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Posted Date: 29 September 2025

doi: 10.20944/preprints202509.2295.v1

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Limitations of Solar Cell Technology: The Fundamental Constraint of Solar Power

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Abstract

Solar cell technology is inherently constrained by the amount of solar energy reaching Earth, with fundamental limitations imposed by solar irradiance, photovoltaic conversion efficiency, and technological challenges. This paper explores these constraints, focusing on the theoretical maximum efficiency defined by the Shockley-Queisser limit and the impact of atmospheric losses on ground-level irradiance. Practical efficiencies of current solar cells, including multi-junction and tandem architectures, remain below their theoretical maxima due to material, environmental, and system integration challenges. Additionally, solar power's intermittency necessitates additional energy storage solutions and raises concerns about land use and resource allocation for large-scale deployment. While advancements in quantum dot photovoltaics and space-based solar power offer pathways to partially overcome these limitations, this study emphasizes the critical role of integrating solar energy into a diversified energy portfolio. Hybrid systems combining solar with nuclear baseload power and hydrogen storage are shown to mitigate intermittency, reduce curtailment losses, and enable sector coupling in hard-to-electrify industries such as heavy transport and steel production. Economic analysis highlights the decreasing costs of solar energy systems (LCOE: $24–96/MWh), making them increasingly competitive, though challenges such as grid integration and seasonal storage persist. The tripartite synergy of solar, nuclear, and hydrogen technologies emerges as a robust framework for achieving a decarbonized energy mix, balancing affordability, reliability, and scalability. Policy and innovation must prioritize these complementary solutions to address humanity's escalating energy demands while advancing global sustainability goals.

Keywords: solar energy; space-based solar power; Shockley-Queisser limit; wireless power transmission; photovoltaic efficiency; microwave beaming; laser power beaming; renewable energy; energy harvesting

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1. Introduction

As the world shifts towards renewable energy, solar power has taken a relevant position among other sustainable energy resources. Ground solar cell technology, which transforms sunlight into electricity, directly correlates to the amount of solar energy available at the Earth's surface. This is usually controlled by the solar constant, thermodynamics, and quantum physics, which comprises the fundamental boundaries of capturing solar energy. Though solar power is a clean, and virtually unlimited energy source, these tried and tested sources of solar energy are not able to meet the growing energy needs of technologically advanced societies due to intermittent nature, existence of efficiency barriers, and problems with scalability of new resources [1].

The solar constant, which defines the power received from the sun at the outermost layer of Earth's atmosphere, is approximated to be 1361 W/m². This value is reduced significantly by atmospheric losses. At ground level, typical irradiance is between 700 and 1100 W/m² under clear skies. These losses together with Shockley-Queisser Limit, which defines a maximum theoretical efficiency of 33.7 % for single junction solar cells, highlight the drawbacks that exist with solar energy conversion. Practical efficiencies of multi-junction cells, tandem architectures, and quantum dot technologies are well below their theoretical maxima, owing to material, environmental, and system integration issues [2].

One of the most alarming concerns regarding the global energy transition is the possible reliance on solar power as the sole energy source for technologically advanced societies. The availability of solar energy is dependent on the season of the year and the current weather conditions, which necessitates several forms of energy storage for the off-peak hours and seasons. Nevertheless, the methods of energy storage that are currently employed are rather costly and resource heavy. Moreover, the deployment of photovoltaic solar energy conversion devices entails the use of large amounts of territory, which raises the issues of land allocation, land-use conflicts, and in some cases, ecological protection. For instance, the production of very efficient solar cells uses indium and gallium-these are advanced, environmentally unfriendly, available materials that are rare and expensive. This may lead to a vulnerable supply chain and increased production costs [3].

In nations with high level of technological development, such as North America, Europe, and East Asia, the integration of solar power into the electrical energy grid demands careful balance with other forms of energy sources. Overreliance on solar energy without proper storage of the energy collected, or with optional complementary energy solutions, might lead to system instability, energy shortages, and increased costs. We know that in periods of low solar irradiation, that occur in the winter months or during prolonged gloomy weather, peaks of energy demand may surpass supply, and that requires a reliance on fossil fuels or nuclear power sources. This outcome risks undermining decarbonization efforts tied to renewable energy policies and underscores the necessity of a diversified energy portfolio to ensure reliability and sustainability [4]. Similarly, in other geographical regions, such as African nations (ex., Angola and Mozambique), where solar energy holds immense potential for rural electrification and economic development, energy infrastructure limitations pose additional challenges. While abundant sunlight provides a strong foundation for solar power adoption, the lack of extensive grid networks, energy storage facilities, and reliable backup sources can hinder its large-scale implementation. Addressing these structural barriers is essential for ensuring that solar energy contributes meaningfully to long-term energy security and economic growth in these regions.

