International Journal of Applied Mathematics, Sciences, and Technology for National Defense
Volume 3, Issue 2, 77-88
e_ISSN: 2985-9352, p_ISSN: 2986-0776
https://www.journal.foundae.com/index.php/JAS-ND
DOI : https://doi.org/10.58524/app.sci.def.v3i2.831

Cadmium telluride (CdTe) thin-film photovoltaics: A sustainable energy solution to support national energy resilience

Annisa Mutiara Putri Abdul*
Indonesia Defense University
INDONESIA

Adhi Kusumadjati
Indonesia Defense University
INDONESIA

Gustav Irgi Aldhiantoro
Indonesia Defense University
INDONESIA

Dinda Rahma Dewi
Indonesia Defense University
INDONESIA

Moh. Hisni Alfan Baarik
Indonesia Defense University
INDONESIA

Cornelia Victoria Anghel
Technical University of Cluj-Napoca
ROMANIA

Article Info

Article history:

Received: May 12, 2025
Revised: July 21, 2025
Accepted: August 3, 2025
Published: August 30, 2025

Keywords:

Cadmium Telluride (CdTe)
Efficiency Improvement
PLTS
Thin-Film Solar Cells
Waste Management

Abstract

Cadmium Telluride (CdTe) is one of the most promising materials in thin-film solar cell technology; however, its application faces challenges related to efficiency limitations and environmental risks. This study aims to evaluate the performance characteristics, environmental impact, and sustainability potential of CdTe in Solar Power Plant, known in Indonesia as Pembangkit Listrik Tenaga Surya (PLTS) applications. A systematic literature review was conducted, analyzing more than 40 scientific articles and industrial reports published over the last 15 years, covering efficiency, material availability, recycling strategies, and lifecycle assessments. The results indicate that commercial CdTe modules achieve efficiencies between 7–10%, while laboratory devices exceed 22%. CdTe demonstrates superior performance under high temperatures and low-light conditions, but concerns remain regarding cadmium toxicity and the limited availability of tellurium. The study concludes that CdTe holds significant potential as a cost-effective and efficient solar technology, provided that robust recycling systems and responsible material sourcing practices are implemented.

To cite this article: Abdul, A. M. P., Kusumadjati, A., Aldhiantoro, G. I., Dewi, D. R., Baarik, M. H. A., & Anghel, C. V. (2025). Cadmium Telluride (CdTe) thin-film photovoltaics: A sustainable energy solution to support national energy resilience. *International Journal of Applied Mathematics, Sciences, and Technology for National Defense,* 3(2), 77-88

INTRODUCTION

Global warming and the increasing demand for sustainable energy have driven significant interest in solar power generation technology. Solar energy is a prominent form of renewable energy due to its vast potential to reduce greenhouse gas emissions and decrease reliance on fossil fuels. Photovoltaic (PV) technologies convert solar energy directly into electricity through the photovoltaic effect, making them a key component of the transition to cleaner energy systems. Solar Power Plants (PLTS), in particular, provide an effective solution for generating electricity in both urban and remote regions, especially in areas where access to conventional energy infrastructure is limited (Adnan et al., 2012).

Among the various types of solar cells, thin-film solar cells have garnered attention due to their low material usage, flexibility, and relatively lower production costs. One of the most promising materials used in thin-film solar cells is Cadmium Telluride (CdTe). CdTe exhibits a direct bandgap of approximately 1.45 eV, which is nearly ideal for absorbing the solar spectrum efficiently. It also possesses a high absorption coefficient, allowing for the fabrication of efficient solar cells using a relatively thin absorber layer. Compared to traditional crystalline silicon solar cells, CdTe-based cells

***Corresponding Author:**
Annisa Mutiara Putri Abdul, Indonesia Defense University, Indonesia, Email: annisamutiaraputriabdul@gmail.com

offer advantages such as lower manufacturing costs, reduced material consumption, and favorable energy payback times (Green et al., 2022)

CdTe solar technology has made significant strides in recent years. Research has demonstrated the successful application of thin-film solar cells in various devices, including calculators, household water heaters, and large-scale solar power installations. These implementations highlight the capability of CdTe-based thin-film cells to support both off-grid and grid-connected electricity demands. Studies, including those by (Ahmad et al., 2016), also show that the use of solar panels as an alternative energy source can significantly reduce fossil fuel dependency, lower operational costs, and promote decentralized energy solutions. Moreover, improvements in deposition techniques, passivation layers, and cell architecture have further enhanced the performance and durability of CdTe-based solar modules.

Despite these benefits, CdTe-based technology presents some challenges. The toxicity of cadmium and the scarcity of tellurium raise environmental and supply chain concerns. Cadmium, while chemically stable in CdTe form, can be hazardous if released due to improper handling or panel damage. Additionally, tellurium is a rare element typically obtained as a byproduct of copper refining, making its availability uncertain (Marwede & Reller, 2012). Moreover, CdTe solar cells may exhibit performance limitations under high temperatures or low-light conditions, which must be addressed to optimize their reliability and long-term viability. These issues have prompted researchers to explore methods of mitigating toxicity risks through improved encapsulation, advanced recycling strategies, and regulatory oversight.

