Ethiopian International Journal of Multidisciplinary Research

pISSN:2349-5707 Volume:13,Issue 5, May -2026 eISSN:2349-5715

METHODS FOR IMPROVING THE EFFICIENCY OF SOLAR CELLS BASED ON THE PHOTOELECTRIC EFFECT: A REVIEW OF MODERN APPROACHES AND THEORETICAL LIMITS

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ABSTRACT. This study aims to systematically analyze the physical foundations of the photoelectric effect and to evaluate modern methods for enhancing solar cell efficiency, with particular attention to recent advances in tandem architectures, perovskite materials, and surface engineering. The research is based on a comprehensive review of peer-reviewed literature published between 2014 and 2024, indexed in Scopus, Web of Science, and IEEE Xplore databases. The analysis reveals that perovskite–silicon tandem cells have achieved certified efficiencies of 33.9% in 2024, while concentrator multijunction devices have surpassed 47.6%. Surface passivation techniques reduce recombination losses by up to 60%, and anti-reflective nanostructures decrease optical losses below 2%.

KEYWORDS: photoelectric effect; solar cell; photovoltaic efficiency; Shockley–Queisser limit; perovskite; tandem solar cell; surface passivation; recombination losses; renewable energy; bandgap engineering.

1. Introduction

The transition toward sustainable energy systems has become one of the defining challenges of the twenty-first century. According to the International Energy Agency (IEA), global electricity demand is projected to increase by approximately 80% between 2022 and 2050, while the share of renewable sources is expected to exceed 60% during the same period [1]. Among the available renewable technologies, solar photovoltaics (PV) hold a central position due to the abundance of solar resources, declining production costs, and continual advances in conversion efficiency.

The fundamental physical principle underlying solar energy conversion is the photoelectric effect, first explained quantitatively by Albert Einstein in 1905 and recognized with the Nobel Prize in Physics in 1921. This phenomenon, in which photons of sufficient energy excite electrons across the bandgap of a semiconductor, forms the basis for all modern photovoltaic devices [2, 3]. Despite the apparent simplicity of this principle, the practical realization of efficient solar cells involves complex interactions among optical, electronic, and thermal processes.

The efficiency of commercial crystalline silicon (c-Si) solar cells has steadily increased from approximately 14% in the year 2000 to a record 27.6% in laboratory devices reported by LONGi Green Energy in 2024 [4]. However, the typical efficiency of mass-produced silicon modules in 2024 still lies in the range of 21–23%, indicating a substantial gap between theoretical, laboratory, and industrial performance. The Shockley–Queisser (S–Q) thermodynamic limit imposes a maximum theoretical efficiency of approximately 33.7% on any single-junction solar cell illuminated by the AM1.5G spectrum [5]. Surpassing this limit requires advanced device architectures such as multijunction or tandem configurations.

In recent years, perovskite solar cells (PSCs) have emerged as a disruptive technology, demonstrating a remarkable rise in certified power conversion efficiency from 3.8% in 2009 to 26.7% in 2024 - an unprecedented rate of progress in photovoltaic history [6, 7]. The integration of perovskite top cells with silicon bottom cells has produced tandem devices with certified efficiencies of 33.9%, breaking the long-standing single-junction barrier [8]. Simultaneously, advanced silicon technologies - including heterojunction (HJT), tunnel oxide passivated contact (TOPCon), and interdigitated back contact (IBC) architectures - continue to push the boundaries of conventional photovoltaics.

The relevance of solar cell efficiency improvement is particularly high for sun-rich regions such as the Republic of Uzbekistan. The country receives an annual solar irradiation of 1,800–2,200 kWh/m², which is among the highest in Central Asia [9]. The Uzbek government, through Presidential Decree PF-158 "On accelerating the transition to a green economy" (2022) and earlier Decree PF-4422 (2019), has set a strategic target to install over 8 GW of solar generation capacity by 2030 [10]. Major projects such as the Nur Navoi solar plant (100 MW, commissioned in 2021), Sherobod (457 MW), and Bo'ka (300 MW) demonstrate the practical scale of national PV deployment. Improving the conversion efficiency of installed modules directly translates into reduced land use, lower levelized cost of electricity (LCOE), and faster payback periods.