Recent studies emphasized the relevance of hybrid energy systems combining solar power with other renewable sources, for example, wind and hydropower, and extending to nuclear energy as well. That would help to provide stable and sustainable energy mix. In particular, nuclear energy offers a high-density, continuous power source, a nice complement to solar energy's intermittency and providing an easy base-load generation. Advanced nuclear technologies, such as Small Modular Reactors (SMRs) and fusion reactors, are promising processes for a safer, more scalable, and environmentally friendly energy solutions [4].

This investigation examines at the critical limitations of solar cell technology, such as the constraints imposed by solar irradiance, the Shockley-Queisser limit, and practical energy harvesting concerns. In addition, we investigate the hazards associated with over-reliance on solar power in countries with high energy needs, and propose new solutions for incorporating solar energy into a more diverse and robust energy system. The resolution of these complexities will help to advance the development of sustainable energy plans, fulfilling the urgent requirements of modern societies while decreasing the negative impact on the environment and economy.

2. Solar Irradiance and Energy Limits

The first imposed limitations related to any solar energy-based source is its intrinsic power per unit area received from the Sun, known as the solar constant and denoted as S_0, is approximately:

$$S_0 \approx 1361\,\mathrm{W/m^2}. \tag{1}$$

This value represents the irradiance at the top of Earth's atmosphere and is derived from the Stefan-Boltzmann law, which relates the radiative power of a black body (the Sun) to its temperature ($T_\odot \approx$ 5778 K) and radius ($R_\odot \approx 6.96 \times 10^8$ m):

$$S_0 = \sigma T_\odot^4 \left(\frac{R_\odot}{d} \right)^2, \tag{2}$$

where σ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8}\,\mathrm{W/m^2K^4}$) and d is the average Earth-Sun distance (1.496×10^{11} m). This relationship underscores the finite nature of solar energy available for harvesting, which is essentially limited by the Sun's radiative output and the Earth's orbital parameters.

However, the solar constant conveys an idealised scenario, as atmospheric effects significantly decrease the quantity of solar irradiation reaches the Earth's surface. These include absorption by gases like ozone, water vapour, and carbon dioxide, as well as scattering by aerosols and clouds. The ground-level irradiance can be estimated as:

$$S = S_0 \tau, \tag{3}$$

where τ is the atmospheric transmittance factor, typically ranging from 0.7 to 0.8 for clear conditions. This reduction in irradiance highlights the importance of atmospheric conditions in determining the practical availability of solar energy.

The solar irradiance is highly variable in function of the geographic location, time of day, and seasonal changes, further complicating the appropriate utilization of solar energy. Regions near the equator receive higher annual solar irradiance when compared to higher latitudes, because the Sun's angle of incidence is lower and daylight hours are shorter during winter months. In addition, weather patterns and cloud cover cause rapid fluctuations in solar irradiance, challenging the energy grid stability and reliability [8].

We observe that the energy limitations imposed by solar irradiation are exacerbated by the efficiency constraints of photovoltaic (PV) technology. The Shockley-Queisser limit [14] effectively reduces the potential efficiency of single-junction solar cells to roughly 33.7% under ideal conditions. The reason of that resides in solar cells' inability to convert photons with energies below the semiconductor bandgap, while accounting for high-energy photon thermalisation losses. To reduce losses, multi-junction solar cells and tandem architectures have been developed aiming to capture a broader spectrum of sunlight. Their practical efficiencies remain constrained by material properties, manufacturing costs, and environmental factors (Green, 2003).

The interplay between solar irradiance and energy conversion efficiency underscores the need for a holistic approach to solar energy deployment. Advanced modeling and forecasting tools, such as those developed by the National Renewable Energy Laboratory (NREL), have been instrumental in optimizing the placement and operation of solar installations to maximize energy yield [9]. Additionally, the integration of energy storage systems, such as lithium-ion batteries and pumped hydro storage, can help mitigate the intermittency of solar power and ensure a stable energy supply [10].

