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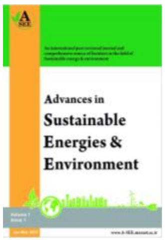

Research Article

Comprehensive Assessment of Solar Cell Technology Localization in Iran: Challenges and Development Strategies

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ABSTRACT

This study provides a comprehensive assessment of solar cell technology localization in Iran using a multidimensional analytical framework. Employing a mixed-methods approach, the research integrates data from: semi-structured interviews with 37 industrial and academic experts; analysis of photovoltaic sector documents; and systematic review of scientific literature (2010-2024). Findings reveal that first-generation crystalline silicon cells have reached Technology Readiness Level (TRL) 8 with over 60% self-sufficiency, though critical value chain segments like polysilicon production remain import-dependent. Second-generation thin-film and third-generation perovskite/quantum dot cells remain in basic research phases at TRL 4 and 2, respectively. SWOT analysis identifies abundant mineral reserves (including 99.99% pure silica) and geographical potential as key strengths for first-generation cells, while reliance on foreign technology and sanctions constitute major threats. Second-generation technologies face material import dependency, while third-generation technologies suffer from skilled labor shortages and inadequate pilot-scale infrastructure. Using Analytic Hierarchy Process (AHP), this study proposes three development scenarios, identifying the balanced approach - simultaneously developing crystalline silicon and perovskite technologies - as optimal given Iran's current realities. Consequently, a six-year development roadmap was formulated, prioritizing: completion of the domestic silicon value chain; development of advanced first-generation architectures; and parallel acquisition of third-generation perovskite technology. This trajectory is expected to culminate in tandem solar cell manufacturing capability. The research provides a scientific foundation for renewable energy policymaking in Iran and similar contexts.

1. Introduction

The global energy system currently grapples with three interconnected crises: escalating energy security risks, accelerating climate change, and worsening electricity supply-demand imbalances [1]. Recent projections indicate that worldwide electricity demand will increase by 70% to 45,000 TWh by 2040, necessitating renewable energy sources to provide 65% of global generation capacity to meet Paris Agreement targets [2]. Among renewable technologies, solar photovoltaic systems have emerged as the dominant solution, accounting for 42% of all renewable capacity expansion [3]. This global transition context holds particular significance for Iran, where electricity demand has grown at an annual rate of 5.7% (Iran Energy Balance Sheet, 2023) while grid losses remain alarmingly high at 15.4% - nearly double the global average of 8.3%. These factors contribute to recurring seasonal shortages of 10-12 GW, with the Ministry of Energy forecasting this deficit could reach 25 GW by 2026 [4].

Iran's solar energy potential remains dramatically underutilized despite possessing world-class resources. The country experiences 280 annual days of full sunshine with average solar irradiance of 5.5 kWh/m²/day, representing a theoretical generation capacity exceeding 600 GW according to the Atlas Solar Iran project. Yet solar PV currently contributes less than 1% of the national energy mix. This

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underdevelopment persists despite compelling economic advantages, with utility-scale solar projects demonstrating a levelized cost of electricity at \$0.025/kWh - 40% lower than gas-fired power plants at \$0.042/kWh.

The environmental benefits are equally significant, as replacing just 20% of Iran's thermal generation with solar power could reduce annual CO_2 emissions by 75 million metric tons. From an energy security perspective, such a transition would substantially decrease reliance on natural gas for power generation, which currently consumes 85 billion cubic meters annually according to 2022 data from the National Iranian Gas Company [5-7].

International experience demonstrates that successful solar energy adoption requires comprehensive localization of the entire value chain. For Iran, this approach offers multiple strategic benefits including 35-40% cost reductions through elimination of import duties and transportation expenses, employment generation potential of 82 direct jobs per megawatt of installed capacity based on EPIA models, and enhanced technology security crucial for mitigating sanction-related vulnerabilities.

The National Solar PV Development Program (2023) has recognized this potential by establishing an ambitious target of 8 GW domestic manufacturing capacity by 2028. However, significant barriers persist, particularly in polysilicon production where Iran remains import-dependent despite possessing 99.99% pure silica reserves. Policy implementation challenges have also emerged, with foreign direct investment flows failing to align with the localization targets outlined in Article 85 of Iran's Sixth Development Plan. Research and development efforts face similar fragmentation, particularly in emerging perovskite technologies which remain at TRL 2-3 without coordinated pilot-scale development [8-13].

Comparative analysis with sanction-constrained economies reveals divergent strategies: While Russia prioritized thin-film CdTe through military-civilian partnerships [14], Turkey achieved 74% c-Si localization via EU technology transfer [15]. Iran's unique position—with silica reserves rivaling China's yet R&D fragmentation similar to India's pre-2010 phase—calls for a hybrid approach [16].

This study makes three primary contributions to addressing these challenges. First, it provides a systematic evaluation of technology readiness levels across crystalline silicon, thin-film, and perovskite photovoltaic technologies in the Iranian context.

Second, it develops an optimized development roadmap using Analytic Hierarchy Process methodology aligned with both Iran's 2025 Vision Document and international climate commitments.

Third, it introduces a novel framework for analyzing solar energy development in sanction-constrained emerging economies, which we term the "dual energy transition challenge."

By integrating mineral resource data, industrial capacity assessments, and research capability evaluations, this work offers actionable policy insights for achieving technological sovereignty in renewable energy systems while addressing urgent energy security and environmental imperatives.

2. Theoretical Framework and Literature Review

Existing research on photovoltaic (PV) technology development has predominantly adopted fragmented approaches, examining technical, economic, or institutional aspects in isolation [17-24]. This study addresses this gap by proposing a comprehensive, systems-oriented framework for analyzing PV localization, integrating four critical dimensions: technological capabilities, mineral resources, industrial competencies, and developmental requirements. The research is guided by three central questions: (1) What are the current technology readiness levels (TRLs) of different PV generations in Iran? (2) What are the key barriers to localizing each technology generation? (3) What optimal strategies can facilitate PV technology development in Iran?

To address these questions, the study employs an innovative theoretical framework that combines established international models with localized adaptations. The NASA TRL scale has been modified to account for Iran's specific industrial conditions, enabling precise assessment of crystalline silicon (TRL 8), thin-film (TRL 4), and perovskite (TRL 2-3) technologies.

Barrier analysis utilizes an integrated SWOT-fuzzy Delphi methodology, incorporating insights from 37 industry and academic experts through structured interviews. Strategy development combines these findings with benchmarking of successful international models, including China's vertically integrated supply chains and Germany's research-industry collaboration frameworks.