Despite extensive global research, several gaps remain in the systematic understanding of efficiency-enhancement strategies. Many published reviews focus on individual technologies in isolation, without providing an integrated comparison of theoretical limits, recent records, and practical trade-offs. Furthermore, the implications for emerging-market deployment, including the technical and economic conditions of Central Asian countries, are rarely discussed.

The aim of this study is to provide a comprehensive analysis of the physical mechanisms underlying solar cell operation and to systematically evaluate modern methods for enhancing photovoltaic efficiency. The research objectives are formulated as follows:

1) to review the theoretical foundations of the photoelectric effect and the Shockley–Queisser limit relevant to solar cell operation;
2) to identify and quantitatively evaluate the principal loss mechanisms that reduce real-world solar cell efficiency;
3) to compare the performance of contemporary efficiency-enhancement strategies, including tandem architectures, surface passivation, and nanostructured light trapping;
4) to assess the implications of recent technological advances for large-scale photovoltaic deployment in solar-rich regions, with Uzbekistan as a representative case.

2. Materials and Methods

The present study employs a structured literature review methodology supplemented by comparative analysis and theoretical evaluation. The research approach was developed in accordance with the PRISMA-style framework adapted for engineering review articles, ensuring transparency and reproducibility of source selection.

The literature search was conducted in three principal scientific databases: Scopus, Web of Science (WoS), and IEEE Xplore. The search covered the period from January 2014 to October 2024 to capture the most relevant developments in the field. The following primary search terms were used in various Boolean combinations: "solar cell efficiency", "photovoltaic", "Shockley–Queisser limit", "perovskite", "tandem solar cell", "surface passivation", "heterojunction", "TOPCon", "multijunction", and "bandgap engineering". An initial pool of 412 articles was identified, which was reduced to 187 after removal of duplicates and 64 after applying inclusion criteria related to subject relevance, methodological rigor, and citation impact.

Inclusion criteria comprised: (a) peer-reviewed publications in journals with an impact factor greater than 2.0 or in IEEE conference proceedings; (b) articles reporting certified efficiency measurements verified by accredited laboratories such as NREL, Fraunhofer ISE, AIST, or CSIRO; (c) studies providing quantitative experimental or theoretical data on efficiency-related parameters. Exclusion criteria included non-English publications without scientific abstracts, opinion pieces, and articles with insufficient methodological description.

In addition to the literature review, the study incorporates publicly available data from the National Renewable Energy Laboratory (NREL) Best Research-Cell Efficiency Chart (2024 edition), Fraunhofer ISE Photovoltaics Report (2024), and the IEA Renewables 2023 report. National-level data on solar deployment in Uzbekistan were sourced from the Ministry of Energy of the Republic of Uzbekistan and the Uzbek Agency for Strategic Reforms.

The analytical framework consisted of three sequential steps. First, the theoretical limits of solar cell operation were derived from the photoelectric effect equations and the Shockley–Queisser model. Second, real-world performance data were aggregated by technology category and benchmarked against the corresponding theoretical limits. Third, the performance gap between laboratory and commercial devices was analyzed in conjunction with cost, scalability, and stability metrics. All quantitative results were cross-verified across at least two independent sources.

3. Theoretical Foundations

3.1. The Photoelectric Effect and Photon–Semiconductor Interaction

The energy of a single photon associated with electromagnetic radiation of frequency ν is given by the Planck–Einstein relation:

$$E = h\nu = hc/\lambda \qquad (1)$$

where $h = 6.626 \times 10^{-34}$ J·s is Planck's constant, $c = 2.998 \times 10^{8}$ m/s is the speed of light in vacuum, and λ is the photon wavelength. The photoelectric effect occurs when an incident photon possesses sufficient energy to excite an electron across the energy gap of the absorbing material. For the external photoelectric effect, the Einstein equation reads:

$$h\nu = A + E_k \qquad (2)$$

where A is the work function of the material and E_k is the kinetic energy of the emitted electron. In semiconductor devices, the more relevant phenomenon is the internal photoelectric effect, in which absorbed photons promote electrons from the valence band to the conduction band, generating electron–hole (e–h) pairs without electron emission [11].

