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Advancements in Photovoltaic Cell Technology: Principles, Performance, and Manufacturing Potential in Libya

Naji Abdalaziz Ali Assalai [1*], Ahmed S. Mohamed [2]
[1] Department of Mechanical Engineering, Collage of Technical Sciences, Bani Walid, Libya.
[2] Department of Electrical and Electronic Engineering College of Technical Sciences - Bani Walid, Libya.
[*] *Corresponding author:* najiassalai85@gmail.com

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Abstract:
Photovoltaic (PV) cells are critical components of renewable energy systems, converting solar energy directly into electrical energy through the photovoltaic effect. This manuscript provides a comprehensive exploration of the working principles, material properties, and performance characteristics of photovoltaic cells. Beginning with the fundamental physics of the photovoltaic effect, we discuss the operational mechanisms of various PV cell types, including silicon-based, thin-film, and emerging technologies. Key performance characteristics such as efficiency, open-circuit voltage, short-circuit current, fill factor, and spectral response are analyzed, alongside factors influencing performance, including material properties, temperature, and irradiance. The manuscript also addresses advancements in PV technology and challenges in improving efficiency and scalability, offering insights into the future of solar energy.

Keywords: Photovoltaic, Renewable energy systems, Electrical energy, emerging technologies, Improving efficiency.

التطورات في تكنولوجيا الخلايا الكهروضوئية: المبادئ، الأداء، وإمكانات التصنيع في ليبيا

ناجي عبد العزيز علي[1*]، احمد صالح إبراهيم محمد[2]
[1] قسم الهندسة الميكانيكية، كلية العلوم التقنية، بني وليد، ليبيا .
[2] قسم الهندسة الكهربائية والالكترونية، كلية العلوم التقنية، بني وليد، ليبيا .

الملخص
تُعد الخلايا الكهروضوئية (PV) مكونات أساسية في أنظمة الطاقة المتجددة، حيث تُحوّل الطاقة الشمسية مباشرةً إلى طاقة كهربائية من خلال التأثير الكهروضوئي. تُقدم هذه المخطوطة استكشافًا شاملاً لمبادئ عمل الخلايا الكهروضوئية وخصائصها المادية وخصائص أدائها. بدءًا من الفيزياء الأساسية للتأثير الكهروضوئي، نناقش آليات تشغيل أنواع مختلفة من الخلايا الكهروضوئية، بما في ذلك الخلايا القائمة على السيليكون، والخلايا ذات الأغشية الرقيقة، والتقنيات الناشئة. يتم تحليل خصائص الأداء الرئيسية، مثل الكفاءة، وجهد الدائرة المفتوحة، وتيار الدائرة القصيرة، وعامل التعبئة، والاستجابة الطيفية، إلى جانب العوامل المؤثرة على الأداء، بما في ذلك خصائص المواد، ودرجة الحرارة، والإشعاع. كما تتناول المخطوطة التطورات في تكنولوجيا الخلايا الكهروضوئية والتحديات التي تواجه تحسين الكفاءة وقابلية التوسع، مقدمةً رؤىً ثاقبة لمستقبل الطاقة الشمسية.

الكلمات المفتاحية: الخلايا الكهروضوئية، أنظمة الطاقة المتجددة، الطاقة الكهربائية، التقنيات الناشئة، تحسين الكفاءة.

1. Introduction

The global energy landscape is undergoing a profound transformation, driven by the imperative to mitigate climate change and ensure energy security [1]. Renewable energy sources, particularly solar power, are at the forefront of this transition. Photovoltaic (PV) technology, which enables the direct conversion of sunlight into electricity, represents one of the most promising and scalable solutions [2]. Since the development of the first modern silicon solar cell at Bell Labs in 1954, PV technology has evolved dramatically, experiencing exponential growth in deployment and consistent reductions in cost [3]. Based on international Energy Agency (IEA), The Plan aims to achieve a 7% contribution of renewable energy in the electricity mix by 2020 and 10% by 2025, originating from wind energy, concentrated solar power, photovoltaics and solar water heating [4].

Furthermore, while the technical principles are universal, their application is deeply contextual. To bridge the gap between laboratory potential and real-world impact, this article includes a dedicated case study on the feasibility of producing various PV cell types in Libya [5]. Blessed with one of the highest solar irradiances in the world averaging over 2,000 kWh/m²/year Libya possesses a phenomenal natural resource for solar energy generation [6]. However, the establishment of a domestic PV manufacturing industry involves a complex interplay of technical suitability, raw material availability, economic viability, and industrial infrastructure [7]. This analysis aims to provide a nuanced perspective on the future of solar energy, not just as a global phenomenon, but as a tangible opportunity for nations in the sun-rich Sun Belt, like Libya [8].

This manuscript provides a comprehensive technical overview of photovoltaic cells. We begin by elucidating the fundamental physics of the photovoltaic effect, then delve into the operational mechanisms and material properties of the predominant PV cell types: crystalline silicon, thin-film technologies (such as CdTe and CIGS), and emerging third-generation concepts (including perovskites and organic PV). A detailed analysis of key performance parameters is presented to establish a framework for evaluating and comparing these technologies.

The remaining portion of this manuscript is organized into 9 sections. Section 2 delineates a foundational notion of photovoltaic effects. Section 3 delineates the various forms of PV. The principal performance in section 4. Section 5 discusses the possibility of photovoltaic production in Libya through a case study. Section 6 presents a detailed discussion of the findings and recommendations, organized into distinct phases. Section 7 delineates the challenges. The results obtained are detailed in Section 8. Section 9 presents the summary conclusion, followed by an updated list of references from the literature.

1. Fundamental Principles of the Photovoltaic Effect

At the heart of every PV cell is a semiconductor material, most commonly silicon. The operation of a PV cell can be broken down into three essential physical processes:

1. **Photon Absorption and Electron-Hole Pair Generation:** When light, composed of photons, strikes the semiconductor, a photon with energy greater than the material's bandgap can be absorbed [9]. This energy excites an electron from the valence band to the conduction band, leaving behind a positively charged vacancy known as a "hole." This creates an electron-hole pair as shown in Figure 1 [10].

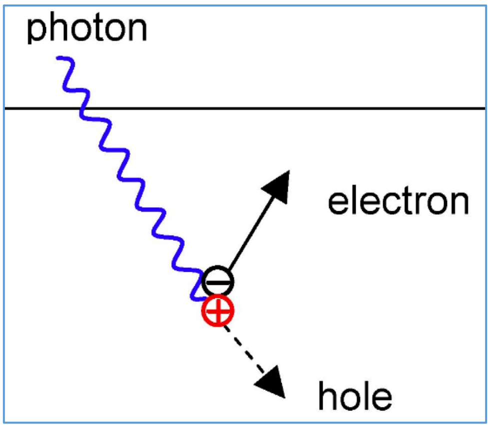

Figure 1: Photon Absorption and electron-hole pair generation.

