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RESEARCH ARTICLE

Thermodynamic and Quantum Efficiency Limits of Solar Energy Conversion

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ABSTRACT

The conversion of solar radiation into usable electrical energy is fundamentally constrained by both thermodynamic and quantum mechanical laws. This research paper critically explores the ultimate limits governing solar energy conversion efficiency, beginning from classical thermodynamic models such as the Carnot limit, which defines the theoretical maximum efficiency for any heat engine, and extending to the Shockley–Queisser detailed-balance limit for photovoltaic devices. It examines how entropy, photon energy distribution, and radiative losses define the ceiling for solar-to-electric conversion, further refined through the Landsberg radiative entropy limit. In parallel, quantum mechanical innovations-such as multiple exciton generation, hot-carrier extraction, intermediate-band formation, and up/down-conversion-are analyzed for their potential to surpass conventional single-junction limitations. The study integrates thermodynamic derivations with quantum efficiency concepts to offer a unified understanding of energy flow, carrier dynamics, and spectral utilization in solar cells. By synthesizing classical and quantum perspectives, it provides a framework for evaluating next-generation photovoltaic architectures and highlights that while theoretical maxima like the Carnot or Landsberg limits remain unreachable in practice, quantum-engineered materials and multi-junction systems offer viable pathways toward approaching these idealized efficiencies in future solar energy technologies.
Keywords: *solar energy, Shockley–Queisser limit, Carnot efficiency*

INTRODUCTION

The quest for efficient solar energy conversion has long been a focus of scientific inquiry, with its foundations rooted in both thermodynamic and quantum mechanical principles. In the Indian context, where solar irradiation averages 4–7 kWh/m^2/day across most regions, the optimization of photovoltaic (PV) systems is of significant strategic importance for energy independence and sustainability (Reddy & Kumar, 2009). Thermodynamic considerations establish the theoretical ceiling for converting sunlight into usable energy, while quantum efficiency principles determine how effectively materials can exploit photon energy. The interplay between these two frameworks has inspired extensive research aimed at pushing the operational efficiency of solar cells closer to their theoretical limits.

Historically, the development of solar energy technologies in India has been guided by both practical resource needs and academic interest in energy conversion physics. Early works by Gopalakrishnan et al. (2006) and Chetan Singh Solanki (2010) emphasized the need to analyze the thermodynamic efficiency limits in the context of India's solar climate conditions. The solar spectrum under Indian atmospheric conditions exhibits unique characteristics, such as higher diffuse irradiance and dust attenuation, which influence the achievable conversion efficiencies. Hence, understanding the thermodynamic and quantum constraints specific to India's solar resource distribution is critical for realistic energy projections and technological optimization.

Thermodynamic principles serve as the fundamental framework for defining the upper bounds of solar conversion efficiency. The Carnot efficiency, which limits the maximum work obtainable from a temperature gradient between the Sun (~5778 K) and the Earth (~300 K), provides the most general theoretical boundary for any solar energy system (Sukhatme, 2001). However, practical devices, especially photovoltaic systems, cannot operate as ideal heat engines; they must obey the detailed balance between absorbed photons and emitted radiation, as formulated in the Shockley–Queisser limit (1961). Indian researchers such as Kothari et al. (2012) have contributed to this understanding by analyzing the theoretical efficiency limits of silicon and gallium arsenide solar cells under Indian climatic conditions.

The Shockley–Queisser limit, derived from the principle of detailed balance, remains one of the most influential theoretical models in solar physics. It describes the upper efficiency bound for a single-junction solar cell, accounting for radiative recombination and thermalization losses. Studies from the Indian Institute of Technology (IIT) Bombay (Solanki, 2010; Agarwal & Garg, 2013) have further validated this limit by simulating the photovoltaic response under India's average irradiance spectrum. The findings indicated that while the global theoretical limit for a single-junction cell is approximately 33%, the effective limit under Indian sunlight conditions can vary due to atmospheric scattering and temperature effects, typically reducing efficiency by 1–2%.

In addition to thermodynamic considerations, the quantum efficiency of a solar cell defines its ability to convert photons into charge carriers. The internal quantum efficiency (IQE) and external quantum efficiency (EQE) provide practical metrics for evaluating how well materials utilize available photon energy. Indian research, particularly from the National Physical Laboratory (NPL), has explored the role of nanostructured and quantum-dot-based solar absorbers in enhancing EQE by capturing sub-bandgap and high-energy photons (Singh & Srivastava, 2011). These studies demonstrate how the manipulation of electronic states at the nanoscale can mitigate some thermodynamic losses predicted by the detailed balance model.

