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Functional materials for solar thermophotovoltaic devices in energy conversion applications: a review

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Fossil fuels are now used to meet over 80% of the world's energy demands, but they have the disadvantages of being unsustainable economically and polluting the environment. Solar energy is also one of the most desired alternative forms of renewable energy due to the quantity of direct sunlight among these sources. Due to the difficulties with solar cells, less than 1% of this energy is harvested and transformed into electricity. Notably, solar thermal and photovoltaic systems are the traditional methods for converting solar energy into electricity. It can be challenging to turn the solar energy captured by these systems into power. In contrast to conventional conversion methods, which involve converting solar energy directly into electricity, this article conducts a thorough investigation of solar thermophotovoltaic devices and the high-tech materials used in solar thermophotovoltaic systems as a solution to the conversion challenges.

KEYWORDS
solar energy, thermophotovoltaic devices, energy conversion applications, renewable energy sources, functional material

Introduction

In 2019, the global energy consumption growth rate declined by +0.6% compared to its ever-increasing trend, contributing to slow economic growth. Consumption in Algeria and Indonesia was dynamic; however, consumption in South Africa, Saudi Arabia, and Nigeria continued to increase (Xu G. et al., 2020; Zhou et al., 2020). Generally, energy consumption is a socio-economic human need, and the energy demand is met by fossil fuels such as carbon and hydrogen compounds, from which petroleum, natural gas, and coal are derived (Sharma and Ghoshal, 2015; Pareek et al., 2020). Coal was one of the first fossil fuels used for steam engines, transportation, and the production of steel, while petroleum was used for fuel in combustion engines and lighting paraffin lamps, and natural gas was used for cooking and to generate electricity (Kalair et al., 2021; Welsby et al., 2021). Nonetheless, the adverse effects of these fossil fuels include, but are not limited to, the emission of nitrous oxide (N_2O) and carbon monoxide (CO). Inhalation of CO causes dizziness and headaches that may lead to death (Vohra et al., 2021; Abbasi et al., 2022). N_2O, on the other hand, generates ground-level ozone, which is harmful to crops and the respiratory system. Moreover, oil and coal contain sulfur, which, in contact with moisture, forms sulfuric acid, resulting in very damaging acid rain (Guenet et al., 2021; Qasim et al., 2021). Greenhouse gases are also one of the most destructive emissions of fossil fuels, causing global warming and disrupting the

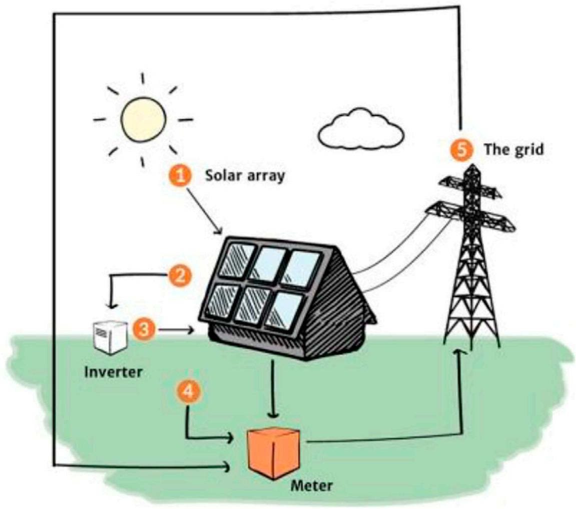

FIGURE 1
Solar energy.

surface temperature of the Earth from sustaining life; consequently, alternative energy sources have been developed (Malhotra, 2020; Shen et al., 2020). This study reviews the innovation in renewable energy sources that are cleaner, more accessible, and derived from natural sources. These sources include wind, geothermal, hydrogen, hydroelectric, biomass, ocean, and solar energy.

Solar energy

The primary source of solar energy, which travels at 3.0×10^8 m per second, is the Sun. The Sun, made up of helium gas and hydrogen, makes this energy in its core through fusion (Kalogirou, 2013; Gong et al., 2019). Fusion involves hydrogen isotopes, and with the transformation of matter, it comes together to form helium atoms, and this transformed matter is given off as radiant energy by the Sun (Okutsu et al., 2021; Kenjo et al., 2022). Radiant energy emitted from the Sun reaches the Earth surface in tiny portions, approximately 1.7 × 1018 W, and these rations are enough to supply the energy needed on Earth (Sisay, 2022). The Sun supplies energy to different parts of the Earth in small fractions per time, making it necessary to capture the solar energy through solar collectors before transforming it into electricity, as shown in Figure 1 (Panwar et al., 2011; Zhang L. et al., 2021).

