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Critical Multi-Criteria Analysis of First- to Fourth-Generation Photovoltaic Technologies

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Abstract

A variety of alternatives for sustainable power generation have been brought about by the quick development of photovoltaic (PV) technology, necessitating the use of structured evaluation frameworks to facilitate well-informed decision-making. Technical performance, economic viability, environmental impact, technological maturity, and future deployment possibilities are all integrated in this study's comprehensive multi-criteria analysis of photovoltaic systems ranging from first to fourth generation. A weighted aggregate technique and normalized indicators were used in a multi-criteria decision analysis framework to assess and rank representative solar technologies. The findings show that while fourth-generation photovoltaic technologies, such as tandem and perovskite-based solar cells, show remarkable efficiency potential and promising future development, crystalline silicon technologies continue to be the best choice for current large-scale deployment because of their high maturity and reliability. While third-generation technologies are now constrained by reduced efficiency and technological preparedness, thin-film technologies offer competitive performance under some climatic circumstances. The results emphasize how crucial it is to match photovoltaic technology choices with smart grid specifications, such as grid flexibility, dependability, and interaction with energy storage systems. For academics, engineers, and legislators involved in the design and implementation of solar systems within contemporary smart grid infrastructures, the suggested multi-criteria framework provides insightful information.

Keywords

Photovoltaic Technologies, Multi-Criteria Analysis, Smart Grid, Renewable Energy, Technology Assessment

1. Introduction

The steady increase in global demand for electricity, combined with environmental concerns related to fossil fuels, highlights the urgent need for a transition to renewable energy sources. In this context, solar photovoltaic energy appears to be one of the most promising solutions due to its availability, reduced environmental impact, and growing competitiveness [1]. According to forecasts by the International Energy Agency (IEA), photovoltaic energy is expected to become the main source of renewable electricity by 2040, playing a crucial role in contributing to more than 90% of the emissions reductions required to meet the targets set by the Paris Agreement [2]. Since Becquerel discovered the photovoltaic effect in 1839, the development of this technology has been characterized by the emergence of four major generations [3]. Currently, the first generation of solar cells, based on crystalline silicon, continues to dominate the market, with performance close to theoretical limits [4]. The second generation has introduced technologies thin films such as CdTe, CIGS, and a-Si with the aim of reducing costs [5].

The third generation has seen the emergence of innovative new materials such as perovskite-based solar cells, organic polymers, and quantum dots, which have quickly achieved remarkable performance levels. Finally, the fourth generation focuses on the study of organic-inorganic hybrid nanostructures such as graphene and carbon nanotubes, offering new opportunities in terms of flexibility, strength, and durability [6] [7]. However, it should be noted that the current scientific literature remains fragmented, with a predominance of studies focusing on improving individual technologies, without a comparative framework for integrated evaluation. In addition, studies place particular emphasis on technical aspects, to the detriment of key factors such as economic sustainability, resource availability, and environmental impact. These shortcomings hinder the ability of researchers, manufacturers, and decision-makers to effectively guide their innovation and investment strategies. The objective of this study is to address these gaps by providing a systematic and comparative review of the four generations of photovoltaic technologies. It is based on a rigorous multi-criteria analysis methodology that incorporates technical indicators (efficiency, stability, lifespan), economic indicators (production costs, kWh competitiveness), and environmental indicators (ecological impact, recyclability). The aim is to present a critical and comprehensive analysis of the strengths and limitations of each generation, with a view to identifying the most promising technological pathways for the global energy transition.

2. Literature Review and Research Gaps

The study of photovoltaic technologies has generated considerable interest in the field of energy research over the past two decades. However, the current study is motivated by the identification of four main gaps in existing assessment methodologies.

First, while numerous studies have examined individual PV generations or specific technologies in isolation, there remains a lack of comprehensive frameworks that systematically compare all four generations using consistent evaluation criteria. Second, existing reviews often focus primarily on technical performance metrics while giving limited attention to the complex interplay between economic viability, environmental sustainability, and commercial scalability. Third, most comparative analyses rely on static assessments that do not adequately account for the rapid evolution of emerging technologies, particularly perovskites and tandem architectures. Finally, previous work has insufficiently addressed the specific challenges and opportunities relevant to developing regions, including the Sahel zone, where energy access and climate adaptation are critical priorities.

This study addresses these shortcomings by constructing a comprehensive evaluation framework that incorporates technical performance, economic indicators, environmental metrics, and technological maturity assessments across all four PV generations, with forward-looking projections to 2035.

2.1. Previous Work

The study of photovoltaic technologies has generated considerable interest in the field of research. The existing literature essentially follows three methods: technology-specific studies, economic evaluations, and comparative schemes. This section critically assesses the current state of knowledge and highlights the main limitations that our research attempts to address. Recent technical reviews have focused on specific technology platforms, providing in-depth analysis within the context of particular hardware systems [4] maintain authoritative tables on solar cell efficiency, updated biannually with certified laboratory data, which serve as the central reference for performance comparison. However, these compilations do not include regular comparative assessments between different technology platforms and offer limited guidance for strategic decision-making. Recent literature is largely dominated by publications dedicated to perovskite technology, due to its rapid progress in terms of efficiency and commercial potential. Jena *et al.* [8]. offer a comprehensive analysis of materials engineering strategies to enhance stability, while park *et al.* [9] focus on improving device structure. These reviews are distinguished by their technical excellence, but they lack the integration of economic and implementation factors that are essential for technology assessment. Work on silicon technology focuses primarily on incremental improvement methods that tend toward theoretical limits. Haschke *et al.* [10] examine advanced cell architectures, setting efficiency targets through 2030. Richter *et al.* [11] offer an in-depth study of the fundamental loss mechanisms that limit silicon performance. However, this research does not adequately address the competing challenges posed by emerging technologies. Examining the learning curve is the most methodical economic approach in quantitative terms. Fraunhofer ISE [12] reports past cost reductions for existing technologies, while Way *et al.* [13] consider future cost prospects for emerging technologies. However, these studies generally examine specific technologies without making a systematic comparison between different platforms. The evaluation of technologies in related fields is addressed in the literature, which can serve as a methodological model. According to Kavlak *et al.* [14], the processes of reducing the costs of lithium-ion batteries are examined, highlighting the expansion of production and investment in research and development as key factors. Li *et al.* [15] develop multi-criteria evaluation models for energy storage technologies, illustrating weighted scoring methods comparable to ours. Few studies attempt to establish a systematic comparison between multiple photovoltaic technology platforms. Parida, *et al.* [16] developed a multi-criteria decision-making framework that incorporates technical, economic, and environmental factors, but applied this methodology to only four technology platforms with limited quantitative rigor. Schmidt *et al.* [17] analyze the technological learning rates of several renewable energy technologies, including several photovoltaic platforms. Their work provides valuable insights into the dynamics of innovation, but does not take into account current performance data and future projections. Victoria *et al.* [18] model optimal technology deployment scenarios using cost optimization, but assume fixed technology characteristics without considering ongoing innovation trajectories.

The current study is motivated by the identification of four main gaps in existing assessment methods. The majority of research focuses on specific technologies, without using systematic comparative frameworks that could provide an objective ranking of technologies and guide strategic decision-making. Current assessments focus on present performance without systematically considering past trends and future forecasts that are crucial for strategic planning. The current literature is largely centered on technical performance measures, often neglecting to integrate economic viability, sustainability aspects, and elements related to technological readiness. The diversity of methodological approaches from one study to another prevents the synthesis of results and limits the capacity for evidence-based decision-making. This study addresses these shortcomings by constructing a systematic evaluation framework that incorporates multiple assessment aspects into quantitative rating methodologies. Unlike current assessments that focus on specific technologies, our method promotes an objective comparison of all major photovoltaic technologies through standardized measurements and clear weighting processes.

2.2. Novelty and Contribution of This Review

This review adds a number of novel insights to the body of knowledge already available on photovoltaic technologies.

First, this work creates an integrated and standardized multi-criteria evaluation framework spanning four technological generations, from crystalline silicon to perovskite-based tandem architectures, in contrast to the majority of previous review studies that concentrate on individual photovoltaic platforms or isolated performance indicators. Technical performance measures, economic competitiveness indicators, environmental sustainability criteria, and Technology Readiness Level (TRL) assessments are all methodically combined into a single decision-support framework by the framework.

Second, in order to facilitate objective cross-technology comparison, this article compiles an extensive and standardized quantitative database from verified worldwide sources. This method strengthens the analytical robustness of technology benchmarking and balances the mostly qualitative character of earlier evaluation studies.

Third, by including estimates until 2035, the current analysis extends beyond descriptions of static technologies. The suggested pathway provides insights that are extremely pertinent for researchers, policymakers, and industry stakeholders engaged in strategic energy planning by connecting the dynamics of technology innovation, industrial maturity, and anticipated deployment potential.

3. Methodology

3.1. MCDA Framework

The Weighted Sum Model (WSM) with $\text{Min} - \text{Max}$ normalization serves as the foundation for the MCDA model that is employed. A set of technical, financial, environmental, and technological standards are used to assess each photovoltaic technology.

3.2. Choosing Evaluation Criteria

The criteria were chosen because they were pertinent to grid integration, long-term sustainability, and solar system performance.

- Conversion efficiency, temperature coefficient, low-irradiance performance, and operational lifetime are examples of technical requirements. Reliability and energy yield are directly impacted by these factors.
- Economic criteria take into account predicted levelized cost of energy (LCOE), operation and maintenance costs, and capital expenditures—all of which are crucial for large-scale deployment.
- Greenhouse gas emissions, material toxicity, recyclability, and land-use impact are all taken into consideration by environmental standards.
- The Technology Readiness Level (TRL) framework, which takes into account each technology's present state of development and commercialization, is used to evaluate technological maturity.
- Scalability, efficiency improvement margin, and interoperability with energy storage and smart grid infrastructures are future possible criteria.

When taken as a whole, these factors offer a comprehensive picture of solar technology performance in contemporary power systems.

3.3. Normalization Rules

For a Benefit-type criterion (higher = better)

$$N = (X - X\_\min)/(X\_\max - X\_\min)$$

Cost-type criterion (smaller = better)

$$N = (X\_\max - X)/(X\_\max - X\_\min)$$

X = value of the technology under study;
$X\_\max$ = highest value observed in the sample;
$X\_\min$ = lowest value observed in the sample.

3.4. Weighting Strategy

Technical performance and economic viability were given more weight than other variables when it came to photovoltaic deployment and smart grid integration. Priorities that are frequently used in solar planning studies are reflected in this weighting method.

3.5. Aggregation and Ranking

A weighted sum model was used to compute the overall performance score of each photovoltaic technology. The final score was obtained by multiplying the normalized criterion values by their corresponding weights. After that, technologies were evaluated based on their overall results, enabling a comparison of different photovoltaic generations.

3.6. Final Aggregation Equation

$$Score_i = \sum_{j=0}^{n} \left(w_i \times N_{ij} \right)$$

where:

$$w_i = weigth\ of\ criterion\ j$$

$$N_{ij} = normalized\ value$$

$$Score_i = overall\ score\ of\ technology\ i$$

The final score range between 0 and 1.

3.7. Worked Example

The multi-criteria assessment framework is shown in **Table 1**, together with the categories, cost and benefit criteria types, and the corresponding weights that were applied in the decision-making analysis (total weight = 1.00).

Technology: First Generation—Monocrystalline Silicon (c-Si).

Table 2 reports the performance values of c-Si technology across all selected criteria, along with the observed minimum and maximum values used for normalization, and the classification of each criterion as either a benefit or a cost attribute.

Table 1. Criteria and weights used.

