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A Comprehensive Review of $SnSe_xTe_{1-x}$ Chalcogenide Thin Films for Next-Generation Photovoltaics

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ABSTRACT

Global energy demand is projected to increase by nearly 1.5-fold by 2050, driven by fossil fuel depletion and the urgency of climate mitigation, thereby positioning thin-film photovoltaics as a critical component of sustainable energy transitions. This review traces the progression of solar-cell absorber materials-from crystalline silicon with efficiencies of ~27% and $CdTe/CuIn_xGa_{1-x}Se_2$ (CIGS) nanoparticle thin films with ~22%-toward earth-abundant chalcogenide ternaries such as $SnSe_xTe_{1-x}$ alloys. These materials exhibit tunable band gaps (0.9-1.5 eV), high absorption coefficients (>10^5 cm^{-1}), and theoretical efficiencies approaching 36% in optimised heterostructures. However, experimental power conversion efficiencies remain limited to about 2.5%, primarily due to intrinsic defects, non-radiative recombination, and challenges in scalable fabrication. Drawing on 2024-2025 data from the Energy Institute and the International Renewable Energy Agency (IRENA), this analysis underscores the non-toxic and earth-abundant advantages of $SnSe_xTe_{1-x}$, while contrasting them with the instability issues in perovskites and the phase complexity in kesterites. The review further highlights strategies such as bandgap engineering, atomic layer deposition (ALD)-based passivation, and multi-junction tandem architectures, along with scalable pulse laser deposition (PLD) routes, as promising approaches to achieving power conversion efficiencies exceeding 30%.

Keywords: $SnSe_xTe_{1-x}$ thin films, chalcogenide photovoltaics, bandgap engineering, thin-film solar cells, renewable energy transition, defect passivation.

INTRODUCTION

The world energy requirements have evolved significantly over the past decade, reflecting changes in technology, population, and economic development. In the pre-industrial era, global energy demand was very low and was mainly met through available natural resources. The Industrial Revolution marked a significant shift, with coal emerging as the dominant energy source and driving rapid industrial and urban growth. After World War II, energy consumption rose sharply as oil became the primary fuel for industrialisation and modern lifestyles. The energy crises of the 1970s prompted diversification toward natural gas, nuclear power, and early renewable technologies. However, the global energy landscape has undergone a drastic transformation due to the depletion of fossil fuel reserves, rising greenhouse gas emissions, and climate change. The global population, which is growing at about 2% annually, continues to intensify demand for energy, economic development, and improved living standards, driving rising consumption. Industrialised nations, which comprise roughly 25% of the global population yet account for approximately 75% of global energy use, are driving this trend. World population is expected to double by the middle of the 21st century [1,2], and economic development will almost certainly continue to grow. Global demand for energy services is expected to increase by as much as an order of magnitude by 2050, while primary-energy demands are expected to increase by 1.5-3 times [2-4]. In the twenty-first century, rising demand from emerging economies and growing awareness of climate change accelerated the shift towards sustainable energy. The rapid expansion of renewable energy, the increasing electrification of transport and industry, the integration of digital technologies, and widespread commitments to carbon neutrality collectively indicate a global transition toward a cleaner, more efficient, and technologically advanced energy system. These challenges have shifted global focus toward sustainable, cleaner, and environmentally compatible energy sources. Renewable energy technologies-especially solar, wind, hydro, geothermal, biomass, and tidal-

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are being adopted globally to ensure energy security, reduce emissions, and support economic development. Solar energy, in particular, is receiving unprecedented attention due to its abundance, scalability, and declining costs.

METHODOLOGY

This review paper was prepared through a systematic literature review across academic databases, including Web of Science, Scopus, Google Scholar, and ScienceDirect, focusing on publications from 2010 to 2025 on thin-film photovoltaics, with particular emphasis on chalcogenide semiconductors such as SnSe, SnTe, and $SnSe_xTe_{1-x}$ alloys [5]. Relevant studies were selected based on material properties (bandgap, absorption coefficient), device performance (PCE, stability), and synthesis techniques, yielding over 150 primary sources, which were categorised into silicon-based, CdTe/CIGS, perovskites, kesterites, and emerging IV-VI compounds. Data extraction involved compiling quantitative metrics-such as efficiency records, toxicity profiles, elemental abundance, and theoretical vs. experimental PCE gaps-into comparative tables and figures, including chronological flowcharts of material evolution. At the same time, qualitative analysis synthesised challenges, such as secondary phase formation, and proposed scalability solutions via bandgap engineering and interface passivation. Synthesis of findings employed a comparative framework to evaluate absorber materials against key performance indicators (e.g., absorption coefficient ~10^5 cm^{-1}, bandgap 0.9-1.5 eV), integrating recent 2024-2025 reports from IRENA and the Statistical Review of World Energy to contextualise global renewable trends. Gaps in the current literature, such as the disparity between SnSe's theoretical efficiency (36.45%) and experimental values (~2.5%), were identified by cross-referencing simulation studies with empirical data, informing future directions such as multi-junction heterostructures and non-toxic deposition methods (e.g., thermal evaporation, sputtering).