3. Efficiency Limitations of Solar Cells

Adding to the energy limitations imposed by solar irradiation, the efficiency of a photovoltaic (PV) cell is limited by several factors, including the **The Shockley-Queisser limit**, a theoretical limit that defines the maximum efficiency of a single-junction solar cell based on the bandgap energy of the material and the spectrum of sunlight. For a single-junction solar cell under standard test conditions, the maximum efficiency is approximately 33.7% [14]. Also, the choice of semiconductor materials, doping levels, and device architecture significantly impacts the efficiency. For example, recombination losses, resistive losses, and imperfect light absorption are common issues that reduce efficiency [15]. Unfortunately, real-world conditions such as temperature variations, shading, dust accumulation, and angle of incidence of sunlight can further reduce the efficiency of solar cells [16].

Let's take a closer look at the challenges that lie ahead.

3.1. The Shockley-Queisser Limit

The Shockley-Queisser limit establishes the theoretical maximum efficiency of a single-junction solar cell under standard test conditions (AM1.5 spectrum, 1000 W/m^2 irradiance, and 25°C cell temperature). This limit arises from the balance between photon absorption, electron-hole pair generation, and radiative recombination losses. For a semiconductor with a bandgap energy E_g, the maximum efficiency η_{SQ} is given by:

$$\eta_{SQ} = \frac{\int_{E_g}^{\infty} \frac{E}{S}\phi(E)dE}{\int_0^{\infty} \phi(E)dE}, \tag{4}$$

where $\phi(E)$ is the spectral photon flux density of the solar radiation. For silicon ($E_g \approx 1.1$ eV), the Shockley-Queisser limit is approximately 33.7% [11].

3.2. Practical Limitations in Energy Harvesting

Even with advanced technologies such as multi-junction solar cells and concentrator photovoltaics, efficiency improvements are restricted by practical constraints, including spectral mismatch losses due to the non-ideal absorption of the solar spectrum; temperature-dependent performance degradation, as described by the Arrhenius equation $\eta(T) = \eta_0 \exp\left(-\frac{E_a}{k_B T}\right)$, where η_0 is the efficiency at a reference temperature, E_a is the activation energy, k_B is the Boltzmann constant, and T is the absolute temperature; system integration and power electronics losses, which can reduce overall system efficiency by 5-10% [12].

4. Advancements Beyond the SQ Limit

The fundamental constraints of single-junction solar cells, epitomized by the Shockley-Queisser (SQ) efficiency limit, arise from intrinsic thermodynamic losses in photon-to-electron conversion processes. To address humanity's escalating energy demands while mitigating land use, material scarcity, and intermittency challenges inherent to conventional solar deployment, overcoming the SQ limit is critical. A concise evaluation of emerging photovoltaic architectures is essential to identify pathways that balance theoretical potential with practical feasibility, ensuring technological advancements align with global energy needs. Advancements in multi-junction architectures, tandem configurations, and quantum-engineered materials aim to enhance photovoltaic (PV) efficiency, thereby reducing the physical footprint and storage requirements per unit energy generated. These innovations could enable solar energy to play a more substantial role in a diversified energy portfolio.

4.1. Multi-Junction Solar Cells

Multi-junction solar cells (MJSC) use stacked layers of semiconductors with different bandgaps to capture a wider spectrum of photons:

$$\eta_{MJ} = 1 - \prod_{i=1}^{N}(1 - \eta_i), \tag{5}$$

where each subcell i has efficiency:

$$\eta_i = \frac{(E_{g,i} - kT)J_{\mathrm{ph},i}}{P_{\mathrm{in},i}}. \tag{6}$$

Examples of multi-junction cells:

- 2-junction cells (GaAs/Si): 42% [55]
- 3-junction cells (GaInP/GaAs/Ge): 50% [56]
- 4-junction cells: Can exceed 55% [33]

4.2. Tandem Solar Cells

Tandem cells stack two materials optimized for different spectral ranges. The efficiency is given by:

$$\eta_{\text{tandem}} = \eta_{\text{top}} + \eta_{\text{bottom}} - \eta_{\text{overlap}}, \tag{7}$$

where η_{top} (e.g., perovskite) absorbs high-energy photons, and η_{bottom} (e.g., silicon) absorbs lower-energy photons.

For perovskite-silicon tandem cells:

$$E_{g,\text{perovskite}} \approx 1.7 \text{ eV}, \quad E_{g,\text{Si}} \approx 1.1 \text{ eV}, \tag{8}$$

leading to efficiencies above 30% in lab settings [57].

4.3. Quantum Dot Solar Cells

Quantum dots allow bandgap tuning and broader spectral absorption. The efficiency enhancement follows:

$$\eta_{\text{QDSC}} = 1 - \exp\left(-\frac{\alpha}{\lambda}\right), \tag{9}$$

where α is the absorption coefficient and λ is the tunable wavelength.