Conversion of solar energy into electricity

A solar cell built from semiconductor materials is one device that is electronically a collector to convert solar energy into electricity (Fukuda et al., 2020; Kim J. Y. et al., 2020). The material used for solar cells must absorb sunlight, which raises electrons in the light to higher-energy states, and then the high-energy electron moves from the cell to an external circuit (Fonash, 2012; Burlingame et al., 2020). Urbanization is constantly increasing global electricity consumption, and like other types of energy, the need to reduce the price of electricity increases its supply, performance, and storage, making solar cell devices a fundamental solution (Asongu et al., 2020; Zhang et al., 2022). Solar thermal systems and photovoltaics are two methods of converting solar energy into electricity (Pasupathi et al., 2020; Rashidi et al., 2020). Solar thermal systems comprise concentrated solar power, which uses solar energy to generate electricity (Javadi et al., 2020; Osorio et al., 2022). The process involves using a solar collector with a mirrored surface to direct sunlight into a standby receiver, which, in turn, heats a liquid. The heated liquid produces steam, which produces electricity (Peuser et al., 2013; Ndukwu et al., 2021). The photovoltaic process of generating electricity involves the use of solar cells made up of silicon, which supplies electricity when the radiant energy from sunlight strikes the cell, triggering the electrons in the cell to move, and this movement of electrons jerks an electric current, switching from solar energy to electricity (Grätzel, 2005; Prabhu and ValanArasu, 2020).

Limitations to the conversion methods

There is an absolute theoretical Shockley–Queisser (SQ) limitation to the efficiency of conventional solar cells (Shockley and Queisser, 1961; Markvart, 2022). The conversion of solar energy to electricity, as shown in Figure 2 by solar cells is established by the photoelectric effect, which is an interaction between the transformed matter and the electromagnetic wave (Guillemoles et al., 2019; Ehrler et al., 2020). During their study, Shockley and Queisser (1961) realized there was a mismatch between the emission angles and absorption; therefore, they proposed that the Sun and solar cells act as black bodies. To this effect, a single layer of solar cells consisting of silicon was detailed through emission angle restrictions, photon recycling, and optical concentration to having an upper limit of a little above 32% for a 1.1eV gap (Lu et al., 2021; Chen et al., 2022).

The SQ limit defines 32%–33.6% as the maximum solar energy conversion efficiency achievable for any solar cell material (Xiang et al., 2019; Kim S. et al., 2020). This limitation, which was developed in 1961, is applicable to the principle of detailed balancing, which equates the photon flux that goes into the solar cell device with the electron or photon flux that goes out of it at different open-circuit conditions (Rühle, 2016; Green and Ho-Baillie, 2019).

Exploring solutions to the theoretical limitations

In recent times, possible ways of increasing the efficiency of solar cells above the absolute limit have been found, namely, by adding multiple layers of solar cells, which increases the incident intensity, the current density, and the voltage (Kim J. Y. et al., 2020;

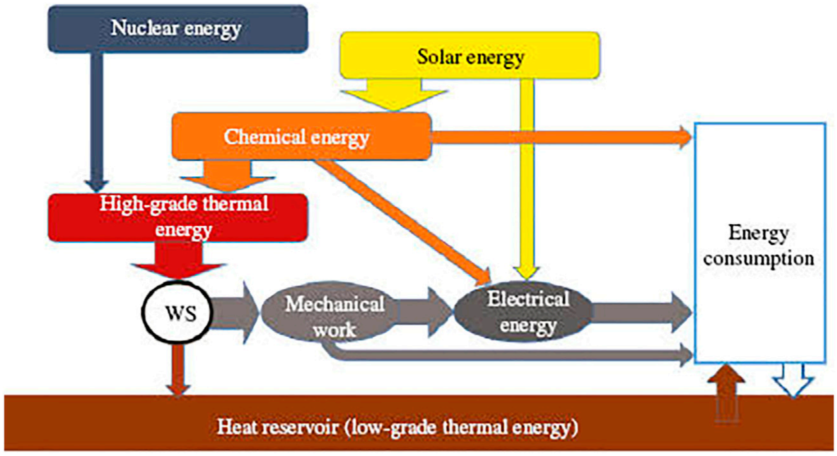

FIGURE 2
Schematic representation of the thermophotovoltaic process.

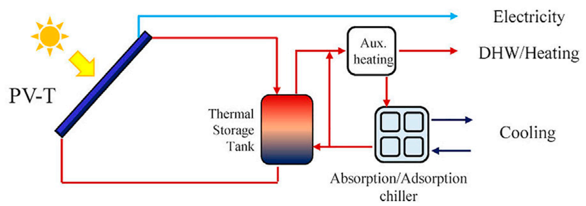

FIGURE 3
Electric power through solar thermophotovoltaic devices.

Park, 2020). Angle restriction filters can also be used to reduce the existing recombination current; multiple semiconductors with several bandgaps can also be used to decrease thermal losses and increase efficiency (Beard et al., 2013; Tennyson et al., 2019). Axelevitch (2018) reviewed the ways of improving the efficiency of single-junction solar cells, with specific attention given to solar cells enhanced with the plasmon. The author described using multi-junction solar cells, down-conversion solar cells, up-conversion solar cells, multiple exciton generation solar cells, solar cells with intermediate bands, and hot carrier solar cells as enhancement mechanisms of solar cells from the SQ limitations (Krügener et al., 2021; Yao and Hou, 2022). The possibility of using nano-structures made up of gold or silver nanoparticles was also discussed, concluding that the combination of an up-converter and a plasmon is a promising solution to the SQ limitation (Chen et al., 2021; Singh and Jen, 2021). The plasmon with extreme energy photons will generate multiple charged carriers under the absorption of one photon, while the up-converter uses the wavelength photons to increase the efficiency of solar cells (Gerislioglu et al., 2019; Huang et al., 2021). Nonetheless, a preferred alternative for exceeding the SQ limitations is the conversion of solar energy to heat first before generating electrical power through solar thermophotovoltaic devices, as shown in Figure 3.