Global energy 2024

The Statistical Review of World Energy 2025 provides a comprehensive assessment of global energy supply, demand, and emissions for 2024, as shown in Fig. 1, revealing an energy system undergoing a rapid yet uneven transition. Global total energy demand grew by 2% in 2024, reaching 592 EJ (Exa joules, 1 EJ = 1018 joules), with non-OECD (Organisation for Economic Co-operation and Development) countries accounting for 63% of total supply and driving global consumption growth. Fossil fuels continued to underpin the energy landscape, accounting for 87% of global energy demand, while renewables expanded at a significantly faster pace than conventional fuels. Electricity demand grew 4%, outpacing total energy demand growth and signalling ongoing global electrification. Asia Pacific remained the central driver of energy trends, contributing 47% of global demand and 68% of global annual demand growth. Renewable energy continued to show the strongest momentum, with wind and solar growing by 16% and accounting for 53% of the global increase in electricity generation. China led global renewable expansion, accounting for 57% of global renewable additions and nearly 60% of renewable power supply growth. Over the past decade, renewable energy has grown at four to five times the rate of total energy demand. Since 2010, renewables and nuclear energy have collectively helped avoid 1,371 EJ of fossil fuel use. significantly improving global energy efficiency. Despite this, carbon emissions reached a record 40.8 $GtCO_2e$, up 1% from 2023 [6]. China and India were responsible for 62% of the global increase in emissions, while Europe and the US recorded modest declines. Fossil fuel combustion remained the dominant source of emissions, accounting for 87% of total energy-related greenhouse gas emissions. The report highlights that global emissions have grown by 2.3% annually since COVID-19, underscoring the difficulty of decoupling energy demand growth from emissions. Oil remained the most significant single energy source, meeting 34% of global demand. Global oil demand grew 0.7%, surpassing 101 Mbb l/d for the first time. OECD oil consumption plateaued, while non-OECD demand increased by 1%. The United States emerged as the world's largest oil producer, accounting for 20% of global output, roughly equal to the combined output of Saudi Arabia and Russia. Oil prices declined by 3%, though they remained significantly above pre-COVID levels. Natural gas production grew to 4,124 bcm, while global demand rose 2.5% after falling the previous year. The US, Russia, Iran, and China accounted for 53% of total production. Asia Pacific recorded the strongest regional growth in gas demand, while African gas demand declined slightly. Gas remained crucial to the global energy mix, meeting 29% of fossil fuel consumption and 25% of total energy demand. Coal demand reached a historic high of 165 EJ, with Asia Pacific accounting for 83% of global consumption and producing the largest regional surplus. China alone

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accounted for 67% of global coal consumption. Despite record renewable investment, coal remained central to electricity generation in China (58% of output) and India (~75%). In contrast, Europe's coal consumption fell 7%, dropping below nuclear energy's contribution for the first time. In the electricity sector, global generation grew 2.6% annually over the past decade. In 2024, renewables (including hydro) supplied 32% of electricity, while wind and solar contributed 15%, a fourfold increase over ten years. Installed solar capacity rose to 1,865 GW, four times the rate of wind additions, with China accounting for 47% of global wind and solar capacity. Grid-scale battery storage saw remarkable growth, doubling to 126 GW, again led by China, which accounted for 60% of global installed capacity [7]. Investment in renewables is increasingly associated with energy security, reducing reliance on imported fuels. China avoided 87 EJ of imports over five years due to renewable expansion, while Europe and the US avoided 63 EJ and 34 EJ, respectively. However, countries heavily reliant on imports-such as Japan and South Korea-realised limited avoided fuel imports, highlighting missed opportunities in renewable deployment. Overall, the 2025 Review concludes that although renewables are accelerating and electrification is expanding rapidly, these advances are not yet sufficient to offset growing global energy demand and continued reliance on fossil fuels. The world remains in a phase of "energy addition" rather than substitution, leading to a disorderly, uneven transition toward a low-carbon future.

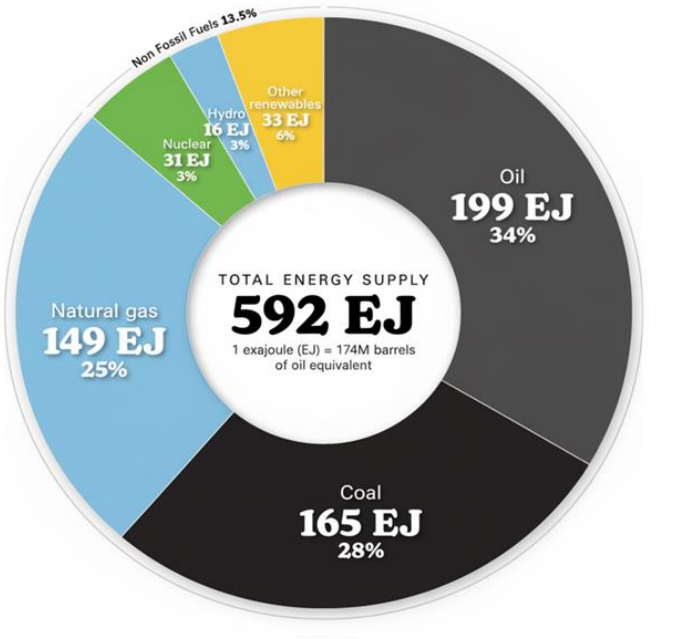


Fig. 1: Global energy consumption [5]

Accelerating clean energy transitions

The "Climate Action Support 2025" report by IRENA outlines urgent global efforts to address climate change by accelerating the adoption of renewable energy and improving energy efficiency. Key points include: The world is experiencing record-high greenhouse gas levels and a warming trend, with 2024 the warmest year on record, necessitating urgent climate action to keep warming below 1.5°C. Renewable power capacity grew by 582 GW in 2024, primarily driven by solar PV and wind, with Asia leading growth (especially China). Global renewable power reached 4,443 GW by the end of 2024, but a more rapid scale-up is required to meet the COP28 UAE Consensus target of tripling capacity by 2030. Energy transition investment surpassed $2 trillion in 2024 but remains well below the $5.6 trillion annually needed through 2030 to stay on a net-zero emissions path by 2050. Technological advances have dramatically lowered costs, making most renewables more competitive than fossil fuels. Battery energy storage systems and digitalisation are essential technology enablers for grid flexibility and higher renewable integration.