Category	Criterion	Type	Weight
Technical	Efficiency (%)	Benefit	0.15
Technical	Lifetime (years)	Benefit	0.10
Technical	Temperature Coefficient	Cost	0.05
Economic	CAPEX ($/Wp)	Cost	0.15
Economic	LCOE ($/kWh)	Cost	0.10
Environmental	Carbon Footprint	Cost	0.10
Environmental	Recyclability (%)	Benefit	0.05
Technological	TRL	Benefit	0.10
Future	Improvement Potential (%)	Benefit	0.10
Total			**1.00**

Table 2. c-Si performance data and normalization parameters.

Criterion	c-Si Value	Min Observed	Max Observed	Type
Efficiency (%)	22	10	30	Benefit
Lifetime (years)	27	10	30	Benefit
Temperature Coefficient	−0.45	−0.60	−0.20	Cost
CAPEX ($/Wp)	0.9	0.3	2.0	Cost
LCOE ($/kWh)	0.04	0.02	0.10	Cost
Carbon (gCO_2/kWh)	45	20	80	Cost
Recyclability (%)	95	60	95	Benefit
TRL	9	4	9	Benefit
Improvement Potential (%)	10	5	30	Benefit

Normalization—Detailed Calculations

- ✓ Efficiency (Benefit):

$$N = (22-10)/(30-10) = 0.60$$

- ✓ Lifetime (Benefit):

$$N = (27-10)/(30-10) = 0.85$$

- ✓ Temperature coefficient (Cost):

$$N = (-20-(-45))/(-20-(-60)) = 0.62$$

- ✓ CAPEX(Cost):

$$N = (2-0.9)/(2-0.3) = 0.65$$

- ✓ LCOE(Cost):

$$N = (0.10-0.04)/(0.10-0.02) = 0.75$$

- ✓ Carbone footprint (Cost):

$$N = (80 - 45)/(80 - 20) = 0.58$$

- ✓ Recyclability (Benefit):

$$N = (95 - 60)/(95 - 60) = 1$$

- ✓ TRL (Benefit):

$$N = (9 - 4)/(9 - 4) = 1$$

- ✓ Improvement Potential (Benefit):

$$N = (10 - 5)/(30 - 5) = 0.20$$

Weighted Score Calculation:

$$\textbf{SCore} = \sum(\textbf{weight} \times \textbf{Normalized Value})$$

$$\begin{aligned}\textbf{Score} = {} & (0.15 \times 0.60) + (0.10 \times 0.85) + (0.05 \times 0.62) + (0.15 \times 0.65) \\ & + (0.10 \times 0.75) + 0.58 + 0.05 + 0.10 + (0.10 \times 0.02)\end{aligned}$$

$$\textbf{Final Score} = 0.61$$

The MCDA framework is applied uniformly to all photovoltaic technologies across generations. The worked example provided using monocrystalline silicon is solely intended to illustrate the calculation procedure and does not represent a generalization of the entire first-generation category.

3.8. Smart-Grid Related Criteria

The link with smart grids has been strengthened by explicitly embedding three operational attributes into the MCDA criteria set: grid flexibility, storage interoperability, and reliability. *Grid flexibility* is assessed through compatibility with advanced inverter functions (Volt/Var control, ride-through capability, ramp-rate limitation) and tolerance to curtailment and rapid irradiance fluctuations. *Storage interoperability* is evaluated via DC/AC coupling compatibility, electrical stability under charge-discharge cycles, and integration with energy-management systems. *Reliability* is measured using annual degradation rate, thermal behavior, cycling stability, and field-proven maturity (TRL). These grid-related attributes influence the ranking beyond efficiency and CAPEX/LCOE by favoring technologies that are electrically stable, thermally robust, and easily integrated with storage and control systems. As a result, a slightly less efficient technology can rank higher if it offers superior controllability, durability, and system-level performance within modern smart-grid environments.

3.9. Sensitivity Analysis

To evaluate the robustness of the ranking findings, a sensitivity analysis was conducted by changing the criteria weights by ±10%. The investigation verified that the primary findings hold true even with slight weight fluctuations.

Application of the Sensitivity Formula in the Present MCDA Study.

Formula used:

For each criterion j, its weight is varied by ± 10, and the global score is recalculated:

$$\boldsymbol{Sensitivity\ j}(\%) = \frac{\boldsymbol{Score}_{+10\%} - \boldsymbol{Score}_{\boldsymbol{initial}}}{\boldsymbol{Score}_{\boldsymbol{initial}}} \times 100$$

The same calculation is performed for -10%.

Practical application in the present context.

Assume the initial MCDA score for $\boldsymbol{c - Si} = 0.61$.

Example—LCOE criterion:

- Initial LCOE weight = 10%;
- Increased weight = 11%;
- Recalculated score = 0.64.

$$\boldsymbol{Sensitivity}_{\boldsymbol{LCOE}} = \frac{0.64 - 0.61}{0.61} \times 100 = 4.9\% (\boldsymbol{Hight\ impact})$$

Example—Recyclability criterion:

- Initial weight = 5%;
- Increased weight = 5.5%;
- Recalculated score = 0.615.

$$\boldsymbol{Sensitivity} = \frac{0.615 - 0.61}{0.61} \times 100 = 0.8\% (\boldsymbol{low\ impact})$$

Table 3 presents the impact of ±10% variations in criteria weights on the overall scores and the ranking of technologies.

Table 3. Sensitivity analysis results (±10%) on technology scores and ranking.

Criterion	Score +10%	Score −10%	Average Variation (%)	Ranking Impact
LCOE	0.64	0.58	±5%	Possible ranking shifts
Efficiency	0.63	0.59	±4%	Favors tandems
Lifetime	0.62	0.59	±3%	Strengthens mature tech
TRL	0.615	0.605	±1.5%	Minor
Recyclability	0.615	0.605	<1%	No change

LCOE and operational lifetime are the main factors that influence utility-scale power plant deployments, and they typically favor established and industrially validated technologies like crystalline silicon (c-Si) and CdTe. The initial CAPEX, on the other hand, is the most important element for off-grid and mini-grid systems, favoring less expensive technologies even if their long-term efficiency is marginally lower. Improved rankings for thermally robust thin-film technologies, which typically sustain performance better under high-temperature circumstances, result from the temperature coefficient and degradation rate becoming crucial for hot-climate installations.

4. Overview of Photovoltaic Generations

4.1. First-Generation Photovoltaic Solar Cells

These cells are called first-generation photovoltaic cells because they were developed in the 1950S. They are produced from wafers 100 to 200 µm thick, cut from blocks of solar-grade silicon [19]. They are also known as conventional, traditional, or wafer-based solar cells. They can be monocrystalline (mono-Si) or polycrystalline (multi-Si) depending on the production method.

4.1.1. Monocrystalline Silicon Solar Cells

First-generation technologies, dominated by crystalline silicon (in mono- and polycrystalline forms) and gallium arsenide (GaAs), are based on thick wafer substrates. Each cell consists of a single silicon crystal and is more efficient, but more expensive, than polycrystalline and thin-film cells. Silicon monocrystals are formed using the Czochralski process into cylindrical ingots called balls. These cylindrical balls are then cut into thin wafers, generally referred to as pseudo-square [20] [21].

Monocrystalline silicon (m-si) solar cells have:

- An efficiency ranging from 15% - 24%;
- A band gap of approximately 1.1 eV;
- A lifespan of 25 years;
- Advantages: Stable, high performance, long lifespan;
- Limitations: High manufacturing cost, increased sensitivity to temperature, absorption issues, material loss [22] [23].

4.1.2. Polycrystalline Silicon Solar Cells

Polycrystalline silicon solar cells are also known as multicrystalline solar cells. Polycrystalline silicon is a material composed of multiple small silicon crystals, used as a raw material for solar photovoltaics. Polycrystalline or multicrystalline silicon cells are manufactured by solidifying a large block of molten silicon in order to orient the crystals in a fixed direction, producing square ingots of cast poly-Si, which are then cut into wafers [24]. Poly-Si cells are widely used in module manufacturing and are less expensive, although less efficient than mono-Si cells. Some photovoltaic cell manufacturers, such as SUNTECH POWER, produce mono-Si and poly-Si modules with similar conversion efficiency and fill factor, respectively 15.38% and 77.52% [25]. On a commercial scale, the conversion efficiency of poly-Si has been reported to be between 13% and 16% [21].

4.1.3. Gallium Arsenide (GaAs) Solar Cells

GaAs-based solar cells are part of a semiconductor composed of a combination of gallium (Ga) and arsenic (As) with the same structure as silicon [21]. They offer higher efficiency and are lighter than silicon photovoltaic cells. However, they are much more expensive than silicon-carbon and mono-Si photovoltaic cells. The increased efficiency of GaAs is due to the alloying of phosphorus (P), antimony (Sb), aluminum (Al), and indium (In), which gives it a multi-junction structure and, as a result, a lower temperature coefficient [21] [26]. These characteristics make GaAs an excellent candidate material for solar cell manufacturing, with efficiencies twice those of silicon [27]. GaAs single crystals can be manufactured using either the Czochralski liquid encapsulation technique or the Bridgman process [19]. Among all materials, GaAs-based solar cells hold the record for efficiency in converting sunlight into electricity, with power conversion efficiencies of 28.8% and 24.1% for laboratory cells and modules, respectively [28]. A major drawback is the high cost of the material for producing high-quality epitaxial layers or substrates, compared to the considerable commercial advantage of silicon [27] [19]. This is largely due to factors such as crystal imperfections and unwanted impurities that reduce device efficiency, making low-cost deposition methods impossible. Indeed, manufacturing a GaAs wafer is very expensive compared to silicon. This limits the large-scale deployment of GaAs solar cells, restricting their use to niche applications (e.g., space communications, where higher efficiencies, better radiation resistance, and better power-to-weight ratios are required), where their specific capabilities justify their exorbitant cost. Cost-effective production processes for GaAs solar cells, involving the reuse of GaAs wafers, have been described [27] [29] [30]. However, they have not been demonstrated in large-scale production [31].

4.2. Second-Generation Photovoltaic Solar Cells

The second generation focuses on thin-film technologies, with the aim of reducing the high costs associated with the first generation. It includes amorphous silicon and cadmium telluride/cadmium sulfide cells [32] [22].

Thin-film cells are considered second-generation photovoltaic cells. They cost less than first-generation cells because they require less silicon. However, their market share is lower due to their lower efficiency. There are different types of thin-film cells [33]. These include amorphous silicon solar cells, which are deposited on a substrate after silane gas is broken down in a plasma-assisted chemical reactor. AS cells offer significant cost-saving potential thanks to their low material consumption and the possibility of producing them in rolls.

Their main disadvantage is their low efficiency (10.1%) and instability in terms of electricity production over time. It has been found that their efficiency decreases by about 20% with prolonged use [34]-[36].

In contrast, cadmium telluride (CdTe) solar cells offer a higher efficiency of around 17%. CdTe cells can be manufactured by chemically depositing CdTe by evaporation onto a substrate. However, their use is limited due to their toxic material content and the limited production of telluride [36].

4.2.1. Amorphous Silicon (a-Si) Solar Cells

Amorphous silicon (a-Si) dominated the development of the thin-film photovoltaic industry for some time due to its low-cost production potential compared to c-Si. However, progress and development were hampered by challenges related to solar conversion efficiency and stability [37]. Amorphous silicon offers a higher absorption coefficient than c-Si, allowing for high absorption of solar radiation. It has a wider bandgap of approximately 1.7 eV, compared to 1.12 eV for c-Si, giving it strong absorption properties. However, this wide bandgap reduces the range of wavelengths that can be absorbed [31]. This is because the selection rules for indirect bandgap semiconductors, which significantly limit the absorption coefficient of c-Si, do not apply to a-Si [38]. But when exposed to real outdoor conditions, their efficiency is in the range of 4 to 8% due to light-induced degradation, known as the Staebler-Wronski effect [39].