Data collection employed a triangulated approach to ensure robustness. Industrial data was sourced from the Renewable Energy and Energy Efficiency Organization (SATBA), covering all active PV manufacturers in Iran, supplemented by structured interviews with technical executives. Academic research output was analyzed through a systematic Scopus review (2010-2024) of Iranian-authored PV publications, with collaboration networks mapped using VOSviewer and Gephi software. This revealed concentrated expertise in c-Si materials but limited cross-institutional collaboration in emerging technologies.

Mineral resource assessments drew on data from the Geological Survey of Iran and Ministry of Industry, Mine and Trade, though economic viability analyses remain preliminary due to absent cost-benefit studies of domestic material processing.

Methodological innovations include the hybrid AHP-SWOT weighting system, which quantifies the relative importance of identified barriers, and an adaptive roadmapping approach that synchronizes technical milestones with policy interventions.

3. Findings and Analysis

3.1 Evaluation of Photovoltaic Cell Generations

The photovoltaic (PV) technology landscape has evolved through four distinct generations, each representing significant advancements in materials and manufacturing approaches. The classification of these generations reflects both historical progression and future-oriented innovation pathways in solar energy conversion technologies.

First-generation PV cells, dominated by crystalline silicon (c-Si) technologies, currently hold over 85% of the global market share. These include monocrystalline silicon (mono-Si) with average module efficiencies of 19-22% and polycrystalline silicon (poly-Si) at 16-18% efficiency. The maturity of c-Si technology is evidenced by its established supply chain and continuous incremental improvements, particularly through Passivated Emitter and Rear Cell (PERC) architectures, which enhance efficiency by 0.8-1% through reduced carrier recombination and improved light trapping. However, fundamental limitations persist, including energy-intensive wafer production processes and theoretical efficiency ceilings (~29% for single-junction devices) [25].

Second-generation thin-film technologies, comprising cadmium telluride (CdTe), copper indium gallium selenide (CIGS), and amorphous silicon (a-Si), collectively account for approximately 6% of global production. While offering advantages in material usage and flexible substrate compatibility, these technologies face constraints in efficiency (CdTe: 18-21%; CIGS: 15-18%) and material availability challenges, particularly for indium in CIGS production. First Solar's CdTe modules have achieved the most commercial success in this category, though scalability remains limited by tellurium supply constraints [26].

Third-generation technologies encompass emerging solutions designed to overcome the Shockley-Queisser limit through novel materials and device architectures. This category includes [27]:

- Perovskite solar cells, demonstrating unprecedented efficiency growth from 3.8% (2009) to over 25.7% (2023) in laboratory settings, yet facing commercialization barriers due to moisture sensitivity and scale-up challenges
- Quantum dot and dye-sensitized solar cells, offering tunable bandgaps but with stability concerns
- Organic photovoltaics (OPVs) with potential for low-cost roll-to-roll manufacturing, though currently limited to niche applications due to sub-15% efficiencies

Fourth-generation concepts represent frontier research directions combining nanomaterials (graphene, carbon nanotubes) with hybrid organic-inorganic structures. While promising theoretical efficiencies exceeding 46% for tandem configurations, these remain predominantly at TRL 2-3, with significant materials science and manufacturing hurdles to overcome [27].

Figure 1 presents the efficiency progression across photovoltaic generations, revealing a clear technological trajectory from established first-generation systems to emerging fourth-generation concepts. The data visualization highlights how laboratory breakthroughs translate - or fail to translate - into commercial applications, with the efficiency gap between champion cells and production modules averaging 15-20% absolute percentage points across all generations. Table 1, compares different generations in terms of advantages, disadvantages, global market share, and production cost.

The comparative analysis reveals several critical insights for technology deployment strategies. While first-generation technologies benefit from established supply chains and predictable performance, emerging technologies offer pathways to overcome fundamental efficiency limitations. The cost-efficiency tradeoffs demonstrate how CdTe maintains competitiveness in utility-scale applications despite lower efficiencies, while perovskite development focuses initially on niche markets where lightweight and flexibility provide added value.

This systematic comparison framework informs subsequent sections analyzing Iran's strategic positioning across these technology generations, particularly in balancing short-term deployment needs with long-term research investments. The data underscore how different technological approaches cater to distinct market segments, suggesting the need for differentiated policy support mechanisms tailored to each generation's maturity level and value proposition.

3.2 Analysis of Global Photovoltaic Technology Development Trends

The global photovoltaic industry is undergoing a complex evolutionary trajectory where cost reduction plays a pivotal role.

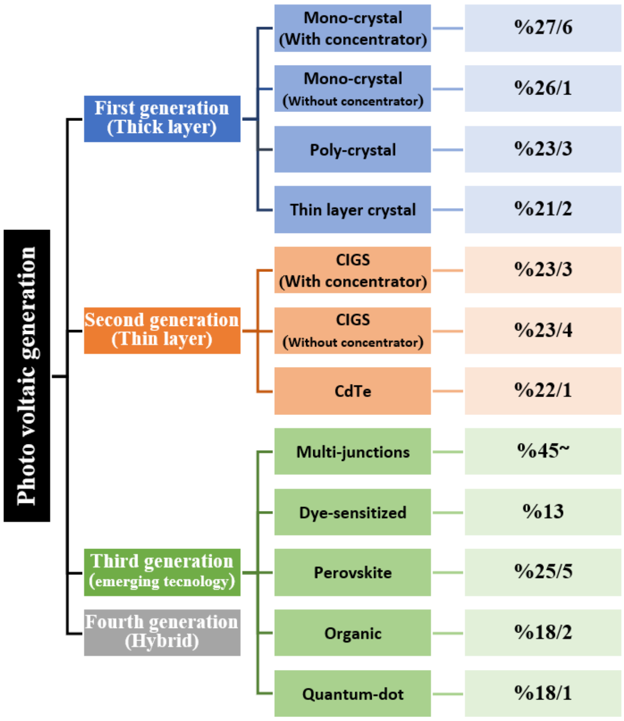


Fig.1. Examples of photovoltaic cell efficiency in different generations

Table 1. Textural attributes of the CuO- supported on numerous CeO2-M (M: SiO2, SBA-15, MCM-48, and MCM-41) composites

