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Systematic review of the study on the efficiency of thin film solar cells

Revisión sistemática del estudio sobre la eficiencia de células solares de película delgada

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Diana Estefanía Aguirre-Ruiz
https://orcid.org/0009-0002-2263-5595
diana.aguirre@espoch.edu.ec
Escuela Superior Politécnica de Chimborazo. Riobamba, Ecuador

Diana Carolina Aguay-Saquicaray
https://orcid.org/0000-0002-2855-3876
diana.aguay@espoch.edu.ec
Escuela Superior Politécnica de Chimborazo. Riobamba, Ecuador

David Sebastián Aguay-Saquicaray
https://orcid.org/0009-0000-2072-2092
david-seb@hotmail.com
Escuela Superior Politécnica de Chimborazo. Riobamba, Ecuador

Alcivar Bladimir Ilbay-Telenchano
https://orcid.org/0009-0002-3242-269X
ilbayalcivar@gmail.com
Escuela Superior Politécnica de Chimborazo. Ambato, Ecuador

Abstract

In the current context of energy transition, thin-film photovoltaic technologies have gained prominence for their potential to offer lighter, more economical and sustainable energy solutions. The study aimed to analyze how film thickness and the type of material used influence the efficiency of solar cells, and to discuss their implications for the photovoltaic industry. To do so, the PRISMA methodology was applied, systematically reviewing twelve research studies published between 2020 and 2025. The selected studies evaluated technologies such as CdTe, perovskites, CIGS, CZTSSe, TiS_3 and new compounds such as doped $AgSbS_2$ and SnO_2. The results showed that both thickness reduction and appropriate choice of materials allow optimization of solar absorption, although challenges such as thermal stability and degradation by environmental factors were also identified. Some technologies, such as perovskites and TiS_3, achieved theoretical efficiencies of up to 22% in submicrometer layers, representing a breakthrough for mobile and architectural applications. It is concluded that not only efficiency, but also factors such as cost, durability and environmental impact are crucial for industrial adoption. It is recommended to continue researching emerging materials, improve cell stability and strengthen recycling and circular economy policies.

Keywords: Photovoltaic cells, thin film, efficiency

Resumen

En el contexto actual de transición energética, las tecnologías fotovoltaicas de película delgada han cobrado protagonismo por su potencial para ofrecer soluciones energéticas más ligeras, económicas y sostenibles. El estudio tuvo como objetivo analizar cómo el grosor de la película y el tipo de material utilizado influyen en la eficiencia de las células solares, y discutir sus implicaciones para la industria fotovoltaica. Para ello, se aplicó la metodología PRISMA, revisando sistemáticamente doce investigaciones publicadas entre 2020 y 2025. Los estudios seleccionados evaluaron tecnologías como CdTe, perovskitas, CIGS, CZTSSe, TiS_3 y nuevos compuestos como $AgSbS_2$ y SnO_2 dopado. Los resultados demostraron que tanto la reducción de grosor como la elección adecuada de materiales permiten optimizar la absorción solar, aunque también se identificaron desafíos como la estabilidad térmica y la degradación por factores ambientales. Algunas tecnologías, como los perovskitas y el TiS_3, alcanzaron eficiencias teóricas de hasta 22% en capas submicrométricas, lo que representa

un gran avance para aplicaciones móviles y arquitectónicas. Se concluye que no solo la eficiencia, sino también factores como el costo, la durabilidad y el impacto ambiental son cruciales para la adopción industrial. Se recomienda continuar investigando materiales emergentes, mejorar la estabilidad de las celdas y fortalecer políticas de reciclaje y economía circular.

Palabras clave: Celdas fotovoltaicas, película delgada, eficiencia

Introduction

Currently, the global energy transition, facilitated by the energy industry and through thin-film solar cells (TFSC), has emerged as one of the most promising technologies for both terrestrial and space applications. Unlike traditional crystalline silicon cells, these cells offer remarkable flexibility in their design and manufacturing, making them an attractive option for a wide variety of applications (Chopra et al., 2024). This versatility is evident not only in the ability to utilize different substrates—whether rigid or flexible, metallic or insulating—but also in the capacity to deposit multiple functional layers using advanced techniques such as physical vapor deposition (PVD), chemical vapor deposition (CVD), electrochemical deposition (ECD), plasma-based technologies, and hybrid approaches (Iqbal et al., 2025).