The main disadvantage of amorphous silicon solar cells is the degradation of power output over time (15 to 35%) to a minimum level, after which they become stable in light [40].

Therefore, to reduce light-induced degradation, a-Si multi-junction solar cells have been developed with improved conversion efficiency. In a recent study, a stable conversion efficiency of 9.1% for single-junction a-Si cells was achieved by depositing a high-quality, low-defect a-Si:H layer [41]. The performance of a-Si solar cells has also been improved [42] by fabricating 2.85 nm silicon nanoparticles on the top layer, which improves internal quantum efficiency as well as light coupling.

4.2.2. Cadmium Telluride (CdTe)

Given global installed capacity, cadmium telluride (CdTe) is the leading thin-film photovoltaic technology. The main attraction of CdTe for photovoltaic applications lies in its high bandgap (1.45 eV), which is ideal for high-efficiency single-junction cells [37]. Thanks to its very high optical absorption power, it is an ideal semiconductor for photovoltaic applications. Its high absorption coefficient is due to a direct bandgap where the maximum energy in the valence band and the minimum in the conduction band are located at the center of the Brillouin zone [37]. This suggests that efficient transfer can occur from the valence band to the conduction band, making simultaneous pulse variation due to lattice vibrations unnecessary. It is therefore an ideal semiconductor for efficient absorption of solar radiation. Yields of 21% and 17.5% for laboratory cells and modules, respectively, have been reported and are among the highest for thin-film solar cells [43] [44] [37]. CdTe technologies use high-throughput manufacturing techniques [45] requiring a high processing temperature of around 600˚C [37]. However, they offer the lowest module costs compared to all photovoltaic technologies on the market today [46]. Environmen-tal concerns, such as the toxicity and scarcity of cadmium, as well as the criticality of tel-lurium [47], have prompted research into alternative material systems using non-toxic and abundant elements that are equally easy to manufacture.

4.2.3. Copper Indium Selenide (CIS) and Copper Gallium Diselenide (CIGS) Solar Cells

In recent years, CIGS cells have become one of the most popular and rapidly developed thin-film solar cells. They compete with other thin-film cells thanks to their high conversion efficiency (21% in the laboratory) [21]. CIS solar cells have been successfully commercialized by many companies. Commercially, module efficiency ranges from 7% to 16% [25] [48] report that CIGS thin-film solar cells degrade only 10% compared to other thin-film cells. The main challenges associated with CIGS lie in the lack of knowledge about certain aspects such as junction activation treatment, interfaces and grain boundaries, and the formation of stable back contacts. Another major problem is the scarcity of indium, which can hamper the production process [49].

4.2.4. Copper, Zinc and Tin Sulfide (CZTS) Solar Cells

The difficulty of finding alternative materials for solar cells based on abundant and non-toxic elements has led to the exploration and development of copper-zinc-tin sulfide (Cu_2ZnSnS_4 or CZTS) in the thin-film photovoltaic industry. CZTS is a quaternary semiconductor with promising optical absorption properties, with a direct bandgap energy of approximately 1.5 eV and a high absorption coefficient in the order of 104 cm^{-1}, enabling it to absorb most of the visible solar spectrum [50]. The CZTS film contains no rare metals or toxic materials and can be combined with a cadmium-free buffer layer to produce completely non-toxic solar cells. Several methods for preparing CZTS solar cells have been described in the scientific literature [51]. The highest solar conversion efficiency currently achieved for solution-processed CZTS-based solar cells is 10.1%. [52]. For pure CZTS-based solar cells manufactured under vacuum, efficiencies of 8.4% have been reported [53]. Record efficiencies in the laboratory have reached 12.6% [54]. A major technological challenge for CZTS solar cell technology lies in managing cationic disorder defects, a phenomenon caused by uncontrolled inter-substitution of zinc and copper cations, resulting in point defects that hinder charge extraction and reduce open-circuit voltage [46].

4.3. Third-Generation Photovoltaic Solar Cells

The third generation was born from the idea of increasing the efficiency of photovoltaic cells by using new materials called nanomaterials. Nanomaterials are innovative materials that are attracting considerable interest due to their intrinsic innovative characteristics [22]. These materials represent much more promising advances in solar technology. Their application has not yet gained momentum, as research on third-generation materials for photovoltaic devices is still ongoing [55].

Some of these characteristics are listed [22].

- The energy band gap of the different layers can be adjusted to the desired value by changing the size of the nanoparticles. This allows for greater flexibility in the design of the solar cell absorber.
- The electrons and holes generated by light have to travel a much shorter distance, which significantly reduces recombination losses.
- The integration of a high-quality silicon nanoparticle film on a silicon solar cell improves conversion efficiency by 50% - 60% in the ultraviolet range of the spectrum.

- Fewer materials are required, which reduces costs.

Third-generation photovoltaic cell technology refers to single-junction solar cells capable of exceeding the Shockley-Queisser limit of 31% to 41% energy efficiency. C-Si (first-generation) solar cells and thin-film solar cells have certain limitations in achieving higher efficiency and must be recognized as photovoltaic technology that meets all the conditions of the golden triangle. Third-generation solar cell technology includes the following types of solar cells [56].

- Dye-sensitized solar cells;
- Quantum dot solar cells;
- Perovskite solar cells;
- Organic solar cells.

To increase the efficiency of a solar cell, it is necessary to absorb all photons from incident sunlight. A single-junction solar cell cannot achieve this goal. This is why a multifunctional solar cell is being considered as a solution.

4.3.1. Dye-Sensitized Solar Cells (DSSC)

Among all the nanomaterial-based solar cell options, dye-sensitized solar cells (DSSCs) are attracting considerable interest and are among the most mature and best understood solar cell technologies. In a DSSC, photons are captured by a photosensitizer that is absorbed by a thin layer of nanocrystalline semiconductor placed on the anode [57].

While other photovoltaic technologies use solid-state semiconductors for electron transfer and photoelectric effect generation, DSSCs use liquid electrolytes (photoelectrochemical cells) to transfer ions to a counter electrode, thereby producing an electric current [31] [56]. DSSCs have achieved efficiencies of up to 12.3% [57] and offer the following advantages: versatility and promising low manufacturing costs; the use of small amounts of inexpensive and readily available materials manufactured using proven processes; simple assembly and flexible modules; compatibility with printing techniques; deposition on various substrates and integration on a wide range of surfaces [31] [56].

The main challenges of DSSC technology include long-term stability under solar irradiation and at high temperatures, low absorption coefficients, and low open-circuit voltages due to interfacial recombination. All these challenges raise the question of their competitiveness compared to traditional solar cell technologies [58].

4.3.2. Quantum Dots (Based on Nanocrystals)

A quantum dot is a nanocrystal produced from a semiconductor material, so small that the laws of quantum mechanics must be taken into account. It is used as a photovoltaic absorbing material in solar cells [59]. This is because it has the advantage of having a band gap and optical and electrical properties that can be easily adjusted by modifying the size of the nanoparticles [60]. This makes it easy to manufacture them to absorb different parts of the solar spectrum, enabling efficient capture of near-infrared photons [31]. QDPVs use solution-processed nanocrystals and are useful for integration into various solar cells. Their preparation methods, operating principles, including the advantages and disadvantages of different QDPV device architectures are detailed in the reference [59]. A record efficiency of 9.2% has been reported in the laboratory [43], and they offer the potential for easy fabrication and stable operation in air. Key challenges include insufficient understanding of QD surface chemistry, low open-circuit voltages, and low charge carrier mobility [31].

The advantages and disadvantages of different QDPV device architectures are detailed in the reference [59]. A record efficiency of 9.2% has been reported in the laboratory [43], and they offer the potential for easy fabrication and stable operation in air. Key challenges include insufficient understanding of QD surface chemistry, low open-circuit voltages, and low charge carrier mobility [31].

4.3.3. Perovskite Based Solar Cells

Extensive research has continued over the years, and a major breakthrough has been achieved thanks to recent polycrystalline films composed of an organic cation (A), an inorganic cation (B), and a halide (X) with the formula ABX3. This organic-inorganic hybrid material is commonly referred to as perovskite material, and subsequently, perovskite-based solar cells [61].

A perovskite solar cell (PSC) is a type of solar cell that incorporates a perovskite-structured compound, typically an organic-inorganic hybrid material based on lead or tin halides, as the active light-absorbing layer. These perovskite-based materials, such as methylammonium lead halides and cesium lead halides, are inexpensive and easy to produce. Over the years, the efficiency of perovskite solar cells on a laboratory scale has improved significantly, from 3.8% in 2009 to 25.7% in 2021 for single-junction designs. In tandem cells combining perovskite and silicon, efficiency has reached 29.8%, exceeding the maximum efficiency achieved by single-junction silicon solar cells. These advances have made perovskite solar cells one of the most efficient solar technologies since 2016. Their potential for even higher efficiency and low production costs makes them commercially attractive, although stability issues remain a key area of research [61].

Perovskite solar cells offer many advantages due to the raw materials used and the manufacturing methods employed, such as various printing techniques, which contribute to their accessibility. Their high absorption coefficient allows ultra-thin films approximately 500 nm thick to capture the entire visible solar spectrum. These characteristics make it possible to create economical, highly efficient, thin, lightweight, and flexible solar modules.

4.4. Fourth Generation Photovoltaic Solar Cells

4GEN technology combines the low cost and flexibility of thin polymer layers with the good stability of nanomaterials such as metal nanoparticles, metal oxides, carbon nanotubes, graphene, and its derivatives. These architectures will retain the advantage of devices that can be transformed into solutions, resulting in low-cost manufacturing, while incorporating nanomaterials to improve dissociation and charge transport within cells. Particular attention is being paid to graphene (G), which has become the nanomaterial with the highest scientific and technological expectations.

Currently, photovoltaic technology is considered a solution to the growing energy challenge and a key element in future global energy production. This review provides a brief description of the state of the art in photovoltaic cells. The various technologies developed to date have been divided into four generations, and the characteristics, advantages, and limitations of each generation, as well as the latest research, have been examined in detail.

5. Complete Technical Database

5.1. Complete Database on Technological Performance

Table 4. Comprehensive database on technological performance.