Cell generation	Cell type	Advantage	Disadvantage	Global market share (%)	Production cost ($/W)
1st	Mono-crystal silicone	• High efficiency (22-26%) • Long lifespan (more than 25 years) • Better performance in low light	• High cost • Higher energy consumption in the production process	30	0.25-0.35
	Poly-crystal silicone	• Lower cost • Simpler production process	• Lower efficiency (15-20%) • Shorter lifespan (10-15 years) • More space wasted	55	0.2-0.3
2nd	Amorph silicone	• Low cost • Flexible • Low temperature production • Better performance in low light	• Low efficiency (10-6%) • Short lifespan (10-15 years) • Faster degradation	2	0.15-0.25
	CdTe	• Low cost • High light absorption • Good performance at high temperatures	• Cadmium toxicity • Limitations on recycling • Moderate efficiency (10-18%)	3	0.20-0.25
	CIGS	• High thermal resistance • Good efficiency • Flexible	• High cost • Complexity of production • Problems with long-term stability	3	0.30-0.40
3rd	Organic	• Lighter weight • Eco-friendly • Flexible • Cheap production	• Very low efficiency (5-12%) • Short lifespan (less than 10 years) • Sensitivity to moisture and UV	<1	0.5-1.00 (Pilot scale)
	dye-Sensitized	• Low cost • Easy to manufacture • Performs in indirect light	• Low efficiency (8-12%) • Problems in long-term stability • Use of liquid electrolyte	<1	0.20-0.35
	Perovskite	• High efficiency (25-30% in the laboratory) • Low production cost • Flexible	• Stability issues (sensitivity to moisture, heat and UV light) • Limitations in production scaling	~0.5 (Growing)	0.10-0.25 (Future Potential)
	Tandem	• Very high efficiency (over 30%) • Optimal use of the light spectrum	• Very high cost • Technological complexity • Challenges in layer bonding	<1 (Special Applications)	0.80-1.50

This cost reduction is being pursued through three primary pathways: (1) development of more economical cell materials with reduced resource consumption, (2) improvement of manufacturing processes to lower production costs, and (3) continuous enhancement of energy conversion efficiency. Recent advancements in materials research demonstrate that both established and emerging technologies are achieving significant cost reductions and performance improvements (Figure 2).

Emerging technologies such as tandem and perovskite solar cells show remarkable theoretical potential (with tandem structures exceeding 46% efficiency) but face substantial commercialization challenges. Tandem cells, which utilize stacked specialized cells to absorb different light spectra, have yet to achieve mass production due to high material costs and complex manufacturing processes.

Perovskite solar cells have exhibited unprecedented efficiency growth from 3.8% in 2009 to over 24% in laboratory settings, but encounter obstacles in long-term stability and module-level performance uniformity. Their moisture sensitivity and scale-up challenges represent critical barriers to commercialization.

Second-generation thin-film technologies, comprising both silicon-based (amorphous and micromorph) and non-silicon (CdTe and CIGS) variants, collectively account for approximately 6% of the market.

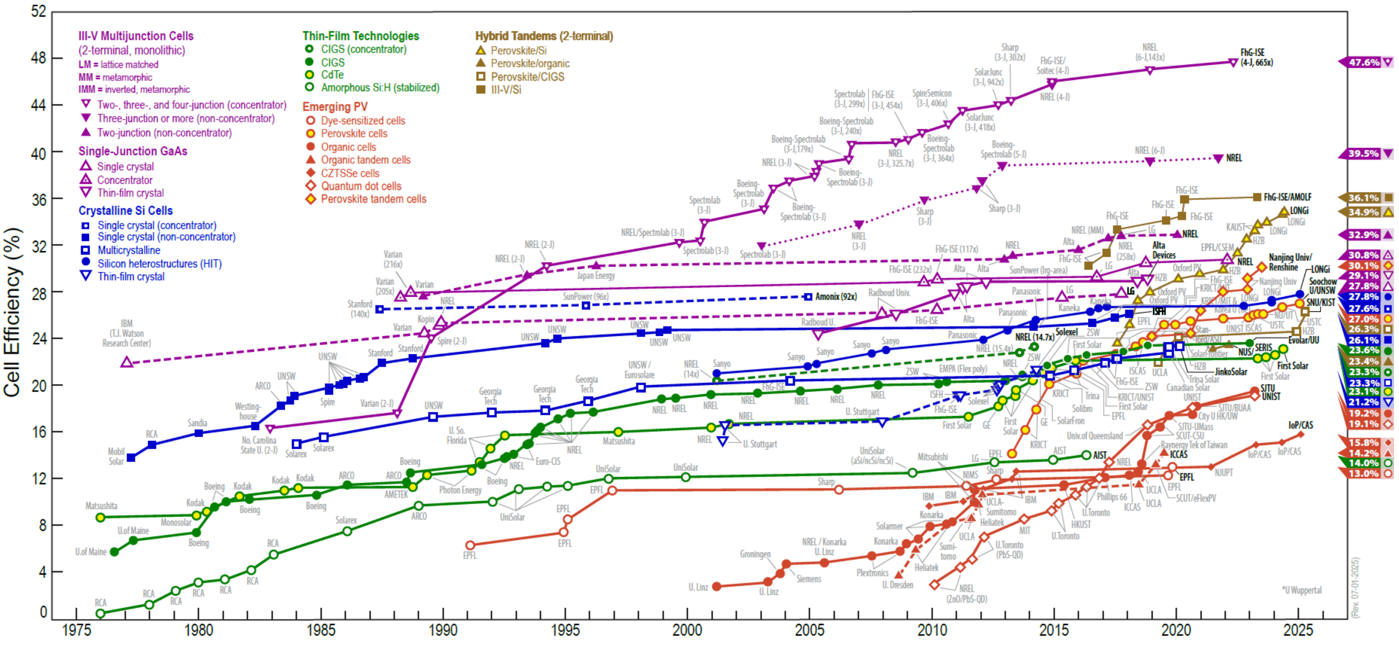


Fig.2. Performance improvement trend (efficiency increase) of different solar cell generations according to the NREL report [28].

While theoretically capable of lower production costs, these technologies have failed to gain significant market share due to lower efficiencies and material supply challenges (particularly indium scarcity for CIGS technology). CdTe technology, led by First Solar, represents the most successful implementation in this category, having achieved 21% efficiency. Figure 3 provides a comprehensive overview of PV technologies and developmental concepts critical to photovoltaic advancement.

Recent developments in bifacial cell technology indicate its transition toward market mainstreaming. These cells ability to utilize reflected light from the ground surface enables energy yield increases of up to 20%. China has emerged as the global leader in both production and practical application of this technology. However, standardization of testing methods and development of accurate performance prediction models remain outstanding challenges in this domain.

The International Technology Roadmap for Photovoltaics (2023 edition) reveals that industry-wide technology development trends are moving toward higher efficiency, lower costs, and improved environmental sustainability. Projections suggest that average commercial module efficiency will reach 25% by 2030, with energy payback time for PV systems decreasing to less than 0.75 years. These advancements, combined with developments in recycling technologies and circular economy approaches, paint a promising future for the photovoltaic industry.

This analysis of global trends provides critical context for evaluating Iran's position in photovoltaic technology development and identifying strategic opportunities for domestic industry growth. The following sections will examine these technologies through the lens of Iran's specific industrial capabilities and resource endowments.