Solar thermophotovoltaics and their devices

There are several technological options for converting primary energy into electricity. A few of them may be converted directly (for example, PV and fuel cells), but the vast majority require the intermediary creation of heat, which is then converted into electricity using a heat engine (Snyder and Toberer, 2008; Shi et al., 2020). Consequently, many other types of heat engines have been invented, but only those based on solid state devices (thermoelectrics and thermionics) have been widely employed, particularly in the energy and aerospace sectors (Mahan and Sales, 1997; Chen et al., 2003), while the dynamic systems (Rankine, Stirling, and Brayton) are still under development until they demonstrate high levels of reliability.

In thermoelectrics, thermal energy is directly converted into electrical energy via thermoelectric modules, which are solid state devices (Snyder and Ursell, 2003; Pei et al., 2012). The "Seebeck effect," which is the appearance of an electrical voltage induced by a temperature gradient across a material, lies at the heart of the conversion process. The inverse of this is the "Peltier effect," which causes a temperature gradient to form when voltage is applied (Tritt, 2011; Pourkiaei et al., 2019). As a result, the performance of the thermoelectric (TE) device is directly dependent on the temperature gradient (DT), the thermoelectric figure of merit (ZT), and the material parameter (Jia et al., 2021; Mao et al., 2021). The thermoelectric efficiency is defined for power generation by combining the Carnot efficiency (DT/Thot) (Zou et al., 2020; Zhang Z. et al., 2021). To increase this efficiency, high ZT values and a significant temperature differential across the thermoelectric material are required (Yang et al., 2021). Mahan and Sofo (1996) studied the electronic structure required to provide a high figure of merit in thermoelectrics, and it was discovered that a delta-shaped transport distribution maximizes thermoelectric properties. Their result indicates that for maximum thermoelectric efficiency, a narrow distribution of the energy of the electrons involved in the transport process is required.

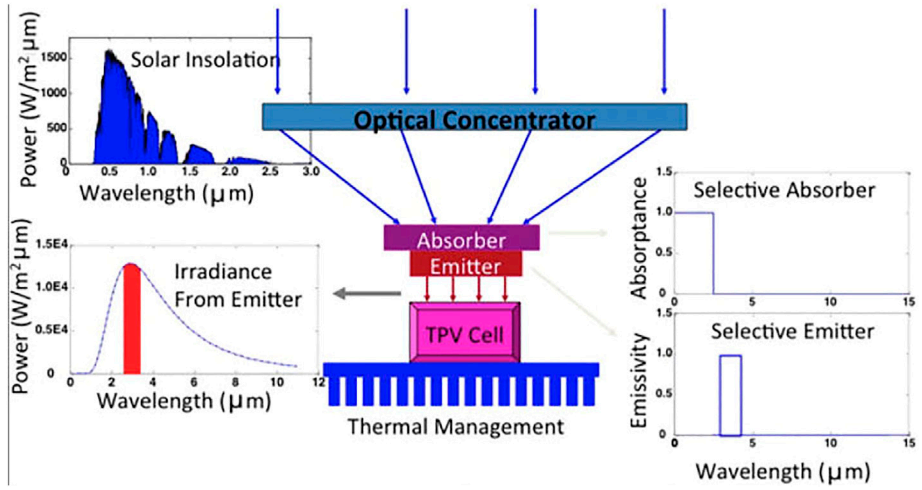

FIGURE 4
Thermal management process.

Nonetheless, according to Sootsman et al. (2009), current thermoelectric devices have a ZT of 0.8 and function at only around 5%–6% efficiency. By raising ZT by a factor of 4 and depending on DT, the estimated efficiency rises to 30%. However, the difficulty in developing high-ZT thermoelectric materials is attaining high electronic conductivity (s), high thermoelectric power (S), and low thermal conductivity (k) in the same solid. These characteristics are governed by the specifics of the electronic structure and the dispersion of charge carriers (electrons or holes) and so cannot be controlled independently. Dresselhaus et al. (2007) discovered a simultaneous increase in power factor and decrease in thermal conductivity using nanocomposites when compared to alloy samples of the same chemical makeup; Nandihalli et al. (2020) studied polymer-based thermoelectric nanocomposites; the level of material performance for output power factor PF = σS^2 and energy conversion efficiency was determined through the dimensionless figure of merit ZT = $\sigma S^2 T/k$ ($\sigma, S, T, and\, K$ are the electrical conductivity, Seebeck coefficient, temperature, and thermal conductivity, respectively). The authors concluded that the trade-off relationships between conductivity and Seebeck coefficient in polymer-based materials, as well as in inorganic thermoelectric (TE) materials, limit the ability to improve TE performance. These issues can be solved, however, by modifying the interfaces between the polymer and inorganic or organic additives. As a result, a suitable manufacturing process is required, in which interfacial density and defects at the interface of nanocomposites may be regulated in order to enhance electrical conductivity and the Seebeck coefficient at the same time. Therefore, significant interest from researchers in developing advanced thermoelectric properties through organic and inorganic nanomaterial-based hybrid nanocomposites has gained popularity among researchers (Bisht et al., 2021).