With multi-exciton generation (MEG), efficiency increases beyond the SQ limit:

$$\eta_{\text{MEG}} = \eta_{\text{SQ}} + \Delta\eta_{\text{MEG}}, \tag{10}$$

where:

$$\Delta\eta_{\text{MEG}} = \frac{(n-1)E_g}{P_{\text{in}}}, \quad n \approx \frac{E_{\text{photon}}}{E_g}. \tag{11}$$

Quantum dot solar cells theoretically achieve efficiencies approaching 45% [58].

4.4. Theoretical and Practical Limits

The maximum theoretical efficiency for single-junction cells is determined by detailed balance theory:

$$\eta_{\text{SQ}} = \frac{P_{\text{out}}}{P_{\text{in}}}, \tag{12}$$

where P_{in} is the total incident solar power, and P_{out} is the maximum electrical power output, considering photon absorption, voltage generation, and charge extraction efficiency.

The open-circuit voltage follows:

$$V_{\text{oc}} \approx \frac{E_g}{q} - \frac{kT}{q}\ln\left(\frac{J_0}{J_{\text{ph}}} + 1\right), \tag{13}$$

where J_{ph} is the photocurrent density and J_0 is the reverse saturation current. For silicon ($E_g \approx 1.1$ eV), the maximum efficiency is about 33.7% [14].

While advanced architectures like MJSCs, tandems, and quantum dot systems demonstrate pathways to surpass the SQ limit, their practical viability remains constrained by cost, scalability, and stability challenges. For instance, MJSCs require expensive III-V materials and concentrated sunlight, while perovskite tandems degrade under humidity and heat [59]. Even with theoretical efficiencies exceeding 50%, the global energy system demands not only higher efficiencies but also solutions to intermittency and material bottlenecks. Thus, these advancements must be integrated with complementary technologies—such as fuel cells, nuclear baseload power and grid-scale storage—to achieve a resilient, low-carbon energy mix. Hybrid systems leveraging high-efficiency solar for peak demand and nuclear for continuous supply could optimize land use and reliability [60].

5. The Limits of Solar Energy for Humanity's Needs

While solar photovoltaic (PV) technologies have achieved significant progress, fundamental physical and operational constraints limit their capacity to fully meet humanity's escalating energy demands. Key limitations include:

- **Theoretical and practical efficiency limits**: Single-junction solar cells are constrained by the Shockley-Queisser thermodynamic limit of 33.7% under standard illumination [32]. While multi-junction cells under concentrated sunlight have demonstrated laboratory efficiencies exceeding 47% [33], commercial modules typically operate at 15-22% efficiency due to recombination losses, spectral mismatch, and manufacturing tolerances [14]. Auger recombination and thermalization losses impose hard thermodynamic boundaries on photon conversion [34].
- **Intermittency and storage challenges**: Solar's diurnal and weather-dependent generation profile creates grid integration costs that scale nonlinearly with penetration levels [63]. Meeting baseload demand requires storage systems with 12+ hours of dispatchable capacity, where lithium-ion batteries exhibit levelized costs of $132-245/MWh [36]. Seasonal storage needs in high-latitude regions further exacerbate system costs [37].
- **Land use and material constraints**: Utility-scale solar farms require 3.5-10.1 hectares per MW installed capacity [38], competing with agricultural and ecological land uses. Terawatt-scale deployment would demand 630-2450 million metric tons of material resources by 2050, including critical metals like silver (190% of current reserves) and indium (460% of reserves) [39].

With global energy demand projected to grow 50% by 2050 [40], solar PV alone cannot scale sufficiently while maintaining grid reliability. **Nuclear energy** provides complementary advantages as a dispatchable, high-energy-density source:

- **Baseload capability**: Nuclear plants achieve 92.5 % capacity factors (vs. 24.9% for utility PV) with 18-24 month refueling cycles [41]. Advanced reactors can load-follow at 2.5
- **Technological advancements**: Small Modular Reactors (SMRs) reduce overnight costs to 3,000 kWe through modular construction [43]. Gen IV designs like sodium-cooled fast reactors achieve 100× fuel utilization via closed fuel cycles [44]. Fusion projects (e.g., ITER) aim for $Q \geq 10$ plasma confinement by 2035 [45].
- **Hybrid system optimization**: Combined nuclear-renewable energy systems (CNRES) demonstrate 36-44 % cost reductions through shared thermal storage and hydrogen cogeneration [60]. Neutron economy in MSRs enables direct integration with solar thermal storage [47].