3.3 Value Chain Analysis of Photovoltaic Cell Generations

3.3.1 Crystalline Silicon (First Generation) Value Chain

The crystalline silicon photovoltaic industry has achieved full maturity, characterized by a vertically integrated global value chain.

China dominates the upstream polysilicon segment, supplying over 80% of global production through industry leaders like Tongwei and GCL-Poly, which operate facilities exceeding 500,000-ton annual capacity. The wafer production stage has seen remarkable technological advancements, with firms such as Longi and JA Solar pioneering diamond wire sawing techniques to reduce wafer thickness to 150µm while minimizing material loss.

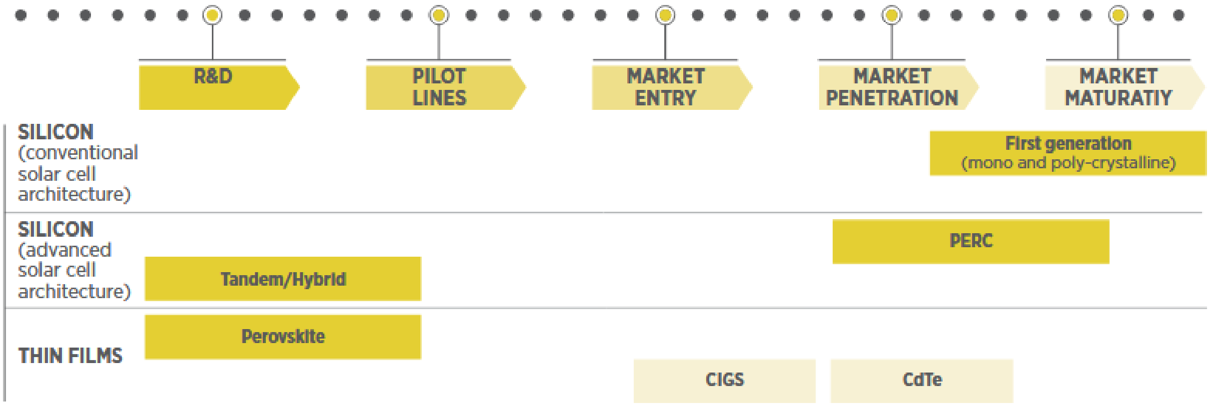
Cell manufacturing has undergone successive technological revolutions, with TOPCon (Tunnel Oxide Passivated Contact) and heterojunction (HJT) architectures now pushing laboratory efficiencies beyond 26%. This mature value chain benefits from economies of scale, with module production costs declining to \$0.20-\$0.25/W for tier-1 manufacturers. However, the industry faces growing pressure to address carbon-intensive production processes, particularly in polysilicon manufacturing where energy consumption averages 60-80 kWh/kg.

3.3.2 Thin-Film (Second Generation) Value Chain

Despite holding merely 5% market share, thin-film technologies exhibit distinct value chain configurations. CdTE leader First Solar has perfected an integrated mining-to-module production model, achieving 8GW annual capacity through proprietary vapor transport deposition technology. Their manufacturing costs have reached \$0.25/W, benefiting from:

- 98% material utilization rates
- 90-minute deposition cycle times
- Closed-loop cadmium recycling systems

The CIGS segment presents greater supply chain complexity, with Japanese firms like Solar Frontier developing specialized indium/gallium sourcing networks. European initiatives such as the Solliance research consortium have established shared R&D infrastructure to overcome material scarcity challenges, though module efficiencies remain constrained at 15-18% for commercial products.



Notes: CIGS = copper-indium-gallium-diselenide; CdTe = cadmium telluride. PERC = passivated emitter and rear cell/contact

Fig.3. Status of various photovoltaic technologies

3.3.3 Emerging Technology (Third Generation) Value Chain

Perovskite and tandem cell technologies are transitioning from laboratory research to pilot-scale production, creating novel value chain dynamics. Oxford PV's 100MW perovskite-silicon tandem production line, developed with Germany's HZB Institute, demonstrates the critical tripartite collaboration between:

1) Academic research centers (providing fundamental material innovations)
2) Chemical suppliers (delivering high-purity precursors)
3) Equipment manufacturers (developing atmospheric processing tools)

South Korea's UNIST has invested $200 million in a dedicated perovskite technology park, highlighting national strategies to capture this emerging market. The value chain remains fragmented but shows accelerating integration, with equipment lead times shrinking from 18 to 6 months as standardization progresses.

This comparative analysis reveals how technological generations necessitate distinct value chain strategies—from the capital-intensive, scale-driven silicon sector to the knowledge-intensive, collaborative emerging technology ecosystem. The findings carry significant implications for industrial policy formulation in developing photovoltaic manufacturing capabilities.

3.4 Raw Material Supply Dynamics in the Global Photovoltaic Industry

The photovoltaic industry's development is profoundly influenced by non-technical factors, particularly raw material supply chain dynamics. China's dominance in polysilicon production, controlling 80% of global output, has created concentrated supply risks for first-generation technologies. Solar-grade silica deposits are geographically constrained, with commercially viable reserves (99.95%-99.99% purity) primarily located in China, the United States, and Norway. German and American firms have achieved production costs below $10/kg through advanced purification technologies, though energy-intensive processes remain problematic, consuming 60-80 kWh per kg of polysilicon produced [29-33].

Second-generation thin-film technologies face acute material criticality issues. The supply chain exhibits extreme concentration, with China, South Korea, and Japan collectively controlling 85% of indium production, while Canada and Peru supply 70% of the world's tellurium. Industry leader First Solar has mitigated these risks through innovative 15-year forward contracts with mining operations, coupled with advanced material recycling achieving 90% recovery rates for tellurium.

Emerging third-generation technologies introduce novel material dependencies. European chemical giants Merck and BASF have established early dominance in specialized perovskite precursors, investing over $200 million annually in R&D. Europe's strategic focus on circular economy solutions has yielded material recovery rates exceeding 95% for lead and organic components through:

- Solvent-based separation techniques
- Vacuum sublimation processes
- Closed-loop manufacturing systems

This materials landscape creates three strategic challenges for industry participants:

1. Supply chain resilience for geopolitically concentrated materials
2. Cost volatility in critical mineral markets
3. Environmental compliance with evolving regulations on material sourcing and recycling

The industry's future competitiveness will increasingly depend on breakthroughs in material efficiency (currently 5-6g silicon/W for c-Si) and alternative chemistries that reduce reliance on constrained resources. Recent developments in silicon kerf recycling and indium-free transparent conductive oxides demonstrate promising pathways toward sustainable material security.