Technology	Efficiency Range (%)	Record Lab (%)	Commercial (%)	Voc (V)	Jsc (mA/cm^2)	FF (%)	Bandgap (eV)	Temp Coeff (%/°C)
First Generation								
c-Si (mono)	20.0 - 26.7	26.7	20 - 22	0.74	42.7	85.2	1.12	−0.45
c-Si (poly)	15.0 - 22.3	22.3	16 - 18	0.67	39.5	81.1	1.12	−0.48
GaAs	25.0 - 28.8	28.8	24 - 26	1.12	29.7	86.5	1.43	−0.25
Second Generation								
a-Si	6.0 - 10.2	10.2	6 - 8	0.87	16.2	72.5	1.70	−0.15
CdTe	17.0 - 22.1	22.1	16 - 18	0.88	31.8	78.9	1.45	−0.36
CIGS	19.0 - 23.4	23.4	15 - 17	0.69	39.1	76.4	1.15	−0.36
CZTS	8.0 - 12.6	12.6	8 - 10	0.66	24.3	68.2	1.50	−0.42
Third Generation								
Perovskite	15.0 - 26.1	26.1	18 - 21	1.19	25.7	85.1	1.55	−0.30
DSSC	8.0 - 12.3	12.3	7 - 9	0.73	22.1	74.2	1.80	+0.05
OPV	12.0 - 18.2	18.2	10 - 12	0.95	26.8	71.3	1.60	−0.20
QD Cells	9.0 - 16.6	16.6	8 - 11	0.62	35.2	68.5	1.30	−0.25
Fourth Generation								
Si/Perovskite	28.0 - 33.7	33.7	25 - 28	1.85	20.1	90.5	Tandem	−0.38
All-Perovskite	25.0 - 28.2	28.2	N/A	2.15	15.8	83.2	Tandem	−0.28
III-V Tandem	35.0 - 44.4	44.4	35 - 40	2.95	17.2	87.8	Tandem	−0.22

Sources: Performance parameters compiled from Green *et al.* (2023) [4], Solar Cell Efficiency Tables, Version 62; NREL, Best Research-Cell Efficiency Chart (2024 Edition); manufacturer datasheets; and peer-reviewed literature. Record laboratory efficiencies correspond to the certified values reported in the NREL and Fraunhofer ISE datasets for the respective year. Commercial efficiency ranges reflect mass-production averages for 2023-2024 modules. Temperature coefficients and electrical parameters are derived from Fraunhofer ISE Photovoltaics Reports and IEA PVPS Task 13 reliability studies. The Si/Perovskite tandem efficiency has been updated to 34.85% based on LONGi (2025) NREL-certified results.

All quantitative information has been systematically validated using various independent sources. Performance indicators have been checked against reports provided by certified testing laboratories such as NREL, Fraunhofer ISE, and AIST, where appropriate. Sector reports extracted from the Bloomberg NEF, IRENA, and IEA databases [62] [63] were used to validate economic data. The principal performance characteristics of representative photovoltaic technologies are compiled in **Table 4**, covering efficiency ranges, record laboratory achievements, commercial performance and key electrical parameters.

5.2. Economic Analysis and Cost Projections

The economic competitiveness study highlights significant cost reductions across all technology platforms, driven by increased production volumes and learning effects, as documented by the International Renewable Energy Agency [63].

Silicon solar panels have seen a decline in production costs, reaching between \$0.20 and \$0.30/Wp (2024), which is equivalent to a 90% decrease compared to 2010 [64]. The learning rate assessment reveals a 20% decrease in costs as production doubles, which is consistent with historical developments in the semiconductor industry [65].

Table 5. Economic and industrial parameters.

Technology	CAPEX (\$/Wp)	OPEX (\$/kWp/yr)	Manufacturing Temp (˚C)	Process Complexity	Material Cost (\$/m^2)	Learning Rate (%)
c-Si (mono)	0.80 - 1.20	15 - 25	1200 - 1400	High	12 - 18	20
c-Si (poly)	0.70 - 1.00	15 - 25	1200 - 1400	High	10 - 15	20
GaAs	8.00 - 15.00	50 - 80	600 - 800	Very High	85 - 120	15
a-Si	0.60 - 0.90	10 - 20	200 - 300	Medium	8 - 12	18
CdTe	0.50 - 0.80	12 - 18	400 - 600	Medium	6 - 10	22
CIGS	0.80 - 1.30	18 - 28	500 - 600	High	15 - 22	19
CZTS	0.40 - 0.70	10 - 15	500 - 550	Medium	5 - 8	25
Perovskite	0.30 - 0.60*	8 - 15	100 - 150	Low	3 - 6	30
DSSC	0.40 - 0.80	12 - 20	80 - 120	Low	8 - 15	25
OPV	0.20 - 0.50	5 - 12	60 - 100	Low	4 - 8	28
QD Cells	0.60 - 1.20	15 - 25	150 - 250	Medium	12 - 20	22
Si/Perovskite	1.20 - 2.00*	20 - 35	Hybrid	Very High	25 - 40	25

Sources: Economic and manufacturing parameters compiled from IRENA, Renewable Power Generation Costs (2023-2024 editions); IEA PVPS, Trends in Photovoltaic Applications and Task 13 Reliability Reports (2023-2024); Fraunhofer ISE, Photovoltaics Report (2023-2024 editions); ITRPV—International Technology Roadmap for Photovoltaics (2023); Bloomberg NEF PV Market Outlook (2023-2024); manufacturer technical datasheets and peer-reviewed literature. Learning rates are derived from historical deployment analyses reported by IEA/IRENA and market studies (BNEF). Manufacturing temperature ranges and process-complexity assessments are based on Fraunhofer ISE process reports, ITRPV roadmaps, and semiconductor fabrication literature. Values marked with (*) denote projected or pilot-scale estimates for emerging technologies (perovskites and tandems).

Thin-film technologies offer competitive cost structures, while providing additional benefits related to reduced silicon material requirements. Due to simplified device design and high-speed vapor transport deposition, CdTe modules have the lowest production costs (\$0.18 - 0.25/Wp) [66]. CIGS production costs remain higher (between \$0.35 and \$0.50/Wp) due to the complex demands of multi-source co-evaporation. However, advances in roll-to-roll processing suggest significant cost reductions are on the horizon [67].

The manufacture of perovskite offers a major economic opportunity, with anticipated costs of less than \$0.15/Wp due to the abundance of raw materials and the low-temperature solution processing method [68]. However, current laboratory expenses exceed \$5.00/Wp due to expensive substrates and inefficient use of materials. To be commercially viable, it is necessary to successfully transition to large-scale production with efficiency rates above 90%.

The analysis of levelized cost of energy (LCOE) projections incorporates investment costs, operating expenses, and performance degradation over the lifetime of the system. The current utility-scale LCOE ranges from \$0.025 to \$0.060/kWh for silicon systems located in high-irradiance locations, competitive with unsubsidized fossil fuel alternatives [69].

Tandem perovskite technologies promise substantial improvements in LCOE through increased efficiency while maintaining moderate costs. Modeling projections indicate a potential LCOE of \$0.015 to \$0.025/kWh for tandem systems achieving 35% module efficiency, representing a 40% to 60% improvement over current silicon benchmarks [70]. **Table 5** reports the main cost and manufacturing indicators for representative photovoltaic technologies, highlighting economic and industrial differences across PV generations.

Table 6. Sustainability and environmental indicators.

Technology	Lifetime (years)	Degradation (%/year)	Energy Payback (years)	Carbon Footprint (g CO_2/kWh)	Material Criticality	Recyclability (%)
c-Si (mono)	25 - 30	0.5 - 0.7	1.5 - 2.5	40 - 50	Low	95
c-Si (poly)	25 - 30	0.6 - 0.8	1.2 - 2.0	35 - 45	Low	95
GaAs	15 - 20	0.3 - 0.5	2.0 - 3.5	60 - 80	Very High	80
a-Si	15 - 20	1.0 - 2.0	1.0 - 1.5	25 - 35	Low	90
CdTe	20 - 25	0.5 - 0.8	1.0 - 1.8	30 - 40	High	85
CIGS	20 - 25	0.6 - 1.0	1.5 - 2.2	35 - 50	High	75
CZTS	15 - 20	0.8 - 1.5	1.2 - 2.0	28 - 38	Low	90
Perovskite	10 - 15*	2.0 - 5.0	0.8 - 1.2	20 - 30	Medium	65
DSSC	8 - 12	1.5 - 3.0	1.0 - 1.8	25 - 40	Low	70
OPV	5 - 10	3.0 - 8.0	0.5 - 1.0	15 - 25	Low	80
QD Cells	8 - 15	2.0 - 4.0	1.5 - 2.5	40 - 60	High	60
Si/Perovskite	20 - 25*	0.8 - 1.2	1.8 - 2.8	45 - 60	Medium	80

Sources: Lifetime, degradation rates, and recyclability values compiled from IEA PVPS Task 13—Performance and Reliability of Photovoltaic Systems (2023-2024 editions) and Fraunhofer ISE—Photovoltaics Report (2023-2024). Energy payback time (EPT) and carbon footprint data derived from peer-reviewed Life Cycle Assessment (LCA) studies, including Fthenakis & Kim (Energy Policy/Progress in Photovoltaics) and Frischknecht *et al.* (ecoinvent/LCA databases), as well as IRENA—Life Cycle Assessment of Electricity Generation Options (latest editions). Material criticality assessments are based on European Commission—Critical Raw Materials Reports (2023) and IEA sustainability analyses. Recyclability rates and end-of-life considerations are referenced from IEA PVPS Task 12—Environmental Profiles of PV Systems (2022-2023) and industry recycling guidelines. Values marked with (*) indicate projected or emerging-technology estimates derived from recent peer-reviewed literature and technology roadmaps (perovskites and tandems).

To assess the environmental and reliability performance of photovoltaic technologies, **Table 6** compiles indicative values for service lifetime, degradation rate, embodied-energy recovery time, life-cycle emissions and recyclability.

5.3. Assessment of Technological Maturity and Market Position

Technology Readiness Level (TRL) assessment: Systematic review of TRL highlights significant disparities in maturity between technology platforms. Silicon-based technologies have reached maximum technological readiness level (TRL-9) with cumulative commissioning of over one terawatt and supply chains established in various geographical regions [71]. Manufacturing processes have efficiency rates of over 95% and adequate quality control standards to guarantee performance over 25 years. Second-generation technologies have varying levels of maturity. Thanks to the commercial success of the first solar cell, which has exceeded 25 GW in cumulative shipments, CdTe has reached TRL-9. In contrast, CIGS remains at TRL-8 due to constraints related to production scale and efficiency issues [72]. Amorphous silicon applications have been limited to specialized segments (consumer electronics), illustrating their TRL-7 classification for terrestrial uses. Emerging technologies range from TRL-4 to TRL-7 depending on specific material systems and device architectures. Single-junction perovskites are approaching TRL-7 through demonstration manufacturing lines [73], while tandem architectures remain at TRL-5-6 pending validation of scaling [74]. Organic photovoltaics have reached TRL-6 for niche applications (IoT sensors, building integration) but remain at TRL-4 for large-scale deployment. The current market largely favors silicon-based technologies (95.2% market share in 2024), reflecting technological maturity and competitive cost advantages [75]. However, projections for the adoption of emerging technologies indicate a potentially significant disruption to the market between now and 2030-2035. Conservative deployment scenarios predict a 5% - 8% market share for perovskite tandems by 2030, concentrated in high-efficiency applications where superior performance justifies modest cost premiums [76]. Aggressive scenarios assuming successful manufacturing scale-up suggest 15% - 20% market penetration, driven by LCOE advantages in large-scale deployments. Global trends in R&D investment reflect growing confidence in the commercialization potential of emerging technologies. Research into perovskites attracted $2.1 billion in investment in 2023, a 40% increase over the previous year [74]. $1.8 billion in funding from venture capital and corporate sources for tandem cell development reflects strong commercial interest. Public sector investment remains focused on developing cutting-edge technologies, with $850 million allocated to next-generation photovoltaic research through national energy programs [77]. The concentration of investment in materials engineering and manufacturing process development suggests that scaling challenges are the main barriers to commercialization. The industrial maturity and commercialization status of major photovoltaic technologies are compiled in **Table 7**, including TRL classification, market share, production capacity and innovation activity.

Table 7. Technological readiness and market data.