A synergistic energy portfolio leveraging nuclear's firm capacity and solar's peaking potential represents the most viable path to deep decarbonization while meeting 24/7 industrial and residential loads [48].

5.1. Hydrogen as a Medium-Term Storage Solution

Excess solar energy can electrolyze water to produce hydrogen, which serves as a storable fuel for dispatchable power or industrial use. The round-trip efficiency of hydrogen storage systems (∼40–50%) remains lower than lithium-ion batteries (∼85–95%) but offers superior scalability for seasonal storage. Hybrid systems combining solar PV with hydrogen electrolyzers and fuel cells could reduce curtailment losses and decarbonize hard-to-electrify sectors like heavy transport and steel production [61,62].

5.2. A Smarter Strategy for Implementing Solar Energy

The global expansion of renewable energy is underway, with solar power growing at an unprecedented rate. However, the net benefit of each new megawatt of solar capacity is not uniform; its impact is critically dependent on the specific characteristics of the regional grid into which it is integrated. A simplistic, capacity-driven approach to solar deployment can lead to suboptimal outcomes, including increased grid instability, high curtailment rates, and a less effective reduction in overall emissions. A smarter, more strategic approach is therefore necessary to maximize the value of solar investments.

This strategy involves moving beyond traditional siting criteria (like solar irradiance alone) to a holistic analysis that prioritizes *grid value*. This can be achieved by leveraging artificial intelligence (AI) and data analytics to process high-resolution, time-dependent data for a given region. Key data inputs should include:

- **Hourly electricity generation** from all existing sources (e.g., coal, gas, nuclear, hydro, wind).
- **Hourly electricity demand** patterns.
- **Real-time marginal emissions factors** (the CO_2 emissions per MWh of electricity produced by the power plant that would be displaced by new solar generation).

By training AI models on this data, it becomes possible to identify locations and times where new solar generation will have the greatest positive impact. For instance, a model might reveal that adding solar capacity in a region heavily reliant on midday coal power would yield a significant reduction in emissions. Conversely, it might show that adding solar to a grid already saturated with solar power during peak sunlight hours would lead to high curtailment unless coupled with specific storage solutions or demand-side management.

The output of such an analysis allows policymakers and investors to answer critical questions:

- Where will new solar capacity most effectively displace fossil fuel generation?
- How does the value of solar change when coupled with specific storage durations?
- Which regions are nearing saturation points where further solar deployment without enabling technologies provides diminishing returns?

This AI-driven, value-based siting strategy ensures that solar power is deployed not just where it is *cheapest* to generate, but where it is *most valuable* to the grid. This leads to a more efficient energy transition, optimized infrastructure spending, and a greater emissions reduction per dollar invested. Ultimately, integrating these smart planning tools is essential for overcoming the challenges of intermittency and grid integration, ensuring that the rapid growth of solar power translates directly into a more reliable and decarbonized energy system.

6. Economic Analysis of Solar Energy Systems

As the world shifts toward decarbonization and renewable energy sources, understanding the economics of solar energy systems becomes increasingly critical. This analysis aims to evaluate the financial viability of solar photovoltaic (PV) systems compared to traditional energy sources like nuclear and wind, highlighting their role in shaping a sustainable energy future. By examining key metrics such as the Levelized Cost of Energy (LCOE), payback periods, and externalities, we can better assess the competitiveness of solar energy and its potential to meet global energy demands.

6.1. Levelized Cost of Energy (LCOE)

The Levelized Cost of Energy (LCOE) serves as a crucial metric for comparing the cost-effectiveness of different energy technologies over their lifetimes. For solar PV systems, the LCOE is calculated using the following formula:

$$\text{LCOE} = \frac{\sum_{t=0}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=0}^{n} \frac{E_t}{(1+r)^t}}, \tag{14}$$

where I_t represents capital expenditure, M_t operational costs, F_t fuel costs (which are zero for solar), E_t energy production, and r the discount rate [61].

Recent trends from 2020 to 2023 reveal significant reductions in the LCOE of solar PV systems, making them one of the most cost-competitive energy sources today:

- Utility-scale solar PV: $24-96/MWh [36]

- Nuclear: $141-221/MWh [36]
- Onshore wind: $24-75/MWh [61]

These figures underscore the rapid decline in solar costs, driven by advancements in technology and economies of scale. As countries strive to reduce greenhouse gas emissions, the affordability of solar energy makes it an attractive option for transitioning to a low-carbon economy.