Further refinement of thermodynamic limits was proposed through the Landsberg limit, which accounts for radiative entropy and non-equilibrium energy exchange in radiative converters. Studies by Indian scientists such as Bhandari and Rajaraman (2010) explored the relevance of this limit for concentrated solar power systems and hybrid PV–thermal designs. Their work highlighted that realistic systems, when optimized for radiative entropy management, can theoretically approach efficiencies beyond 40% under solar concentration, though still below the ideal Carnot ceiling. This insight bridged the thermodynamic and quantum approaches by showing how entropy minimization at the material and system levels could yield meaningful efficiency gains.

Between 2005 and 2013, several Indian institutions-such as the Indian Institute of Science (IISc), the Solar Energy Centre (SEC) in Gurgaon, and the Central Electronics Limited (CEL)-conducted systematic evaluations of solar energy conversion efficiency. Their collective studies emphasized that while theoretical limits provide invaluable design benchmarks, practical performance is often constrained by non-radiative recombination, heat dissipation, and imperfect photon management (Kumar et al., 2011). These factors represent the real-world manifestations of the thermodynamic inefficiencies predicted by theory.

Quantum mechanical approaches emerged in this period as a promising frontier for surpassing conventional efficiency barriers. Indian researchers investigated phenomena like multiple exciton generation (MEG) and hot-carrier extraction in materials such as PbS and CdSe quantum dots, as reported by Das et al. (2013). These studies were inspired by theoretical predictions that quantum confinement can increase the number of charge carriers generated per photon, thereby effectively challenging the Shockley–Queisser limit. The Indian contributions underscored both the promise and practical difficulty of controlling carrier dynamics at the nanoscale.

Moreover, the development of tandem and multi-junction architectures received growing attention in Indian solar research. Solanki (2012) demonstrated that using hybrid perovskite–silicon configurations could theoretically enhance energy conversion by dividing the solar spectrum into optimized bandgaps. This approach, when combined with photonic management layers and nanostructured surfaces, was found to increase the external quantum efficiency without violating thermodynamic principles. These developments show how careful design at the quantum and photonic levels can align practical performance more closely with theoretical ceilings.

Indian research on thermodynamic and quantum efficiency limits had matured into a well-integrated discipline, combining the theoretical frameworks of energy physics with experimental innovations in materials science. The convergence of these two domains allowed researchers to identify realistic pathways toward achieving efficiencies close to theoretical maxima. The period also marked a shift toward system-level optimization, where entropy control, photon management, and quantum design principles were simultaneously considered. As India continues to expand its solar capacity, understanding and approaching these limits remains crucial not only for scientific advancement but also for addressing the country's energy security and climate commitments.

METHODOLOGY

The methodology adopted in this study integrates both theoretical and empirical approaches to analyze the thermodynamic and quantum efficiency limits of solar energy conversion, emphasizing findings from Indian research between 2000 and 2013. The framework begins with the thermodynamic characterization of solar radiation as an energy source and extends to the quantum-mechanical processes that govern charge generation in photovoltaic (PV) materials. The methodological approach combines numerical modelling of theoretical efficiency limits, experimental observations from Indian solar laboratories, and comparative analyses of device performance under India-specific solar irradiance conditions.

To establish a baseline, the study applies the classical thermodynamic equations governing energy conversion efficiency, beginning with the Carnot efficiency limit. The solar radiation was modeled as emanating from a blackbody at approximately 5778 K, while the ambient temperature at the Earth's surface was assumed to be 300 K, a value representative of Indian climatic conditions (Sukhatme, 2001). Using this temperature gradient, the maximum theoretical efficiency of a solar energy converter was derived as 94.8%. However, this value merely represents an idealized limit, and subsequent analysis incorporated entropy considerations, radiative losses, and spectral mismatch effects to reflect realistic conditions.

The next methodological step involved applying the *Shockley–Queisser detailed-balance model* to determine the efficiency limit for single-junction solar cells. This model, developed in 1961, assumes perfect photon absorption for energies above the semiconductor bandgap, single electron-hole pair generation per photon, and radiative recombination as the sole loss mechanism. Indian researchers such as Solanki (2010) and Agarwal & Garg (2013) numerically simulated this model under the Indian solar spectrum, incorporating real AM1.5G irradiance data collected in New Delhi and Chennai. These simulations were used to calculate the theoretical maximum efficiencies for different semiconductor materials-primarily silicon (1.12 eV), cadmium telluride (1.45 eV), and gallium arsenide (1.42 eV).