The fundamental mechanism of charge separation in a p–n junction is illustrated in Figure 1.

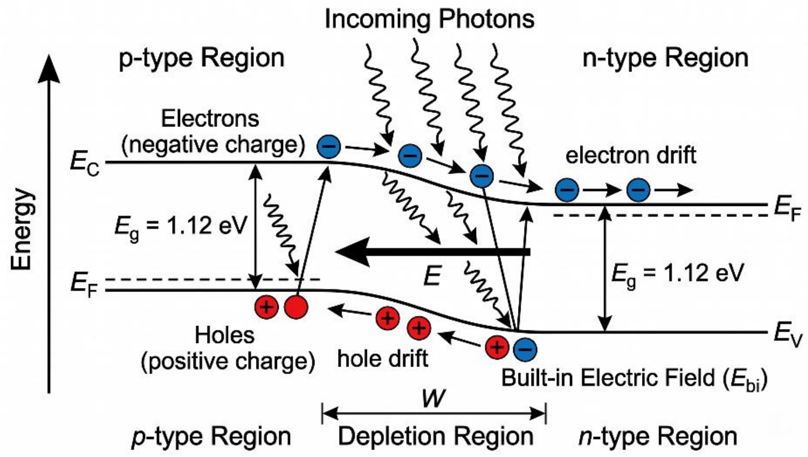

Figure 1. Schematic energy band diagram of a p–n junction in a silicon solar cell, illustrating the generation and separation of electron–hole pairs under illumination

The fundamental absorption condition in a semiconductor with bandgap E_g requires that the photon energy satisfies $E \geq E_g$. Photons with $E < E_g$ pass through the material without absorption (sub-bandgap losses), while photons with $E > E_g$ lose their excess energy through thermalization to the lattice (above-bandgap losses). Together, these two loss mechanisms account for approximately 50% of the incident solar power and represent the primary intrinsic limitation of single-junction devices.

3.2. Solar Cell Operating Parameters

The performance of a photovoltaic device is characterized by four principal parameters: the open-circuit voltage V_{oc}, the short-circuit current density J_{sc}, the fill factor FF, and the power conversion efficiency η. The conversion efficiency is defined as:

$$\eta = (V_{oc} \cdot J_{sc} \cdot FF) / P_{in} \qquad (3)$$

where P_{in} is the incident power per unit area (typically 1000 W/m² under AM1.5G standard test conditions). The fill factor, which describes the "squareness" of the current–voltage characteristic, is given by:

$$FF = (V_{mp} \cdot J_{mp}) / (V_{oc} \cdot J_{sc}) \qquad (4)$$

where V_{mp} and J_{mp} denote the voltage and current density at the maximum power point. For high-quality silicon solar cells, FF values typically exceed 0.83, while perovskite devices have reached FF values above 0.85 [12]. The open-circuit voltage is fundamentally bounded by the bandgap energy:

$$V_{oc} < E_g / q \qquad (5)$$

where q is the elementary charge. The actual V_{oc} is reduced from this thermodynamic limit by recombination losses, with the deficit $V_{oc,deficit} = E_g/q - V_{oc}$ serving as a practical figure of merit for material quality.

3.3. The Shockley–Queisser Limit

The maximum theoretical efficiency of a single-junction solar cell under non-concentrated AM1.5G illumination, derived from detailed-balance considerations, was first calculated by Shockley and Queisser in 1961 [5]. The limit reaches its maximum value of approximately

33.7% at an optimal bandgap of $E_g \approx 1.34$ eV. The major intrinsic loss mechanisms incorporated in the S–Q analysis are summarized as follows:

- sub-bandgap transmission losses (~19% of incident power for $E_g = 1.34$ eV);
- thermalization of high-energy photons to the band edge (~33%);
- Boltzmann (entropy-related) losses associated with finite-area emission of solar radiation (~7%);
- radiative recombination losses, which are unavoidable in any working device (~5%).

