization.[167]

For PV technologies, integration with existing building materials (Building Integrated PVs) offers a commercial pathway. For TEs, integration into automotive, aerospace, and industrial sectors for waste heat recovery. While silicon-based PV technology is well-established, emerging technologies like perovskite solar cells and advanced TEs need further development and validation before large-scale commercialization.[168,169] There is a growing trend toward decentralized energy systems, where localized energy harvesting. This trend favors the adoption of PV and TE systems at the consumer and community levels. The integration of PV and TE systems with smart grids, energy storage, and IoT-enabled devices is expected to enhance the commercial viability and adoption of these technologies.[170] Emphasizing the recyclability of materials and components in

Fig. 12 Challenges and prospects of sustainable energy harvesting.

PV and TE systems aligns with broader market trends toward a circular economy, potentially boosting the commercial appeal of sustainable energy harvesting technologies. Fig. 12 illustrates key challenges and prospects in sustainable energy harvesting. It highlights efficiency limitations, material and cost constraints, and environmental impacts as major hurdles. The figure also points toward emerging solutions, including advanced nanomaterials, hybrid systems, and innovative device architectures.

Author contributions

Nadia Anwar conceptualization, investigation, methodology, writing – original draft, writing – review & editing; Muqarrab Ahmed review & editing; Shaheen Irfan review & editing; Muhammad Adnan software, review & editing. Shern-Long Lee funding acquisition, writing – review & editing; Phuong V. Pham funding acquisition, investigation, project administration, supervision, writing – review & editing. Chandra Sekhar Rout review & editing.

Conflicts of interest

I, together with the co-authors, confirm that this manuscript has not been published elsewhere, neither accepted for publication, nor under editorial review for publication elsewhere.

Data availability

This is a review article and does not involve the generation of new datasets. All data and sources discussed are available in the cited literature.

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