Thin-film solar cells are advantageous due to their minimal material usage and increasing efficiency. The three primary technologies for thin-film solar cells include amorphous silicon (α-Si), copper indium gallium selenide (CIGS), and cadmium telluride (CdTe) (Sotavento & Ebong, 2023). These techniques confer specific benefits to device engineering, allowing for the optimization of essential layers such as the back contact, buffer layer, absorbing layer, and rear reflector. This level of customization has led to a gradual improvement in device performance, a critical aspect for their commercial viability. As manufacturing progresses toward large-scale production aimed at covering extensive areas, such as commercial solar panels or applications integrated into infrastructures, the complexity of the processes increases significantly (Cepeda & Sierra, 2020).

Thin-film solar cells have solidified their position as a promising alternative to traditional crystalline silicon solar cells, distinguished by their low cost, flexibility, and ability to be applied to unconventional surfaces (Lara, 2021). The efficiency of these cells is closely related to the thickness of the active material and the type of semiconductors used. Recent research has revealed that materials such as cadmium telluride (CdTe), copper indium gallium selenide (CIGS), and perovskites can achieve efficiencies exceeding 22% under laboratory conditions (DS New Energy, 2021).

The thickness of the active material is a crucial factor in energy conversion efficiency. For example, studies have shown that ultra-thin silicon solar cells, with a thickness of approximately 1 μm, can achieve efficiencies greater than 20% through advanced texturing techniques that enhance light absorption. However, it is essential to consider that reducing thickness below certain limits may lead to decreased efficiency due to minority carrier recombination and optical losses.

There are different types of solar cells, each presenting distinct characteristics based on their crystalline structure and manufacturing method. Monocrystalline cells, made from a single continuous crystal, stand out for their high efficiency, although their production cost is high. In contrast, multicrystalline cells, composed of several large crystals in random orientation, offer lower performance but at a more accessible cost. On the other hand, polycrystalline cells, which consist of multiple much smaller crystals (ranging from 1 μm to 1 mm), sacrifice even more efficiency, although their production costs are reduced, especially in the case of thin-film technologies. Hybrid devices, combining monocrystalline and polycrystalline layers, maximize the advantages of both structures through deposition techniques. Finally, amorphous cells, primarily made with hydrogenated silicon, are the most economical but also exhibit the lowest performance, experiencing rapid efficiency degradation in the first months of use (Balenzategui, 2021).

Regarding materials, perovskites have demonstrated significant potential, achieving efficiencies of up to 25.7% in heterojunction cells. Additionally, recent research has shown that $Sb_2(S_xSe_1)_3$ solar cells can achieve efficiencies of up to 35.5% through simulations and optimizations of parameters such as carrier density and active material thickness (Saif et al., 2023).

These innovations have important implications for the photovoltaic industry, where reducing thickness and utilizing advanced materials could lower production costs and expand the range of applications for solar cells. Criollo et al. (2024) indicate that new photovoltaic technologies allow for higher energy conversion efficiencies while reducing costs through the implementation of new materials, with the latter being a key criterion for subsequent large-scale implementation. Furthermore, ultra-thin and flexible solar cells can be integrated into curved or mobile surfaces, opening new possibilities in sectors such as construction, portable electronics, and energy generation in urban environments (Vélez & Grijalva, 2020). Additionally, improvements in efficiency and

cost reductions could accelerate the global adoption of solar energy, contributing to sustainability and energy transition goals.

This study aims to investigate the efficiency of thin-film solar cells as a function of thickness and the type of material used, which is fundamental for advancing photovoltaic technology. The combination of innovative materials and advanced manufacturing techniques has the potential to transform the way we generate and utilize solar energy.

Methodology

This study employs a qualitative approach, utilizing an exploratory method and conducting a systematic integrative review within a deductive framework. The systematic review was carried out following the PRISMA model, which allows for the analysis and synthesis of existing evidence regarding the efficiency of thin-film solar cells based on thickness and material used, and discusses the implications for the photovoltaic industry.

In the research study, a comprehensive review of the scientific literature was conducted to analyze the efficiency of thin-film solar cells, focusing on two fundamental variables: the thickness of the absorbing material and the type of material used in their fabrication. To this end, various databases such as Scopus, ScienceDirect, Dialnet, SciELO, and Google Scholar were consulted, as well as other specialized repositories in materials science, energy engineering, and photovoltaic technology.