Compared to thermoelectrics, thermionic energy converters are power generators and their thermal management process is shown in Figure 4. The thermionic converter uses heat as its source of energy and transfers energy through mechanical work at no point during its operation. As a result, it is classified as a fuel cell or a photovoltaic cell (Herring and Nichols, 1949; Schwede et al., 2010).

Thermophotovoltaics (TPV) is a solid state alternative to thermoelectric and thermionic converters, which is very efficient. The two most prevalent methods for harnessing solar energy are photovoltaic, in which sunlight directly excites electron–hole pairs in a semiconductor, and the solar-thermal technique, in which sunlight powers a mechanical heat engine (Daneshvar et al., 2015; Burger et al., 2020). Photovoltaic systems directly convert solar radiation into electricity and are used to generate power from solar energy. Another approach uses a solar collector to convert Sun photons to thermal energy, which is then used in a thermal engine to generate electricity (Joshi et al., 2009; Lupangu and Bansal, 2017).

Photovoltaic power generation is intermittent and only efficiently utilizes a fraction of the Sun spectrum, but the inherent irreversibilities of tiny heat engines make the solar-thermal technique best suited for utility-scale power facilities. As a result, hybrid solutions for solar power generation are becoming increasingly important. Solar thermophotovoltaics (STPV) can also be referred to as systems that collect and re-emit solar light as heat radiation before directing it to photovoltaic cells (Hosenuzzaman et al., 2015; Das et al., 2018). With the STPV system, optimization may involve selecting an emitter spectrum and reflecting the unused portion of the radiation from the receiver back to the emitter surface. STPV systems' primary features are modularity, portability, the absence of moving parts, pollution-free operation, great efficiency, and high-power densities. Typically, the goal is to enhance photovoltaic conversion efficiency by matching the spectrum of the light to the bandgap of the cell (Davies and Luque, 1994; Wang et al., 2019). Solar thermophotovoltaics promise to leverage the benefits of both optimal approaches by converting sunlight into thermal emission tuned to energies that are directly above the photovoltaic bandgap. This is achieved by using a hot absorber–emitter with high efficiency and harnessing the entire solar spectrum, scalability and compactness due to their solid state nature, and dispatchability due to the ability to store energy using thermal or chemical means (Kohiyama et al., 2016; Chen et al., 2020).

STPV systems have a variety of possible applications, including electrical and thermal energy supply, grid-independent storage appliances, waste-heat recovery, and space and aerospace power applications. However, at high working temperatures, effective sunlight collection in the absorber and spectrum control in the emitter are extremely difficult (Datas and Martí, 2017; Gupta et al., 2018); because of this limitation, earlier experimental demonstrations have had a conversion efficiency of approximately or below 1%. Hence, a number of factors influence solar thermophotovoltaic efficiency, including the sunlight concentration ratio, absorber/emitter temperature/efficiency, photon recycling efficiency, and TPV cell characteristics (Bitnar et al., 2013; Zhou et al., 2016).

In a study of STPV systems, a newly developed Fresnel lens was used, and the calculated system efficiency with a tungsten emitter achieved 35%. The system comprised a solar concentrator, an absorber emitter, a spectrum filter, PV cell arrays, a bottom reflector, and a cooling system. A parabolic reflector was utilized as the concentrator in this case. The emitter might be composed of grayscale or spectrum-selective material. Forty GaSb cells were linked in series and positioned on the cooling system's inner surface. The bottom surface totally reflected heat radiation, ensuring that it was absorbed completely by the cells (Zenker et al., 2001; Khvostikov et al., 2007). The solar collector collects the Sun's rays, which subsequently radiate to the absorber surface area. The absorber was a critical component of the STPV system, acting as a spectrum-selective surface that transforms solar light into thermal energy. This surface increases solar energy absorption in the visible and near-infrared ranges while minimizing heat emission in the infrared region (Chaudhuri, 1992; Nam et al., 2014).

Hence, the absorber surface must function at elevated temperatures with a high energy density to achieve thermal stability. Another selective surface that radiates heat energy toward the PV cell is the emitter. According to the SQ limit, a single-junction solar PV has a significant limitation in utilizing solar energy because photons with less than the required energy to generate electron–hole pairs are practically useless, while photons with more energy than the bandgap result in excess energy at the PV surface and reduce efficiency (Mojiri et al., 2013; Abbas et al., 2022). As a result, by customizing the bandgap, emitters give the most efficient spectrum for the PV cell.