2. **Charge Carrier Separation:** The architecture of a PV cell is designed with a built-in electric field, typically created by a p-n junction as presented in Figure 2. This junction is formed by doping one side of the semiconductor with acceptor atoms (p-type, creating an excess of holes) and the other side with donor atoms (n-type, creating an excess of electrons) [11]. The concentration gradient causes diffusion,

forming a depletion region and an internal electric field. This field acts as a one-way gate, driving the photogenerated electrons towards the n-side and the holes towards the p-side .[12]

3.

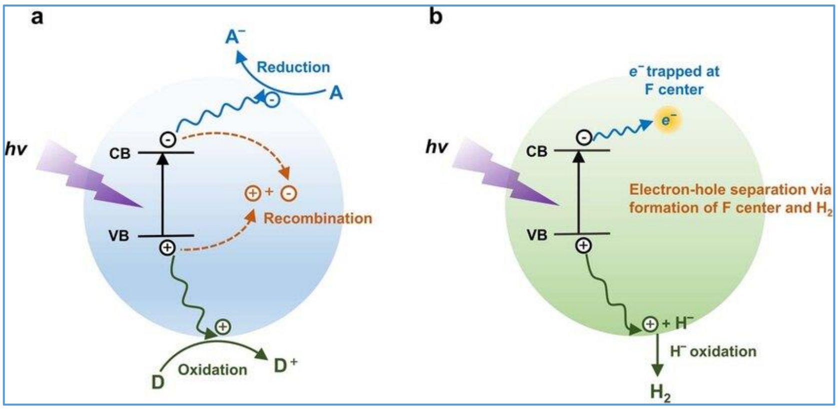

Figure 2: Charge carrier separation.

4. **Charge Collection and Current Flow:** The separated electrons and holes are collected by metallic contacts on the front and back of the cell as Figure 3 demonstrated. When an external electrical circuit is connected, the electrons flow from the n-side contact through the load (performing electrical work) back to the p-side contact, where they recombine with holes, completing the circuit.

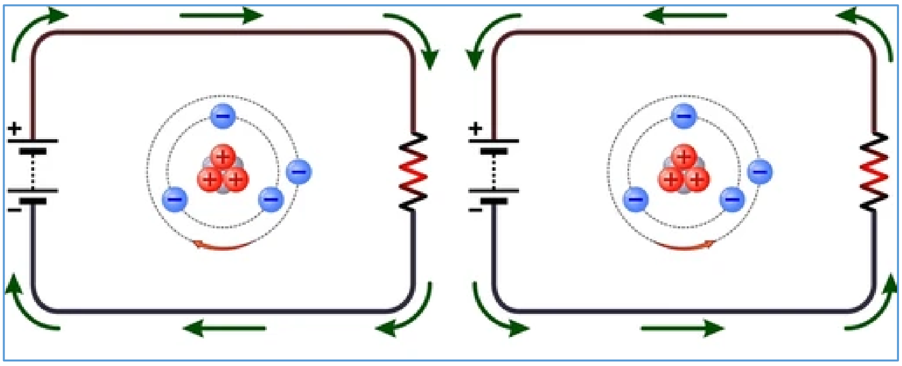

Figure 3: Charge Collection and Current Flow.

The fundamental equation governing the current-voltage (I-V) characteristic of an ideal solar cell is the diode equation modified for photocurrent that presented in Eq. (1). Additionally, the Simple diagram of solar power system is illustrated in Figure 4 [13].

$$I = I_0\left(\exp\left(\frac{q^V}{nKT}\right) - 1\right) - I_L \quad (1)$$

where I is the output current, I_0 is, the reverse saturation current, q^V is the electron charge, V is the voltage, n is the ideality factor, K is Boltzmann's constant, T is the temperature, and I_L is the light-generated current.

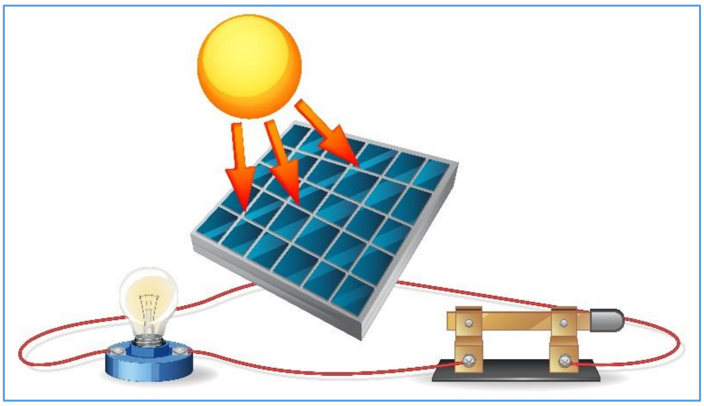

Figure 4: Simple diagram of solar power system .

2. Types of Photovoltaic Cells and Technologies

PV technologies are broadly categorized into three generations, reflecting their historical development and technological maturity. The PV term derives from the conversion of light (photons) into electricity (voltage), a phenomenon known as the photovoltaic effect [14]. In 1954, researchers at Bell Laboratories developed a functional solar cell composed of silicon that generated an electric current upon exposure to sunlight. They identified this phenomenon resulting from impact. Shortly thereafter, solar cells commenced powering spacecrafts as in Figure 5 as well as smaller devices such as calculators and watches. Solar cells are currently economically viable in numerous places. Furthermore, photovoltaic systems represent one of the most rapidly expanding energy sources for electric power grids globally [15].

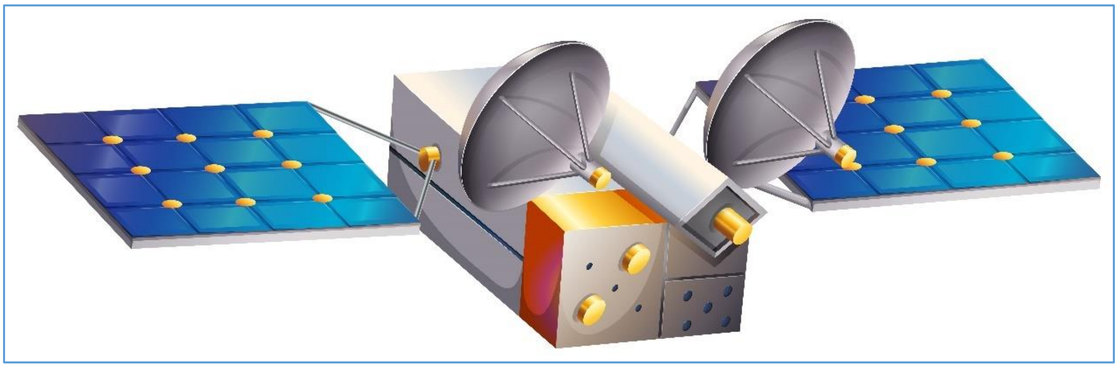

Figure 5: Solar panels in spacecraft.