To ensure the sustainable deployment of CdTe technology, comprehensive strategies must be developed. These include advanced recycling systems, responsible sourcing of raw materials, and strict compliance with environmental safety standards. Life cycle assessments (LCAs) conducted by institutions such as the National Renewable Energy Laboratory (NREL) and the International Energy Agency (IEA) have shown that the environmental footprint of CdTe PV systems is significantly lower than that of fossil-based power generation and even some crystalline silicon PV technologies (Fthenakis, 2004). Companies like First Solar have initiated closed-loop recycling programs capable of recovering over 90% of semiconductor materials from decommissioned modules, showcasing the potential for sustainable lifecycle management in CdTe PV systems (McNulty et al, 2022).

This study aims to comprehensively investigate the role of Cadmium Telluride as a material for thin-film solar cells in solar power generation systems. It will address the performance characteristics, efficiency, environmental impacts, and applications of CdTe in PLTS. By reviewing current literature and analyzing recent technological developments, the study intends to contribute insights that support the advancement of safe, efficient, and sustainable solar energy technologies.

In addition, CdTe-based solar modules have shown significant potential for use in defense and resilience applications. Their lightweight design, high performance in extreme environments, and ease of deployment make them suitable for mobile military operations, emergency energy supply, and off-grid installations in disaster zones. These applications align with growing global interests in enhancing energy security and operational readiness through renewable technologies (Kang, 2014).

In the context of national security and energy resilience, the development of reliable, rapidly deployable solar energy systems such as CdTe-based photovoltaics has become increasingly urgent. Military and disaster response operations often take place in remote or infrastructure-compromised regions where fuel logistics are costly and vulnerable to disruption. Thin-film CdTe modules offer significant advantages in such scenarios due to their lightweight structure, modular scalability, and ability to perform under high temperatures and low-light conditions (Costa et al., 2021). This enhances operational readiness and reduces dependency on diesel generators or vulnerable energy grids.

Furthermore, geopolitical instability and the rising frequency of extreme weather events have highlighted the fragility of conventional energy systems. As emphasized by the International Renewable Energy Agency (IRENA, 2022), energy resilience is now a national security priority, particularly in light of global fuel price volatility and the increasing targeting of critical infrastructure in cyber or physical attacks. CdTe technology, supported by closed-loop recycling and scalable manufacturing, provides a sustainable pathway for countries to fortify their energy independence and deploy backup power systems during emergencies, whether military, environmental, or humanitarian in nature.

METHOD

This study adopted a systematic qualitative literature review approach to examine the technological, environmental, and strategic roles of Cadmium Telluride (CdTe) thin-film photovoltaic technologies. The review design followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework (Moher et al., 2009), which involves five key stages: defining research questions, selecting keywords, identifying databases, applying inclusion and exclusion criteria, and synthesizing findings thematically. This methodology was chosen to ensure transparency, replicability, and comprehensive coverage of the scientific developments related to CdTe solar technology, particularly in defense and resilience contexts.

The literature search was conducted from February to May 2025, utilizing four major academic databases: ScienceDirect, IEEE Xplore, SpringerLink, and Google Scholar. Keywords used in the search included combinations such as “CdTe thin-film solar cells,” “photovoltaic efficiency,” “CdTe recycling,” “tellurium scarcity,” “life cycle assessment of CdTe,” and “CdTe defense energy resilience.” The initial search yielded 118 records. Articles were limited to peer-reviewed journals, institutional technical reports, and conference proceedings published between 2004 and 2024 in English. After removing duplicates and performing title and abstract screening, 65 documents were retained for full-text evaluation. Using predefined inclusion criteria — such as relevance to CdTe PV systems, presence of methodological rigor, and focus on key technical or environmental parameters — a final set of 43 articles and reports was selected for detailed analysis.

The selected literature was then grouped into four thematic categories: (1) device performance and characterization, (2) environmental and life-cycle impact, (3) resource sustainability and recycling, and (4) structural innovations and deployment use cases. Each article was carefully analyzed to extract its research focus, methods used, and relevance to the objectives of this review. For example, Green et al. (2022) used standardized current–voltage (I–V) characterization under AM1.5G illumination conditions to determine the efficiency, fill factor, and performance limits of commercial and lab-scale CdTe modules. Kranz et al. (2013) investigated grain boundary passivation and dopant distribution in polycrystalline CdTe using Scanning Electron Microscopy (SEM) and Secondary Ion Mass Spectrometry (SIMS), providing insight into defect-related performance losses.