3.5 The Status of Development for Different Generations of Solar Cell Technologies in Iran

3.5.1. Research Trends and Industrial Alignment

Analysis of the research data reveals that studies in photovoltaic technologies in Iran have followed a notable trend over the past fifteen years (2009–2024). Figure 4, which illustrates the trajectory of scientific publications by Iranian researchers, shows that the number of articles increased from 18 in 2009 to 391 in 2021, reflecting a remarkable growth rate of 2,172%. This upward trend continued until 2021 but experienced a relative decline in 2022 and 2023, possibly due to factors such as economic developments and shifts in research priorities.

A noteworthy observation from the analysis of research collaboration networks (Figure 5) is that most studies were conducted individually by independent researchers, with limited effective collaboration between research institutions and universities.

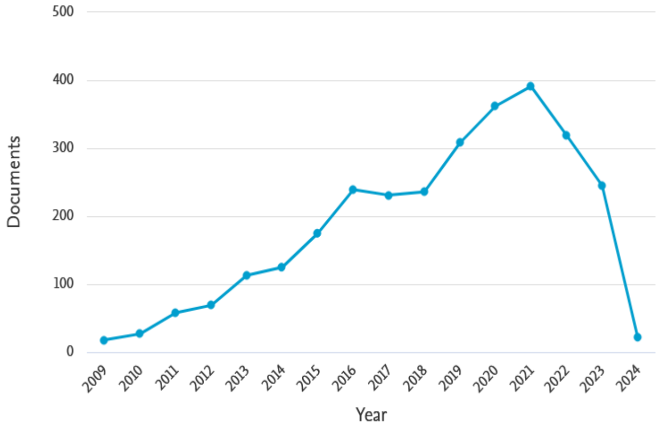


Fig.4. Number of articles published in the field of photovoltaic technology by Iranian researchers between 2009 and 2024

This fragmentation in research may be one of the reasons for the lack of practical and commercially viable outcomes.

To better understand the thematic distribution of research, a content analysis of articles was conducted using keyword mining (Figure 6). The results indicate that nanotechnology attracted the most attention, accounting for 34% of studies. This was followed by dye-sensitized solar cells (22%), perovskite cells (19%), and organic cells (12%). Interestingly, research on silicon-based cells, which form the backbone of the global photovoltaic industry, constituted only 8% of the total studies.

A temporal analysis of keywords (Figure 7) reveals that researchers have recently shifted their focus toward emerging technologies such as perovskites. This trend may reflect the Iranian scientific community's efforts to keep pace with global advancements in the field. However, the neglect of applied research on silicon-based cells—which currently dominate the global market—warrants further consideration. A closer examination of studies on first-generation (silicon) solar cells shows that research in this area has not only been limited in quantity but has also remained confined to basic topics, with no studies on advanced architectures such as PERC in Iran. In contrast, there is a significant focus on third-generation technologies, particularly perovskite and dye-sensitized cells, likely due to their scientific appeal and potential for publication in high-impact international journals. Nevertheless, a noticeable gap exists between academic research and industrial needs in this sector.

Interdisciplinary collaboration analysis indicates that while nanotechnology has been applied across all generations of solar cells, these collaborations have largely been superficial and have not contributed to the development of indigenous technical knowledge. This highlights the need to revise research policies and direct studies toward addressing industrial challenges.

In summary, while the quantity of photovoltaic research in Iran has grown significantly, its thematic distribution does not fully align with the country's industrial needs. This misalignment may be a key factor in the gap between academic research and industrial development in this field. To bridge this gap, it is essential to establish stronger connections between research centers, universities, and industry, ensuring that research priorities are determined based on real industrial demands and domestic potential.

3.5.2 Value Chain Analysis of Different Photovoltaic Cell Generations in Iran

A comparative examination of the global photovoltaic technology value chain against Iran's current status reveals significant technological and structural gaps. In the first-generation solar cell sector, despite Iran's substantial silica reserves, the country's participation remains largely confined to cell production and module assembly, while facing critical deficiencies in vital segments such as solar-grade polysilicon production and silicon wafer manufacturing.

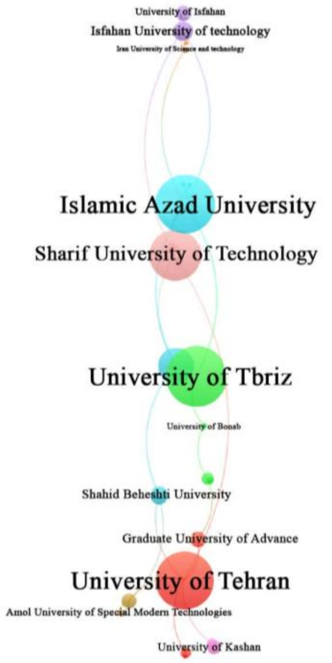


Fig.5. Diagram of cooperation between Iranian institutions in the field of photovoltaic technology

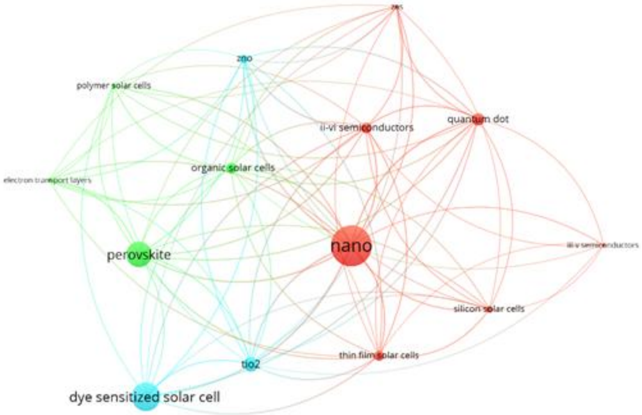


Fig.6. Co-occurrence chart of selected keywords in the field of solar cell technology

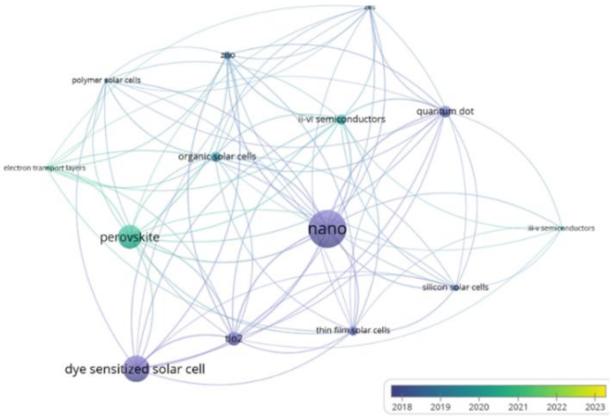


Fig.7. Matching chart of co-occurrence of selected keywords in the field of solar cell technology with the publication time of articles

The second-generation technologies confront fundamental developmental challenges due to the complete absence of specialized infrastructure for producing key raw materials like cadmium telluride (CIGS) or copper indium gallium selenide. Notably, some of these materials, including indium and tellurium, exist as byproducts in Iran's copper and zinc mines, yet remain untapped due to underdeveloped extraction and refining technologies. Regarding third-generation technologies, while Iran maintains a relatively strong academic research foundation in this domain, the lack of scalable industrial and laboratory infrastructure severely constrains the translation of knowledge into practical applications.