Another innovative STPV system offers electrical energy that is passed via the solid oxide electrolyzer cell (SOEC) to create hydrogen. The ultimate purpose of an electrolyzer cell is to create hydrogen from the intake water. Heat and power are required for the electrolyzer cell to perform this feat. Thus, a steam electrolyzer that runs at high temperatures is an effective way to significantly cut energy use (Charache et al., 1999; Dashiell et al., 2006). Consequently, the efficiency of numerous intermediary energy conversion processes is critical to the performance of STPV. The absorber converts optically focused sunlight into heat, the absorber temperature increases, heat conducts to the emitter, and the hot emitter thermally radiates toward the photovoltaic cell, where radiation is eventually harnessed to excite charge carriers and create electricity (Kohiyama et al., 2020; Hou et al., 2023).

The overall efficiency η stpv can be expressed as a product of the optical efficiency of concentrating sunlight (η o), the thermal efficiency of converting and delivering sunlight as heat to the emitter (η t), and the efficiency of generating electrical power from the thermal emission (η tpv) (Tervo et al., 2020):

$$\eta\,\text{stpv} = \eta\,\text{o}\,\eta\,\text{t}\,\eta\,\text{tpv}.$$

The TPV efficiency η tpv hinges on the spectral properties and temperature of the emitter. A spectrally selective emitter should have a high emittance for energies above the photovoltaic bandgap (Eg) and a low emittance for energies below the bandgap. To excite enough thermal modes for substantial emission above the bandgap, the emitter temperature should ideally be high enough that Planck's blackbody peak coincides with the bandgap; in other words, by Wien's displacement law (Tian et al., 2021)

$$T_e^{opt} \approx 2336\,[\text{K eV} - 1] \cdot \text{Eg}.$$

The emitter's high-temperature operation faces two major obstacles to a successful STPV power conversion: efficiently collecting sunlight to meet T_e^{opt} and preserving spectral selectivity at raised temperatures. For the absorber, one approach to effectively enhance the intrinsic solar absorptivity of materials is to use macrocavity geometries. Because of the high aspect ratio of the cavity needed to enhance absorption, this approach typically requires high levels of optical concentration to reach T_e^{opt}. A high optical concentration necessitates sophisticated systems with poor optical efficiencies (η o ≈ 65%). Tungsten has poor inherent spectrum selectivity as an emitter at T_e^{opt} because its emissivity at low photon energies (<Eg) increases with temperature, accompanied by an increase in electrical resistance. Ultimately, depending on the intrinsic spectral properties of materials for their absorber–emitter performance is limited with experimental STPV conversion efficiencies. Hence, to improve the performance of the absorber–emitter, the design of structured surfaces with spectral properties approaching those of ideal STPV components is achieved with simulation studies using realistic nanophotonic surfaces, which predict STPV efficiencies exceeding 40% (Bhatt et al., 2020).

Solar thermal generators, which offer very high energetically dense thermal storage, are an eventual alternative to solar PV because an STPV system requires a broadband absorber capable of absorbing the entire solar spectrum, a narrowband emitter capable of converting the absorber's absorbed energy in the form of heat to photons in a narrowband spectrum just above the bandgap of the PV cell, and a low bandgap PV cell capable of effectively generating electron–hole pairs while avoiding thermalization losses (Xu Y. et al., 2020).

The broadband absorber and narrow band emitter create an intermediate structure that may be built with metamaterials and their two-dimensional metasurface equivalents (Liu et al., 2019). Metasurfaces have the special benefit of being compact and having a high absorptance. To produce strong absorptance across a wide range of incidence angles, both the absorber and the emitter should be angle-insensitive (Anggraini et al., 2022). The major goal in both circumstances is to maximize the absorptance profile since, according to Kirchhoff's Law, absorptance equals emittance in thermodynamic equilibrium; furthermore, because the STPV system must function under high-temperature settings, the materials used to construct the absorbers and emitters are carefully chosen from a limited number of refractory materials (Azzali et al., 2021; Bendelala and Cheknane, 2022). Nevertheless, oxidation is a significant issue when employing refractory materials (Rana et al., 2021). Most refractory metals with high melting points oxidize at significantly lower temperatures and pressures. Tungsten (W), rhenium (Re), tantalum (Ta), and titanium nitride (TiN) are refractory metals with extremely high melting temperatures of 3695.15 K, 3458.15 K, 3290.15 K, and 3203.15 K, respectively. Ongoing research on absorbers, emitters, and STPV systems in general is hampered by non-planar three-dimensional (3D) or multilayer designs and reduced efficiency (Tong, 2018). Fabrication of 3D designs is inherently complex for the primary lens (or mirror), the absorber, the PV cell, and a photon recuperator mechanism, which are the key components of TPV systems (Palfinger, 2006).

Hence, the TPV efficiency is optimized by optimizing three parameters: absorber, PV cell temperatures, and cell voltage. When photons of above-bandgap energy released by the heat emitter are absorbed by the PV cell, the photovoltaic effect produces electron-hole pairs (EHPs) (i.e., photogeneration) (Zou et al., 2020; Ren et al., 2021; Zheng et al., 2021). When EHPs in a PV cell are recombined, photons with energies larger than the bandgap are released (i.e., radiative recombination). The above-bandgap spectral radiation released by the PV cell quantum efficiency (Qe) is mostly the result of radiative recombination (Prentice, 1999). Although Qe comprises a free carrier and lattice emission in the PV cell, its contributions are unimportant to photogeneration or radiative recombination. The photocurrent flows through the external circuit as EHPs produced by photogeneration and radiative recombination undergo charge separation and migrate to electrodes (Sahoo and Mishra, 2018). Charge carriers that are lost due to recombination (non-radiative, radiative, and surface recombination) are unable to contribute to photocurrent production. Internal quantum efficiency is defined as the ratio of the number of created EHPs that may be employed for photocurrent production to the number of absorbed photons (Goodnick and Honsberg, 2022).