Technology	Lifetime (years)	Degradation (%/year)	Energy Payback (years)	Carbon Footprint (g CO_2/kWh)	Material Criticality	Recyclability (%)
c-Si (mono)	25 - 30	0.5 - 0.7	1.5 - 2.5	40 - 50	Low	95
c-Si (poly)	25 - 30	0.6 - 0.8	1.2 - 2.0	35 - 45	Low	95
GaAs	15 - 20	0.3 - 0.5	2.0 - 3.5	60 - 80	Very High	80
a-Si	15 - 20	1.0 - 2.0	1.0 - 1.5	25 - 35	Low	90
CdTe	20 - 25	0.5 - 0.8	1.0 - 1.8	30 - 40	High	85
CIGS	20 - 25	0.6 - 1.0	1.5 - 2.2	35 - 50	High	75
CZTS	15 - 20	0.8 - 1.5	1.2 - 2.0	28 - 38	Low	90
Perovskite	10 - 15*	2.0 - 5.0	0.8 - 1.2	20 - 30	Medium	65
DSSC	8 - 12	1.5 - 3.0	1.0 - 1.8	25 - 40	Low	70
OPV	5 - 10	3.0 - 8.0	0.5 - 1.0	15 - 25	Low	80
QD Cells	8 - 15	2.0 - 4.0	1.5 - 2.5	40 - 60	High	60
Si/Perovskite	20 - 25*	0.8 - 1.2	1.8 - 2.8	45 - 60	Medium	80

Sources: Lifetime, annual degradation rates, and recyclability values compiled from IEA PVPS Task 13—Performance and Reliability of Photovoltaic Systems (2023-2024 editions) and Fraunhofer ISE—Photovoltaics Report (2023-2024). Energy Payback Time (EPT) and carbon footprint data are derived from peer-reviewed Life Cycle Assessment (LCA) literature, including Fthenakis & Kim (Progress in Photovoltaics / Energy Policy) and Frischknecht *et al.* (ecoinvent LCA databases), as well as IRENA—Life Cycle Assessment of Electricity Generation Options (latest editions). Material criticality assessments are based on European Commission—Critical Raw Materials Reports (2023) and complementary IEA sustainability analyses. End-of-life management and recyclability rates are referenced from IEA PVPS Task 12—Environmental Profiles of PV Systems (2022-2023) and industry recycling guidelines. Values marked with (*) indicate projected or emerging-technology estimates derived from recent peer-reviewed literature and technology roadmaps (perovskites and tandems).

6. Analysis and Discussion of Results

6.1. Historical Evolution and Efficiency Trajectories

Figure 1 illustrates the remarkable evolution of photovoltaic efficiency from the first silicon solar cell at Bell Laboratories (6%, 1954) to current world records exceeding 34% for tandem architectures. The progression reveals distinct advancement trajectories across the four photovoltaic generations.

First-generation crystalline silicon technologies demonstrated sustained improvements over seven decades, progressing from 6% (1954) to 26.81% [78] Green *et al.* [4]. The Kaneka heterojunction cell achieving 26.7% in 2017 [4] represented a significant milestone, approaching the Shockley-Queisser single-junction theoretical limit of 33.7% [79]. Second-generation thin-film technologies (CdTe, CIGS) achieved commercial viability through manufacturing cost advantages, with current records of 22.1% and 23.4% respectively [4]. Third-generation perovskite solar cells represent the most rapid efficiency advancement in photovoltaic history, progressing from 3.8% (2009) to 27.0% (USTC 2024-2025, NREL certified [4]), matching first-generation performance in just 15 years. However, operational lifetime limitations (10 - 15 years current state) constrain immediate commercial deployment despite impressive efficiency records. Fourth-generation silicon-perovskite tandem cells achieve the breakthrough shown in **Figure 1**: the LONGi tandem certified at 34.85% efficiency 2025 [80] [4] exceeds the single-junction theoretical limit through multi-junction photon harvesting, validating efficiency gains of 8+ percentage points compared to either technology alone.

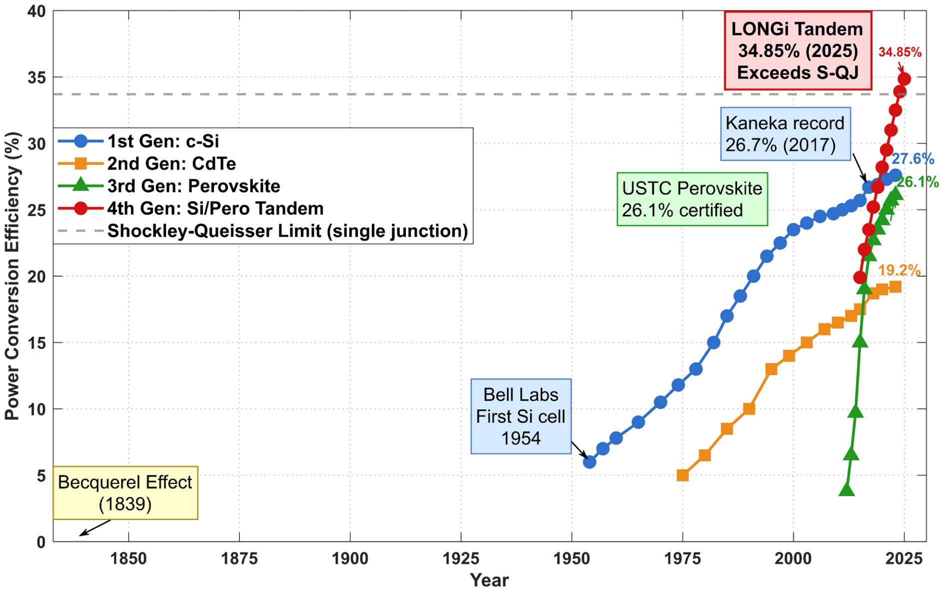

Figure 1. Progression of photovoltaic cell efficiencies by technology generation (1954-2025), highlighting the recent dominance of silicon-perovskite tandem cells beyond the Shockley-Queisser limit. Data from Green *et al.* [4].

6.2. Multicriteria Comparison of PV Technologies

The multicriteria analysis (**Figure 2**) reveals distinct performance profiles across photovoltaic generations using eight evaluation criteria spanning technical performance, commercial maturity, economic competitiveness, and environmental sustainability.

First-generation crystalline silicon demonstrates the most balanced profile (overall score 8.3/10), excelling in commercial viability (9.5/10) with 95.2% global market share [63], manufacturing maturity (10/10) with production exceeding 100 GW/year, and scalability (10/10). Laboratory efficiency of 26.81% [4] approaches theoretical limits while maintaining 27.5-year operational lifetime and 95% recyclability. Second-generation thin films achieve superior cost competitiveness (CdTe: 8.5/10) with CAPEX of \$0.50 - 0.80/Wp [63] [69] and environmental performance including 1.4-year energy payback time. However, tellurium scarcity constrains long-term scalability despite First Solar's closed-loop recycling achieving 85% material recovery. Third-generation perovskites (score 6.6/10) demonstrate exceptional efficiency 27.0% [4] and environmental credentials: shortest energy payback time (1.0 year), lowest carbon footprint (25 gCO_2eq/kWh), and projected manufacturing costs of \$0.30 - 0.60/Wp. Critical challenges remain in operational lifetime (10 - 15 years versus 25+ years required) limiting commercial deployment despite reaching TRL-7 demonstration manufacturing in 2024 Source spécifiée non valide. Fourth-generation silicon-perovskite tandems (5.5/10) achieve record efficiency 34.85% [4] but face pre-commercial status (TRL-6), elevated projected costs ($1.20 - 2.00/Wp), and manufacturing complexity. The analysis highlights fundamental trade-offs: mature technologies offer deployment readiness but limited improvement potential, while emerging technologies demonstrate superior performance characteristics requiring stability validation and manufacturing scale-up. Although this assessment is global in scope, the results are particularly relevant for developing regions and Sahelian countries, where rapid demand growth, high solar resource, and constrained public budgets sharpen the trade-offs between cost, reliability, and sustainability. The multi-criteria framework highlights that technologies combining low LCOE, robust environmental performance, and high technological maturity are especially suitable for accelerating clean electrification and climate adaptation in these contexts. From a system-planning perspective, the proposed multi-criteria framework can directly inform technology choices across application segments: mature crystalline-silicon and CdTe platforms remain preferable for large-scale desert plants, while lightweight perovskite and OPV concepts are more promising for building-integrated PV and portable off-grid systems."

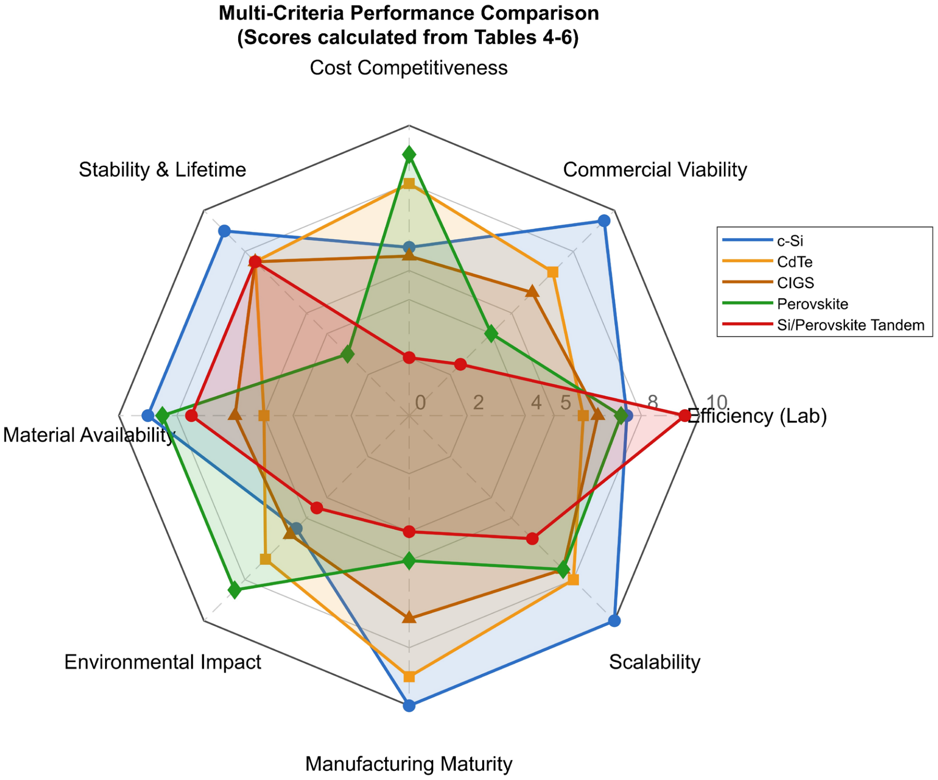

Figure 2. Multi-criteria performance comparison of photovoltaic technologies using radar chart (scale 0 - 10).

By mapping each technology to its optimal deployment niche, the framework supports more granular PV portfolio strategies that balance near-term bankability with long-term innovation opportunities.

6.3. Economic Analysis and LCOE Trends

The economic competitiveness of photovoltaic technologies has transformed dramatically, with global weighted average levelized cost of electricity (LCOE) declining 90% from \$0.460/kWh (2010) to \$0.044/kWh (2023), as documented by IRENA [63] and shown in **Figure 3**. This remarkable cost reduction positions solar photovoltaics as the most cost-competitive electricity generation technology in most global markets.