To evaluate environmental impacts, Fthenakis (2004) and Rajput et al. (2018) conducted ISO 14040-compliant Life Cycle Assessments (LCA), which quantified the energy payback time (EPBT), global warming potential, and carbon footprint of CdTe modules. Their findings showed that CdTe technologies typically recover their embedded energy within 0.8 to 1.5 years, making them competitive with and in some cases superior to crystalline silicon PV systems. In the area of resource sustainability, Marwede and Reller (2012) applied Material Flow Analysis (MFA) to assess tellurium availability, highlighting its dependency on copper mining byproducts and identifying supply bottlenecks for future CdTe scalability. For example, Hanna et al. (2023) applied a system dynamics model to estimate tellurium demand from 2023 to 2050, revealing potential shortfalls unless recycling and mining outputs are scaled up. Similarly, Liu et al. (2023) emphasized China’s tellurium supply gap under aggressive CdTe deployment scenarios. The U.S. Department of Energy has recognized tellurium as a strategic material for clean energy technologies, emphasizing its critical role in achieving national energy goals (USDOE SETO, 2025). Weng et al. (2023) explored recycling technologies by applying chemical recovery methods and quantifying Cd and Te recovery efficiency using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES), reporting recovery rates of over 90% from decommissioned panels.

Structural innovations were also examined, including the work of Rahman (2022) and Ravindra et al. (2016), who outlined the typical multilayer configuration of CdTe modules — consisting of glass, transparent conductive oxide (TCO), buffer layer, absorber layer, and back contact — and discussed the role of buffer junction quality in improving electron transport and reducing recombination. Furthermore, Katepalli et al. (2023) introduced tandem cell designs using semi-transparent CdTe layers combined with additional wide-bandgap absorbers, modeled via TCAD simulations to maximize spectral utilization. Encapsulation strategies to mitigate heavy metal leaching were also analyzed, particularly in the study by Ramos-Ruiz et al. (2017), who subjected broken CdTe modules to simulated landfill conditions and used leachate analysis to quantify cadmium and tellurium release with and without encapsulant protection.

The methodological diversity in the selected studies reflects the multidisciplinary nature of CdTe research, spanning materials science, environmental engineering, and systems deployment. By synthesizing these studies under a common framework, this review identifies prevailing trends, technological breakthroughs, and remaining challenges in the use of CdTe for sustainable and resilient energy systems — particularly in defense, disaster response, and remote infrastructure contexts.

Efficiency and Performance of CdTe Solar Cells

The use of Cadmium Telluride (CdTe) as a semiconductor material in thin-film solar cells has been extensively studied due to its promising electrical properties and compatibility with low-cost production techniques. (Green., 2024a; Green., 2024b) reported that CdTe cells consistently achieve high efficiencies in both laboratory and commercial modules, with advantages over other thin-film technologies such as Copper Indium Gallium Selenide (CIGS). In addition, due to its direct bandgap and high light absorption coefficient, CdTe enables efficient light absorption even in thin layers, reducing material usage and production costs (Scarpulla et al., 2023).

Several studies have compared the performance of CdTe cells under various environmental conditions. (Costa et al., 2021) demonstrated that CdTe modules yield high energy in hot and humid climates, outperforming silicon-based modules under similar conditions. (Daniel-Durandt & Rix, 2025) emphasized that the thermal stability of CdTe makes it suitable for desert and tropical environments, where temperature fluctuations often degrade other photovoltaic technologies. These findings support the expansion of CdTe solar panel use in regions with challenging weather conditions.

Environmental Issues and Recycling Strategies

Despite its many advantages, CdTe technology has received criticism due to the toxicity of cadmium and the scarcity of tellurium. Fthenakis (2004) conducted a life cycle impact analysis showing that although cadmium in CdTe modules is chemically stable, improper disposal can pose environmental risks. In response, Weng et al., 2023 and other manufacturers have implemented closed-loop recycling programs capable of recovering more than 90% of Cd and Te elements, significantly reducing the environmental footprint of CdTe modules. Furthermore, research by Scarpulla et al., (2023) indicated progress in encapsulation materials and recycling protocols that can mitigate long-term risks.

Material Availability and Resource Sustainability

One of the major concerns surrounding the large-scale adoption of Cadmium Telluride (CdTe) photovoltaic technology is the limited availability of tellurium, a critical component in CdTe solar cells. Tellurium is not mined directly in significant quantities but is primarily obtained as a byproduct of copper refining, making its supply heavily dependent on the global copper industry. Several researchers have highlighted that tellurium's byproduct nature significantly constrains scalability for CdTe PV technologies in the long term (Kavlak et al., 2014; Zweibel, 2010; McNulty & Jowitt, 2022). This indirect production path leads to uncertainty in the long-term availability of tellurium, especially as demand for CdTe solar panels increases. (Marwede & Reller, 2012) highlighted the importance of improving material efficiency and developing recycling technologies to ensure a sustainable supply chain for tellurium. Without significant advances in these areas, the scalability of CdTe-based solar technologies may face serious constraints. Additionally, integrating CdTe layers into flexible substrates has been proposed as a solution to improve material usage and enable broader application in areas such as building-integrated photovoltaics (BIPV), which could reduce raw material intensity and enhance deployment potential. Therefore, addressing the sustainability of tellurium supply is not only a matter of resource availability, but also of ensuring the long-term viability of CdTe in meeting renewable energy targets.