For specific commercially relevant materials, the S–Q limits are: silicon ($E_g = 1.12$ eV) - 32.0%; gallium arsenide ($E_g = 1.42$ eV) - 33.5%; methylammonium lead iodide perovskite ($E_g \approx 1.55$ eV) - 30.5%; and cadmium telluride ($E_g = 1.50$ eV) - 31.0%.

The dependence of the theoretical efficiency limit on bandgap energy, together with the position of the most relevant absorber materials, is shown in Figure 2.

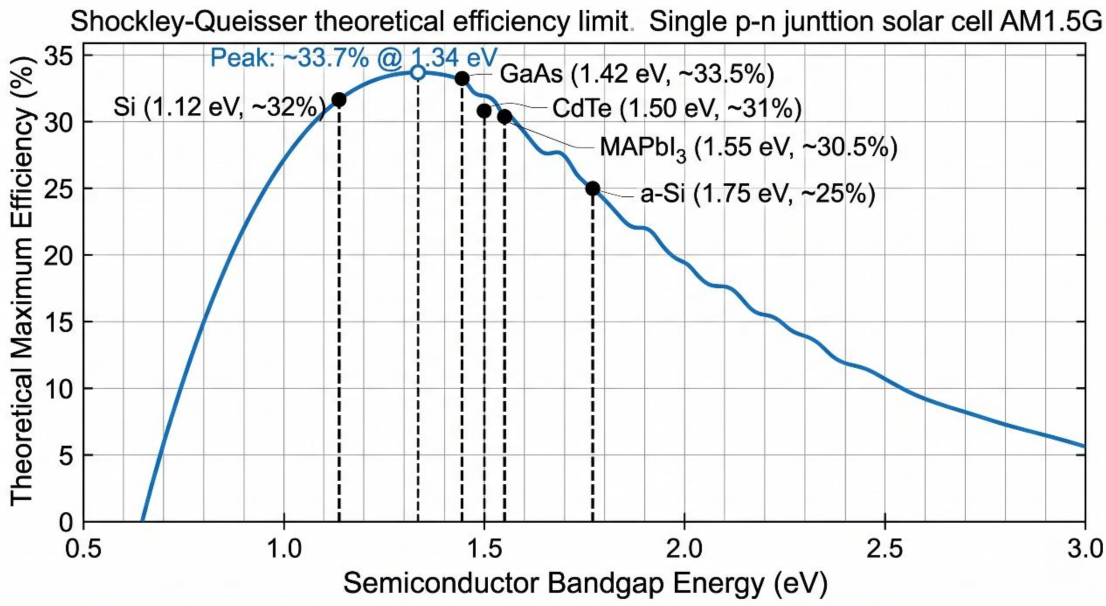

Figure 2. Shockley–Queisser efficiency limit as a function of semiconductor bandgap energy under AM1.5G illumination, with reference points for major photovoltaic materials

The most direct route to surpass the S–Q limit is the use of multijunction or tandem architectures, in which two or more sub-cells with complementary bandgaps absorb different portions of the solar spectrum [13].

4. Results

4.1. Principal Efficiency Loss Mechanisms

Real-world solar cells exhibit efficiencies considerably lower than the Shockley–Queisser limit due to several practical loss mechanisms. The relative contributions of these losses for a typical commercial monocrystalline silicon module are summarized in Table 1.

Table 1. Distribution of efficiency losses in a commercial c-Si solar cell (η = 22%)

Loss mechanism	Loss type	Contribution, %	Mitigation strategy

Loss mechanism	**Loss type**	**Contribution, %**	**Mitigation strategy**
Sub-bandgap transmission	Intrinsic	19	Tandem cells
Thermalization	Intrinsic	33	Tandem, hot-carrier cells
Optical reflection	Extrinsic	3–10	AR coatings, texturing
Bulk recombination (SRH)	Extrinsic	2–5	Material purity
Surface recombination	Extrinsic	3–8	Surface passivation
Series resistance	Extrinsic	1–3	Contact engineering
Temperature effects	Operational	4–10	Cooling, materials

The temperature dependence of solar cell efficiency is particularly relevant for hot-climate regions such as Uzbekistan, where module temperatures regularly reach 60–75 °C in summer months. The temperature coefficient of efficiency for crystalline silicon, $\beta = -0.40$ to $-0.45\%/°C$, implies a 12–15% relative reduction in power output between 25 °C (standard test conditions) and 55 °C (typical operating temperature) [14]. Perovskite cells exhibit a notably lower temperature coefficient ($\beta \approx -0.10$ to $-0.30\%/°C$), making them attractive candidates for hot-climate deployment, although stability remains a challenge.