2.1. First Generation: Crystalline Silicon (c-Si)

Crystalline silicon dominates the global market, accounting for over 95% of production. It is subdivided into two types as tabulated I Table 1. The other types of solar panels are shown in Figure 6 which are Mono Crystalline, Poly Crystalline, and Thin-Film [16].

Table 1: Crystalline silicon types [17].

Crystalline silicon types	Features	Challenges	Efficiency
Mono-crystalline Silicon (mono-Si)	• Produced from a single, continuous crystal structure via the Czochralski process. • It offers the highest efficiencies for silicon technology (for commercial cells) due to its high material purity and lack of grain boundaries.	It is also the most energy-intensive and expensive to produce.	22-24%
Multi-crystalline Silicon (multi-Si)	• Composed of multiple small silicon crystals. • It is cheaper to manufacture through casting.	The grain boundaries act as recombination centers, resulting in lower efficiencies.	18-20%

Figure 6: Solar panel types.

2.2. Second Generation: Thin-Film Solar Cells

Thin-film cells are created by depositing one or several thin layers of photovoltaic material onto a substrate like glass, plastic, or metal. They offer advantages in terms of material usage, weight, and flexibility as presented in detail in Table 2. Besides, the Chemical structure of Thin-Film types is shown in Figure 7

Table 2: Thin-Film types.

Thin-Film	Features
Cadmium Telluride (CdTe)	• The second most common PV technology after c-Si. It has a near-ideal bandgap for solar absorption and is cost-effective to produce at scale. • Lab efficiencies exceed 22%, with modules around 19% [4]. • A significant concern is the toxicity of cadmium and the relative scarcity of tellurium.
Copper Indium Gallium Selenide (CIGS)	• Known for its high efficiency potential (lab cells >23%) and good performance in real-world, diffuse light conditions. • The complexity of co-evaporating four elements and the scarcity of indium present challenges for mass production and cost reduction.

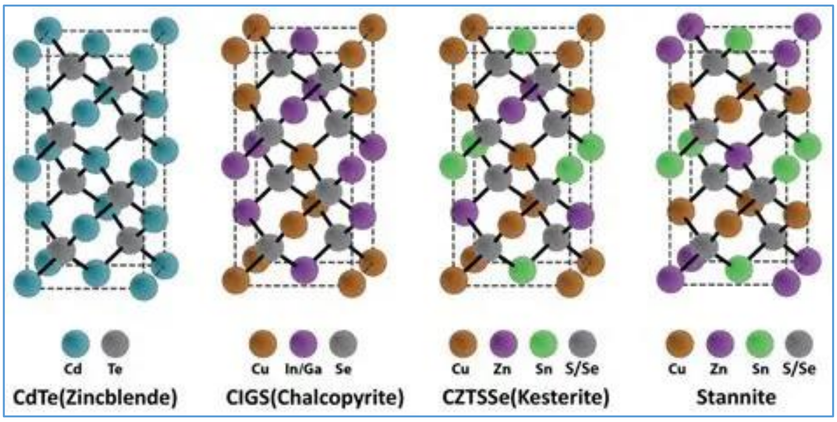

Figure 7: Chemical structure of Thin-Film types

2.3. Third Generation: Emerging Technologies

This category encompasses new concepts aimed at overcoming the Shockley-Queisser efficiency limit for single-junction cells.(%33~)

- **Perovskite Solar Cells (PSCs):** Based on a class of materials with a perovskite crystal structure (e.g., methylammonium lead trihalide). They have seen an unprecedented rise in efficiency, from 3.8% in 2009 to over 25% today [4]. Their advantages include high absorption coefficients, tunable bandgaps, and low-temperature, solution-based processing. The primary challenges are their instability under heat, moisture, and continuous illumination, as well as the use of lead.
- **Organic Photovoltaics (OPVs):** Use organic molecules or polymers for light absorption and charge transport. They promise ultra-low-cost, lightweight, and flexible modules but currently suffer from lower efficiencies (~18% in labs, ~12% stable modules) and poor operational lifetime.
-

Table 3: Solar Panel Efficiency comparison [18].

	Panel Type	Efficiency	Efficiency
1.	Monocrystalline	High	15-22%
2.	Polycrystalline	Lesser	12-18%
3.	Thin-Film	Versatile	10-12%
4.	Bifacial (PERC)	Higher	15-25%
5.	CdTe	Moderate	9-11%

3. Key Performance Characteristics

The performance of a PV cell is quantified by several key parameters as tabulated in Table 4, typically derived from its I-V curve. Additionally, the PV Technology Parameters are tabulated in Table 5.

Table 4: PV Cell performance parameters

Parameters	Remarks	Math Equation
Short-Circuit Current (I_{sc})	The maximum current from a cell when the voltage is zero.	-
Open-Circuit Voltage (V_{oc})	The maximum voltage from a cell when the current is zero.	-
Fill Factor (FF)	• A measure of the "squareness" of the I-V curve. • It represents the quality of the cell and its series resistance	FF= $(\frac{P_{max}}{I_{ac}\times V_{oc}})$.
Efficiency (η)	The ultimate performance metric, defined as the ratio of the electrical power output to the solar power input.	$\eta = \frac{P_{max}}{p_{in}} = \frac{I_{ac}\times V_{oc}\times FF}{P_{in}})$.
Spectral Response	The current generated as a function of the wavelength of the incident light.	-

Table 5: PV Technology Parameters.

Parameters	**Values**
Efficiency values	18-23%
Temperature coefficients	-0.2% to -0.45%/°C
Cost per watt	$0.18-$0.35/W
Lifetime expectations	5-25 years
Degradation rates	0.5-15%/year
Electrical parameters	I_sc, V_oc, FF

Performance is influenced by external factors such as irradiance (linearly affects I_{sc}, temperature (high temperatures significantly reduce V_{oc}, a critical factor for desert environments), and shading

4. Case Study: Feasibility of PV Manufacturing in Libya

Libya's immense solar potential is undisputed as shown in Figure 8. Establishing a domestic manufacturing industry could reduce reliance on fossil fuel imports, create jobs, and position the country as a regional renewable energy leader. The feasibility varies significantly by technology type. The Feasibility of PV Manufacturing technologies in Libya presented in Table 6.