RESULTS AND DISCUSSION

Cadmium Telluride (CdTe) is a stable crystalline compound composed of cadmium and tellurium. It is extensively used in thin-film solar cells, particularly as the absorber layer in photovoltaic (PV) modules. One of the primary advantages of CdTe is its high energy conversion efficiency compared to other thin-film materials. Typically, CdTe modules achieve efficiencies between 7% and 10%, with lab-scale devices exceeding 22% due to improvements in layer composition and junction engineering (Rahman, 2022). CdTe solar cells have gained significant attention due to their potential to deliver cost-effective and scalable photovoltaic technology. Unlike traditional crystalline silicon (c-Si) cells, CdTe cells require less semiconductor material and can be deposited using low-temperature techniques, which reduces overall production costs. Moreover, the CdTe semiconductor has a nearly ideal bandgap of around 1.45 eV for terrestrial solar energy absorption, which enhances its photovoltaic efficiency under standard test conditions.

The typical CdTe solar cell structure consists of a glass substrate, a transparent conductive oxide (TCO) such as SnO_2, a buffer layer like CdS or CdS_xTe_{1-x}, followed by the CdTe absorber layer, and a metal contact at the bottom (Rahman, 2022). This multilayer configuration ensures efficient photon absorption and electron-hole pair separation. The CdS layer forms a p-n junction with CdTe, facilitating the flow of charge carriers. The overall design aims to minimize reflection, optimize charge transport, and suppress recombination losses, which are critical for achieving high device performance.

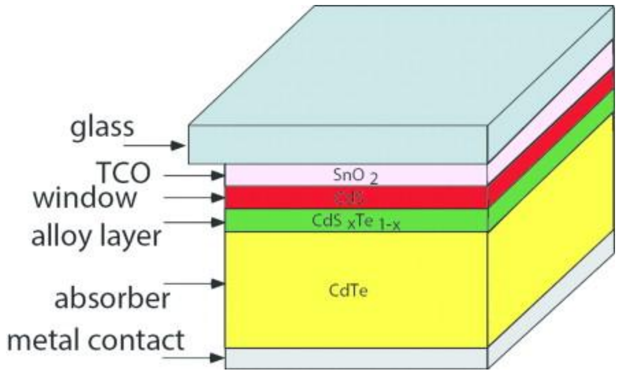


Figure 1. Structure of a typical CdTe solar cell including layers of SnO_2, CdS, CdS_xTe_{1-x}, CdTe, and a metal contact (Ravindra et al., 2016).

The performance of CdTe cells depends significantly on the thickness and stoichiometry of the absorber layer. Increasing the CdTe layer thickness to approximately 6.0 µm enhances electrical characteristics such as open-circuit voltage (Voc), short-circuit current density (Jsc), and fill factor (FF). Studies indicate that optimized configurations produce a Voc of 0.894 V and a Jsc of 31.99 mA/cm^2, making them competitive with other technologies (Kranz et al., 2013).

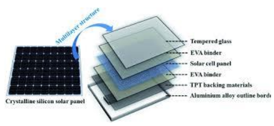
Advanced doping techniques have been extensively explored to optimize the performance of CdTe-based solar cells by improving carrier concentration, reducing series resistance, and enhancing junction quality. Doping involves the intentional introduction of impurity atoms into the CdTe crystal lattice to manipulate its electrical properties. Among the most widely studied dopants is phosphorus (P), which serves as an acceptor dopant when substituted into tellurium (Te) sites, thereby increasing hole concentration and enhancing the p-type conductivity of the CdTe absorber. Kranz et al. (2013) reported that phosphorus doping not only reduced bulk resistivity but also improved the fill factor (FF) and open-circuit voltage (Voc) by enhancing the grain boundary properties and suppressing deep-level traps. Similarly, Ravindra et al. (2016) emphasized the role of phosphorus in improving junction quality and reducing series resistance, thereby increasing the overall efficiency of the device.

Other group-V elements, such as arsenic (As) and antimony (Sb), have also been explored for doping purposes, showing promising results in enhancing carrier lifetime and device stability (Perkins et al., 2017). However, these dopants often require high-temperature activation and precise control of concentration to avoid compensating defects. In addition to substitutional doping, chlorine (Cl) activation is a widely adopted technique during post-deposition annealing, which improves crystallinity and passivates grain boundaries, as reported by Scarpulla et al. (2023). The formation of cadmium chloride ($CdCl_2$) compounds during this process promotes grain growth and interface passivation, which significantly boosts carrier collection efficiency and reduces shunt pathways.

In parallel with dopant engineering, considerable efforts have been made to replace the conventional cadmium sulfide (CdS) buffer layer, which presents challenges such as suboptimal band alignment and cadmium-related toxicity. Alternative materials such as zinc magnesium oxide (ZnMgO), tin telluride (SnTe), and zinc stannate (Zn_2SnO_4) are being developed to address these issues. ZnMgO, for instance, offers a tunable wide bandgap (~3.3–3.6 eV) that allows greater transmittance of short-wavelength light, thereby increasing photocurrent density (Scarpulla et al., 2023). SnTe has shown better lattice matching with CdTe and reduced interfacial recombination, improving the junction quality and enabling higher open-circuit voltages (Katepalli et al., 2023). Additionally, Zn_2SnO_4 exhibits favorable conduction band alignment and excellent optical transparency, making it a strong candidate to replace CdS while maintaining efficient charge separation.