Advanced NF-TPV device ideas, particularly hybrid devices with NF-TPV integrated with a thermionic device or light-emitting diode and NF-TPV devices with multi-junction PV cells, are gaining research interest (Song et al., 2022). The trade-off between resistance and shading losses in the frontside is mitigated by serial integration of thermionic and thermophotovoltaic devices as a means of resolving the difficulties in an NF-TPV device. The near-field thermophotovoltaic (nTiPV) device with a thermionic cathode [i.e., LaB6] and an anode [i.e., BaF2] is positioned on the emitter and PV cell sides of the NF-TPV device, respectively (Datas and Vaillon, 2021). Electrons are emitted from the heated cathode and transmitted to the anode through the thermionic effect in nTiPV devices, along with photons. Electrons passing through the anode and reaching the top side of the PV cell negate the accumulated holes caused by the photovoltaic effect (Qiu et al., 2022). As a result, an electrical connection is created via the vacuum, eliminating the necessity for a frontside contact electrode. Additionally, electrons arriving at the PV cell's backside electrode are given to the emitter cathode, releasing the extra-potential of thermionic and photovoltaic effects. The elimination of the trade-off between series resistance and shading losses opens the door to significantly improved performance, even for scaled NF-TPV devices (Song et al., 2022). The space charge effect creates an electrostatic potential within the vacuum gap, acting as a potential barrier to thermionic transfer. When the vacuum gap approaches the near-field regime, not only is photon transport accelerated but also thermionic electron transport since the electric potential barrier is reduced (Khalid et al., 2016; Xiao et al., 2017).

As a result, with no frontside contact electrode, increased photocurrent from evanescent modes may be successfully transported to the emitter side cathode. At a realizable vacuum gap of 100 nm and an emitter temperature of 1000 K, the power density of the nTiPV device was 3.7 times and 10.7 times higher than that of the NF-TPV device in the same operation condition with 'ideal (i.e., series resistance is 0 mΩ)' and 'realistic (i.e., series resistance is 10 mΩ)' conditions, respectively. With a 1-cm^2 macro-scale device area with the same vacuum gap and emitter temperature parameters, the nTiPV device had a power density of 6.73 W/cm2 and 18% conversion efficiency (Jang et al., 2016). As a result of the trade-off between resistive and shading losses, the nTiPV device may be promising for the macro-size application of NF-TPV conversion. Fabrication of the anode and cathode with sufficiently low work-functions, which is required for improved thermionic emission in the near-field domain, still remains a problem for the specified application (Song et al., 2022).

In contrast to PV cells, a light-emitting diode (LED) produces luminescence by radiative recombination of bias-driven injected charge carriers. If the TPV device's passive emitter is replaced with an active emitter, such as an LED, the PV cells' above-bandgap absorption can be boosted due to the electroluminescence created by the LED. A PV-LED hybrid device of this type is known as a thermophotonics (TPX) device. If the nearfield idea is implemented in the TPX device, it is evident that the evanescent mode will improve both PV and LED performances, resulting in a better power density. This gadget works by driving the LED with a portion of the electricity provided by the PV cell (Sadi et al., 2020).

A near-field TPV (nTPX) device used AlGaAs ternary semiconductors in both the PV cell and the LED. Using rigorous balancing analysis, they simulated the photon flow that conveys chemical potential and the non-radiative recombination rate. When the LED and PV cell temperatures were 600 and 300 K, respectively, at the 10-nm vacuum gap, their nTPX device could create 9.6 W/cm^2 of electrical power with a conversion efficiency of 9.8%. With the same temperature difference, the suggested nTPX device exceeded the record-high power output density and conversion efficiency of a conduction-based thermoelectric generator. A TPX device's performance is generally more sensitive to emitter side temperature (i.e., LED temperature) than a TPV device. First and foremost, bandgap alignment between the LED and PV cells is required for high-performance TPX devices. Since the bandgap energy depends on the temperature, the performance of TPX devices could be degraded even if the temperature of the LED slightly deviates from the optimum point. In addition, because parameters of the non-radiative recombination rate, such as Auger and SRH recombination lifetimes (?Auger and ?SRH) and intrinsic carrier concentration (??), are also functions of the temperature, the increase in LED temperature can result in

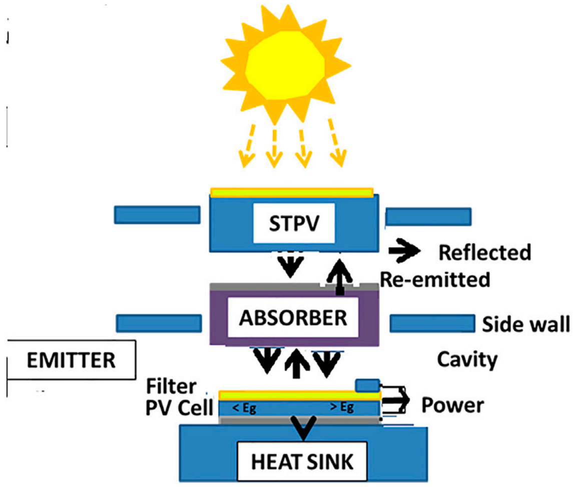

FIGURE 5
STPV and its energy flow flowchart.

detrimental effects on the TPX performance; in other words, as the LED temperature increases, ?Auger and ?SRH decrease and ?? increases (Legendre and Chapuis, 2022).