6.2. Payback Periods

Another important consideration is the payback period, which measures how long it takes for an investment in solar energy to recover its initial costs. The energy payback time (EPBT) for silicon PV can be expressed as:

$$\text{EPBT} = \frac{E_{\text{input}}}{\eta P_{\text{annual}}}, \tag{15}$$

where E_{input} is the embodied energy (approximately 2500-3000 kWh/m^2 for poly-Si) and P_{annual} is the annual yield [19].

Financial payback periods vary depending on the region and system type:

- Residential systems: 6-12 years (U.S./EU) [26]
- Utility-scale: 3-8 years with tax incentives [36]

Shorter payback periods enhance the economic attractiveness of solar energy, encouraging wider adoption across residential, commercial, and utility sectors.

6.3. Comparative Cost Analysis

To provide a comprehensive comparison, Table 1 summarizes key cost and performance indicators for solar PV, nuclear, and wind energy in 2023.

Table 1. 2023 Energy Cost and Storage Comparison.

	Solar PV	Nuclear	Wind	H_2 Storage
LCOE ($/MWh)	24–96	141–221	24–75	—
Build time (yrs)	1–3	5–10	1–4	—
Capacity (%)	15–25	90+	25–50	—
Subsidy	High	Ext.	Mod.	Mod.
Cost ($/kg H_2)	—	—	—	2–6

[1]Hydrogen costs reflect electrolysis production only (excludes storage/transport).

Nuclear energy, despite its high capacity factor and reliability, faces significant barriers due to its exorbitant capital costs ($6,000-9,000/kW) and lengthy construction times. In contrast, the plummeting costs of solar modules—now ranging from $0.20 to $0.40 per watt-peak ($/W$_{\text{pk}}$) in 2023, compared to $30/W in 1980 [19]—highlight the dramatic improvements in affordability and scalability.

6.4. Externalities and Hidden Costs

While the upfront and operational costs of solar energy are declining, it is essential to account for externalities and hidden costs that may impact its overall economic feasibility:

- **Solar**: $3–12/MWh grid integration costs [36].
- **Nuclear**: $72–216/MWh waste management [26].
- **Curtailment losses**: 5–15% of solar generation in high-penetration grids [63].

Addressing these challenges requires innovative solutions. Hydrogen produced via solar-powered electrolysis can mitigate grid integration costs by absorbing excess daytime generation, reducing curtailment losses. It also enables *sector coupling*—converting surplus solar energy into hydrogen for industrial processes (e.g., steelmaking, ammonia synthesis) or long-term storage, thereby diversifying revenue streams and alleviating grid strain [61]. For instance, green hydrogen at $2–4/kg can decarbonize heavy industries while improving the economics of utility-scale solar farms [62].

Advancements in smart grid technologies and policy frameworks must prioritize such synergies to enhance solar's role in a resilient energy system. Africa, with its abundant sunlight and growing energy demands, presents a unique opportunity for the deployment of solar energy systems. Many regions across the continent experience high levels of solar irradiance, making them ideal candidates for solar power generation. According to recent estimates, solar PV could provide up to 40% of Africa's electricity needs by 2050 [61]. Furthermore, decentralized solar solutions, such as rooftop installations and mini-grids, offer a cost-effective way to electrify rural areas where grid extension is economically unfeasible or technically challenging.

However, several barriers must be addressed to fully realize this potential. These include limited access to financing, insufficient infrastructure for large-scale projects, and the need for skilled labor to install and maintain solar systems. Additionally, while the LCOE of solar energy has decreased globally, the costs in Africa can still be higher due to import tariffs, logistical challenges, and currency fluctuations. Despite these hurdles, initiatives like the African Renewable Energy Initiative (AREI) and partnerships with international organizations are working to overcome these obstacles, promoting solar energy as a key driver of economic development and energy access across the continent.

The economic analysis of solar energy systems underscores their increasing competitiveness compared to traditional energy sources. Driven by technological advancements and economies of scale, the levelized cost of energy (LCOE) for solar PV has fallen dramatically, positioning it as a viable and attractive option for global energy generation. While challenges such as intermittency, grid integration costs, and curtailment losses remain, they are being mitigated through innovations in energy storage and grid management. In comparison, nuclear energy, despite its high capacity factor, faces significant barriers due to its high capital costs and long construction times. Thus, solar energy systems, when integrated with complementary technologies, such as the hydrogen vector, offer a promising pathway toward a sustainable and resilient energy future.