4.2. Modern Strategies for Efficiency Enhancement

The strategies for enhancing solar cell efficiency can be classified into four broad categories: (a) advanced architectures (tandem and multijunction); (b) novel absorber materials (perovskites, quantum dots, organic semiconductors); (c) interface and surface engineering; and (d) optical management (anti-reflection, light trapping, plasmonic enhancement).

Tandem and multijunction architectures represent the most direct approach to surpass the Shockley–Queisser limit. By stacking two or more sub-cells with complementary bandgaps, these devices absorb different portions of the solar spectrum at near-optimal efficiency. The current world record of 47.6%, achieved in 2022 by Fraunhofer ISE using a four-junction GaInP/GaAs/GaInAsP/GaInAs concentrator cell at 665× concentration, demonstrates the upper bound of this strategy [15]. For non-concentrated terrestrial applications, the perovskite–silicon two-junction tandem has reached 33.9% certified efficiency in 2024, jointly developed by LONGi and KAUST [8].

The structural concept of a perovskite–silicon tandem solar cell, including the spectral allocation between sub-cells, is presented in Figure 3.

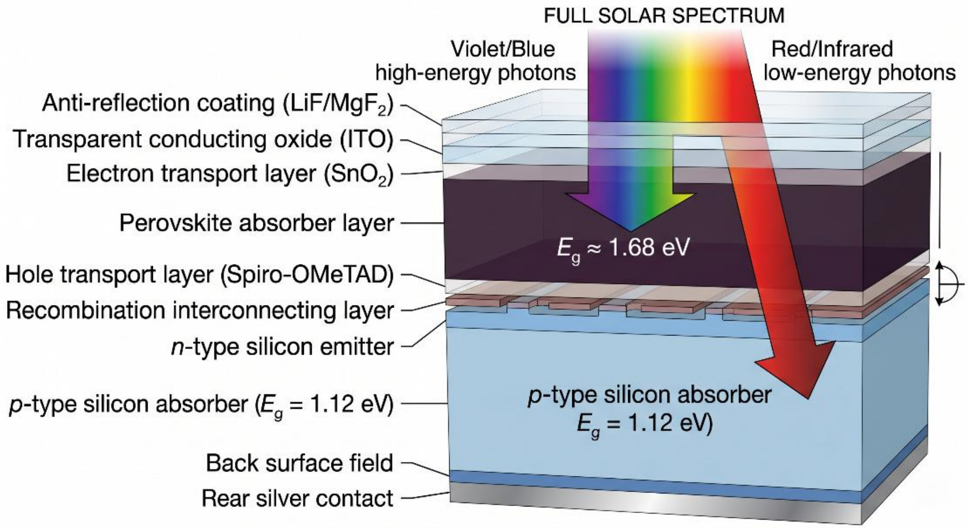

Figure 3. Cross-sectional structure of a monolithic perovskite–silicon tandem solar cell, showing the spectral splitting of incident sunlight between the wide-bandgap perovskite top cell and the silicon bottom cell

Surface passivation has emerged as a key enabling technology for advanced silicon devices. The introduction of ultra-thin tunnel oxide layers (1.0–1.5 nm) combined with heavily doped polycrystalline silicon (TOPCon technology) reduces surface recombination velocities below 5 cm/s, compared to 100–300 cm/s in conventional Al-BSF cells. Heterojunction (HJT) cells employing intrinsic and doped amorphous silicon layers achieve similar passivation quality, with implied open-circuit voltages exceeding 750 mV [16].