High-tech materials for solar thermophotovoltaic devices

Conventional photovoltaic materials convert solar energy directly to electricity; hence, they undergo theoretical limitations. However, ways of increasing the overall efficiency are to convert solar energy first to heat and then use the heat to generate electrical energy (Nevala et al., 2019, Hassan et al., 2020). Table 1 shows the solar thermophotovoltaic devices and the devices used for this application are referred to as solar thermophotovolataics (STPV). Devices used for this application are referred to as solar thermophotovoltaics (STPV), with the flowchart shown in Figure 5. STPV pairs low-efficiency conventional solar cells with an added layer of high-tech material that helps in multiplying the SQ limitation, making it possible for the cells to generate more power (Alam and Khan, 2019; Wong et al., 2020). The device works on the principle of dispersing waste solar energy as heat inside the solar cell, a by-product of the nuclear/chemical reactions or mechanical work (Jayawardena et al., 2020; Gong et al., 2021). The heat is then absorbed by the transitional component at temperatures that will allow this component to produce thermal radiation. The configurations of the cell and the high-tech materials used in the devices are fine-tuned to the right wavelengths for the cell to capture light, which improves its efficiency (Guillemoles et al., 2019).

According to Jayawardena et al. (2020), perovskite cells mixed with lead–tin as an absorber can achieve a fill factor above 80% by post-treating the absorber with guanidinium bromide. The authors showed that the post-treatments were favorable in aligning the cathode and anode interfaces, thus enabling a bipolar extraction, which resulted in the device having an area of 0.43 cm^2, a fill factor above 80% and 14.4% power conversion efficiency. Rau et al. (2005) proposed using fluorescent collectors with photonic structures, which act as an omnidirectional spectral band stop-filter, to enhance the efficiency of photovoltaic solar cells, and they concluded that the combination of fluorescent collectors with photonic structures can close the theoretical SQ limitation while saving about 99% of the solar cell material. Thus, the authors recommended more research should be focused on the potential of two- to three-dimensional photonic structures used with fluorescent collectors. Briggs et al. (2013) developed an up-converter solar cell using thermodynamics to exceed the SQ limitation. The results showed that the efficiency of the solar cell increased from 28% to 34% with an increase in the up-converter quantum yield and capacity. Jia et al. (2016) reported the use of silicon nanocrystals built into the dielectric matrix as a promising

TABLE 1 Literature review on solar thermophotovoltaic devices.

Solar thermophotovoltaic (STPV) device	Experimental approach	Findings	Efficiency improvement	References
STPV with a carbon nanotube absorber with a 1D Si/SiO_2 photonic crystal emitter	Physical and chemical vapor deposition	Device is compact and planar than conventional devices	3.2%	Lenert et al. (2014), Fink et al. (1998), Wu et al. (2021), and (Wu et al. (2023)
STPV with a multi-walled carbon nanotube absorber and 1D Si/SiO_2 PhC emitter and the InGaAsSb PV cell	Mathematical modelling and experimental procedures via electrolysis	Overall efficiency of the device is 34% more than conventional devices	17%	Daneshpour and Mehrpooya (2018)
Solid oxide electrolysis cells	Thermodynamic modelling and experimental procedures via electrolysis	The model has a better performance than low-temperature systems	14%	Ferrero et al. (2013)
STPV using simulated solar energy	Thermodynamic modelling and experimental procedures via electrolysis	Temperature stability, no heat exchange of fluids, and easy to fabricate	6.2%	Ungaro et al. (2015)
STPV with a micro-textured absorber and nanostructure multilayer metal-dielectric-coated selective emitter	Thermodynamic modelling and experimental procedures via electrolysis	The highest STPV system efficiency so far	8.4%	Bhatt et al. (2020)
STPV and phase-change materials (PCMs)	Theoretical analysis	Cost reduction and high efficiency	-35%	Datas et al. (2013)

high-tech material for solar cells. Conversely, the material did not exceed the SQ limitation; therefore, the authors investigated the maximum efficiency of the material, and they stated that the practical limit of the solar cell's efficiency was 32%. Based on these results, they made suggestions for further studies to figure out the reason for the limitation and the proposed solution for improving the performance of the cell.