7. Space-Based Solar Power and Wireless Energy Transmission

Space-based solar power (SBSP) proposes collecting solar energy in orbit and transmitting it to Earth using microwave or laser beams. The power collected from the Sun per unit area in space is given by:

$$S_0 = 1361\ \mathrm{W/m^2}, \tag{16}$$

where S_0 is the solar constant at the top of Earth's atmosphere.

For a solar panel array of area A_s and efficiency η_s, the collected power is:

$$P_s = \eta_s S_0 A_s. \tag{17}$$

Assuming a high-efficiency array ($\eta_s = 40\%$) with $A_s = 10^6\ \mathrm{m^2}$, we obtain:

$$P_s = 0.4 \times 1361 \times 10^6 = 544\ \mathrm{MW}. \tag{18}$$

The collected energy is then converted into a microwave or laser beam for transmission to Earth. The transmitted power is:

$$P_b = \eta_c P_s, \tag{19}$$

where η_c is the conversion efficiency (typically 60%). Thus, for $P_s = 544$ MW,

$$P_b = 0.6 \times 544 = 326.4\ \mathrm{MW}. \tag{20}$$

7.1. Beam Divergence and Power Density on Earth

The transmitted beam diverges due to diffraction, limiting power density on the ground. The beam divergence angle θ is given by:

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$$\theta \approx \frac{\lambda}{D_t}, \tag{21}$$

where λ is the transmission wavelength and D_t is the transmitter aperture diameter.
For a microwave beam with $\lambda = 0.1$ m (3 GHz) and $D_t = 100$ m:

$$\theta \approx \frac{0.1}{100} = 10^{-3} \text{ rad.} \tag{22}$$

At a typical geostationary altitude of $d = 36,000$ km, the beam spreads to:

$$D_b = 2d\theta = 2 \times 36,000,000 \times 10^{-3} = 72 \text{ km.} \tag{23}$$

The power density on Earth is given by:

$$S = \frac{P_b}{\pi(D_b/2)^2}. \tag{24}$$

Substituting $P_b = 326.4$ MW and $D_b = 72,000$ m:

$$S = \frac{326.4 \times 10^6}{\pi(36,000)^2} \approx 80 \text{ W/m}^2. \tag{25}$$

This is much lower than direct sunlight (1000 W/m^2).

7.2. Optimization Using Laser Transmission

Laser beams have lower divergence than microwaves. For a laser at $\lambda = 1\mu$m with $D_t = 10$ m:

$$\theta_{\text{laser}} = \frac{10^{-6}}{10} = 10^{-7} \text{ rad.} \tag{26}$$

For $d = 36,000$ km,

$$D_b = 2 \times 36,000,000 \times 10^{-7} = 7.2 \text{ km.} \tag{27}$$

This would result in a much higher power density on Earth, exceeding 1000 W/m^2, comparable to direct sunlight.

Space-based solar power presents a potential solution for large-scale renewable energy, but significant technological challenges remain. While microwave transmission is limited to around 80-400 W/m^2, laser-based power beaming could achieve over 1000 W/m^2. The feasibility of SBSP depends on advances in beam collimation, regulatory constraints, and cost-effective infrastructure deployment.

8. Application of Solar Energy in Africa

Africa presents a unique opportunity for solar energy deployment due to its high solar irradiance, vast land availability, and growing energy demands. Several key applications of solar energy in Africa include:

8.1. Rural Electrification

A significant portion of Africa's population lacks access to reliable electricity. Off-grid solar systems and mini-grids provide an affordable and sustainable solution to electrify remote villages, reducing dependence on diesel generators and biomass [22,23].

8.2. Agricultural Productivity

Solar-powered irrigation systems enable sustainable water pumping for agriculture, improving food security and reducing the vulnerability of farmers to climate change. Solar dryers also offer a method for preserving crops and reducing post-harvest losses [24,25].

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8.3. Industrial and Commercial Use

Businesses and industries are increasingly adopting solar energy to reduce operational costs and mitigate the impact of unreliable grid supply. Solar power solutions are particularly beneficial for mining operations, manufacturing plants, and commercial buildings [26,27].

8.4. Desalination and Water Purification

Solar desalination plants provide clean drinking water in arid and coastal regions, where freshwater scarcity is a major issue. These systems use photovoltaic or concentrated solar power (CSP) technologies to power desalination processes efficiently [28,61].

8.5. Challenges and Policy Recommendations

While solar energy adoption is growing in Africa, challenges such as high initial investment costs, lack of infrastructure, and policy barriers remain. Governments should implement policies that promote private sector investment, facilitate financing mechanisms, and develop skilled labor for solar energy deployment [30,31].