The combined implementation of advanced doping strategies and novel buffer materials represents a critical direction in enhancing the performance and stability of CdTe solar cells. These innovations contribute significantly to the reduction of recombination losses, increase in minority carrier diffusion length, and optimization of optical and electrical interfaces, all of which are essential to pushing CdTe device efficiency toward the 25% theoretical limit and enabling its application in high-demand, resilience-based environments such as defense and off-grid power systems. Table 1 provides a comparative summary of different solar technologies based on multiple metrics, including efficiency, cost, and market share.

Table 1. Comparative data of major solar cell technologies

	A-SI	**CIS / SIGS**	**CdTe**	**Crystalline**
Full Name	Amorphous Silicon	Copper Indium (Gallium) Diselenide	Cadmium Telluride	Crystalline Silicon
Example of Application				
Module Efficiency	5-8%; triple juncyion up to 10%	9-12%	7-10%	13-18%
Capital costs (US&/Watt)	US$ 2-3	US$ 2-3	US$ 1.5	US$ 0.8±
Manufacturing Cost (US&/Watt)	US$ 1.5-2	US$ 1.5-2	US$ 1.3-2	US$ 2.5-3±
Share of solar market(06)	4.7%	0.2%	2.7%	92.4%
Pros/Pro	More mature, similar process to familiar TFT-LCD panels, uses 1/100 silicon of crystalline solar cells	Thin and flexible, more efficient than A-SI	Low manufacturing cost, relatively high efficiency in non-peak conditions	Very mature technology, with well-established supply chains and technologies
Cons/Kontra	Low efficiency, durability	Potential indium shortage	Cadmium is toxic, potential tellurium shortage	Raw material shortage has prevented natural price declines
Representative Companies	Energy Conversion Devices, Sharp, Kanaka, China Solar	Nanosolar, DayStar, Miasole, Honda, Shell	Fisrt Solar, Antec	Motech, E-Ton, Trina Solar, Suntech, Sharp, Q-Cells

Building on the comparative insights presented in Table 1, CdTe emerges as a strategically viable photovoltaic solution for applications requiring high thermal tolerance, low maintenance, and rapid deployment—characteristics crucial for defense and remote energy systems. While crystalline silicon offers superior efficiency, its sensitivity to high temperatures and heavier structure can limit mobility in tactical or off-grid operations. In contrast, the favorable performance of CdTe in diffuse light and extreme climates positions is well for mission-critical applications such as forward-operating bases, emergency shelters, and unmanned surveillance platforms. Furthermore, the potential to integrate CdTe with lightweight encapsulation and flexible substrates supports innovation in portable solar power for security, field communications, and autonomous platforms. These attributes underscore CdTe's growing role not only in utility-scale projects but also in energy-resilient infrastructure that aligns with national defense and climate adaptation strategies (Costa et al., 2021; Ramos-Ruiz et al., 2017).

CdTe cells have moderate efficiency (7–10%) and relatively low capital and manufacturing costs (USD 1.3–2/Watt). They outperform amorphous silicon (a-Si) in efficiency and stability but are slightly behind crystalline silicon (c-Si) which leads the market with over 92% share due to its mature manufacturing infrastructure. CdTe's strength lies in its low temperature coefficient and better performance in diffuse light, making it ideal for deployment in hot or cloudy environments (USGS, 2008).

In the current photovoltaic market landscape, crystalline silicon (c-Si) continues to dominate, commanding over 90% of global market share due to its mature manufacturing infrastructure, high absolute efficiency (typically 18–22% for modules), and well-established supply chains (USGS, 2008). Its extensive industrial ecosystem, including long-term warranties and bankability, makes it the default choice for large-scale installations. However, crystalline silicon also has limitations, especially in high-temperature regions where its performance degrades due to a relatively high temperature coefficient. In contrast, CdTe modules exhibit better thermal stability, improved diffuse light response, and lower cost per watt, making them suitable for utility-scale deployments in tropical and desert climates where silicon panels underperform (Costa et al., 2021). CdTe's simplified manufacturing process, shorter energy payback time (typically <1.5 years), and scalability through vapor transport deposition or close-spaced sublimation methods contribute to its growing adoption in specific market segments (Fthenakis, 2004).

Despite these advantages, significant environmental and material challenges hinder the widespread acceptance of CdTe technology. The primary concern stems from the use of cadmium (Cd), a toxic heavy metal classified as a Group 1 carcinogen by IARC. While cadmium is chemically stable within the CdTe compound, improper handling, damage, or disposal of panels—especially in landfills—can lead to leaching into soil and water, causing bioaccumulation in ecosystems. Additionally, tellurium (Te) is a rare and geopolitically sensitive element, mostly obtained as a byproduct of copper refining. As highlighted by Marwede and Reller (2012), the limited and uncertain availability of tellurium poses a bottleneck for large-scale CdTe PV expansion, particularly as demand for thin-film technologies increases globally. Without alternative sourcing strategies or efficient recovery methods, reliance on Te risks supply insecurity and price volatility.