Nanostructured anti-reflection coatings - including SiO_2/TiO_2 multilayers, SiN_x graded-index films, and biomimetic moth-eye structures - have reduced average surface reflection from 30–35% (bare silicon) to less than 2% across the relevant solar spectrum. Plasmonic nanoparticles, although extensively studied, have so far failed to enter mass production due to parasitic absorption and stability issues.

The performance comparison of leading solar cell technologies is presented in Table 2.

Table 2. Certified record efficiencies of major PV technologies (NREL Chart, October 2024)

Technology	Record η, %	Year	Bandgap, eV	Status
Mono-Si (TOPCon)	27.1	2024	1.12	Mass production
Mono-Si (HJT)	27.3	2024	1.12	Mass production
Mono-Si (back-contact)	27.6	2024	1.12	Pilot production
GaAs (thin film)	29.1	2019	1.42	Specialized

Technology	Record η, %	Year	Bandgap, eV	Status
CdTe (thin film)	22.4	2022	1.50	Mass production
CIGS (thin film)	23.6	2023	1.0–1.7	Mass production
Perovskite (single)	26.7	2024	1.55	Pre-commercial
Perovskite–Si tandem	33.9	2024	1.68/1.12	R&D / pilot
3J concentrator	44.4	2013	multiple	Space / CPV
4J concentrator	47.6	2022	multiple	Laboratory
Quantum dot	18.1	2020	tunable	Research
Organic	19.2	2023	1.5–2.0	Niche

4.3. Quantitative Impact of Efficiency Gains on PV Deployment

The impact of efficiency improvement on system-level economics can be quantified through the levelized cost of electricity (LCOE), area utilization, and balance-of-system (BoS) costs. An increase in module efficiency from 21% (typical 2024 commercial) to 30% (anticipated tandem product by 2027) would reduce the required installation area by approximately 30% for the same energy output. For utility-scale projects such as Sherobod (457 MW) in Uzbekistan, this corresponds to a saving of approximately 280 hectares of land and proportional reductions in mounting structures, cabling, and labor.

Table 3 summarizes the projected impact of efficiency gains on key economic indicators for a representative 100 MW utility-scale project under typical Central Asian conditions.

Table 3. System-level impact of module efficiency on a 100 MW PV plant (Uzbekistan reference)

Indicator	η = 21% (baseline)	η = 25%	η = 30%
Required area, ha	210	176	147
Module count, thousand	220	185	155
BoS cost, M USD	32.5	28.2	24.1

Indicator	**η = 21% (baseline)**	**η = 25%**	**η = 30%**
LCOE, USD/MWh	38–42	32–36	27–31
Annual yield, GWh	215	215	215

5. Discussion

The analysis presented in Section 4 demonstrates that the gap between the current commercial efficiency of silicon modules (~22%) and the Shockley–Queisser limit (32% for silicon) is rapidly narrowing, with HJT and TOPCon technologies already exceeding 27% in laboratory devices. The remaining ~5 percentage points represent the practical ceiling for single-junction silicon, beyond which only tandem and multijunction architectures can provide further improvement. This conclusion is consistent with the observations of Schmidt et al. [16] and Green et al. [4], who argue that single-junction silicon is approaching its asymptotic limit.

Perovskite–silicon tandem cells appear to offer the most promising near-term pathway for surpassing the 30% commercial threshold. Recent results from LONGi (33.9%, 2024), Helmholtz-Zentrum Berlin (32.5%, 2023), and Oxford PV (28.6% commercial-area module, 2024) indicate that the technology is rapidly transitioning from research to pre-commercial production [8, 17]. Nevertheless, three principal challenges remain. First, long-term operational stability of perovskite layers in outdoor conditions - particularly under combined humidity, temperature, and UV stress - has not yet been demonstrated at the 25-year warranty level required for commercial deployment. Second, the use of lead in the most efficient perovskite formulations raises environmental and regulatory concerns, particularly in jurisdictions with strict RoHS-type frameworks. Third, the scaling of high-efficiency perovskite manufacturing from cell-level to module-level introduces additional losses that must be addressed.