The report highlights the importance of Nationally Determined Contributions (NDCs) under the Paris Agreement [8]. As of late 2025, 104 countries had submitted updated NDCs 3.0 with more ambitious renewable energy and energy efficiency targets, aligned with the UAE Consensus. These NDCs outline sectoral commitments,

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including renewable energy expansion, electric vehicles, clean cooking, and a phase-out of fossil fuels. Challenges include mobilising finance, addressing regulatory frameworks, and building capacity. IRENA actively supports countries worldwide (102 countries engaged) with technical assistance on NDC development, renewable resource assessment, policy, finance, energy transition technologies, and capacity building. Regional overviews show varying but progressive renewable energy additions and energy efficiency improvements, with Africa focusing on expanding access and resource assessment, Asia Pacific on scaling deployment, and Europe and Latin America setting ambitious climate targets and policy measures. The report also addresses the critical roles of climate finance, carbon markets, and international co-operation in bridging investment gaps and facilitating technology deployment, emphasising that clean energy transitions will bring socioeconomic and environmental co-benefits globally. Ecological and health concerns have driven a global shift toward renewable energy, offering cleaner, more sustainable alternatives. Renewable sources like solar, wind, and hydropower produce little to no pollution or greenhouse gases, mitigate climate change, and have rapidly declining costs, making them increasingly competitive. The shift to renewables also promotes energy security by diversifying supply and reducing dependence on finite resources. Though renewable energy also faces challenges such as intermittency and infrastructure needs, it is critical for achieving sustainable development and a low-carbon future, offering a necessary transition away from the disadvantages of conventional fuels, from extraction to global environmental impact and ultimately to sustainable alternatives.

Renewable energy sources derive from natural processes that continuously replenish themselves, offering sustainable alternatives to finite fossil fuels. Primary renewable sources include solar, wind, hydropower, biomass, and geothermal energy, each harnessing natural phenomena to produce electricity, heat, or fuel with far lower environmental impacts. Solar energy is captured via photovoltaic cells or concentrated solar power systems, providing a vast, widely accessible resource. Wind energy utilises the kinetic energy of moving air to generate power, often in land-based and offshore installations. Hydropower exploits the energy from flowing or falling water, historically the largest source of renewable electricity worldwide. Biomass energy derives from organic materials such as plant residues and waste, which can be converted into heat, electricity, or biofuels. Geothermal energy taps into the Earth's internal heat for power generation and direct use applications. Collectively, these renewables help reduce greenhouse gas emissions, enhance energy security, and provide cleaner energy options, which are essential for mitigating climate change and achieving sustainable development goals. Solar energy is the radiant light and heat from the Sun, harnessed as one of the most abundant and versatile renewable resources, capable of meeting global energy needs many times over with minimal environmental impact. The IRENA Renewable Capacity Statistics 2025 report highlights record growth and ongoing challenges in the worldwide energy transition. In 2024, renewable energy capacity increased by a historic 585 GW, as shown in Fig.2, expanding global renewable power stock by 15.1%. Renewables accounted for 92.5% of all new power additions, predominantly driven by solar (452 GW) and wind (113 GW) energy. Despite this progress, major disparities remain, with China, the United States, and the European Union responsible for 83.6% of new capacity, while Africa and other regions lag. By the end of 2024, renewables accounted for 46.2% of total installed power capacity globally, rapidly approaching fossil fuels, which stood at 47.3%. Yet, the current growth trajectory remains insufficient to meet the COP28 goal of tripling renewable capacity to over 11 TW by 2030. To achieve this, annual additions must exceed 1,120 GW, requiring an accelerated growth rate of 16.6% per year, above the 15.1% recorded in 2024. Solar and wind dominate expansion, accounting for 97.5% of renewable capacity growth, reflecting their cost-effectiveness and scalability. Other renewables, such as hydropower, bioenergy, and geothermal, grew modestly but remain quantitatively less significant. The report underscores the urgency for faster deployment globally, addressing financing and technology access disparities to ensure a just and inclusive transition [8].

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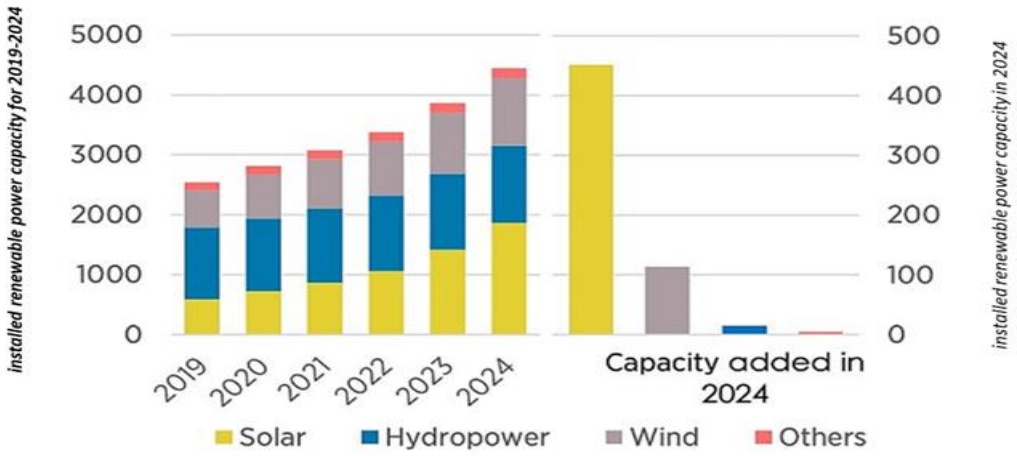


Fig. 2: Renewable power capacity growth [8]

Solar energy harvesting

Its limitless supply and global accessibility set solar energy apart. The Earth receives approximately 173,000 TW of solar energy continuously-thousands of times higher than present global energy requirements. Efficient capture, conversion, and storage of this energy are essential for achieving long-term sustainability. The Sun emits electromagnetic radiation across the UV, visible, and IR spectra via nuclear fusion, providing an inexhaustible source of clean power [9]. Only about 51% of solar radiation reaches Earth's surface, creating both a technical challenge and a design opportunity for efficient solar energy conversion systems.