To address these sustainability concerns, manufacturers have initiated circular economy approaches, particularly through closed-loop recycling systems. Companies such as First Solar have pioneered large-scale recycling programs capable of recovering over 90% of cadmium and tellurium from end-of-life modules using chemical separation, distillation, and solidification processes (McNulty et al, 2022). These systems reduce the environmental footprint, prevent heavy metal leakage, and enable reintroduction of recovered materials into the production cycle. Nevertheless, widespread adoption of these technologies is limited by high operational costs, lack of regulatory infrastructure in developing countries, and insufficient consumer awareness about solar waste management.

In parallel, encapsulation technologies and back contact innovations have been developed to reduce leakage risk and prolong module lifespan. Ramos-Ruiz et al. (2017) conducted leachate experiments simulating landfill conditions and found that multilayer glass encapsulants and polymer barrier films significantly reduced the release of cadmium ions, even after mechanical damage. Encapsulation acts as both a physical and chemical barrier that restricts water and oxygen ingress, preventing corrosion and ion diffusion. Moreover, alternative back contact materials such as molybdenum and copper-indium-based alloys are under investigation to replace traditional metals that degrade over time or catalyze interface reactions. These advances collectively improve module safety, reduce environmental hazards, and align with international e-waste directives (e.g., RoHS and WEEE regulations).

On the research frontier, efforts are concentrated on enhancing performance metrics while minimizing ecological impacts. Innovations include doping the CdTe absorber with group V elements like phosphorus or antimony to increase hole concentration and junction quality (Kranz et al., 2013; Ravindra et al., 2016), implementing buffer layer alloys such as CdS_xTe_{1-x} for improved band alignment, and integrating tandem architectures to surpass single-junction efficiency limits (Dizaj & Assari, 2024). Recent studies have also explored machine learning techniques to detect defects and predict failure in real-time. For example, Kirschenmann et al. (2021) applied convolutional neural networks (CNNs) to infrared images of CdTe crystals, enabling precise 3D mapping of grain-boundary defects. Additionally, the use of flexible substrates—such as polymers or metal foils—has opened new applications in portable defense systems, unmanned platforms, and rapid-deployment solar kits for disaster response, underscoring CdTe's role in enhancing national energy resilience.Another area of exploration includes tandem solar cells, where CdTe is used in conjunction with other semiconductors to surpass the single-junction efficiency limit. Furthermore, machine learning techniques have been applied to analyze and visualize defect distributions in CdTe crystals using infrared microscopy combined with neural network learning. For instance, Kirschenmann et al. (2021) used a convolutional neural network to classify and map grain-boundary defects in CdTe crystals imaged via infrared microscopy, enabling accurate 3D defect visualization across over 100 crystal samples.

From an economic perspective, CdTe modules present a favorable energy payback time (EPBT). According to studies by (Fthenakis, 2004), CdTe panels can recover the energy used in their manufacturing process within 0.8 to 1.5 years, depending on geographical deployment. This makes them highly attractive for projects aiming to minimize carbon footprint over the system's lifetime.

Additionally, the reduced material input and relatively straightforward fabrication process of CdTe-based modules provide a major advantage over crystalline silicon (c-Si) technologies in terms of manufacturing scalability and deployment speed. Unlike c-Si cells, which require high-purity silicon ingots, slicing, texturing, and high-temperature diffusion processes, CdTe modules can be manufactured using low-temperature deposition techniques such as close-spaced sublimation (CSS), metal-organic chemical vapor deposition (MOCVD), or vapor transport deposition (VTD). These techniques enable direct deposition of CdTe films onto large-area substrates such as glass or metal foil, significantly reducing energy consumption and capital equipment requirements (Fthenakis, 2004; Scarpulla et al., 2023). As a result, the energy payback time (EPBT) for CdTe modules is often as short as 0.8–1.5 years, compared to 2–4 years for crystalline silicon modules, depending on geographical deployment (Rajput et al., 2018).

This simplified production chain also makes CdTe an attractive option for rapid deployment in emerging markets, particularly in regions where local industrial capacity or silicon-based supply chains are underdeveloped. The ability to integrate CdTe cells into roll-to-roll flexible substrates or prefabricated modules further accelerates assembly, logistics, and field installation, which is especially valuable for defense applications, disaster response, or electrification of remote communities. Moreover, CdTe fabrication produces less silicon kerf waste and requires fewer rare-earth metals or high-purity chemicals, which contributes to lower lifecycle emissions and reduced reliance on vulnerable global supply routes (Wichrowska et al, 2019; IRENA, 2022). While the production of CdTe still faces raw material constraints (e.g., tellurium availability), its superior manufacturability allows for faster scale-up and localization of production capacity, offering strategic advantages for countries aiming to improve energy resilience while reducing technological dependence on established silicon markets.