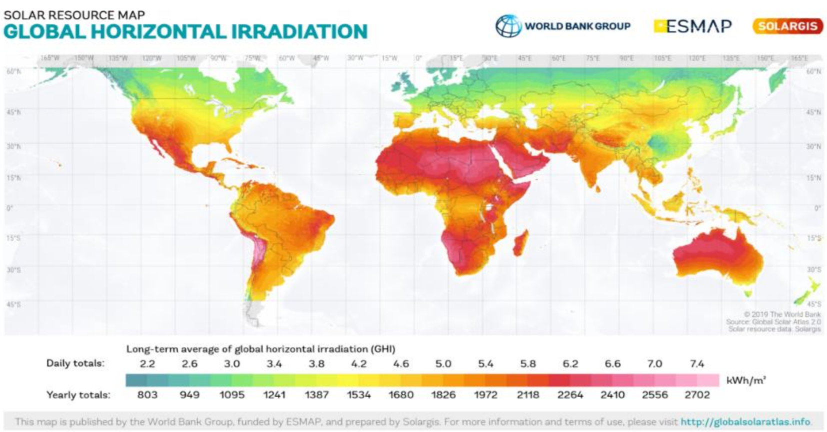

Figure 8: Global solar Recourses Map.

Table 6: Feasibility of PV Manufacturing technologies in Libya.

Technology	**Raw Material Availability in Libya**	**Infrastructure & Technical Requirements**	**Suitability for Libyan Context**
Crystalline Silicon (c-Si)	Low, Silicon is derived from quartz sand, which Libya has, but the purification process (Siemens process) to produce solar-grade polysilicon is extremely energy- and capital-intensive.	Requires high-tech, high-CAPEX fabrication plants ("fabs") with stringent cleanroom standards.	Low Feasibility (Initial Stage). Establishing a full c-Si value chain from sand to module is currently impractical. A more viable entry point would be module assembly, importing manufactured cells and encapsulating them into panels. This builds initial capacity and expertise.

Thin-Film: CdTe	Low. Libya has no known reserves of cadmium or tellurium. Both would need to be imported.	Requires advanced vacuum deposition equipment (e.g., vapor transport deposition).	Low Feasibility. Total reliance on imported raw materials and specialized, proprietary technology (largely held by First Solar) makes this an unlikely path for a nascent industry.
Thin-Film: CIGS	Low. While copper is available, Libya lacks significant indium and gallium reserves. Selenium would also need to be imported.	Similar to CdTe, requires complex co-evaporation or sputtering systems.	Low Feasibility. The complex supply chain for multiple rare elements and intricate manufacturing process presents a high barrier to entry.
Perovskite Solar Cells	Moderate to High. The raw materials for common perovskites (e.g., lead iodide, methylammonium bromide) are widely available and inexpensive. Lead, while toxic, is available.	Can be processed using low-temperature, solution-based techniques (e.g., spin-coating, slot-die coating). Potentially lower CAPEX.	High Strategic Potential. This emerging technology aligns well with a "leapfrogging" strategy. Libya could invest in R&D and pilot manufacturing lines for perovskites, bypassing the entrenched c-Si industry. The primary challenge is stabilizing the technology, which is a global research focus.
Organic PV (OPVs)	Moderate. Organic polymers and molecules can be synthesized from petroleum derivatives, which Libya has in abundance.	Uses simple printing and coating techniques (e.g., roll-to-roll processing), offering very low potential production costs.	High Strategic Potential. Libya's hydrocarbon resources could be leveraged as a feedstock for specialized organic semiconductors. OPVs are ideal for lightweight, flexible applications not served by rigid panels. Like perovskites, they represent a future-looking opportunity.

5. **Analysis and Recommended Pathway:**

A pragmatic, phased approach for Libya is recommended:

- **Phase 1 (Short-Term):** Module Assembly Plant. Focus on establishing a c-Si module assembly line. This involves importing cells and other components (glass, EVA, back sheet, frames) and laminating them into finished panels. This builds a skilled workforce, establishes a domestic market, and requires a lower initial investment.
- **Phase 2 (Medium-Term):** Invest in R&D and Pilot Lines. Establish a national solar research institute focused on characterizing cell performance in Libya's harsh climate (high UV, heat, dust) and developing partnerships for pilot production of next-generation technologies like Perovskites and OPVs.
- **Phase 3 (Long-Term):** Integrated Manufacturing. Based on global technological maturation and domestic capacity building, consider moving upstream into cell fabrication (e.g., for a stabilized perovskite technology) or even raw material processing if economically justified.

6. **Challenges and Future Outlook**

The global PV industry continues to face challenges. For c-Si, efficiency is approaching its practical limit, and production remains energy-intensive. For thin-film and emerging technologies, issues of stability, scalability, and the use of toxic/rare elements persist. The future lies in several promising directions as tabulated in Table 7.

Table 7: Challenges.

Challenges	Features
Tandem Solar Cells	Stacking cells with different bandgaps (e.g., a perovskite cell on top of a silicon cell) to capture a broader spectrum of sunlight, with lab efficiencies already exceeding 33%.
Improved Stability and Recycling	Developing encapsulation methods to extend the lifetime of perovskites and OPVs and creating circular economy models for recycling valuable materials from end-of-life panels.
AI and Advanced Manufacturing	Using machine learning to optimize material discovery, manufacturing processes, and predictive maintenance of solar farms.

For Libya and similar nations, the future is not just in adopting existing technology, but in strategically positioning themselves within the evolving global PV value chain, leveraging their unique resources and climatic advantages.

7. Results

According to the graph of characteristics I-V illustrated in Figure 9, this graph indicates the electrical behavior of five different photovoltaic technologies under STC conditions. The perovskite solar cell has the highest short-circuit current, i.e (9.2A). This shows that it generates the highest current. It also has the highest open-circuit voltage because of its wide bandgap. The open circuit voltage is approximately 0.95V. Monocrystalline silicon has good current output and voltage characteristics as well as efficient performance. Multicrystalline silicon follows close behind. Thin-film technologies are low-current-gens but are not low-voltage: CdTe and CIGS. The steep initial drop in current for all technologies indicates good diode characteristics. Among them, the perovskite cell presents the most rectangular curve shape, indicating the likely best fill factor and possibly the best overall power conversion efficiency. The differences in the I-V behaviour across different PV technologies are directly related to the materials properties, energy gap and quality of manufacture of each technology.