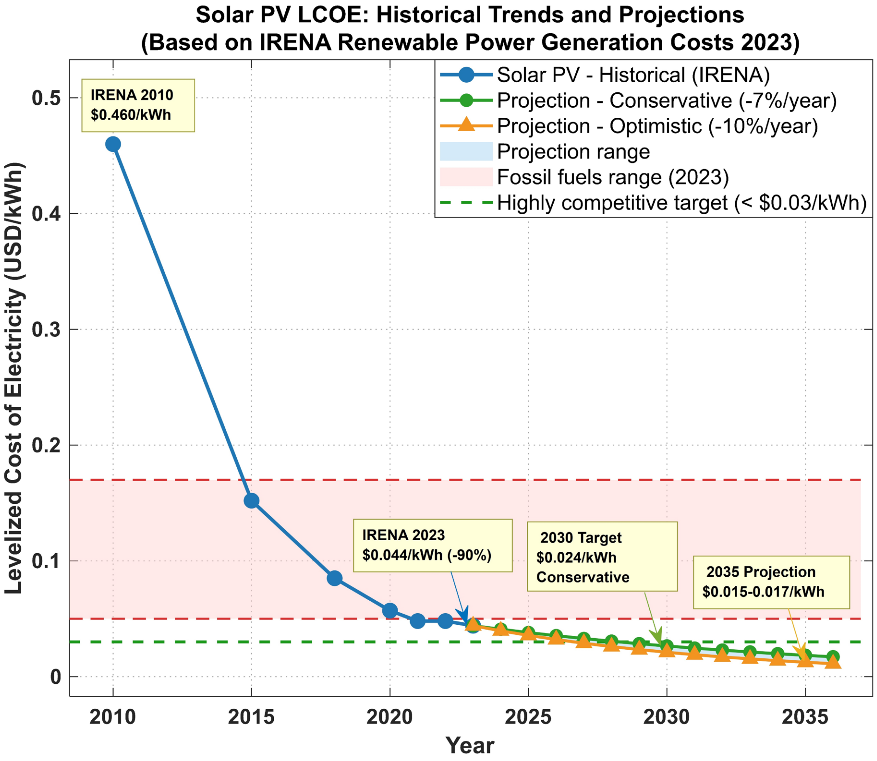

Figure 3. Solar photovoltaic levelized cost of electricity (LCOE): historical data and projections (2010-2035).

The LCOE decline reflects convergent cost reduction mechanisms. Module prices decreased from \$1.80/Wp (2010) to approximately \$0.20/Wp (2023) through manufacturing scale economies and technological improvements [63] [69]. Balance-of-system components demonstrated parallel reductions of 60% - 75% through standardization and accumulated learning. Financing costs declined substantially as solar transitioned from perceived high-risk technology to mature infrastructure, with weighted average cost of capital decreasing from 7% - 10% to 3% - 5% for utility-scale projects in investment-grade markets [69].

Projections to 2035 (**Figure 3**) indicate continued LCOE reductions through incremental technology improvements and sustained manufacturing scale expansion. Conservative scenarios project global weighted average LCOE declining to \$0.026/kWh (2030) and \$0.018/kWh (2035), representing an additional 60% reduction from 2023 levels [63]. Optimistic scenarios incorporating accelerated perovskite commercialization suggest LCOE could reach \$0.015/kWh by 2035, approaching marginal operating costs of existing fossil fuel plants. Regional variations will persist based on irradiation levels, land costs, and policy frameworks, with lowest LCOE values (\$0.01 - 0.02/kWh) achieved in high-insolation regions with supportive regulatory environments [63] [69].

6.4. Technology Maturity and Commercialization Roadmap

Technology Readiness Level (TRL) assessment provides systematic evaluation of photovoltaic technologies' progression from fundamental research (TRL 1 - 3) through development (TRL 4 - 8) to full commercial deployment (TRL 9). **Figure 4** illustrates TRL evolution trajectories, revealing diverse maturation timescales and highlighting the gap between laboratory efficiency achievements and commercial manufacturing readiness.

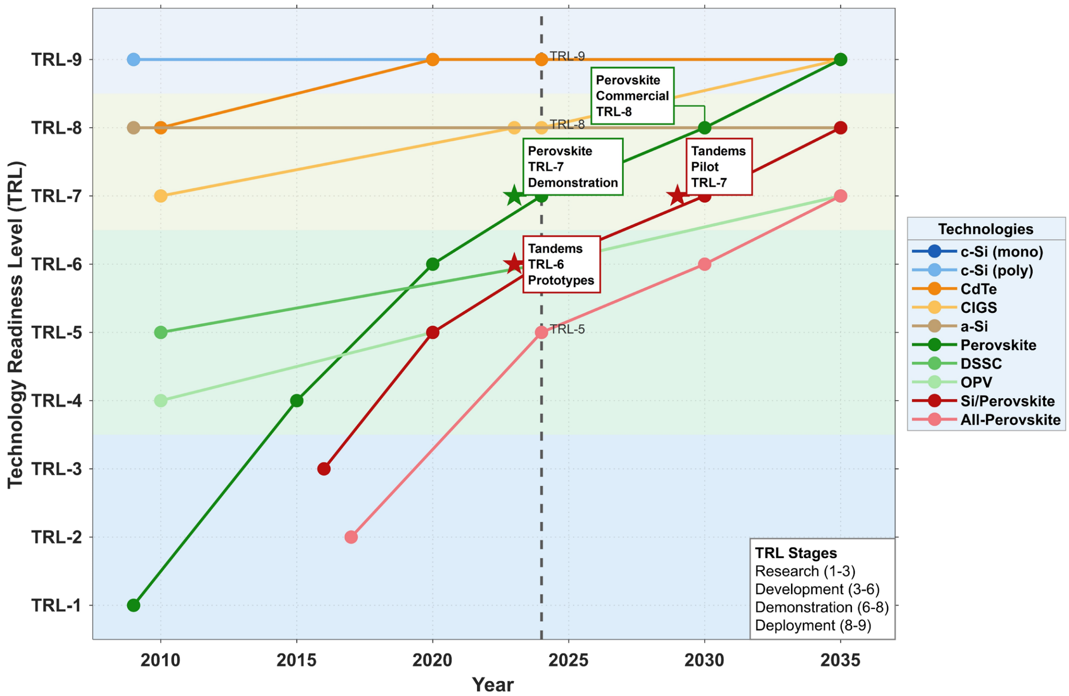

Figure 4. Photovoltaic technology roadmap with Technology Readiness Level (TRL) evolution (2010-2035).

First-generation crystalline silicon technologies maintain TRL-9 status with mature commercial manufacturing exceeding 100 GW annual global production capacity [71]. Second-generation thin films demonstrate varied maturity: CdTe achieved TRL-9 through First Solar's integrated manufacturing (8+ GW annual capacity), while CIGS remains at TRL-8 with production below 1 GW/year [73] [71]. Third-generation perovskites represent the most dynamic TRL progression, advancing from proof-of-concept (TRL-1, 2009) to demonstration manufacturing (TRL-7, 2024) in just 15 year [71] [73]. Oxford PV and other manufacturers have demonstrated pilot-scale processes (1 - 100 MW/year), validating manufacturability. However, transition to TRL-8 and TRL-9 requires demonstration of 25+ year operational stability under field conditions.

Fourth-generation tandem architectures currently operate at TRL-6 (prototype demonstration), with silicon-perovskite tandems showing most rapid advancement [77] [71] [69]. Manufacturing challenges include precise optical coupling between subcells and sequential processing complexity. Economic viability requires that efficiency premiums 34.85% versus 26.81% for c-Si alone [4] offset manufacturing cost increases estimated at 50% - 100%. Projections indicate potential TRL-7 achievement by 2027-2030 and limited commercial deployment (TRL-8) by 2030-2035, though timelines depend critically on stability validation and manufacturing yield improvements [71] [73] [77].

6.5. Environnement Impact and Sustainability Assessment

Life cycle environmental assessment reveals significant performance variations across photovoltaic technologies in energy payback time (EPT), carbon footprint, and end-of-life recyclability (**Figure 5**). These sustainability metrics provide essential context beyond efficiency and cost considerations, particularly as global deployment scales toward multi-terawatt capacities.

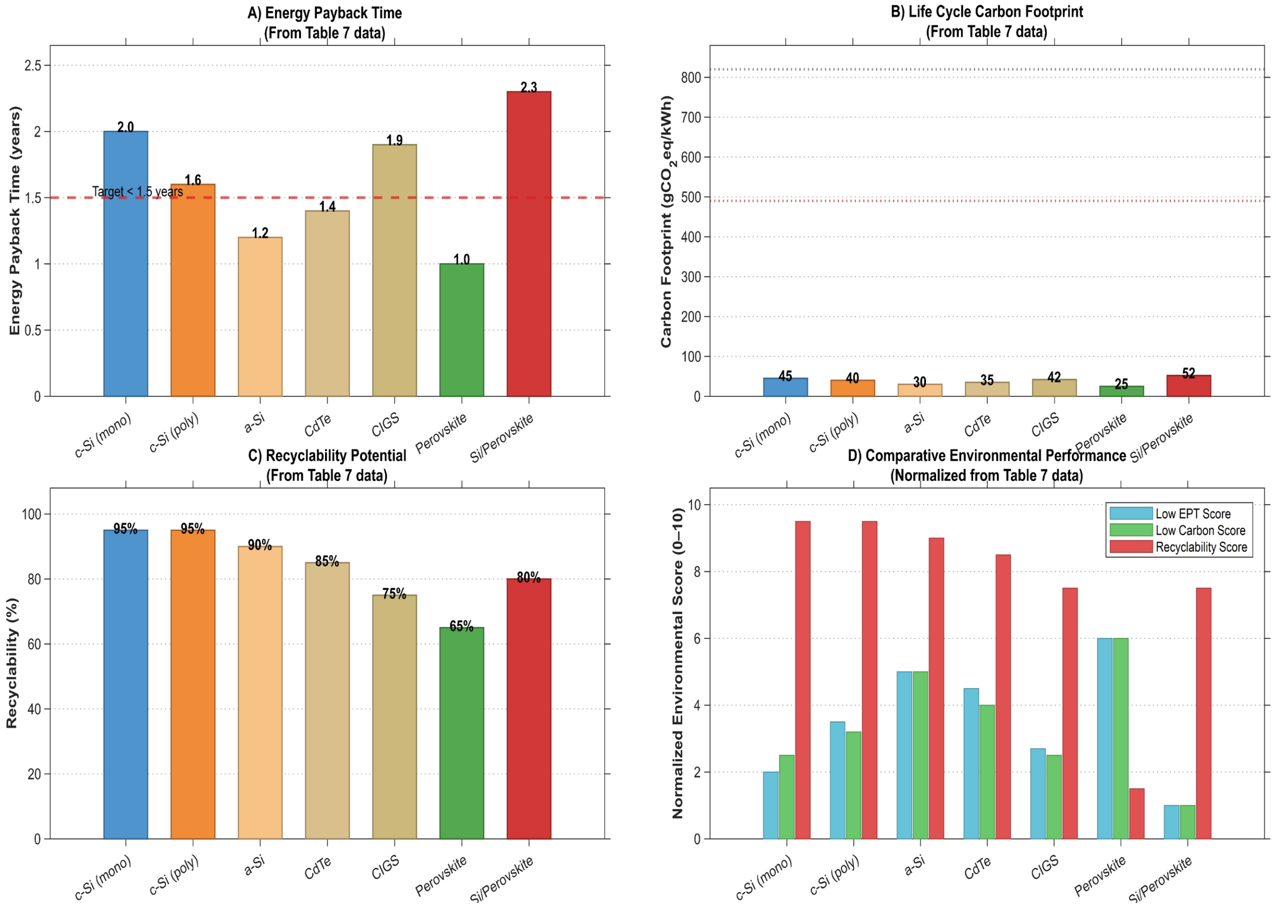

Figure 5. Environmental assessment of photovoltaic technologies based on energy, carbon and recyclability metrics.