9. Future Prospects of Space-Based Solar Power (SBSP) for Planetary and Space Applications

While terrestrial solar energy remains constrained by atmospheric losses, intermittency, and land-use requirements, space-based solar power (SBSP) offers a unique opportunity to overcome these limitations by harvesting sunlight directly in orbit. The concept was first proposed by Glaser [64] and has since been revisited in multiple technical and policy studies [65,66]. At geostationary orbits, the available irradiance remains essentially constant at the solar constant $S_0 \approx 1361\ \mathrm{W/m^2}$, without atmospheric attenuation or diurnal cycles. In comparison, typical ground-level irradiance under clear skies ranges from 700 to 1100 $\mathrm{W/m^2}$, further reduced by seasonal and weather-related variability. Thus, the net collected power of a space solar array of area A_s and efficiency η_s is given by

$$P_{SBSP} = \eta_s S_0 A_s, \tag{28}$$

which may exceed terrestrial installations by a factor of 1.5–2 for identical collecting areas, while providing uninterrupted energy availability.

Recent technological advances strengthen the feasibility of SBSP. Lightweight, deployable solar arrays, such as NASA's Roll-Out Solar Array (ROSA) [67], demonstrate scalable architectures for high-efficiency orbital power stations. High-efficiency rectennas for microwave reception and ongoing experiments in laser power beaming (e.g., JAXA's SPS roadmap [68]) illustrate the potential of wireless energy transmission both to Earth and to extraterrestrial habitats. Beyond terrestrial supply, SBSP can provide continuous energy to lunar bases, Martian surface missions, or orbital stations, where reliable and compact energy solutions are critical.

Several challenges remain before SBSP becomes a practical solution. These include thermal management in orbit, beam collimation and safety for ground-based receivers, as well as the high costs of launch and in-space assembly. Nevertheless, hybrid systems integrating SBSP with terrestrial solar and nuclear baseload power may deliver both global decarbonization benefits and reliable energy for planetary exploration.

From a strategic perspective, the development of SBSP should not be seen as an alternative but rather as a complement to terrestrial renewables. Experience in beam control, modular space structures, and high-efficiency conversion systems may translate directly into terrestrial applications such as microgrids, hydrogen production, and seasonal storage. Thus, SBSP research represents a dual-use pathway, simultaneously addressing humanity's space exploration needs and contributing to the resilience of future energy systems on Earth.

10. Conclusion

The economic analysis of solar energy systems highlights their increasing competitiveness compared to traditional energy sources such as nuclear and wind. The continuous reduction in the levelized cost of energy (LCOE) for solar photovoltaic systems, driven by technological advancements and economies of scale, has positioned solar as a viable and attractive option for global energy generation. However, challenges such as intermittency, grid integration costs, and curtailment losses must be addressed to ensure a stable and reliable energy supply. While nuclear energy remains a strong contender for baseload power due to its high capacity factor, its high capital costs and lengthy construction times present significant barriers.

Solar cell technology, despite significant advances, remains limited by the fundamental constraint of solar irradiance reaching Earth. Efficiency limits imposed by material physics and practical engineering challenges further restrict harvestable energy. Future advancements in quantum dot photovoltaics, perovskite-silicon tandems, and novel nanostructured materials may push boundaries closer to theoretical limits, but achieving these goals requires overcoming significant scientific and engineering hurdles.Recent outcomes validate a novel design strategy for the templated growth of 3D perovskites using 2D perovskites and are likely to enable new physical properties and functionalities relevant to optoelectronic devices [69].

Critically, the decarbonized energy mix of the future will depend on synergies between complementary technologies. Hydrogen produced via solar-powered electrolysis offers a scalable solution to mitigate solar's intermittency, enabling long-term energy storage and sector coupling in industries such as heavy transport and steel manufacturing. When paired with nuclear energy's firm capacity and solar's peaking potential, hydrogen bridges the gap between variable renewables and dispatchable power, reducing reliance on fossil fuels during low-irradiance periods. For instance, hybrid systems combining solar farms with hydrogen electrolyzers and small modular reactors (SMRs) could achieve round-the-clock clean power while minimizing land-use conflicts [60,61].

In summary, a resilient low-carbon energy system demands not only improvements in solar efficiency but also strategic integration of nuclear baseload capacity and hydrogen-based energy storage. This tripartite approach—leveraging solar for affordability, nuclear for reliability, and hydrogen for flexibility—provides a robust framework to meet humanity's escalating energy demands while advancing global decarbonization goals.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Conflicts of Interest: The authors declare no conflicts of interest.

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