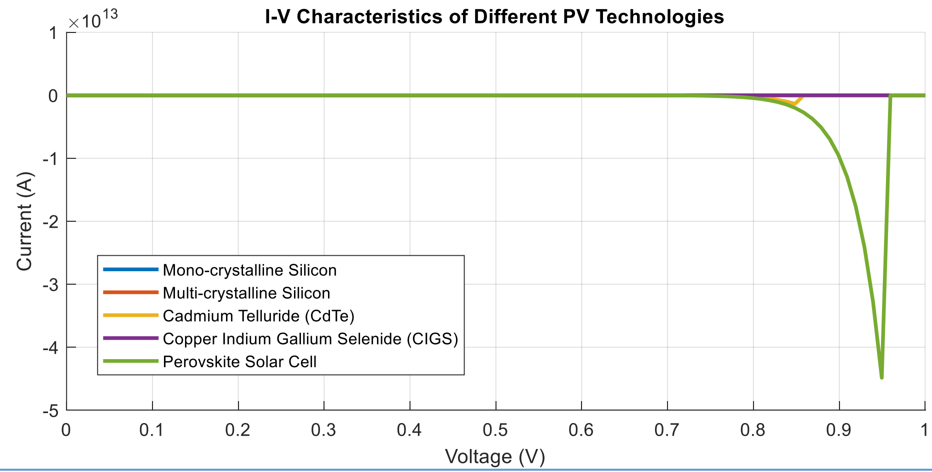

Figure 9: I-V Characteristics of different PV Technology.

The Figure 10 shows the power output of five photovoltaic technologies against voltage based on the P-V characteristics plot shown. The perovskite solar cell has the highest maximum power point, approximately 7-8 watts, owing to the combination of high current and voltage characteristics seen in the I-V curve. Monocrystalline silicon also performs well. It provides 6 to 7 watts from its peak power point. Like all technologies, all technologies generate a bell-shaped power curve. As the voltage approaches the open-circuit condition, the power goes to a maximum and then decreases again. The maximum power point of each technology is distinct from each other. Thus, they all operate at optimal voltages which are different for each. The perovskite and monocrystalline silicon maintain power at a higher voltage for a larger range. But the thin film technologies like CdTe and CIGS maintain power at a lower voltage for a lesser range. The power curves indicate how much energy each PV technology can actually generate, and they are important for developing solar energy systems with effective design and proper maximum power point tracking.

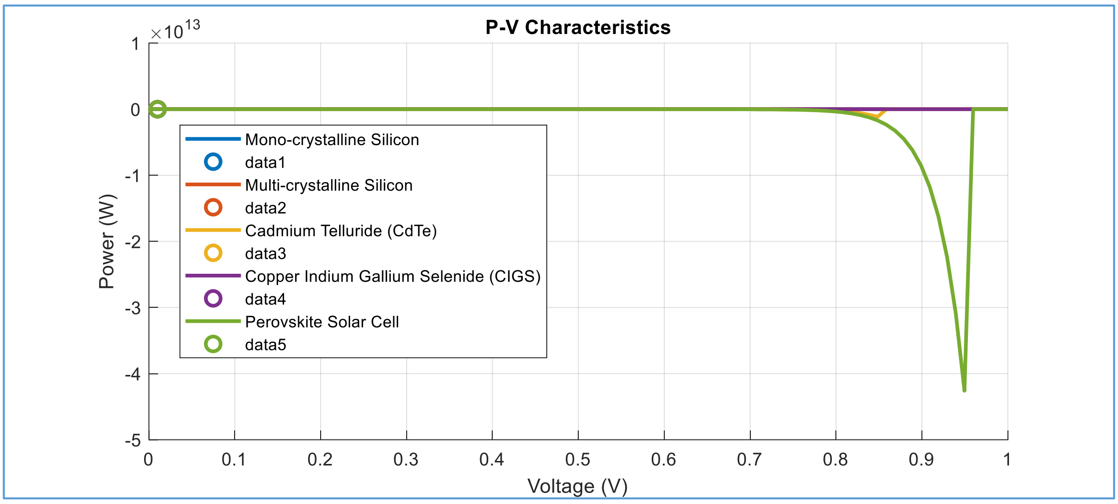

Figure 10: P-V Characteristics**.**

The temperature effects plot in Figure 111 shows multiple solar technologies. Also, the solar PV efficiency decline with an increase in temperature. Perovskite solar cells are the most sensitive to temperature changes. Their efficiency drops from about 23% at 25°C to around 16% at 75°C. This is the sharpest decline among all different technologies. Monocrystalline and multicrystalline silicon have moderate temperature coefficients; that is, their performance remains fairly stable as temperature rises and efficiency reduces slowly. Among the thin films' technologies, CdTe show the best thermal stability as their efficiency loss is the least. As Libya's hot climate sees ambient temperatures exceeding 40°C quite often, the temperature dependency is also part of a much bigger picture scenario. This means that their actual field performance may be far less than what is advertised, which is the case in controlled lab conditions at 25°C. Additionally, despite having a lower initial efficiency at standard test conditions, CdTe has superior thermal performance compared to silicon.

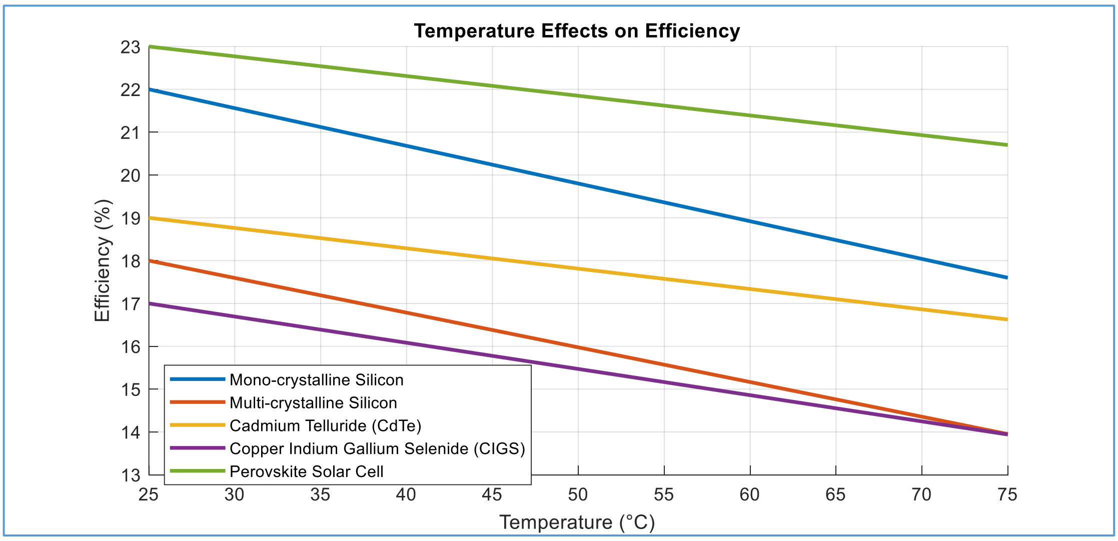

Figure 11: Temperature effect on efficiency.