CONCLUSION

Cadmium Telluride (CdTe) is a promising material for thin-film solar cell technology, offering high efficiency, low production costs, and excellent performance under high-temperature and low-light conditions. Its nearly ideal bandgap of approximately 1.45 eV and strong light absorption properties make it well-suited for solar power generation, particularly in utility-scale and off-grid applications. Despite these advantages, CdTe technology faces notable challenges, particularly concerning the toxicity of cadmium and the limited availability of tellurium, which is a byproduct of copper mining. These concerns underscore the need for sustainable practices, including advanced recycling systems, safer encapsulation methods, and responsible resource sourcing. Companies like First Solar have demonstrated the feasibility of closed-loop recycling systems, recovering over 90% of materials from end-of-life panels and setting a benchmark for industry-wide sustainability.

To further strengthen the viability of CdTe technology, future research should focus on developing modules with enhanced durability and environmental safety, particularly for deployment in harsh operational environments involving high humidity, temperature fluctuations, and mechanical stress. Investigating novel encapsulation materials and flexible substrates could facilitate the integration of CdTe modules into portable defense systems and remote off-grid installations. Moreover, the implementation of real-time monitoring combined with AI-based diagnostics presents a promising pathway to improving predictive maintenance and fault detection in field conditions. Finally, comprehensive long-term studies are required to assess the scalability of tellurium recovery and recycling processes, ensuring sustainable material supply for future large-scale deployment of CdTe photovoltaics.

AUTHOR CONTRIBUTIONS

A.M.P.A. conceived the original research idea, led the literature review, and drafted the initial manuscript. A.K. designed the methodology and contributed to structuring the analytical framework. G.I.A. was responsible for conducting the simulations and interpreting technical data. D.R.D. and M.H.A.B. assisted with data processing and contributed to the initial manuscript editing. C.V.A. contributed to the conceptual development, validated the scientific content, and critically reviewed the final version of the manuscript.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

REFERENCES

Adnan, S., Khan, A. H., Haider, S., & Mahmood, R. (2012). Solar energy potential in Pakistan. *Journal of Renewable and Sustainable Energy, 4*(3). https://doi.org/10.1063/1.4712051

Ahmad, T., Sobhan, S., & Nayan, M. F. (2016). Comparative analysis between single diode and double diode model of PV cell: Concentrate different parameters effect on its efficiency. *Journal of Power and Energy Engineering, 4*(3), 31–46. https://doi.org/10.4236/jpee.2016.43004

Costa, S. C. S., Kazmerski, L. L., & Diniz, A. S. A. C. (2021). Impact of soiling on Si and CdTe PV modules: Case study in different Brazil climate zones. *Energy Conversion and Management: X, 10*, 100084. https://doi.org/10.1016/j.ecmx.2021.100084

Daniel-Durandt, F. M., & Rix, A. J. (2025). The long-term influence of wind and temperature on performance and degradation within a utility-scale photovoltaic plant. *IET Renewable Power Generation, 19*(1). https://doi.org/10.1049/rpg2.13182

Dizaj, M. H., & Assari, A. (2024). Using tandem method in cadmium-telluride cells to increase solar cell efficiency. *The 8th International Conference on Applied Researches in Science and Engineering 2024*, 1-15.

Fthenakis, V. M. (2004). Life cycle impact analysis of cadmium in CdTe PV production. *Renewable and Sustainable Energy Reviews, 8*(4), 303–334. https://doi.org/10.1016/j.rser.2003.12.001

Kavlak, G., McNerney, J., & Trancik, J. E. (2014). Metals production requirements for rapid photovoltaics deployment. *arXiv preprint*. https://arxiv.org/abs/1501.03039

Green, M. A., Dunlop, E. D., Hohl-Ebinger, J., Yoshita, M., Kopidakis, N., Bothe, K., Hinken, D., Rauer, M., & Hao, X. (2022). Solar cell efficiency tables (Version 60). *Progress in Photovoltaics: Research and Applications, 30*(7), 687–701. https://doi.org/10.1002/pip.3595

Green, M. A., Dunlop, E. D., Yoshita, M., Kopidakis, N., Bothe, K., Siefer, G., & Hao, X. (2024a). Solar cell efficiency tables (Version 63). *Progress in Photovoltaics: Research and Applications, 32*(1), 3–13. https://doi.org/10.1002/pip.3750

Green, M. A., Dunlop, E. D., Yoshita, M., Kopidakis, N., Bothe, K., Siefer, G., Hinken, D., Rauer, M., Hohl-Ebinger, J., & Hao, X. (2024b). Solar cell efficiency tables (Version 64). *Progress in Photovoltaics: Research and Applications, 32*(7), 425–441. https://doi.org/10.1002/pip.3831

Hanna, F., Nain, P., & Anctil, A. (2023). Material availability assessment using system dynamics: The case of tellurium (2023–2050). *Progress in Photovoltaics: Research and Applications*, 32(4), 253-266. https://doi.org/10.1002/pip.3760

International Renewable Energy Agency (IRENA). (2022). *Enhancing energy resilience: Policies for secure and sustainable power systems*. https://www.irena.org/publications