Energy payback time demonstrates strong correlation with manufacturing process intensity. Third-generation perovskites achieve the shortest EPT (1.0 year) due to low-temperature solution processing (<150˚C) and thin active layers, enabling rapid energy return on investment. Second-generation thin films follow closely (CdTe: 1.4 years, a-Si: 1.2 years) benefiting from reduced material consumption. First-generation crystalline silicon exhibits longer EPT (monocrystalline: 2.0 years, polycrystalline: 1.6 years) reflecting energy-intensive silicon purification and wafer crystallization. All technologies achieve EPT well below 25 - 30-year operational lifetimes, returning 10 - 25 times more energy than consumed in fabrication. Carbon footprint analysis (**Figure 5**) demonstrates that all photovoltaic technologies achieve dramatic greenhouse gas emission reductions compared to fossil fuel alternatives (coal: ~820 gCO_2eq/kWh, natural gas: ~490 gCO_2eq/kWh). Perovskites demonstrate lowest life cycle emissions (25 gCO_2eq/kWh), with thin films (30 - 35 gCO_2eq/kWh) and c-Si (40 - 45 gCO_2eq/kWh) achieving 16 - 33× lower emissions than fossil alternatives. End-of-life recyclability varies substantially: c-Si demonstrates highest recyclability (95%) through established processes recovering aluminum, glass, silicon, and silver. CdTe benefits from First Solar's closed-loop recycling (85% recovery). Perovskites and tandems face uncertainty (65% - 80% estimated) due to complex layer structures and absence of established industrial recycling processes.

7. Conclusions

This study integrated technical, economic, environmental, technological, and future-focused factors to give a comprehensive multi-criteria analysis of photovoltaic technologies from the first to the fourth generation. A systematic comparison of several photovoltaic concepts was made possible by the suggested evaluation methodology, which highlighted each concept's advantages, disadvantages, and potential for deployment.

Because of their high maturity, dependability, and economic competitiveness, first-generation crystalline silicon technologies continue to play a major role in modern power systems. However, if stability and durability issues are sufficiently resolved, fourth-generation photovoltaic technologies—especially tandem and perovskite-based solar cells—show exceptional efficiency potential and offer a promising route for the deployment of next-generation photovoltaic systems.

Particularly for dispersed generation and high-temperature applications, second-generation thin-film technologies show promise as a cost, performance, and environmental impact compromise. On the other hand, because of their lower efficiency and lack of technological preparedness, third-generation photovoltaic technologies are now restricted to specialized applications. The results highlight the need for technology choices to be in line with system-level goals, such as grid flexibility, dependability, and long-term sustainability, from the standpoint of smart grids. While developing high-efficiency technologies may be crucial to future intelligent power systems when paired with energy storage and sophisticated grid management techniques, mature solar technologies are well suited for rapid integration into current smart grid infrastructures.

Future studies should concentrate on long-term degradation evaluation, system-level validation of new solar technologies, and the incorporation of sophisticated decision-making tools to facilitate dynamic smart grid planning. The suggested multi-criteria framework can be expanded to incorporate scenario-based studies and regional limitations, giving policymakers and energy planners more direction.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Hossain, M.S., Abboodi Madlool, N., Al-Fatlawi, A.W. and El Haj Assad, M. (2023) High Penetration of Solar Photovoltaic Structure on the Grid System Disruption: An Overview of Technology Advancement. *Sustainability*, **15**, Article 1174. https://doi.org/10.3390/su15021174

[2] International Energy Agency (2024) World Energy Outlook. IEA Publication.

[3] Zaidi, B. (2018) Introductory Chapter: Introduction to Photovoltaic Effect. In: *Solar Panels and Photovoltaic Materials*, InTech, 1. https://doi.org/10.5772/intechopen.74389

[4] Green, M.A., Dunlop, E.D., Yoshita, M., Kopidakis, N., Bothe, K., Siefer, G., *et al.* (2023) Solar Cell Efficiency Tables (Version 62). *Progress in Photovoltaics: Research and Applications*, **31**, 651-663. https://doi.org/10.1002/pip.3726

[5] Siebentritt, S. (2006) Wide-Gap Chalcopyrites. Springer.

[6] Aydin, E., Allen, T.G., De Bastiani, M., Razzaq, A., Xu, L., Ugur, E., *et al.* (2024) Pathways toward Commercial Perovskite/Silicon Tandem Photovoltaics. *Science*, **383**, eadh3849. https://doi.org/10.1126/science.adh3849

[7] Rivera, P.J.V. (2023) Development and Advanced Characterization of Materials for Integration into the Tunnel/Recombination Junction of Two Terminals Silicon/Perovskite Tandem Solar Cells. Thèse de doctorat, Université Grenoble Alpes.

[8] Jena, A.K., Kulkarni, A. and Miyasaka, T. (2019) Halide Perovskite Photovoltaics: Background, Status, and Future Prospects. *Chemical Reviews*, **119**, 3036-3103. https://doi.org/10.1021/acs.chemrev.8b00539

[9] Park, N.G. and Zhu, K. (2020) Scalable Fabrication and Coating Methods for Perovskite Solar Cells and Solar Modules. *Nature Reviews Materials*, **5**, 333-350. https://doi.org/10.1038/s41578-019-0176-2

[10] Haschke, J., Dupré, O., Boccard, M. and Ballif, C. (2018) Silicon Heterojunction Solar Cells: Recent Technological Development and Practical Aspects—From Lab to Industry. *Solar Energy Materials and Solar Cells*, **187**, 140-153. https://doi.org/10.1016/j.solmat.2018.07.018

[11] Richter, A., Hermle, M. and Glunz, S.W. (2013) Reassessment of the Limiting Efficiency for Crystalline Silicon Solar Cells. *IEEE Journal of Photovoltaics*, **3**, 1184-1191. https://doi.org/10.1109/jphotov.2013.2270351

[12] Fraunhofer Institute for Solar Energy Systems ISE (2022) Photovoltaic Module Technology Roadmap. Fraunhofer ISE.

[13] Way, R., Ives, M.C., Mealy, P. and Farmer, J.D. (2022) Empirically Grounded Technology Forecasts and the Energy Transition. *Joule*, **6**, 2057-2082. https://doi.org/10.1016/j.joule.2022.08.009

[14] Kavlak, G., McNerney, J. and Trancik, J.E. (2018) Evaluating the Causes of Cost Reduction in Photovoltaic Modules. *Energy Policy*, **123**, 700-710. https://doi.org/10.1016/j.enpol.2018.08.015

[15] Li, P., Wang, Z., Wang, J., Guo, T. and Yin, Y. (2021) A Multi-Time-Space Scale Optimal Operation Strategy for a Distributed Integrated Energy System. *Applied Energy*, **289**, Article 116698. https://doi.org/10.1016/j.apenergy.2021.116698

[16] Parida, B., Iniyan, S. and Goic, R. (2011) A Review of Solar Photovoltaic Technologies. *Renewable and Sustainable Energy Reviews*, **15**, 1625-1636. https://doi.org/10.1016/j.rser.2010.11.032

[17] Schmidt, O., Melchior, S., Hawkes, A. and Staffell, I. (2019) Projecting the Future Levelized Cost of Electricity Storage Technologies. *Joule*, **3**, 81-100. https://doi.org/10.1016/j.joule.2018.12.008

[18] Victoria, M., Haegel, N., Peters, I.M., Sinton, R., Jäger-Waldau, A., del Cañizo, C., *et al.* (2021) Solar Photovoltaics Is Ready to Power a Sustainable Future. *Joule*, **5**, 1041-1056. https://doi.org/10.1016/j.joule.2021.03.005

[19] Goodrich, A., Hacke, P., Wang, Q., Sopori, B., Margolis, R., James, T.L., *et al.* (2013) A Wafer-Based Monocrystalline Silicon Photovoltaics Road Map: Utilizing Known Technology Improvement Opportunities for Further Reductions in Manufacturing Costs. *Solar Energy Materials and Solar Cells*, **114**, 110-135. https://doi.org/10.1016/j.solmat.2013.01.030

[20] Tyagi, V.V., Rahim, N.A.A., Rahim, N.A. and Selvaraj, J.A./. (2013) Progress in Solar PV Technology: Research and Achievement. *Renewable and Sustainable Energy Reviews*, **20**, 443-461. https://doi.org/10.1016/j.rser.2012.09.028

[21] Kumar, M. and Kumar, A. (2017) Performance Assessment and Degradation Analysis of Solar Photovoltaic Technologies: A Review. *Renewable and Sustainable Energy Reviews*, **78**, 554-587. https://doi.org/10.1016/j.rser.2017.04.083

[22] Sharma, P. and Goyal, P. (2020) Evolution of PV Technology from Conventional to Nano-Materials. *Materials Today*: *Proceedings*, **28**, 1593-1597. https://doi.org/10.1016/j.matpr.2020.04.846

[23] Pastuszak, J. and Węgierek, P. (2022) Photovoltaic Cell Generations and Current Research Directions for Their Development. *Materials*, **15**, Article 5542. https://doi.org/10.3390/ma15165542

[24] El Chaar, L., lamont, L.A. and El Zein, N. (2011) Review of Photovoltaic Technologies. *Renewable and Sustainable Energy Reviews*, **15**, 2165-2175. https://doi.org/10.1016/j.rser.2011.01.004

[25] Akinyele, D.O., Rayudu, R.K. and Nair, N.K.C. (2015) Global Progress in Photovoltaic Technologies and the Scenario of Development of Solar Panel Plant and Module Performance Estimation—Application in Nigeria. *Renewable and Sustainable Energy Reviews*, **48**, 112-139. https://doi.org/10.1016/j.rser.2015.03.021

[26] Deb, S.K. (1998) Recent Developments in High Efficiency Photovoltaic Cells. *Renewable Energy*, **15**, 467-472. https://doi.org/10.1016/s0960-1481(98)00206-7

[27] Miles, R.W. (2006) Photovoltaic Solar Cells: Choice of Materials and Production Methods. *Vacuum*, **80**, 1090-1097. https://doi.org/10.1016/j.vacuum.2006.01.006

[28] Dambhare, M.V., Butey, B. and Moharil, S.V. (2021) Solar Photovoltaic Technology: A Review of Different Types of Solar Cells and Its Future Trends. *Journal of Physics:*

Conference Series, **1913**, Article 012053. https://doi.org/10.1088/1742-6596/1913/1/012053

[29] Yablonovitch, E., Gmitter, T., Harbison, J.P. and Bhat, R. (1987) Extreme Selectivity in the Lift-Off of Epitaxial Gaas Films. *Applied Physics Letters*, **51**, 2222-2224. https://doi.org/10.1063/1.98946

[30] Cucchiella, F., D'Adamo, I. and Rosa, P. (2015) End-of-Life of Used Photovoltaic Modules: A Financial Analysis. *Renewable and Sustainable Energy Reviews*, **47**, 552-561. https://doi.org/10.1016/j.rser.2015.03.076

[31] Jean, J., Brown, P.R., Jaffe, R.L., Buonassisi, T. and Bulović, V. (2015) Pathways for Solar Photovoltaics. *Energy & Environmental Science*, **8**, 1200-1219. https://doi.org/10.1039/c4ee04073b

[32] Luceño-Sánchez, J.A., Díez-Pascual, A.M. and Peña Capilla, R. (2019) Materials for Photovoltaics: State of Art and Recent Developments. *International Journal of Molecular Sciences*, **20**, Article 976. https://doi.org/10.3390/ijms20040976

[33] Goetzberger, A., Hebling, C. and Schock, H. (2003) Photovoltaic Materials, History, Status and Outlook. *Materials Science and Engineering*: *R*: *Reports*, **40**, 1-46. https://doi.org/10.1016/s0927-796x(02)00092-x

[34] Guerrero-Lemus, R. and Martínez-Duart, J.M. (2013) Concentrated Solar Power. In: *Renewable Energies and* CO_2: *Cost Analysis*, *Environmental Impacts and Technological Trends*, Springer, 135-151.