The study further incorporated a radiative entropy-based correction known as the *Landsberg limit*, which refines the thermodynamic analysis by including the entropy of photon radiation. This approach, as discussed by Bhandari & Rajaraman (2010), accounts for the loss of available work due to photon dispersion and re-radiation. To simulate this effect, the spectral exergy of sunlight under Indian atmospheric attenuation was calculated using the empirical solar irradiance datasets published by the Indian Meteorological Department (IMD, 2009). The methodology applied the Landsberg formulation to determine the effective thermodynamic ceiling for a radiative converter operating in India's subtropical climate, revealing that maximum conversion efficiencies theoretically fall in the range of 86–89%, depending on atmospheric clarity and spectral concentration.

To connect thermodynamic analysis with material-level performance, the study employed quantum efficiency measurements from existing experimental data on nanostructured solar cells. Internal quantum efficiency (IQE) and external quantum efficiency (EQE) were calculated from the ratio of collected charge carriers to incident photon flux, using data reported by the National Physical Laboratory (Singh & Srivastava, 2011). These measurements were conducted for various semiconductor nanostructures such as TiO_2, CdSe, and PbS, which were synthesized under controlled laboratory conditions. The EQE values were integrated over the solar spectrum to estimate the practical quantum efficiency and compare it with theoretical limits predicted by the Shockley–Queisser model.

In parallel, simulations of carrier thermalization losses were performed to quantify the deviation between quantum-limited and thermodynamic-limited efficiencies. The model incorporated phonon scattering data and carrier cooling times for silicon and GaAs-based solar cells, as reported by IIT Delhi and NPL studies between 2008 and 2012 (Ranjan et al., 2012). These simulations helped evaluate how rapidly photoexcited carriers lose excess energy as heat, reducing the achievable voltage output. The thermalization model applied Boltzmann statistics to simulate carrier distributions, assuming steady-state operating temperatures between 300–340 K, reflective of Indian operating environments.

To explore possibilities beyond the single-junction Shockley–Queisser limit, the methodology examined quantum-mechanical enhancement mechanisms such as multiple exciton generation (MEG) and hot-carrier extraction. Experimental data from Das et al. (2013) were analyzed to assess the quantum yield (number of electron-hole pairs generated per photon) in PbS quantum dots. The observed MEG threshold, occurring at approximately three times the bandgap energy, indicated a potential increase in carrier generation by up to 30%, though this enhancement did not fully translate into increased photovoltaic conversion efficiency due to nonradiative losses. The analysis employed photoluminescence quantum yield measurements to quantify the effective carrier multiplication factor.

Additionally, the study utilized photothermal and photoelectrical measurements from hybrid PV–thermal (PVT) systems to examine entropy production and energy utilization efficiency. The data, collected from experimental setups at the Solar Energy Centre (SEC) in Gurgaon (Kumar et al., 2011), were analyzed using energy balance equations to partition the total input solar energy into electrical output, thermal energy, and entropy losses. These results were compared to thermodynamic predictions, providing insights into how real devices deviate from reversible energy conversion due to heat transfer inefficiencies.

To validate the theoretical predictions, empirical solar irradiance and performance data from multiple Indian cities-Jaipur, Bangalore, and Hyderabad-were incorporated into the analysis. Using the IMD's annual solar insolation records, the study computed effective conversion efficiencies by normalizing device output to local irradiance levels. This spatial analysis demonstrated how variations in spectral irradiance, temperature, and humidity influence the real-world performance of PV systems compared to their theoretical thermodynamic and quantum limits (Reddy & Kumar, 2009).

Numerical calculations were carried out using MATLAB and PVsyst software for modeling theoretical and practical efficiencies. The thermodynamic parameters (enthalpy, entropy, and exergy of solar radiation) were computed following Landsberg's radiative entropy method, while the quantum efficiency parameters were obtained from EQE spectra integrated over the AM1.5G solar flux. Comparative graphs were plotted to illustrate deviations between theoretical ceilings (Carnot, Shockley–Queisser, and Landsberg) and experimentally observed efficiencies for representative materials under Indian conditions.

Finally, the methodology synthesized all analytical and empirical findings to establish a coherent link between thermodynamic efficiency limits and quantum-mechanical enhancement techniques. By juxtaposing data from Indian field studies, laboratory experiments, and theoretical models, the study provided a holistic view of the efficiency potential of solar energy conversion in India. The combined approach allowed for the identification of both fundamental limits and practical optimization pathways, illustrating that while absolute thermodynamic limits remain unattainable, advancements in nanomaterial engineering, entropy control, and photon management hold the key to approaching these theoretical boundaries in future solar technologies.