Concentrator multijunction technology, while reaching the highest absolute efficiencies (47.6%), remains constrained to specialized applications such as space photovoltaics and high-DNI (direct normal irradiance) terrestrial sites, due to high cost and complex tracking requirements. For Central Asian conditions, including Uzbekistan, the cost-effectiveness of CPV is debatable; preference is currently given to flat-panel silicon and emerging tandem technologies.

The relevance of efficiency-enhancement strategies for Uzbekistan must be evaluated in the context of national energy planning. The government has committed to expanding solar capacity from approximately 0.4 GW in 2022 to 8 GW by 2030, requiring the deployment of approximately 1.0–1.2 GW per year over the next six years [10]. At the current commercial module efficiency (21–22%), this would require approximately 25 km^2 of installed module area annually. A transition to next-generation 28–30% modules by 2027 - coinciding with anticipated tandem commercialization - could reduce this footprint by 25–30%, thereby alleviating land-use pressure and reducing logistical costs.

From a technical standpoint, the high ambient temperatures characteristic of the Uzbek summer (often exceeding 40 °C) impose a particular penalty on silicon-based modules. The relative advantage of perovskite and CIGS technologies, with their lower temperature coefficients, may justify their selective deployment despite higher initial costs. Furthermore, the integration of bifacial modules - which can generate an additional 10–15% energy through rearside albedo collection - appears especially promising in regions with high ground reflectance, including parts of the Kyzylkum and Karakum desert margins [18].

Beyond hardware, the economic viability of advanced PV technologies depends critically on financing structures, grid integration, and workforce capacity. The reduction in LCOE associated with higher efficiency (Table 3) is substantial - moving from 21% to 30% efficiency reduces LCOE by approximately 30%, from 40 USD/MWh to 28 USD/MWh under reference Uzbek conditions. This places utility-scale solar in direct competition with the cheapest natural gas generation and fully justifies continued investment in efficiency research.

It is important to acknowledge limitations of the present study. First, the analysis relies primarily on certified laboratory efficiencies, which can deviate substantially from field performance due to soiling, degradation, and module-level losses. Second, cost projections (Table 3) involve inherent uncertainty associated with global supply-chain dynamics and silver/silicon commodity prices. Third, the Uzbekistan-specific economic data are based on publicly available reports, and detailed plant-level data remain proprietary.

6. Conclusion

This study provided a systematic analysis of efficiency-enhancement methods for solar cells based on the photoelectric effect, integrating theoretical, technological, and deployment-oriented perspectives. The principal findings can be summarized as follows.

First, the Shockley–Queisser limit imposes a fundamental ceiling of approximately 33.7% on single-junction solar cell efficiency, and current high-efficiency silicon technologies (HJT, TOPCon, IBC) have approached within 5 percentage points of this limit, leaving limited room for further gains within the single-junction paradigm.

Second, perovskite–silicon tandem cells, with their certified efficiency of 33.9% in 2024, represent the most credible near-term pathway toward exceeding the single-junction barrier and entering the 30% commercial efficiency regime by 2027–2030. Successful commercialization will require resolving long-term stability, lead toxicity, and large-area uniformity challenges.

Third, surface passivation, anti-reflective nanostructures, and bandgap engineering have collectively reduced extrinsic loss mechanisms below 5% of incident solar power in the best laboratory devices, demonstrating the maturity of these enabling technologies.

Fourth, for solar-rich emerging markets such as Uzbekistan, the transition from commercial 21% modules to advanced 28–30% modules during the 2025–2030 period would reduce the required deployment area by 25–30% and the levelized cost of electricity by approximately 30%, while supporting national green-economy targets.

Future research should prioritize: (a) operational stability of perovskite-based devices under combined environmental stress; (b) lead-free perovskite alternatives with retained electronic quality; (c) cost-effective tandem manufacturing pathways suitable for emerging markets; and (d) integrated system-level studies quantifying the economic impact of efficiency gains under specific climatic and policy conditions, including those of Central Asia.

The continued advancement of solar cell technology, supported by interdisciplinary research and informed national policy, will play a decisive role in achieving the global energy transition and meeting the United Nations Sustainable Development Goal 7 on affordable and clean energy.

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