Trupke et al. (2002) tried generating a multiple electron–hole pair, a down-conversion high-energy photon, in enhancing the efficiency of solar cells. The authors detailed that there was an increment in the efficiency of the solar cell from 30.9% to 39.63%. They investigated the reason why intermediate-band solar cells could not exceed the SQ limitation, and they realized that the restriction was attributed to the radiative recombination through the intermediate band, yet they stated that suppressing the radiative recombination by introducing a quantum ratchet to the intermediate band can enhance the solar cell efficiency; therefore, the authors recommended using quantum ratchets as a more effective alternative to single-gap solar cells. On the other hand, Wang et al. (2013) used carrier transport and photon recycling simulation to figure out the reasons why thin-film GaAs solar cells did not exceed the SQ limitation by studying a single-junction thin-film solar cell and the influence of the design parameters. The authors concluded that an increment in efficiency will occur via enhancements on the backside mirror reflectivity above 95%, thus naming the series resistance and the back mirror reflectivity as the two important factors to focus on when creating high-efficiency thin-film solar cells, while Schaller et al. (2006) showed that charge carriers in large portions can enhance the performance of solar cells by increasing the photon to exciton conversion by 700%.

Xu et al. (2015) used nanostructured solar cells as photovoltaic devices, which under a 1.5 solar illumination showed a maximum efficiency of about 42%. However, they reported that the device did not exceed the theoretical limit for planar devices with optical concentrations, even though it exceeded the SQ limitations for non-planar devices. The authors attributed the failure to reach the SQ limitations to the principle of detailed balance with good knowledge of the absorption in the device structure. They recommended that nanostructured devices should be developed with limited absorption at wavelengths and angles very different from the incident illumination. More so, the improvement of the devices should come from the open-circuit voltage with non-radiative recombination and good-quality surface passivation. Mann et al. (2016) showed that large absorption of the cross sections is not responsible for the enhancements of solar cells using nanophotonic materials for photovoltaics; however, increasing the directivity bounds, which consist of the nanoscale concentrations in macroscopic solar cells, and the maintenance of high short-circuit currents are the significant voltage enhancement factors. Bierman et al. (2016) developed a high-tech nanophotonic crystal that was used to emit the desired wavelengths of light when heated while integrated into a system vertically aligned with carbon nanotubes, which serve as absorbers while operating at about 1,000 ℃. When the crystal was heated, it continued to give out light that matches the band of wavelengths that the solar cell uses to convert to electric current. The carbon nanotube enables all the energy of the photons to get converted to heat, which, in turn, re-emits light that matches the solar cell's peak efficiency through the nanophotonic crystal. The authors, using an absorber, solar stimulator, photovoltaic receiver, and filter all in one device, argue that a device coupled with a thermal storage system could provide continuous on-demand electrical power. They recommended further studies on increasing the current laboratory size of the device for commercial purposes (Chan et al., 2013; Davids et al., 2020).

Future recommendations

The literature has shown that converting solar energy into heat and then from heat into electricity is an efficient way of exceeding the SQ limitation. This knowledge has sparked significant interest in using solar thermophotovoltaic devices, where photons from a hot emitter are used to transverse a vacuum gap that is absorbed by the solar cell and used to generate electricity. Nonetheless, recent reports have shown that the temperature of the emitter is still too low to give off a photon flux sufficient for the photovoltaic cell, thus limiting the service life of these devices. New approaches use thermophotovoltaic energy conversion mechanisms such as photon-assisted tunneling with a bipolar grating-coupled complementary metal–oxide–silicon tunnel diode or a micro thermophotovoltaic generator, and these are recommended solutions to increase the efficiency. Solar thermophotovoltaic devices lack suitable structural designs that overcome the thermal losses experienced with current fabrication techniques, which can be improved. Thus, further studies need to be conducted to enhance current designs. The real implementation of an NF-TPV device is extremely challenging because it requires maintaining a high-temperature difference in the sub-micron gap between the low-bandgap PV cell and the emitter. In addition, the temperature of the PV cell should be kept near room temperature to prevent performance degradation. Therefore, a thermally isolated emitter would be desirable for a real system. Furthermore, innovative materials that can be used as absorbers, and emitters should be explored for long-term thermal stability. Ways to reduce the cost of setting up the existing thermophotovoltaic systems are few, and cheaper alternatives should also be investigated.

Conclusion

In this paper, we discussed how the world's demand for energy consumption led to the development of fossil fuels; however, economical sustainability and environmental pollution have created a need for cleaner energy sources. Solar energy was outlined as a preferred alternative source of renewable energy attributed to its availability and sustainability; however, the efficiency of this source of energy in its conversion mechanism to electrical power is limited. Therefore, we presented a literature review on different solar thermophotovoltaic devices, materials, and methods researchers have used in exceeding the theoretical limitations, and future recommendations and solutions were shown. Surveying the studies presented, it is clear that nanomaterials as advanced functional materials can enhance the efficiency of solar thermophotovoltaic devices. In general, solar energy is a significant source for fulfilling the required energy demands.

Author contributions

MD: conceptualization, writing, and editing of the manuscript. PP: supervision, writing, and editing of the manuscript. EM: writing and editing of the manuscript. NL: writing and editing of the manuscript. MS: writing and editing of the manuscript. AA: writing and editing of the manuscript. FO: review, writing, and editing of the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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