Global mission of solar energy

The global mission of solar energy programs, as depicted in Fig.3, seeks to harness the Sun's inexhaustible energy to realise a sustainable, clean, and secure energy future, confronting pressing challenges such as climate change, energy insecurity, and environmental degradation while advancing green economic growth and universal energy access. Central to this vision is the promotion of clean, renewable power generation to curtail greenhouse gas emissions and mitigate global warming, alongside reducing fossil fuel dependence to enhance energy security, particularly in developing nations abundant in solar resources yet constrained by infrastructure deficits. These initiatives prioritise equitable energy access for underserved populations, spur technological innovation in photovoltaics, energy storage, and smart grids, and catalyse international collaboration to fortify the renewable ecosystem, ultimately fostering green employment and alignment with Sustainable Development Goals (SDGs) for an environmentally responsible, economically viable, and socially inclusive global energy transformation [9,10].

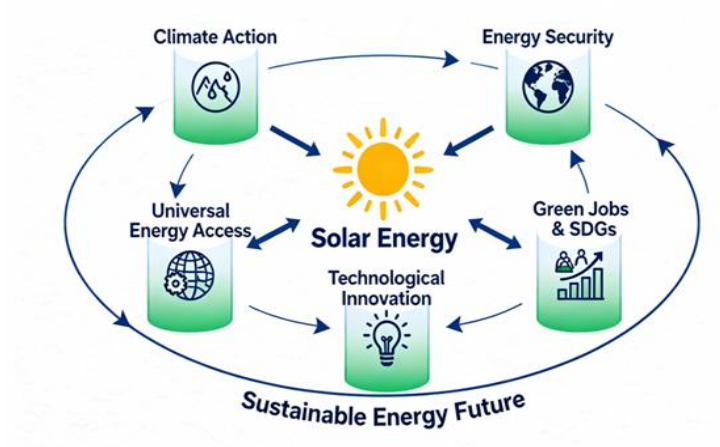


Fig. 3: Global mission of solar energy

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Solar energy harvesting

The Sun, a massive sphere of hot plasma at the heart of our solar system, emits energy in the form of photons that make up the solar spectrum. If even a fraction of the Sun's immense energy could be efficiently harnessed, it would be sufficient to meet all global electricity demands. The Sun's composition primarily includes about 75% hydrogen and 25% helium, structured into four key layers: the core, photosphere, chromosphere, and corona, as depicted in Fig. 4. Solar energy is generated in the Sun's core through nuclear fusion, where hydrogen nuclei fuse to form helium, releasing tremendous heat and light energy. This fusion occurs at extremely high temperatures reaching approximately 15 million degrees Celsius in the core, while the Sun's surface temperature is about 5,505 °C (5,778 K) [11]. The dominant fusion pathway is the proton-proton (PP) chain reaction, which converts hydrogen into helium and emits vast amounts of energy as electromagnetic radiation. Energy produced in the core travels outward through the radiation and convection zones to the photosphere, from which it radiates into space. Additionally, the Sun employs the carbon-nitrogen-oxygen (CNO) cycle, which uses these elements as catalysts to facilitate hydrogen-to-helium fusion. The Sun fuses around 620 million metric tonnes of hydrogen every second, powering the constant flow of radiant energy.

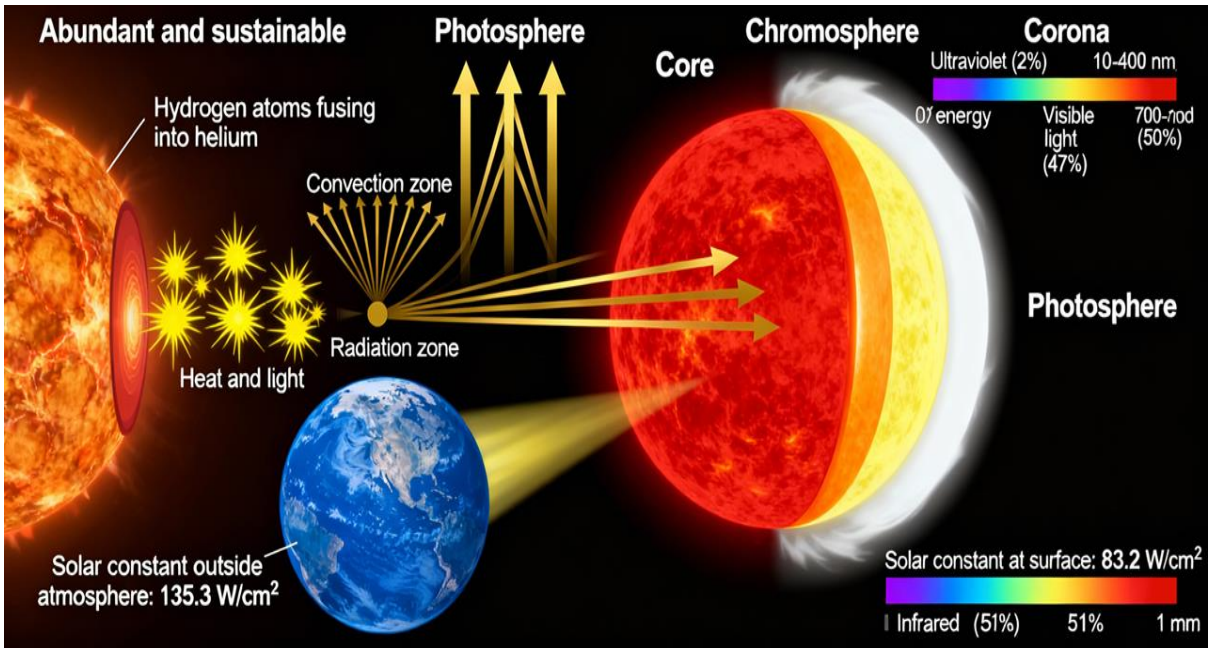


Fig. 4: Structure of the Sun, Nuclear Fusion Process, Solar Spectrum, and Solar Energy Flow to Earth