The search process was based on strategically selected key terms, such as "thin-film solar cells," "material efficiency," "absorption layer thickness," "photovoltaic performance," and "semiconductor materials for solar cells." Additionally, Boolean operators (AND, OR) were utilized to optimize the retrieval of relevant articles, ensuring a rigorous approach that encompassed both empirical and theoretical studies on the relationship between the physical properties of the active layers and the overall efficiency of the device.

Table 1

Search strategy for research

Database	Keywords with Boolean Operators
Scopus	"Thin film solar cells" AND ("Material efficiency" OR "Conversion Efficiency") AND ("Layer thickness" OR "Absorption thickness") AND "Photovoltaic industry"
Web of Science	"Solar cell efficiency" AND ("Thin film" OR "thin-film") AND ("CdTe" OR "CIGS" OR "Perovskite") AND ("Material selection" OR "Film thickness")
Google Scholar	("Células solares de película delgada" OR "Thin film solar cells") AND ("Eficiencia" OR "Rendimiento") AND ("Material" AND "Grosor") AND "Industria fotovoltaica"
Redalyc	"Eficiencia energética" AND ("Células solares" OR "Tecnología fotovoltaica") AND ("Película delgada" OR "Material semiconductor") AND "Grosor de capa activa"
Scopus	"Semiconductor materials" AND "Light absorption" AND ("Thin film Technology") AND ("Photovoltaic performance" OR "Power conversion efficiency")

To ensure the quality and relevance of the selected studies, inclusion and exclusion criteria were utilized, defined according to the PRISMA guidelines.

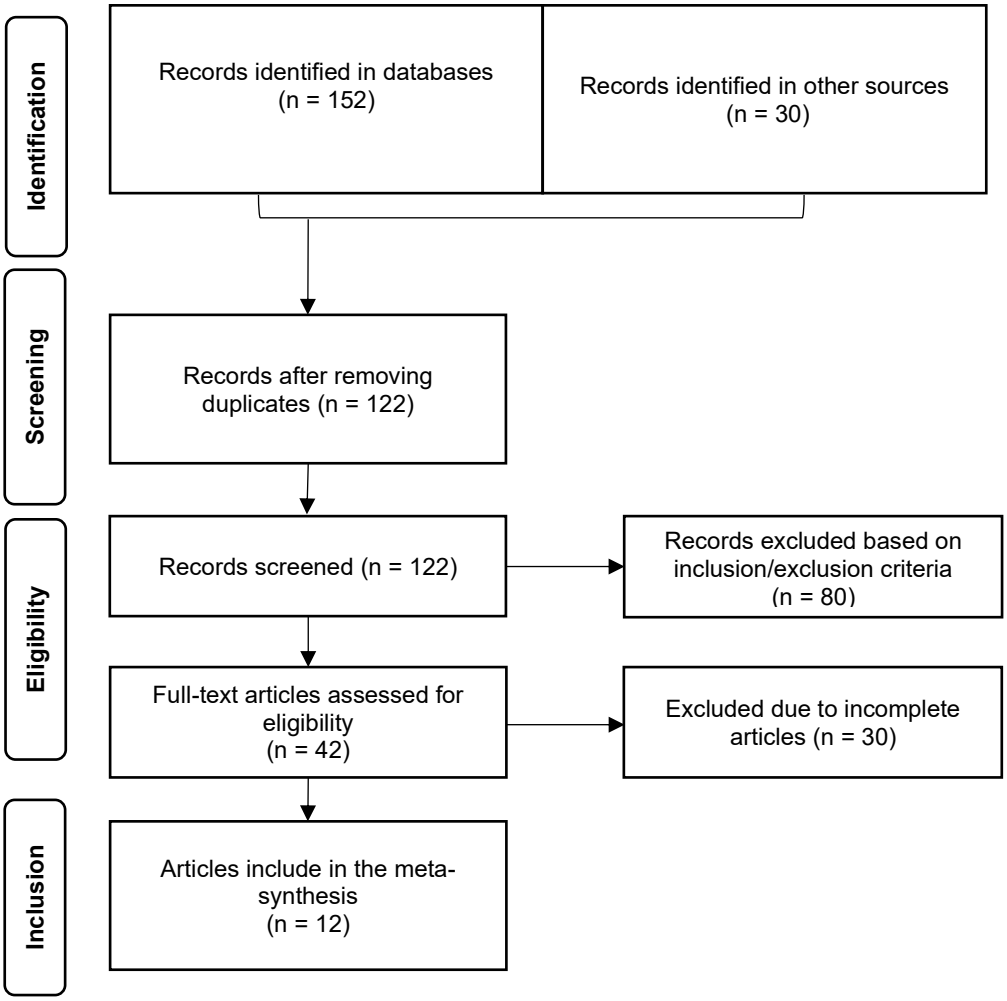
Inclusion criteria:

- Research published between 2020 and 2025.
- Studies in Spanish and English.
- Works addressing competencies in topics of efficiency of thin film solar cells in relation to thickness and material used, and discussing implications for the photovoltaic industry.

Exclusion criteria:

- Duplicate articles or those in languages other than Spanish or English.
- Studies without full text access.
- Opinion articles or those lacking a defined methodology.
- Articles outside the accepted publication deadline.

Figure 1
PRISMA flow diagram



Results and discussion

Table 2
Results of the systematic review

No.	Author	Title	Findings	Efficiency of thin film solar cells in the photovoltaic industry
1	(Grima et al., 2021)	Design, Fabrication, and Characterization of p-CdTe/n-CdS Solar Cells in Thin Films	The resulting cells were characterized by X-ray diffraction (XRD) and optical absorption (OA), while the efficiency (η) of each cell was measured using the current-voltage (I-V) characteristic analysis technique, showing an average η of ~5%. The short-circuit current is relatively low, likely due to a high value of	Aimed at the production of CdTe/CdS solar cells through a low-cost methodology, achieving an average efficiency of 5%. Although not competitive with commercial technologies, the proposal is attractive due to its simplicity in design and

			shunt resistance (Rsh). A module will be constructed with these cells, and its characterization will be the subject of future work.	fabrication, making it viable for low-budget applications.
2	(Martínez & Seminario, 2021)	Perovskite Solar Cells as an Alternative for Rural Electrification in Peru	It is recommended to address the energy needs of various regions in the country, leveraging solar energy, especially in rural areas, which show higher poverty rates, as access to electricity is always associated with improved living conditions. In this regard, PSCs present themselves as a solution to the latent energy requirement in remote areas.	An approach applied to the Peruvian social context, where perovskite solar cells stand out as an efficient alternative for rural electrification. While no specific efficiency value is detailed, the high laboratory yields offered by these technologies are recognized.
3	(Criollo et al., 2024)	Technological Evolution of Photovoltaic Solar Generation: A Review of the Literature in the Last Decade	Recent advances in the field of photovoltaic energy have identified emerging technologies with high efficiency potential, including multifunctional solar cells, perovskite, organic, and thin-film heterojunctions. These variants have surpassed, in many cases, the efficiency of traditional crystalline silicon cells, positioning themselves as promising alternatives. However, their mass adoption faces technical and economic limitations.	Emerging thin-film technologies, including perovskites, organic, and heterojunctions, have achieved efficiencies that surpass traditional silicon. However, they emphasize the technical and economic challenges that hinder their mass commercialization.
4	(Hernández et al., 2023)	Modeling Energy Efficiency of Photovoltaic Solar Panels	The development and implementation of photovoltaic systems have acquired a strategic role within energy and environmental policies, distinguished by their capacity to generate clean electricity from solar radiation. The systems integrate various electrical and electronic components, among which photovoltaic modules represent the core operational unit for energy conversion.	The study on energy efficiency from a climatic and operational perspective. Although they do not directly study thin film cells, their analysis of factors such as temperature and panel tilt is crucial for optimizing the performance of any photovoltaic technology.
5	(Chopra et al., 2024)	Thin Film Solar Cells: An Overview	Thin film solar cells (TFSC) have a promising approach for terrestrial and space photovoltaic energy, capable of using a variety of substrates (flexible or rigid, metallic or	The versatility of thin film solar cells in both terrestrial and space contexts. The analysis highlights how the diversity of deposition techniques and substrates