Building upon this analysis, several strategic pathways emerge for developing Iran's photovoltaic value chain. For first-generation technologies, establishing specialized consortia in partnership with reputable international firms could effectively address existing technological gaps. Such collaborations could facilitate technology transfer for solar-grade polysilicon production and wafer-cutting equipment, an economically viable approach given Iran's abundant silica reserves and relatively low energy costs. Concurrently, advancing applied research in sophisticated cell architectures like TOPCon and HJT could generate substantial added value.

In the second-generation technology sector, prioritizing the extraction of raw materials from domestic sources and mining byproducts presents a viable starting point. Establishing processing facilities to recover indium from zinc concentrates and tellurium from copper anode slimes could significantly reduce import dependence. Subsequent steps could involve attracting foreign investment to establish thin-film pilot production lines through technological cooperation with leading nations such as Germany or Japan.

For third-generation technologies, Iran could strategically leverage its existing academic potential through targeted participation in international research initiatives. The establishment of joint research centers with globally recognized institutions, coupled with investments in scalable laboratory infrastructure, could mitigate development risks. Furthermore, formulating national standards for materials and equipment would contribute to domestic market expansion.

The critical success factor across all these scenarios lies in forging robust connections between industry and academia while fostering regional cooperation. Iran's geographical positioning offers the potential to emerge as a regional hub for photovoltaic technology development. However, realizing this potential requires the formulation of a coherent, time-bound strategic roadmap supported by the unwavering commitment of all stakeholders. This comprehensive approach would enable Iran to bridge existing technological divides while capitalizing on its unique advantages in the renewable energy sector.

3.5.3 Raw Material Status in Iran

Iran possesses significant potential in photovoltaic raw materials, with over 80 high-quality silica mines distributed across various regions. Notable examples include the Aranfud mine in Hamedan, producing 99.99% pure silica with an annual capacity of 1,000 tons, and the Abder mine with an annual production capacity of 10,000 tons. Furthermore, major lead and zinc mines such as Mehdiabad and Angouran, along with copper mines like Sarcheshmeh, could serve as valuable sources of raw materials for second and third-generation solar cells.

Despite these substantial resources, Iran's photovoltaic industry faces multiple challenges. The lack of advanced material processing technologies, absence of specialized downstream industries, and technical limitations in extracting materials from low-grade deposits represent major obstacles to industry development. Additionally, the nonexistence of a domestic market for specialized photovoltaic materials has diminished investment incentives in this sector.

Several strategic approaches could transform these challenges into opportunities. Developing international collaborations with leading material processing companies, investing in applied research for low-grade material extraction, and establishing a complete value chain from mining to solar cell production constitute viable solutions. Moreover, formulating national standards for photovoltaic raw materials and creating a comprehensive database of strategic reserves could facilitate better planning for industry development.

Global experiences demonstrate that photovoltaic industry development requires a systematic and comprehensive approach encompassing all value chain segments. Within this framework, special attention to raw material supply - the foundation of this industry - holds critical importance. By leveraging its rich mineral resources and implementing targeted investments in related technologies, Iran can achieve a prominent position in this strategic industry. The establishment of specialized research centers focusing on material purification and processing technologies, coupled with incentive packages for domestic manufacturers, could accelerate the realization of this potential while reducing dependence on imported materials. This integrated approach would enable Iran to capitalize on its natural advantages while addressing current technological gaps in the photovoltaic value chain.

3.5.4 Comparative Analysis of Different Generations of Solar Cells in Iran

An evaluation of photovoltaic technologies in Iran reveals significant disparities in the developmental status across different generations of these technologies. These differences manifest not only in technological maturity but also in industrial activity levels, research output, and the nature of prevailing challenges. First-generation crystalline silicon photovoltaic technology, benefiting from decades of prior investment, demonstrates relatively higher technological readiness. In contrast, while second and third-generation technologies have gained attention in academic circles, they have yet to establish substantial footholds in Iran's industrial sector.

The uneven distribution of scientific research across generations reflects distinct orientations within Iran's research community. A predominant focus on emerging technologies like perovskites has coincided with comparatively less attention to improving conventional photovoltaic technologies. This research imbalance persists despite each generation facing unique challenges that necessitate differentiated development strategies.

Table 2 provides a comprehensive comparison of these generations across multiple dimensions, highlighting how their distinct characteristics demand tailored strategic approaches. The analysis underscores that effective development of Iran's photovoltaic sector requires generation-specific strategies that account for varying levels of technological maturity, industrial infrastructure, and research capabilities. For first-generation technologies, the priority lies in modernizing existing production capabilities, while second-generation solutions demand infrastructure development for thin-film production. Third-generation technologies, though promising, require focused efforts to bridge the gap between laboratory research and industrial-scale applications.

This comparative assessment reveals that Iran's photovoltaic development cannot follow a one-size-fits-all approach. Rather, it requires a nuanced, generation-specific roadmap that leverages existing strengths while systematically addressing technological gaps. The strategic implications extend beyond technical considerations to encompass policy formulation, investment prioritization, and human capital development, each requiring careful alignment with the unique requirements of different photovoltaic generations.

4. Discussion and Analysis of Results

4.1 SWOT Analysis

A comprehensive assessment of the localization of photovoltaic technologies in Iran reveals a combination of relative advantages and structural challenges that require careful analysis to formulate effective strategies. This evaluation examines four key dimensions: strengths, weaknesses, opportunities, and threats.

4.1.1 Strengths

The core strengths of Iran's photovoltaic industry lie primarily in its rich mineral resources, including high-purity silica and base metals essential for solar cell production. Mines such as the Aranfoud mine in Hamedan, with silica purity levels of 99.99%, provide significant potential for developing the value chain of first-generation photovoltaic technologies. Additionally, recent investments in production and research infrastructure—particularly in crystalline silicon—along with the approval and implementation of the National Solar Silicon Value Chain Program, demonstrate the country's commitment to advancing this strategic industry.

4.1.2 Weaknesses

The sector's primary weaknesses stem from heavy reliance on imported advanced equipment and technical expertise. This dependence is particularly evident in critical areas such as solar-grade polysilicon production and thin-film deposition equipment. Furthermore, a shortage of skilled professionals in specialized fields, such as advanced cell design and process optimization, poses another challenge that hinders industry growth.