Upon reaching Earth, solar energy appears as electromagnetic waves encompassing a broad spectrum of wavelengths. This solar spectrum varies with atmospheric conditions and altitude, and is often classified by air mass (AM) units. Outside Earth's atmosphere (AM0), the solar constant-total solar irradiance-is about 1353 W/m². At the Earth's surface, this value decreases to around 1000 W/m² under AM1 conditions and further to about 832 W/m² under AM1.5 due to atmospheric absorption and scattering [12]. The solar spectrum is divided into three primary regions: ultraviolet (UV, <0.38 µm), visible light (0.38–0.78 µm), and infrared (IR, >0.78 µm). The UV region contributes approximately 2% of the total energy, the visible region accounts for about 47%, and the IR region delivers the largest share at 51% of the solar energy reaching Earth. Fig. 5 (a-b) illustrates these spectral components, highlighting the colour band visible to the human eye. Of the total solar radiation incident on Earth, about 51% passes through and reaches the surface, while the atmosphere reflects roughly 35% back into space and absorbs the remaining 14%.

Earth continuously receives an average of about 173,000 terawatts (TW) of solar energy, which exceeds global energy consumption by thousands of times. This vast, renewable energy source, derived directly from the Sun's fusion process, is the most plentiful and sustainable resource for powering human civilisation.

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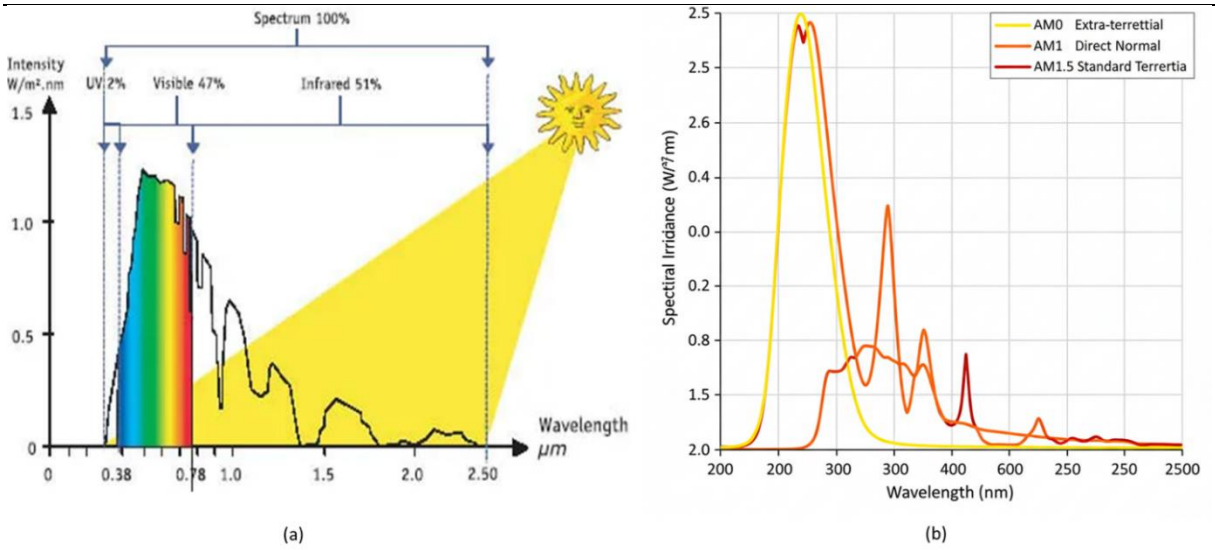


Fig. 5: (a) The spectrum of solar radiation, (b) spectral distribution of solar energy and atmospheric effects

Photovoltaic effect and solar cells

Photovoltaic (PV) solar cells convert incident photons into electrical energy via semiconductor materials, typically structured as p-n junctions [13,14]. The operation hinges on bandgap properties and carrier-separation mechanisms, which are influenced by material composition, crystal structure, and thin-film architecture.

Photovoltaic principle

The photovoltaic effect is the process by which solar cells convert sunlight directly into electricity. When sunlight, composed of photons, strikes a semiconductor solar cell (usually silicon), the photons' energy is absorbed, exciting electrons and freeing them from their atomic bonds. This generates electron-hole pairs [15].

The solar cell has a p-n junction formed by p-type and n-type semiconductor layers as shown in Fig. 6, which creates an internal electric field. This electric field drives the separated electrons towards the n-type layer and holes towards the p-type layer, thus preventing recombination and enabling charge separation. The free electrons are then collected by metal contacts on the solar cell surface, generating an electric current that can flow through an external circuit to power electrical devices. This flow of electrons constitutes usable electrical energy [15,16].

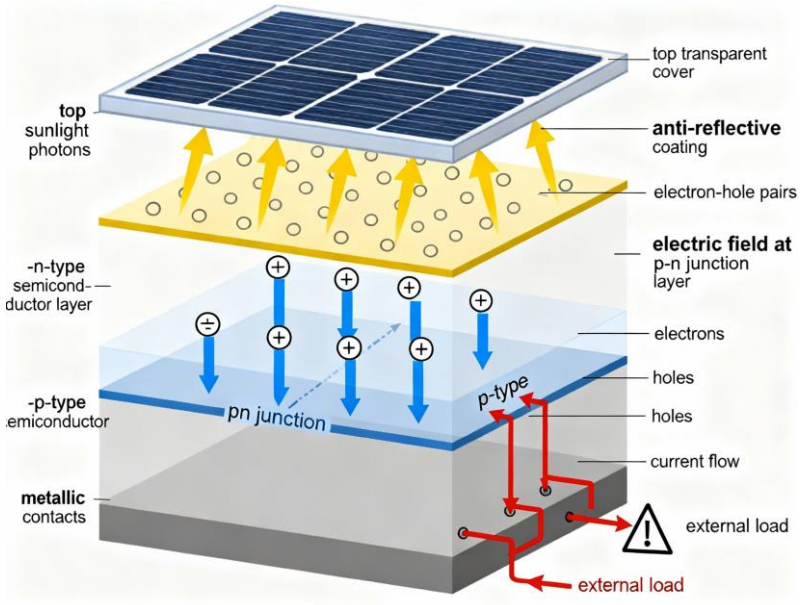


Fig. 6: Principle of photovoltaic effect

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Semiconductors in photovoltaics