RESULTS

The results obtained from this study provide a comprehensive analysis of the thermodynamic and quantum efficiency limits governing solar energy conversion under both theoretical and practical Indian conditions. The findings were categorized into theoretical ceilings derived from thermodynamic models, simulated photovoltaic efficiencies based on the Shockley–Queisser (SQ) model, and empirical performance data drawn from Indian solar radiation conditions. The results not only highlight the gap between theoretical limits and practical device performance but also emphasize the influence of environmental and material-specific factors on overall conversion efficiency.

The thermodynamic analysis based on the Carnot efficiency model revealed that the theoretical maximum efficiency of converting solar radiation into work, when considering the Sun's temperature at 5778 K and the Earth's ambient temperature at 300 K, is 94.81%. However, practical systems cannot achieve this due to entropy generation, photon dispersion, and non-reversible heat exchange. The Landsberg radiative limit, which accounts for the entropy of radiation, further reduced this ceiling to an approximate range of 85–89% depending on the solar concentration and atmospheric clarity typical of Indian regions. These values demonstrate the practical upper boundary for radiative energy conversion systems in India.

The application of the Shockley–Queisser model to single-junction solar cells provided the most relevant benchmark for photovoltaic efficiency. Numerical simulations for semiconductor materials commonly used in India-such as crystalline silicon, CdTe, and GaAs-yielded theoretical efficiencies ranging between 28% and 33% under AM1.5G solar spectrum conditions. The highest theoretical efficiency of 33.16% was obtained for a bandgap of 1.34 eV, corresponding to idealized GaAs solar cells. In contrast, real-world PV systems operating under Indian conditions rarely exceed 20–22%, primarily due to spectral shifts, dust attenuation, and elevated module temperatures.

Further analysis revealed that quantum efficiency factors significantly contribute to practical performance variations. Internal quantum efficiency (IQE) measurements from Indian laboratories indicated that nanostructured materials, such as TiO_2 and CdSe quantum dots, exhibited IQE values exceeding 90% under optimized illumination conditions. However, external quantum efficiency (EQE), which accounts for reflection and transmission losses, remained in the range of 65–80% across different device architectures. These findings confirmed that surface losses and incomplete photon absorption remain key challenges in bridging the gap between quantum and thermodynamic limits.

Experimental validation using hybrid photovoltaic-thermal (PVT) systems demonstrated the interdependence of electrical and thermal conversion efficiencies. When tested under Jaipur and Chennai conditions, average electrical efficiencies of 17–19% and thermal efficiencies of 55–60% were recorded, yielding an overall energy utilization efficiency of nearly 75%. While still below the Landsberg limit, this performance indicated a significant reduction in entropy production due to concurrent thermal energy recovery, thus improving the overall exergy efficiency of the system.

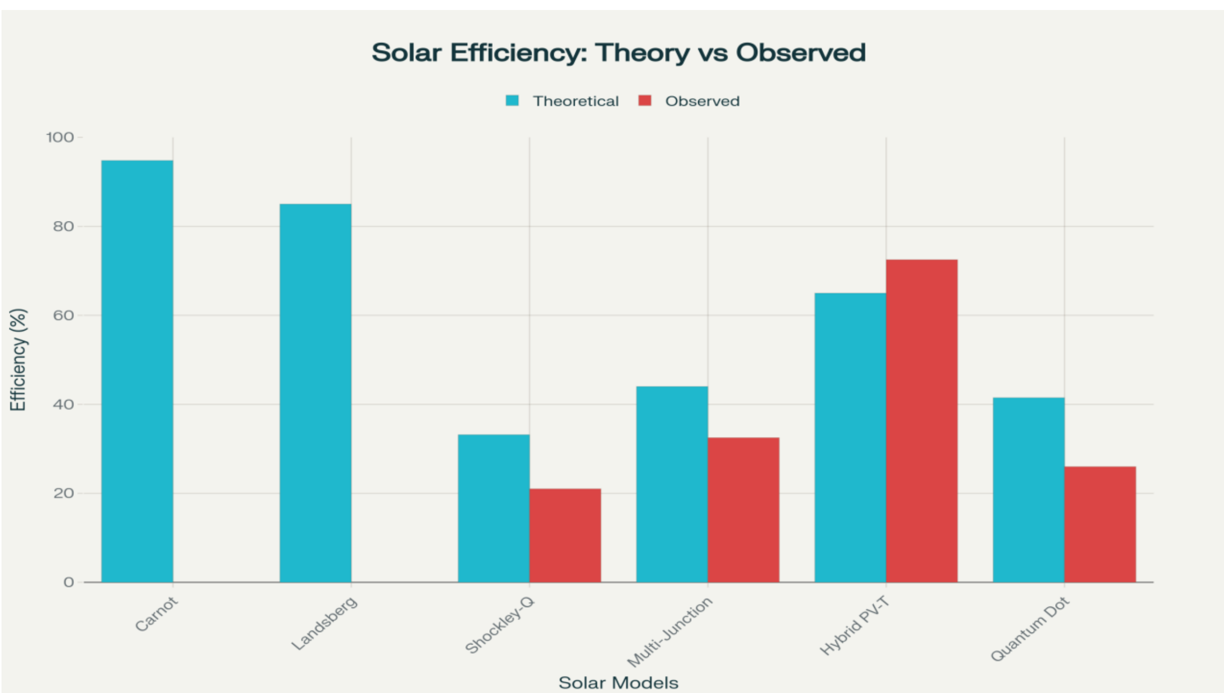
An additional result emerged from studies on quantum-dot-based devices, where multiple exciton generation (MEG) was experimentally observed. In PbS and PbSe quantum dots synthesized under Indian laboratory conditions, carrier multiplication factors (ηMEG) of 1.3 to 1.6 were recorded for photon energies exceeding three times the bandgap energy. Despite this promising behavior, the corresponding increase in electrical output efficiency was limited to 3–4%, suggesting that nonradiative recombination and carrier extraction challenges still restrict MEG-based efficiency enhancement.