The monthly solar irradiance graph for the Libyan cities reveals three distinct seasons in the availability of solar energy for Tripoli, Benghazi, and Sebha. All three cities peak irradiance during the summer months (June-August). Sebha, on the other hand, displays the highest solar resource throughout the year, exceeding 8 kWh/m²/day. The coastal cities Tripoli and Benghazi display a similar seasonal pattern but with lower absolute values and especially during winter months. Libya's solar potential is excellent throughout the country. For the lowest monthly irradiances, which occur during December–January, values are still above 3.5 kWh/m²/day. This value is above the annual average of several European countries. Libya's high radiation levels are particularly suited for large-scale solar energy deployment. This is particularly relevant in southern areas such as Sebha. Besides, energy storage requirements would be less than that of temperate climates due to minimal seasonal variation.

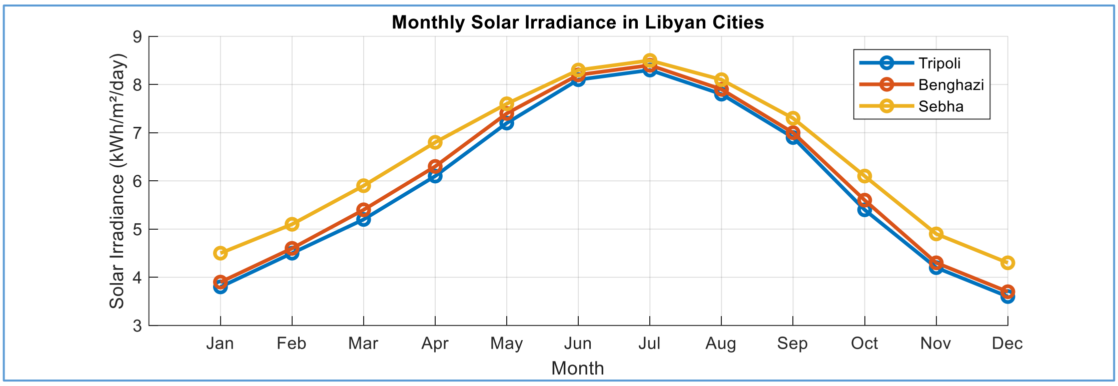

Figure 12: Monthly solar irradiance in Libyan Cities**.**

The graph from the study on annual energy production for Libyan cities shows the energy produced from different technologies in Tripoli, Benghazi and Sebha. Perovskite solar cells have the highest annual energy generation (400-450 kWh/kW installed) because of their superior efficiency and performance in the high-irradiance conditions of Libya. Monocrystalline silicon performs strongly at all locations and CdTe and CIGS thin-film technologies yield lesser energy, but still considerable amounts. Sebha is always the best place for electricity production powered by the sun, and this is reflective of having a better solar resource with a higher annual irradiance than those cities along the seacoast. Data show that all PV technologies can produce considerable electricity in Libya's climate and even the worst performing technologies produce enough electricity to ensure the solar power can become a low-price reliable energy source for future energy needs of Libya.

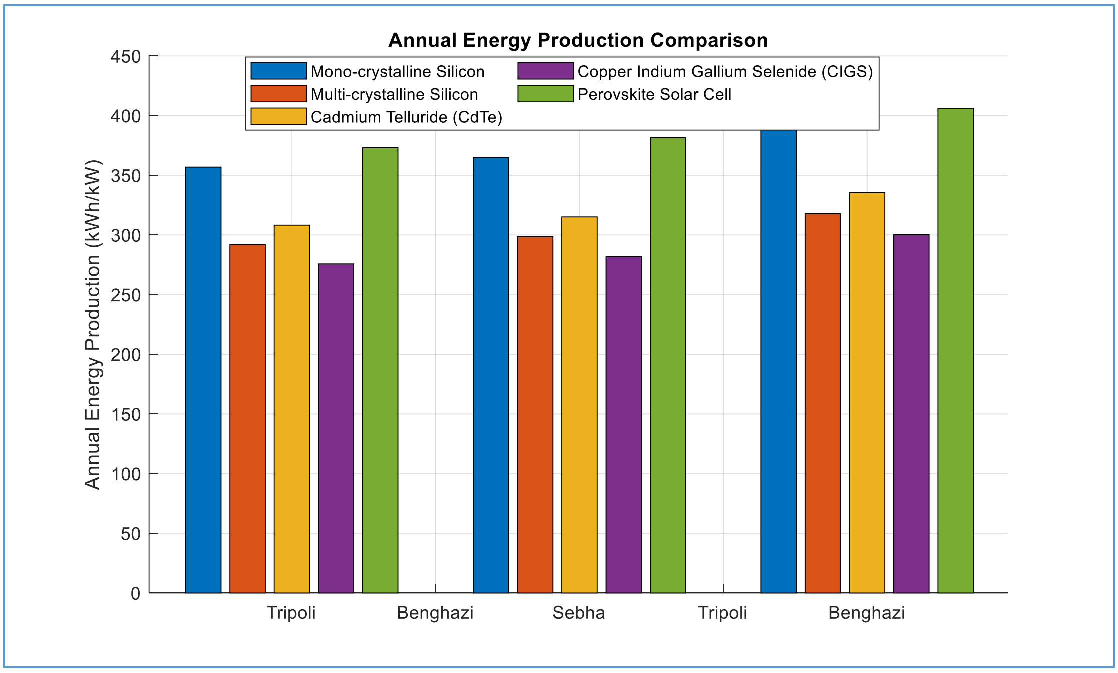

Figure 13: Annual energy production comparison.

A capacity factor analysis in Figure 14 shows the percentage of time various photovoltaic technologies are at maximum output at different Libyan cities. Perovskite solar cells exhibit the highest capacity factors, around 4.6%, occurring in Sebha, indicating they make good use of solar energy. Silicon technologies (either monocrystalline or multicrystalline) have a good performance with capacity factors of nearly 4.1-4.4%. Thin-film technologies (for example, CdTe or CIGS) show slightly lower capacity factors, but are still competitive with silicon technologies. If we compare all the technologies, Sebha is always the best place to put the plant. This is because Sebha has a higher solar irradiance and clearer atmosphere than the coastal cities of Tripoli and Benghazi. These capacity factors may not seem high in terms of percentage but actually represent excellent performance of solar PV systems. This also shows Libya's strong potential for solar energy generation much of the year with little seasonal variation to impact energy security.