There is a rising demand for renewable energy as fossil fuel assets and other resources are insufficient to meet the world's increasing energy requirements. Developing renewable and sustainable energy sources and devices has been essential to meet global energy demands [17]. Photovoltaic electricity is considered one of the most promising solutions for sustainable energy needs. Extensive research has been dedicated to the development of thin-film photovoltaics, which not only lowers the production costs of solar cells but also supports green energy initiatives worldwide. In recent years, significant progress has been achieved in this field [18-20]. Power generation from photovoltaic (PV) solar cells has gained attention due to rapid technological advances and the development of alternative materials [21].

Initially, the Silicon industry dominated 80% of the solar market, with crystalline silicon solar cells reaching a record efficiency of 25%. However, silicon-based solar cells utilise an absorber layer thickness of 100 µm. Furthermore, the requirement for producing single-crystal absorber substrates significantly increased manufacturing costs [22]. On the contrary, thin-film solar cell (TFSC) technology relies on direct-bandgap absorber materials such as cadmium telluride (CdTe) and copper indium gallium diselenide (CIGS). Due to these materials' high absorption coefficient (~10^5 cm^{-1}), a thicker absorber layer is not required, enabling reliable performance with thin films of 1-2 µm that absorb nearly all incident solar radiation [6]. CdTe has reached a maximum power conversion efficiency (PCE) of 22.1%, while CIGS has 22.6% [23]. However, CdTe contains the toxic element Cadmium (Cd) and the rare-earth element Telluride (Te), and CIGS contains the expensive elements Indium (In) and Gallium (Ga); further, Selenium (Se) is toxic [24,25]. Further, researchers around the globe are exploring earth-abundant, cheap, and non-toxic materials-based solar cells. Perovskite thin films have recently garnered significant attention for their potential in next-generation solar cells, surpassing their Silicon counterparts due to their promising advantages, including high efficiency, lower costs, flexibility, and tunable optoelectronic properties [26,27]. However, perovskite-based solar cells face stability and toxicity challenges, limiting their commercial viability. Kesterite materials, Copper zinc tin Sulphide (CZTS), are also a part of the present initiative [25,28]. The parameters of some key absorber layers used for the fabrication of photovoltaic cells are presented in Table 1 [29].

Table 1: Key parameters of single-junction terrestrial cell measured under the global AM1.5 spectrum (1000 W/m^2) at 25C (IEC 60904-3: 2008 or ASTM G-173-03 global) [29]

Classification	**Efficiency**	**Area**	**V_{oc} (V)**	**J_{sc} (mA/cm2)**	**FF (%)**
Si (crystalline)	25.0 ± 0.5	4.00 (da)	0.706	42.7	82.8
CIGS (thin-film)	23.6 ± 0.4	0.899 (da)	0.767	38.30m	80.5
CIGSSe (sub module)	20.3 ± 0.4	526.7 (ap)	0.683	39.55	75.1
CdTe (thin-film)	22.4 ± 0.3	0.450 (da)	0.900	31.4	79.3
CZTS (thin-film)	11.4 ± 0.3	0.204 (da)	0.746	21.79	69.9
CZTSSe (cell)	12.1 ± 0.3	1.066 (da)	0.538	35.29k	63.6
Perovskite (thin-film)	26.1 ± 0.5	0.051 (da)	1.201	25.73	84.6
Organic (thin-film)	19.2 ± 0.3	0.033 (da)	0.914	26.61	79.0
Dye sensitised	13.0 ± 0.4	0.116 (da)	1.040	15.55	80.4

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ap (aperture)

da (designated illuminated area)

However, the probability of the formation of secondary phases in the (CZTS) is high due to the involvement of more elements (Cu, Zn, Sn and S). The pure CZTS phase has a narrow region in the phase diagram, but controlling its composition is challenging [25]. Thus, the research efforts have been focused on identifying alternative materials to address these challenges. Efforts are on to explore alternative materials that are less toxic and more cost-effective. Some binary IV-VI compounds are attracting more attention in the pursuit of new semiconductor thin-film materials for solar energy [30-33]. Among these, Tin chalcogenides, especially SnSe and SnTe, have emerged as promising candidates. In addition to their desirable physical properties, the abundance, low toxicity, and low environmental impact of the constituent elements are additional advantages for large-scale application [34-38]. The $SnSe_xTe_{1-x}$ ($0 \leq x \leq 1$) semiconductor alloy-based thin films show variation in their energy bandgap (E_g) due to changes in composition and thus absorb different regions of the E.M. spectrum [39]. The element Sn, which has been replaced with Cd in research on IV-VI semiconductor compounds to create ecologically friendly absorber layers for photovoltaic devices [33]. Due to its high absorption coefficient (10^5 cm^{-1} at the visible region) and forbidden gap energy in the range of 0.9-1.5 eV, SnSe, a p-type semiconductor material, has been studied as an additional alternative absorber layer for the heterojunction solar cells in addition to the alternative material SnTe [39]. The highest theoretical simulation-based efficiency reported to date for the SnSe solar cell is about 36.45% for the n-CdS/p-SnSe/p+/$CuInSe_2$/p^{++}-WSe_2 heterostructure device—modelling and efficiency enhancement of SnSe thin-film solar cell with a thin CIS layer. At the same time, its experimental efficiency is only 2.5%, providing ample scope for further research on thin-film solar cells. $SnSe_xTe_{1-x}$ has shown improvements in high photosensitivity, crystalline structure, and strength [40]. With a direct bandgap of roughly 1.24 eV and a high absorption coefficient (~10^4 cm^{-1}), tin selenide (SnSe) has been used successfully as an absorber layer in solar cell topologies [41]. By altering the tellurium (Te) and selenium (Se) composition, the alloy equivalent $SnTe_xSe_{1-x}$ ($0 \leq x \leq 1$) exhibits a variable bandgap, enabling it to absorb light across the entire electromagnetic spectrum [42]. $SnTe_xSe_{1-x}$ thin films have demonstrated potential for thermoelectric devices that convert waste heat into energy, as well as for solar applications. Zinc Telluride (ZnTe) is a chalcogenide material belonging to A^{II}-B^{VI} semiconductors. It exhibits a direct bandgap of 2.26 eV, an absorption coefficient of ~10^5 cm^{-1}, and an electron affinity of ~ 3.53 eV [43-47]. It is a promising material due to its potential applications in various electronic devices, including light-emitting diodes, solar cells, photosensors, photodetectors, thin-film transistors, and laser diodes [48]. The chronology of the different materials for photovoltaic applications is shown in Fig. 7.