			insulating) for the deposition of different layers (contact, buffer, absorber, reflector, etc.) using various techniques (PVD, CVD, ECD, plasma-based, hybrid, etc.). Proper understanding of thin film deposition processes can help achieve high-efficiency devices over large areas.	has allowed for the development of high-efficiency, scalable, and flexible devices. The research validates the role of TFSC as an adaptable solution for different environments, reinforcing their industrial potential.
6	(Kishore et al., 2025)	Phase Evolution in Thin Films of AgSbS2 Synthesized via a Two-Step Process	The study explores the influence of stacking order and sulfurization pressure on the phase evolution, structural properties, and optoelectronic performance of thin films of AgSbS2. Higher pressures favored the pure cubic phase of AgSbS2 with greater compactness, while lower pressures promoted impurities and reduced film quality.	Examines thin films of $AgSbS_2$, achieving a modest efficiency of 0.95%. Although this value is low, the study is significant for its focus on phase control and material purity, which could enhance future efficiencies.
7	(Reyes, 2023)	Study of Photovoltaic Behavior and Stability in Hybrid Perovskite Solar Cells as a Function of Temperature	Solar cells have become one of the most promising technologies in the field of solar energy. A study was conducted on the thermal stability of perovskite solar cells based on double cation perovskite FAMA (MA-Methylammonium and FA-Formamidinium), also known as double cation.	The thermal behavior of hybrid perovskite solar cells shows efficiencies around 20%, though they are influenced by environmental conditions. Despite their high efficiency, the stability of perovskites represents an obstacle to their adoption in the industrial sector. Therefore, improving their thermal resistance and durability is a crucial step to facilitate their transition from the laboratory to the market.
8	(Ceh, 2024)	Modulation of Properties of Mg-Doped SnO2 Thin Films with Application in MTO/CdTe Solar Cells Fully Fabricated by Sputtering	MTO films were obtained by incorporating magnesium (Mg) atoms into thin films of SnO2 using the reactive RF-Sputtering technique and Mg chips, which were distributed over the surface of the metallic Sn target. The incorporation of Mg into the SnO2 thin films was controlled by varying the amount of chips from 0.2 to 1.2 g. The structural, chemical, morphological, optical, and electrical properties of the thin films were characterized by X-ray Diffraction (XRD), X-ray	The modification of Mg-doped SnO_2 thin films for CdTe cells reveals how variations in doping directly influence the structure and, consequently, the performance of the device. Although a specific efficiency figure is not presented, the analysis enriches knowledge on how to optimize materials to enhance the performance of thin film cells in the industrial sector.

			Photoelectron Spectroscopy (XPS), Scanning Electron Microscopy (SEM), Atomic Force Microscopy (AFM), Spectrophotometry, and Hall Effect, respectively.	
9	(Mukwevho et al., 2025)	Methodological Approaches for Resource Recovery from Panels at the End of Their Life Cycle Across Different Generations of Photovoltaic Technologies — A Review	Projections of global photovoltaic waste driven by the expansion of solar system installations highlight the influx of waste streams that pose an environmental burden if sustainable waste management measures are not adopted. Crystalline silicon and thin film PV technologies have shown sufficient advances in resource recovery technologies for industrial use in a circular economy.	Efficiency is critical, but research on the recycling of photovoltaic technologies, including thin films, highlights a crucial aspect: sustainability. The viability of these technologies is not only measured in terms of their energy efficiency but also in their environmental impact.
10	(Ahmed et al., 2025)	Carbon Nanomaterials in Coatings: A Review Focused on Thin Film Photovoltaic Solar Cells	Thin film solar cells are at the forefront of renewable energy harvesting, offering numerous benefits over their traditional counterparts, which exhibit lower efficiency and stability, rapid degradation, higher costs, and shorter lifespans. Carbon nanomaterials are unique materials that encompass desirable properties for application in thin film solar cells, making them potential materials for photovoltaic applications.	The use of carbon nanomaterials, such as graphene and nanotubes, in thin film solar cells presents significant advantages. These materials not only enhance light absorption but also increase device stability, potentially resulting in higher efficiencies and reduced costs.
11	(Villegas et al., 2024)	Optical Properties of TiS3 as a New Thin Film for Single and Tandem Solar Cells	An active layer of titanium trisulfide (TiS_3) with a thickness of only 140 nanometers is projected to achieve a maximum energy conversion efficiency close to 22%, according to the theoretical limits established by the Shockley–Queisser model. This result is significant as it suggests that even at submicrometer scales, TiS_3 can offer competitive performance compared to conventional solar technologies based on silicon or thick perovskites.	TiS_3 stands out as a promising active material in thin film solar cells. Simulations suggest that efficiencies could reach up to 22% with films as thin as 140 nm. This could facilitate the creation of lightweight and flexible devices. Such a level of theoretical efficiency positions TiS_3 as a formidable competitor against traditional technologies, especially in mobile applications and architectural integration.