Katepalli, A., Wang, Y., & Shi, D. (2023). Solar harvesting through multiple semi-transparent cadmium telluride solar panels for collective energy generation. *Solar Energy, 264*, 112047. https://doi.org/10.1016/j.solener.2023.112047

Kranz, L., Gretener, C., Perrenoud, J., Schmitt, R., Pianezzi, F., La Mattina, F., Blösch, P., Cheah, E., Chirilă, A., Fella, C. M., Hagendorfer, H., Jäger, T., Nishiwaki, S., Uhl, A. R., Buecheler, S., & Tiwari, A. N. (2013). Doping of polycrystalline CdTe for high-efficiency solar cells on flexible metal foil. *Nature Communications, 4*, 2306. https://doi.org/10.1038/ncomms3306

Liu, B., Chen, J., Li, M., & Wang, H. (2023). CdTe PV sustainability study in China: Supply and demand perspective of tellurium. *SSRN*. https://doi.org/10.2139/ssrn.4782097

Marwede, M., & Reller, A. (2012). Future recycling flows of tellurium from cadmium telluride photovoltaic waste. *Resources, Conservation and Recycling, 69*, 35–49. https://doi.org/10.1016/j.resconrec.2012.09.006

McNulty, B. A., & Jowitt, S. M. (2022). Byproduct critical metal supply and demand and implications for the energy transition: A case study of tellurium supply and CdTe PV demand. *Renewable and Sustainable Energy Reviews, 168*, 112838. https://doi.org/10.1016/j.rser.2022.112838

NREL. (2020). *CdTe PV: Real and perceived environmental, health and safety risks*. National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy03osti/33561.pdf

NREL. (2025). *Cadmium telluride photovoltaics perspective paper*. U.S. Department of Energy, SETO. https://www.energy.gov/sites/default/files/2025-01/DOE%20SETO%20CdTe%20Photovoltaics%20Perspective%20Paper.pdf

Perkins, C. L., Beall, C., Reese, M. O., & Barnes, T. M. (2017). Two-dimensional cadmium chloride nanosheets in cadmium telluride solar cells. *ACS Applied Materials & Interfaces, 9*(24), 20561–20565. https://doi.org/10.1021/acsami.7b03613

Rahman, K. S. (2022). Cadmium telluride (CdTe) thin film solar cells. In *Comprehensive Guide on Organic and Inorganic Solar Cells* (pp. 65–83). Elsevier. https://doi.org/10.1016/B978-0-323-85529-7.00009-8

Rajput, P., Singh, Y. K., Tiwari, G. N., Sastry, O. S., Dubey, S., & Pandey, K. (2018). Life cycle assessment of the 3.2 kW cadmium telluride (CdTe) photovoltaic system in composite climate of India. *Solar Energy, 159*, 415–422. https://doi.org/10.1016/j.solener.2017.11.060

Ramos-Ruiz, A., Wilkening, J. V., Field, J. A., & Sierra-Alvarez, R. (2017). Leaching of cadmium and tellurium from cadmium telluride (CdTe) thin-film solar panels under simulated landfill conditions. *Journal of Hazardous Materials, 336*, 57–64. https://doi.org/10.1016/j.jhazmat.2017.03.070

Scarpulla, M. A., McCandless, B., Phillips, A. B., Yan, Y., Heben, M. J., Wolden, C., Xiong, G., Metzger, W. K., Mao, D., Krasikov, D., ... Hayes, S. M. (2023). CdTe-based thin film photovoltaics: Recent advances, current challenges and future prospects. *Solar Energy Materials and Solar Cells, 255*, 112289. https://doi.org/10.1016/j.solmat.2023.112289

Springfield Center. (2020). *Sustainability evaluation of CdTe PV environmental impacts*. Technical white paper. https://www.townofmanlius.org/DocumentCenter/View/1795

United States Department of Energy – Solar Energy Technologies Office (USDOE SETO). (2025). *A secret ingredient to US clean energy*. *Metal Tech News*.

https://www.metaltechnews.com/story/2022/12/07/tech-metals/a-secret-ingredient-to-us-clean-energy/1169.html

United States Geological Survey (USGS). (2008). *Tellurium*. Mineral Commodity Summary. https://www.usgs.gov

Weng, Y., Yang, G., Li, Y., Xu, L., Chen, X., Song, H., & Zhao, C. X. (2023). Alginate-based materials for enzyme encapsulation. *Advances in Colloid and Interface Science, 318*, 102957. https://doi.org/10.1016/j.cis.2023.102957

Wichrowska, K., Wosinski, T. Z., Domagala, J. Z., et al. (2021). Structural defects in MBE-grown CdTe heterojunctions for photovoltaic applications. *Semiconductor Science and Technology*, 36(4), 045022. https://doi.org/10.1088/1361-6641/abbd0d

Zweibel, K. (2010). The impact of tellurium supply on cadmium telluride photovoltaics. *Science, 328*(5979), 699–701. https://doi.org/10.1126/science.1182840