[35] Shah, A., Torres, P., Tscharner, R., Wyrsch, N. and Keppner, H. (1999) Photovoltaic Technology: The Case for Thin-Film Solar Cells. *Science*, **285**, 692-698. https://doi.org/10.1126/science.285.5428.692

[36] Hayat, M.B., Ali, D., Monyake, K.C., Alagha, L. and Ahmed, N. (2019) Solar Energy-A Look into Power Generation, Challenges, and a Solar-Powered Future. *International Journal of Energy Research*, **43**, 1049-1067. https://doi.org/10.1002/er.4252

[37] Kilner, J.A., Skinner, S.J., Irvine, S.J. and Edwards, P.P. (2012) Functional Materials for Sustainable Energy Applications. Elsevier.

[38] Zhou, Y. (2015) Eco and Renewable Energy Materials. Springer.

[39] Staebler, D.L. and Wronski, C.R. (1977) Reversible Conductivity Changes in Discharge-Produced Amorphous Si. *Applied Physics Letters*, **31**, 292-294. https://doi.org/10.1063/1.89674

[40] McCann, M.J., Catchpole, K.R., Weber, K.J., *et al.* (2001) A Review of Thin-Film Crystalline Silicon for Solar Cell Applications. Part 1: Native Substrates. *Solar Energy Materials and Solar Cells*, **68**, 135-171. https://doi.org/10.1016/s0927-0248(00)00242-7

[41] Salabaş, E.L., Salabaş, A., Mereu, B., Caglar, O., Kupich, M., Cashmore, J.S., *et al.* (2016) Record Amorphous Silicon Single-Junction Photovoltaic Module with 9.1% Stabilized Conversion Efficiency on 1.43 M2. *Progress in Photovoltaics*: *Research and Applications*, **24**, 1068-1074. https://doi.org/10.1002/pip.2760

[42] Chowdhury, F.I., Alnuaimi, A., El-Atab, N., Nayfeh, M. and Nayfeh, A. (2016) Enhanced Performance of Thin-Film Amorphous Silicon Solar Cells with a Top Film of 2.85 Nm Silicon Nanoparticles. *Solar Energy*, **125**, 332-338. https://doi.org/10.1016/j.solener.2015.12.030

[43] Kazmerski, L., Gwinner, D. and Hicks, A. (2010) Best Research Cell Efficiencies. *National Renewable Energy Laboratory*, **2**, 1-2.

[44] Green, M.A., Dunlop, E.D., Hohl-Ebinger, J., Yoshita, M., Kopidakis, N. and Hao, X. (2021) Solar Cell Efficiency Tables (Version 58). *Progress in Photovoltaics*: *Research*

and Applications, **29**, 657-667. https://doi.org/10.1002/pip.3444

[45] Ferekides, C.S., Marinskiy, D., Viswanathan, V., Tetali, B., Palekis, V., Selvaraj, P., *et al.* (2000) High Efficiency CSS CdTe Solar Cells. *Thin Solid Films*, **361**, 520-526. https://doi.org/10.1016/s0040-6090(99)00824-x

[46] Schmalensee, R. (2015) The Future of Solar Energy: An Interdisciplinary MIT Study. Energy Initiative, Massachusetts Institute of Technology.

[47] Fthenakis, V. and Weibel, K. (2003) CdTe PV: Real and Perceived EHS Risks (No. NREL/CP-520-33561). National Renewable Energy Lab(NREL).

[48] Vick, B.D. and Neal, B.A. (2012) Analysis of Off-Grid Hybrid Wind Turbine/Solar PV Water Pumping Systems. *Solar Energy*, **86**, 1197-1207. https://doi.org/10.1016/j.solener.2012.01.012

[49] Pandey, A.K., Tyagi, V.V., Selvaraj, J.A., Rahim, N.A. and Tyagi, S.K. (2016) Recent Advances in Solar Photovoltaic Systems for Emerging Trends and Advanced Applications. *Renewable and Sustainable Energy Reviews*, **53**, 859-884. https://doi.org/10.1016/j.rser.2015.09.043

[50] Vasekar, P.S. and Dhakal, T.P. (2013) Thin Film Solar Cells Using Earth-Abundant Materials. In: *Solar Cells-Research and Application Perspectives*, Intechopen, 145-168.

[51] Ramasamy, K., Malik, M.A. and O'Brien, P. (2012) Routes to Copper Zinc Tin Sulfide Cu_2ZnSnS_4 a Potential Material for Solar Cells. *Chemical Communications*, **48**, Article 5703. https://doi.org/10.1039/c2cc30792h

[52] Barkhouse, D.A.R., Gunawan, O., Gokmen, T., Todorov, T.K. and Mitzi, D.B. (2012) Device Characteristics of a 10.1% Hydrazine-Processed $Cu_2ZnSn(Se, S)_4$ Solar Cell. *Progress in Photovoltaics*: *Research and Applications*, **20**, 6-11. https://doi.org/10.1002/pip.1160

[53] Shin, B., Gunawan, O., Zhu, Y., Bojarczuk, N.A., Chey, S.J. and Guha, S. (2013) Thin Film Solar Cell with 8.4% Power Conversion Efficiency Using an Earth-Abundant Cu_2ZnSnS_4 Absorber. *Progress in Photovoltaics*: *Research and Applications*, **21**, 72-76. https://doi.org/10.1002/pip.1174

[54] Wang, W., Winkler, M.T., Gunawan, O., Gokmen, T., Todorov, T.K., Zhu, Y., *et al.* (2014) Device Characteristics of CZTSSe Thin-Film Solar Cells with 12.6% Efficiency. *Advanced Energy Materials*, **4**, Article 1301465. https://doi.org/10.1002/aenm.201301465

[55] Seroka, N.S., Taziwa, R. and Khotseng, L. (2022) Solar Energy Materials-Evolution and Niche Applications: A Literature Review. *Materials*, **15**, Article 5338. https://doi.org/10.3390/ma15155338

[56] Parisi, M.L., Maranghi, S. and Basosi, R. (2014) The Evolution of the Dye Sensitized Solar Cells from Grätzel Prototype to Up-Scaled Solar Applications: A Life Cycle Assessment Approach. *Renewable and Sustainable Energy Reviews*, **39**, 124-138. https://doi.org/10.1016/j.rser.2014.07.079

[57] Yella, A., Lee, H., Tsao, H.N., Yi, C., Chandiran, A.K., Nazeeruddin, M.K., *et al.* (2011) Porphyrin-Sensitized Solar Cells with Cobalt (II/III)-Based Redox Electrolyte Exceed 12 Percent Efficiency. *Science*, **334**, 629-634. https://doi.org/10.1126/science.1209688

[58] Miles, R.W., Hynes, K.M. and Forbes, I. (2005) Photovoltaic Solar Cells: An Overview of State-of-the-Art Cell Development and Environmental Issues. *Progress in Crystal Growth and Characterization of Materials*, **51**, 1-42. https://doi.org/10.1016/j.pcrysgrow.2005.10.002

[59] Emin, S., Singh, S.P., Han, L., Satoh, N. and Islam, A. (2011) Colloidal Quantum Dot Solar Cells. *Solar Energy*, **85**, 1264-1282. https://doi.org/10.1016/j.solener.2011.02.005

[60] Sargent, E.H. (2012) Colloidal Quantum Dot Solar Cells. *Nature Photonics*, **6**, 133-135. https://doi.org/10.1038/nphoton.2012.33

[61] Zheng, H., Liu, G., Zhu, L., Ye, J., Zhang, X., Alsaedi, A., *et al.* (2018) The Effect of Hydrophobicity of Ammonium Salts on Stability of Quasi-2D Perovskite Materials in Moist Condition. *Advanced Energy Materials*, **8**, Article 1800051. https://doi.org/10.1002/aenm.201800051

[62] Bloomberg NEF (2024) New Energy Outlook. https://italianelfuturo.com/wp-content/uploads/2025/01/847353_NEO24_ExecSum.pdf

[63] International Renewable Energy Agency (2024) Renewable Power Generation Cost in 2023. IRENA, Abu Dhabi.

[64] Fraunhofer Institute for Solar Energy Systems ISE (2024) Photovoltaics Report 2024. Fraunhofer ISE.

[65] Waldau, L.J. (2024) PV Status Report 2024. European Commission Joint Research Centre.

[66] First Solar (2024) Annual Report 2023. First Solar Inc. https://investor.firstsolar.com/financials/annual-reports/default.aspx

[67] Smith, B., Woodhouse, M., Horowitz, K., Silverman, T., Zuboy, J. and Margolis, R. (2021) Photovoltaic (PV) Module Technologies: 2020 Benchmark Costs and Technology Evolution Framework Results. National Renewable Energy Laboratory (NREL), NREL/TP-7A40-78173. https://doi.org/10.2172/1829459

[68] Correa-Baena, J., Saliba, M., Buonassisi, T., Grätzel, M., Abate, A., Tress, W., *et al.* (2017) Promises and Challenges of Perovskite Solar Cells. *Science*, **358**, 739-744. https://doi.org/10.1126/science.aam6323

[69] Lazard (2024) Levelized Cost of Energy Analysis—Version 17. Lazard Ltd, USA. https://www.energy.gov/sites/default/files/2024-12/34-%20Exh.%20FF-%20Lazard%27s.pdf

[70] Haegel, N.M., Atwater, H., Barnes, T., Breyer, C., Burrell, A., Chiang, Y., *et al.* (2019) Terawatt-Scale Photovoltaics: Transform Global Energy. *Science*, **364**, 836-838. https://doi.org/10.1126/science.aaw1845

[71] VDMA (2024) International Technology Roadmap for Photovoltaic. https://www.qualenergia.it/wp-content/uploads/2024/06/ITRPV-15th-Edition-2024-2.pdf

[72] Zweibel, K. (2010) The Impact of Tellurim Supply on Cadmium Telluride Photovoltaics. *Sciences*, **328**, 699-701.

[73] Oxford PV (2024). https://www.oxfordpv.com/press-releases/oxford-pv-solar-sustainability-initiative

[74] PV Tech (2024) Global Solar Investment Reaches Records $ 2.1 Billion for Perovskites in 2023. PV Tech Media. https://www.pv-tech.org/global-solar-investment-broke-record-to-reach-us239-billion-in-h1-2023

[75] IHS Market (2024) Global PV Market Outlook 2024. SP Global Market Intelligence, London.

[76] Wood Mackenzie (2024) Global Solar PV Market Outlook 2024. Wood Mackenzie Ltd.

[77] Department of Energy (2024) Solar Energy Technologies Office Fiscal Year 2024

Funding Program. Office of Energy Efficiency and Renewable Energy, USA.

[78] LONGI Solar (2023) LONGI Archives Record-Breaking Efficiency in Tadem Solar Cells. https://www.afsiasolar.com/longi-achieves-record-breaking-efficiency-in-tandem-solar-cells

[79] Yoshikawa, K., Kawasaki, H., Yoshida, W., Irie, T., Konishi, K., Nakano, K., *et al.* (2017) Silicon Heterojunction Solar Cell with Interdigitated Back Contacts for a Photoconversion Efficiency over 26%. *Nature Energy*, **2**, Article 17032. https://doi.org/10.1038/nenergy.2017.32

[80] National Renewable Energy Laboratory (2025) Best Research-Cell Efficiency Chart. https://www.researchgate.net/figure/National-Renewable-Energy-Laboratory-NREL-2025-Best-Research-Cell-Efficiency-Chart_fig2_397376153