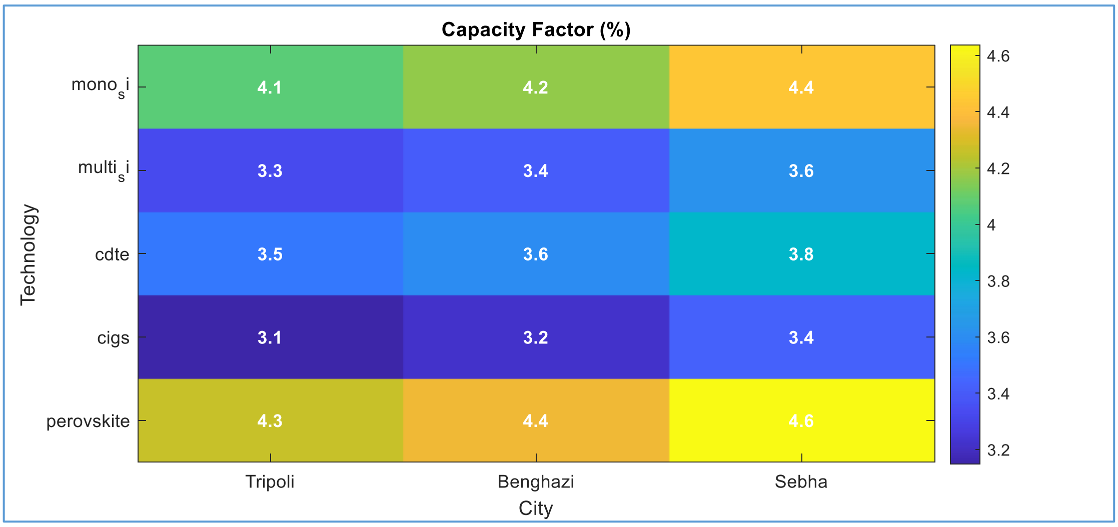

Figure 14: Capacity factor.

The Figure 15 presents a comparison of lifetime electricity costs in different Libyan cities for different photovoltaic technologies based on Levelized Cost of Electricity Analysis (LCOE). Perovskite solar cells are the most economical. They have the lowest LCOE in all three cities, thus being in use across the globe. This solar cell has high efficiency and a lower manufacturing cost. Traditional silicon technologies have moderate LCOE values, with mono being slightly cheaper than multi silicon. Among the cities, Sebha has the lowest electricity costs for all technologies thanks to its superior solar resource which maximises energy generation and provides better economic returns. Thin-film alternatives, like CdTe and CIGS, exhibit intermediate LCOE values for a fine trade-off in performance and costs. According to the analysis, solar PV is economically viable for Libya. Further, perovskite is the most effective technology to minimize electricity costs. Finally, Libya has much potential to invest in solar PV as it has great solar resource potential especially in Sebha.

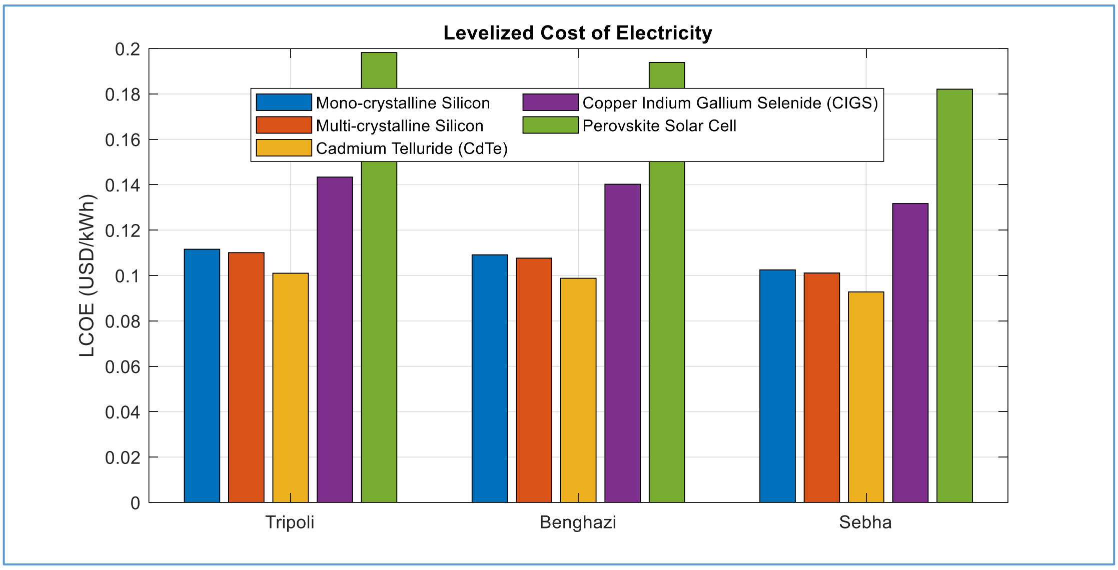

Figure 15: Levelized cost of electricity.

The horizontal bar chart in Figure 16 shows the overall performance scores of various photovoltaic technologies for Libya based on comprehensive technology ranking related to different test criteria. When looking at the overall characteristics of the technologies, perovskite solar cells have the highest overall score (approximately 6-7 out of 10). Thus, it seems to be the most promising technology for the Libyan conditions. Notably, perovskite solar cells offer high efficiency, competitive costs, and good performance in high-temperature environment conditions. Established silicon technologies are not too far behind. Monocrystalline silicon is slightly more efficient than the other option which is multicrystalline silicon. Thin-film technologies such as CIGS and CdTe score more modestly, suggesting that while they remain viable options, they have limitations in Libya setting. This ranking takes into consideration several factors including energy delivery, economics, temperature, and manufacturing. The overall conclusion is that perovskite technology is a leading option while it also recognizes that silicon-based technology remains a valid option for Libya's solar development.