The results obtained from the various studies examined provide a comprehensive overview of the current state and prospects of thin film solar cells (TFSC) in the photovoltaic industry. This technology, known for its

lightweight, flexibility, and low-cost potential, presents a viable alternative to traditional crystalline silicon, although it still faces technical and economic challenges that restrict its widespread adoption.

Research by Grima et al. (2021) reveals that although CdTe/CdS cells have relatively low efficiency (~5%), their production through simple and economical methodologies allows for implementation in projects with limited budgets. The link between manufacturing simplicity and economic viability serves as a common thread in the evolution of TFSC, where maximizing efficiency is not always prioritized, but rather a balance between performance and accessibility.

Martínez and Seminario (2021) highlight the social dimension of these technologies, emphasizing the role of perovskite cells as an effective energy alternative for electrifying rural areas that are not connected to the grid, demonstrating that photovoltaic technology should not be evaluated solely by its technical metrics, but also by its capacity to promote energy inclusion and sustainable development.

Criollo et al. (2024) enrich this discussion by showing that emerging technologies, such as perovskites, organic cells, and heterojunctions, are achieving efficiencies that surpass those of crystalline silicon. In a similar vein, Reyes (2023) addresses one of the greatest challenges of perovskite cells: their instability under environmental conditions. Kishore et al. (2025) and Ceh (2024) focus on the development and modification of new materials to enhance the performance of thin films. Specifically, $AgSbS_2$ and Mg-doped SnO_2 emerge as promising options that, while not yet achieving high efficiency levels, offer innovative pathways to optimize structural and optical properties, essential aspects for improving the overall performance of these technologies.

Ahmed et al. (2025) introduce the use of carbon nanomaterials, such as graphene and nanotubes, in the active layers of thin film cells, where these innovative materials not only improve light absorption but also enhance device stability, providing smart solutions that do not significantly increase production costs. Meanwhile, Villegas et al. (2024) present TiS_3 as a material with high potential, capable of achieving theoretical efficiencies close to 22% using extremely thin films; this discovery is particularly relevant for applications where weight and flexibility are critical, such as in portable devices or in integrated architectural solutions (BIPV).

In practical application, Hernández et al. (2023) emphasize that factors such as tilt angle, ambient temperature, and local climatic conditions play a crucial role in the actual efficiency of photovoltaic systems. Mukwevho et al. (2025) highlight the importance of proper end-of-life management for solar panels, emphasizing that material circularity will be essential to avoid negative environmental impacts. Simultaneously, Sivasankar et al. (2025) underscore advancements in materials such as CIGS, CdTe, and CZTSSe, positioning them as leaders in the industry due to their scalability, efficiency, and versatility in various applications, including mobile solutions and building-integrated systems.

Conclusions

The efficiency of thin film solar cells is profoundly determined by the type of material used, as evidenced by studies examining technologies such as CdTe, CIGS, CZTSSe, perovskites, $AgSbS_2$, and TiS_3. Each of these materials presents unique electronic, optical, and structural characteristics that influence their energy performance. For instance, TiS_3 according to Villegas et al. (2024) and hybrid perovskites according to Reyes (2023) have achieved both theoretical and practical efficiencies of up to 22% and 20% respectively, highlighting their competitive appeal against crystalline silicon. Furthermore, their capacity allows for optimized material use, reducing both the weight and cost of the panel, which is essential for portable and architectural applications. Nevertheless, the stability and durability of these emerging materials remain a challenge for large-scale adoption. In the special case of perovskites, environmental factors such as temperature, humidity, and UV radiation can adversely affect their long-term performance, indicating that while efficiency is an important aspect, industrial viability requires developing solutions that balance both performance and operational stability.

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