4.1.3 Opportunities

The rapidly expanding regional market for renewable energy and Iran's strategic geographic position serve as key drivers for industry development. Moreover, recent government support policies—including targets for 30,000 MW of solar power generation, tax exemptions, and special incentives for solar power plant development—have created a favorable environment for investment in this sector.

4.1.4 Threats

The industry faces threats from foreign competitors offering lower-cost, higher-quality technologies, which could impact the domestic market. Additionally, technological sanctions and restricted access to advanced equipment and expertise present further challenges for the development of cutting-edge technologies in the country.

Table 3 summarizes the SWOT matrix for the localization of photovoltaic technology in Iran. This analysis highlights the need for a balanced approach that leverages Iran's inherent advantages while addressing critical vulnerabilities. Strategic initiatives should focus on reducing technological dependencies, fostering domestic expertise, and capitalizing on regional market opportunities to establish a competitive and sustainable photovoltaic industry. The findings underscore the importance of coordinated efforts between policymakers, industry stakeholders, and academic institutions to overcome existing barriers and achieve long-term growth in this vital sector.

The combination of these factors underscores the necessity for adopting intelligent strategies to capitalize on opportunities

Table 2. Comparison of different generations of solar cells in Iran

Index	first generation (silicon)	second generation (thin film)	third generation (perovskite)
TRL Level	7-8	2-3	2-3
Active Companies	8 companies	0	0
Scientific Articles	8%	12%	41%
Main Challenge	Silicon value chain completion	Lack of domestic market	Instability

Table 3. SWOT analysis of photovoltaic technology localization in Iran

Strengths	**Weaknesses**
• Rich mineral reserves (high-grade silica) • Recent investments in production infrastructure	• Strong dependence on imported equipment and technical knowledge • Lack of skilled manpower in specialized fields
Opportunities	**T**hreats
• Growth of the regional renewable energy market • Government support policies (tax exemptions, facilities)	• Competition from foreign technologies with better prices and quality • Technology sanctions and limited access to advanced equipment

while mitigating threats. The SO strategy (leveraging strengths to exploit opportunities) could focus on expanding solar product exports to regional markets by capitalizing on Iran's raw material advantages. The ST strategy (using strengths to counter threats) should emphasize developing alternative technologies based on domestic resources. The WO strategy (overcoming weaknesses by seizing opportunities) may involve attracting foreign investment for technology transfer and specialized workforce training. The WT strategy (minimizing weaknesses while avoiding threats) must prioritize applied research to reduce import dependence and enhance self-sufficiency.

This analysis reveals that successful localization of photovoltaic technologies requires a balanced approach combining domestic resource development, targeted acquisition of foreign technologies, and strengthened regional cooperation. Furthermore, special emphasis on cultivating specialized human capital and fostering effective collaboration between research institutions and industry represents fundamental prerequisites for overcoming existing challenges. The strategic implementation of these complementary approaches, supported by coherent policy frameworks and sustained investment, could position Iran as a competitive player in the regional photovoltaic market while progressively reducing its technological dependencies. Ultimately, the transition from technology consumer to innovator demands long-term commitment across all levels of the value chain, from material processing to advanced manufacturing and system integration.

4.2 Development Scenarios

Given the rapid technological advancements in the global photovoltaic industry and the significant disparities in the development levels of different PV generations in Iran, we need to formulate coherent and operational strategies. The country's current technological capabilities, mineral resources, financial capacity, and specialized human resources influence the feasibility of various development pathways. In this context, three plausible scenarios with different approaches and risk levels can be envisioned, each with its own advantages and challenges. These scenarios are based on a comprehensive analysis of the current situation and successful international experiences, providing a framework for policymaking and decision-making in this strategic field:

4.2.1 Conservative Scenario

This scenario primarily focuses on completing and optimizing the value chain of first-generation PV technologies (crystalline silicon). Key priorities include developing high-quality solar-grade polysilicon production technology, localizing silicon wafer manufacturing, and upgrading cell and module production lines. With existing infrastructure and a technology readiness level (TRL) of 7-8 in this field, this represents the lowest-risk path. The main advantage is the potential for quick returns on investments and short-term revenue generation. However, its major limitation is insufficient attention to emerging technologies and the risk of technological obsolescence in the long term. Implementing this scenario requires significant investment and focus on transferring key technologies such as polysilicon production and wafer slicing.

4.2.2 Balanced Scenario

This scenario pursues parallel development of first-generation and perovskite technologies. While completing the crystalline silicon value chain, resources are also allocated to perovskite R&D. The advantage lies in balancing short-term needs (production and employment) with preparation for future PV industry transformations. For perovskites, the focus would be on developing stable lab prototypes, encapsulation methods, and production scale-up. The main challenge is the need for greater financial and human resources to manage two distinct technology lines simultaneously. Estimates suggest allocating 60% of investments to first-generation and 40% to perovskite technologies under this scenario.

4.2.3 Progressive Scenario:

This boldest pathway focuses on tandem cell technology (combining perovskite and silicon). While maintaining minimal first-generation production capacity, primary resources would be directed toward next-generation technologies. The key advantage is positioning at the forefront of technological innovation with potential for high efficiencies (above 30%). This path requires establishing strategic collaborations with leading global research centers, attracting international experts, and heavy investment in basic and applied research. Major challenges include high technological risk, need for massive investment, and uncertainty about commercialization timelines. This scenario best suits countries with strong research foundations and substantial financial capacity.

Each scenario suits different economic, technological, and human resource conditions. The conservative approach fits periods of financial constraints needing short-term results. The balanced scenario represents an optimal choice for medium-capacity countries seeking to keep pace with global advancements. The progressive scenario suits countries aiming for leadership in future technologies with sufficient research and financial resources.

For Iran, considering current sanctions, financial limitations, and available specialized human resources, the balanced scenario appears more suitable. It maintains existing production capacity and employment while enabling participation in future PV industry transformations. However, successful implementation requires a detailed program with quantitative targets and clear timelines, coupled with robust policy support and international cooperation mechanisms to mitigate inherent risks. This middle path could potentially position Iran to gradually transition toward more advanced technologies as its capabilities mature.