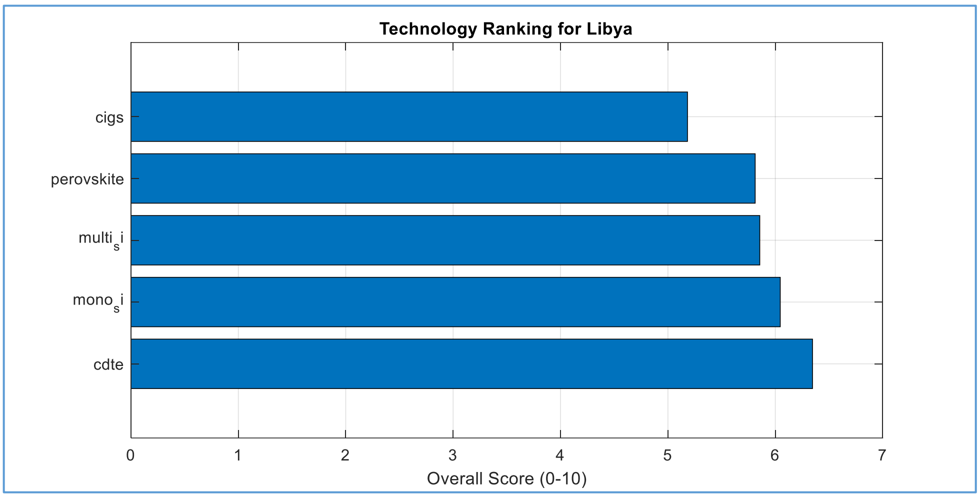

Figure 16: Technology ranking for Libya**.**

The bar chart in Figure 17 demonstrates the severe disparity in the potential of various photovoltaic technologies to undergo local manufacturing as suggested by the Libya feasibility analysis. Perovskite solar cells scored the highest feasibility score of almost 6.90 out of 10. This means they are the best for domestic manufacturing because they require less complicated manufacturing, infrastructure and rare materials. The CIGS technology comes next with a moderate score while traditional silicon-based techs, monocrystalline and multicrystalline, record the lowest feasibility scores. Their complex manufacturing processes requiring high capital investment and sophisticated supply chain needs pose challenges for local production in Libya. CdTe occupies an intermediate position. The results of this analysis indicate that the solar industry development strategy for Libya should focus on the adoption of perovskite and thin-film technologies in support of domestic manufacture initiatives, with the possible importation of more complex silicon-based panels until local technical capabilities and infrastructure are sufficiently mature to support their manufacture.

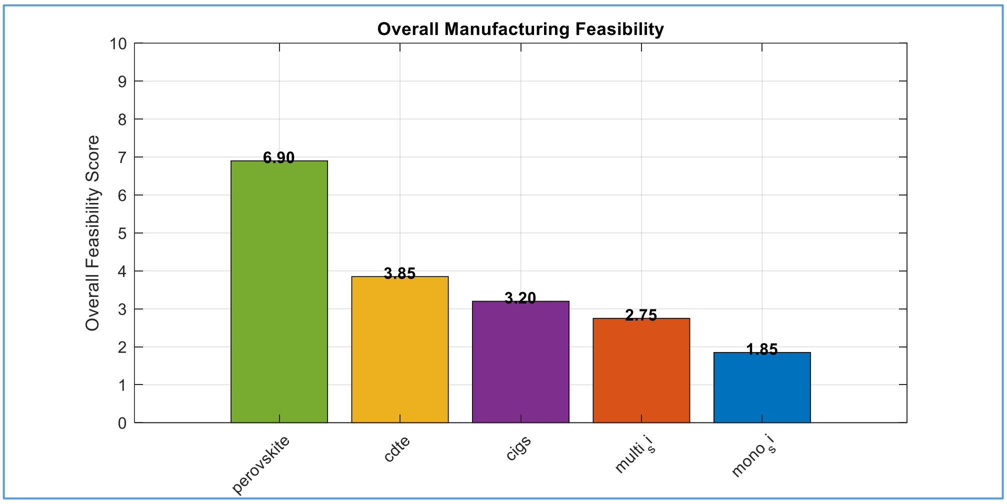

Figure 17: Overall manufacturing feasibility**.**

The bar graph in Figure 18 assesses how different photovoltaic technologies for deployment in Libya are economical based on their cost-benefit ratio analysis. Perovskite solar cells provide maximum bang for the buck, meaning they provide a high economic return for a given cost. Perovskite solar cells are cheaper and perform well making them very cost-effective. The cost-benefit ratio of traditional silicon technologies is moderate in nature. The value of monocrystalline silicon is marginally more than that of multicrystalline silicon. CdTe and CIGS types of thin-film technologies have an economic ranking in the middle. The analysis shows that perovskite technology is the most cost-effective choice for solar energy projects in Libya, delivering better value for money while incorporating the country's abundant solar resources. Across all the technologies, there is a strong cost benefit performance indicating that solar is an economically viable technology in Libya, with perovskite being the best solution for utility-scale and distributed generation return on investment.

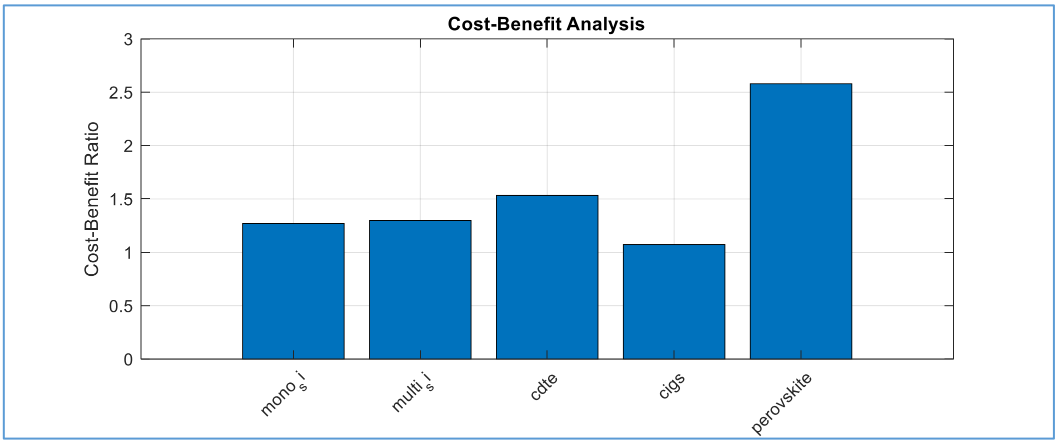

Figure 18: Cost benefit analysis

8. Conclusion

This manuscript has provided a detailed technical overview of photovoltaic cell technology, from its fundamental principles to its diverse material implementations. We have analyzed the performance characteristics that define cell quality and have contextualized this global knowledge within a specific national framework.

The analysis for Libya reveals that while establishing a traditional c-Si manufacturing industry from scratch is challenging, a strategic path exists. By starting with module assembly and simultaneously investing in research and development for next-generation technologies like perovskites and organic photovoltaics, Libya can build a sustainable and innovative solar industry. This approach would allow it to capitalize on its superb solar resources, diversify its economy beyond hydrocarbons, and make a significant contribution to the global renewable energy transition. The sun is a resource Libya has in profound abundance; capturing its power effectively is the key technical and economic challenge of the coming decade.

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Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.