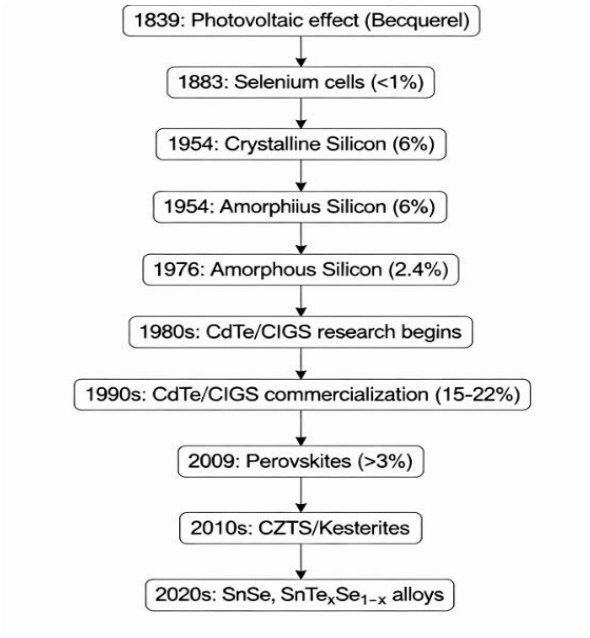


Fig. 7: Evolution of photovoltaic absorber materials: Chronological timeline

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In addition to the above text, the historical improvement in photovoltaic technologies is commonly summarised using the National Renewable Energy Laboratory's chart (Fig. 8), which compiles record conversion efficiencies reported by leading laboratories across all prominent solar-cell families. This dataset shows that multi-junction devices based on III–V compound semiconductors occupy the very top of the efficiency landscape, with recent concentrator cells from institutes such as Fraunhofer ISE approaching efficiencies near one-half under high illumination, but at the expense of complex epitaxial growth, sophisticated device designs and correspondingly high costs that confine them mainly to space and concentrator applications. In contrast, crystalline silicon technologies, which dominate commercial deployment because of mature manufacturing and material abundance, have progressed steadily from early values around 10% in the 1970s to nearly 27–28% in today's champion cells, thus operating close to the Shockley-Queisser limit for a single-junction Si device. Thin-film technologies such as CdTe and CIGS occupy an intermediate position, combining lower material use and potentially cheaper module fabrication with record efficiencies in the low-to-mid-20% range. Over roughly the past decade, the NREL chart also documents the rapid ascent of perovskite and perovskite/silicon tandem cells, with perovskite single-junction records moving from a few percent to above 25% and monolithic tandems recently surpassing 33%, clearly indicating that tandem and multi-junction concepts based on perovskites and silicon are emerging as leading candidates for next-generation high-efficiency photovoltaic technologies.

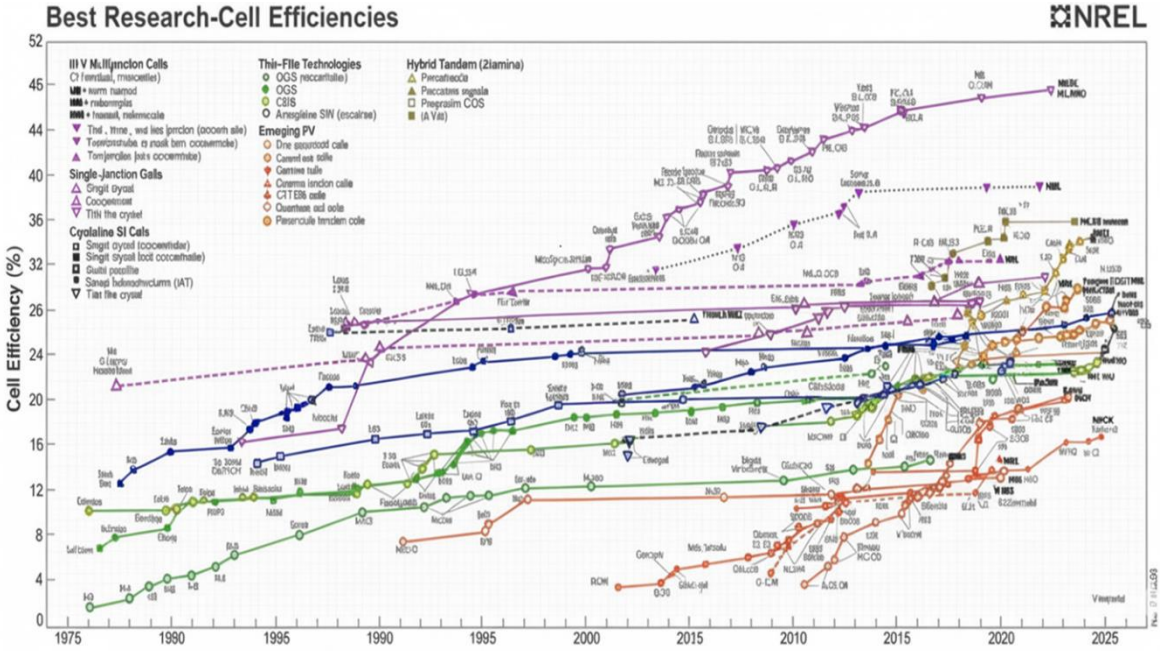


Fig.8: Efficiencies of various photovoltaic cells documented by the National Renewable Energy Laboratory (NREL), USA.