4.3 Roadmap for Localization of Solar Cell Technology in Iran

Based on comprehensive analyses and evaluation of various scenarios, a strategic roadmap has been developed for photovoltaic technology development in Iran. This roadmap encompasses two distinct yet overlapping phases:

a) Technology Transition Phase (Years 1-5):

The primary objectives focus on completing the solar silicon value chain through:

- Establishment of high-purity solar-grade polysilicon production facilities
- Localization of thin wafer production technology (<160 µm thickness)
- Commissioning of advanced silicon cell production lines featuring modern architectures (PERC and TOPCon)
- Development of ancillary industries including:
    - Anti-reflective glass manufacturing
    - Aluminum frame production
    - High-purity chemical supply chains

This phase prioritizes achieving 85% localization in first-generation PV technology while simultaneously building foundational capabilities for next-generation technologies. Key performance indicators include achieving cell efficiencies exceeding 22% for mass-produced modules and reducing production costs by 30% through localized manufacturing.

b) Advanced Technology Development Phase (Years 2-6):

Concurrent with later stages of the transition phase, this period emphasizes:

- Creation of advanced research laboratories for third-generation PV technologies
- Development and prototyping of perovskite-silicon tandem cells
- Specialized human capital development through:
    - Targeted academic programs
    - International exchange initiatives
    - Industry-academia collaboration schemes
- Strategic international partnerships with leading research institutions focusing on:
    - Materials science
    - Device physics
    - Manufacturing processes

The roadmap incorporates cross-cutting enablers including:

- Establishment of a national PV technology certification center
- Development of standardized testing protocols
- Creation of a specialized technology incubator network
- Implementation of a comprehensive intellectual property management system

As illustrated in Figure 8, the phased approach ensures continuity between technology generations while allowing for adaptive resource allocation based on emerging global trends and domestic capabilities. Critical path analysis identifies polysilicon production technology acquisition and perovskite stability research as the most time-sensitive components requiring prioritized attention.

This structured yet flexible approach positions Iran to progressively advance from technology adoption to innovation, with periodic reviews every 18 months to incorporate technological breakthroughs and market developments. The roadmap's success hinges on synchronized public-private investments totaling approximately $850 million over the six-year period, with expected returns including creation of 12,000 direct jobs and establishment of a $1.2 billion domestic PV industry by year 6.

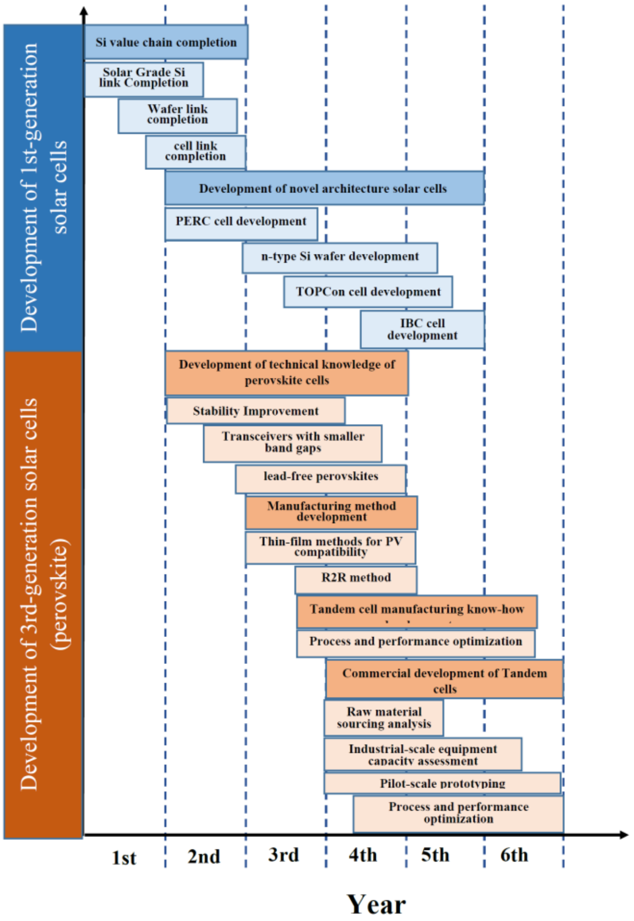


Fig.8. Proposed roadmap for the development of different generations of solar cells in the country

5. Conclusions and Recommendations

This study presents a comprehensive evaluation of Iran's capabilities for localizing solar cell technology, employing multidimensional analytical frameworks to assess the current status and development strategies.

The key findings reveal that first-generation (crystalline silicon) solar cells, with a technology readiness level of 8 and approximately 60% self-sufficiency, represent the most advanced PV technology in Iran.

In contrast, second and third-generation technologies remain primarily in early research stages, facing challenges such as dependence on imported raw materials, shortage of specialized human resources, and inadequate infrastructure. The SWOT analysis highlights strengths like abundant mineral reserves alongside weaknesses including reliance on foreign technologies.

Based on the research findings, the following strategic actions are essential for advancing photovoltaic technologies in Iran:

a) Policy Recommendations

The formulation of long-term supportive policies is crucial to accelerate solar cell technology development. These should incorporate:

- Tax incentives for renewable energy companies
- Special financing facilities for investments in raw material and equipment production
- Preferential tariffs for domestically manufactured products
- Establishment of specialized task forces involving the Ministries of Energy, Industry, and Science to enhance inter-sectoral coordination

b) Research Priorities:

Given the dispersion of academic research and its misalignment with industrial needs, research priorities should be realigned with actual industry challenges. This requires:

- Creating collaborative networks among universities, research centers, and industry
- Directing research toward solving practical problems
- Investing in international joint projects for emerging technologies like tandem and perovskite cells
- Establishing technology roadmaps with clear milestones for different PV generations

c) Industrial Development

Industrial strategy should focus on:

- Completing the first-generation solar cell value chain through technology transfer and foreign investment
- Developing pilot production lines and scalable laboratory infrastructure for second and third-generation technologies
- Forming specialized consortia combining domestic and international companies
- Implementing quality assurance systems to meet international standards
- Developing domestic certification capabilities for PV components

To support the implementation of the proposed strategies and address persistent knowledge gaps, the following research avenues are critical:

- Economic & Supply Chain Analyses: Detailed feasibility of domestic raw material extraction versus imports, and developing optimization models for the local solar manufacturing supply chain.
- Policy & Technology Impact: Quantifying the effects of government incentives on industry growth and creating predictive models to evaluate emerging solar technologies within Iran's energy market.
- Environmental & Comparative Studies: Conducting lifecycle assessments of various PV technologies under local conditions and benchmarking against successful international renewable energy programs.

This research demonstrates that through coordinated planning, targeted investment, and enhanced international cooperation, Iran can achieve a competitive position in the strategic solar cell industry. The proposed roadmap provides a realistic pathway for gradual technology advancement while considering Iran's current capabilities and constraints. Successful implementation will require sustained commitment from all stakeholders, periodic performance evaluations, and adaptive strategies responsive to technological breakthroughs and market dynamics.

The transition from technology consumer to innovator demands parallel development of technical capabilities, human capital, and policy frameworks. By addressing these dimensions holistically, Iran can simultaneously meet its domestic renewable energy targets while positioning itself as a regional leader in photovoltaic technology development.

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