Challenges

Chalcogenide semiconductors, particularly $SnSe_xTe_{1-x}$ ternary alloys, exhibit promising optoelectronic properties for thin-film photovoltaic applications, yet several persistent challenges impede their transition from laboratory prototypes to commercial viability. A primary limitation lies in the short carrier lifetimes, primarily due to high recombination rates induced by intrinsic defects, such as vacancies and anti-site disorders, prevalent in these multi-component systems. These defects elevate non-radiative recombination centres, significantly reducing the open-circuit voltage (V_{oc}) and fill factor (FF) in fabricated devices, with experimental efficiencies stagnating around 2.5% compared to theoretical maxima exceeding 36% in simulated heterostructures. Concurrently, elevated defect densities—often exceeding 10^{16} cm^{-3}-arise from challenges in achieving stoichiometric control during deposition processes such as thermal evaporation or sputtering, exacerbating band tailing and energy broadening, and thereby degrading absorption efficiency across the visible spectrum. Scalable synthesis represents another formidable barrier, as current laboratory-scale techniques, including molecular beam epitaxy (MBE) and chemical bath deposition, struggle to achieve uniformity over large areas (>100 cm^2) required for industrial roll-to-roll processing. Interface passivation at critical junctions, such as $SnSe_xTe_{1-x}$ /CdS

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or $SnSe_xTe_{1-x}$ /back contact interfaces, remains suboptimal, leading to Fermi-level pinning and increased series resistance that curtail short-circuit current density (Jsc). Moreover, environmental stability under accelerated conditions reveals rapid degradation due to oxidation of Sn and Se/Te chalcogens, resulting in phase segregation and up to 50% efficiency loss within 1000 hours, underscoring the need for robust encapsulation strategies.

Future scope

To overcome these hurdles, future investigations must prioritise bandgap engineering through precise compositional tuning of the Se:Te ratio, enabling tunable absorption from 0.9-1.5 eV to optimise lattice matching in tandem architectures with wide-bandgap perovskites or a-Si. Integration into multi-junction devices holds transformative potential, where $SnSe_xTe_{1-x}$ could serve as a mid-bandgap absorber (Eg ≈1.2 eV) in triple-junction configurations, potentially surpassing 30% efficiency via current matching and spectral splitting, as validated by recent SCAPS-1D simulations incorporating thin CIS interlayers. Advancements in interface engineering, including atomic layer deposition (ALD) of Al_2O_3 or ZnO passivation layers, are imperative to suppress surface recombination velocities below 10^3 cm/s and enhance hole selectivity at the rear contact. Scalable synthesis optimisation-via high-throughput methods such as close-space sublimation (CSS) or pulsed laser deposition (PLD)-should target defect densities $<10^{15}$ cm-de 3 and film thicknesses of 1-2 μm with >95% uniformity, facilitating the development of pilot-scale modules. Long-term stability enhancements through alloying with earth-abundant dopants (e.g., Na, Cu) and hybrid encapsulation with graphene barriers will be crucial, alongside comprehensive techno-economic analyses to benchmark against CdTe/CIGS benchmarks under IEC 61646 standards. These concerted efforts, informed by ongoing global research, position $SnSe_xTe_{1-x}$ as a frontrunner in sustainable, non-toxic thin-film photovoltaics.

CONCLUSIONS

Chalcogenide semiconductors, exemplified by $SnSe_xTe_{1-x}$ ternary thin films, have emerged as a compelling class of earth-abundant, non-toxic absorber materials poised to address the limitations of conventional thin-film photovoltaics, such as CdTe and CIGS, which face toxicity and scarcity concerns. Their tunable bandgap, high absorption coefficient, and p-type conductivity enable efficient photon harvesting across the solar spectrum, with theoretical efficiencies approaching 36% in advanced heterostructures, far surpassing current experimental benchmarks of ~2.5%. This review has elucidated the evolution of photovoltaic absorber materials, from silicon dominance to thin-film innovations, underscoring $SnSe_xTe_{1-x}$'s potential in fostering sustainable energy solutions amid escalating global demands projected to rise 1.5-fold by 2050. Despite these advantages, persistent challenges-including short carrier lifetimes, high defect densities, scalability constraints, suboptimal interface passivation, and environmental instability-must be systematically resolved to unlock commercial viability. Future research trajectories emphasise bandgap engineering via Se:Te compositional gradients, integration into multi-junction tandems with perovskites, atomic layer deposition for interface optimisation, and scalable techniques such as close-space sublimation for large-area deposition with defect densities below 10^{15} cm^{-3}. Concurrently, alloying strategies and graphene-based encapsulation promise enhanced stability under IEC 61646 protocols, bridging the gap to efficiencies competitive with established technologies. In summary, $SnSe_xTe_{1-x}$ chalcogenides represent a paradigm shift toward eco-friendly, cost-effective photovoltaics, aligning with global sustainability goals and the COP28 target to triple renewable capacity by 2030. Sustained interdisciplinary efforts in materials synthesis, device architecture, and techno-economic modelling will propel these materials from niche research to widespread deployment, significantly advancing the transition to a low-carbon energy future.

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