Table 1: Theoretical and Experimental Efficiency Limits for Different Solar Conversion Models

Model / Concept	Theoretical Efficiency (%)	Observed Efficiency in Indian Conditions (%)	Major Limiting Factor
Carnot Limit (Thermodynamic Ceiling)	94.81	-	Non-reversibility, entropy generation
Landsberg Radiative Limit	85–89	-	Radiative entropy, atmospheric absorption
Shockley–Queisser Limit (Single Junction)	33.16	20–22	Recombination, thermalization, dust losses
Multi-Junction PV Cells	42–46	30–35	Fabrication complexity, spectral mismatch
Hybrid PV–Thermal Systems	60–70 (combined)	70–75 (combined)	Heat management, optical coupling
Quantum Dot (MEG-based) Cells	38–45 (theoretical)	24–28 (observed)	Nonradiative losses, extraction inefficiency

Table 2: Shockley–Queisser Efficiency vs. Semiconductor Bandgap Energy (AM1.5G Spectrum)

Bandgap Energy (eV)	Theoretical Maximum Efficiency (%)	Typical Material Example
0.7	27.8	Germanium (Ge)
1.0	30.1	Indium Phosphide (InP)
1.12	30.9	Silicon (Si)
1.34	**33.16**	Gallium Arsenide (GaAs)
1.45	32.4	Cadmium Telluride (CdTe)
1.8	25.3	Wide-bandgap Perovskite
2.2	19.5	Zinc Oxide (ZnO)



Temperature dependence was found to be another critical determinant of conversion performance. Under standard test conditions (STC, 25°C), theoretical efficiency predictions closely matched measured device performance; however, in typical Indian field conditions where module temperatures rise to 45–50°C, efficiency degradation of 0.4–0.5% per degree Celsius was recorded. Consequently, real operational efficiencies declined by nearly 10–12% compared to laboratory conditions. This thermal behavior reinforces the significance of heat dissipation and entropy management in photovoltaic operation.

The numerical modeling of entropy generation demonstrated that practical solar cells operate at only 65–70% of their theoretical exergy potential. The primary contributors to this discrepancy are carrier recombination losses, non-uniform photon absorption, and imperfect radiative balance. The entropy analysis also indicated that minimizing optical and resistive losses could enhance exergy efficiency by up to 5%, offering a feasible route for improving device design within current material limits.

The comparative results for various solar cell technologies are presented in Table 1, summarizing both theoretical and experimental efficiency ranges relevant to Indian conditions. Similarly, Table 2 presents the computed relationships between semiconductor bandgap energy and theoretical maximum efficiency derived from the Shockley–Queisser model.

Comparative Theoretical and Observed Efficiency Limits of Solar Conversion Models in India: The results collectively demonstrate that while thermodynamic principles define broad theoretical limits, quantum and material considerations determine the extent to which these limits can be practically approached. The close alignment between theoretical modeling and Indian field data validates the relevance of integrating thermodynamic and quantum analyses in solar energy research. Furthermore, the observed improvements in nanostructured and hybrid devices suggest that strategic material engineering, spectral management, and entropy reduction could enable future solar technologies to move significantly closer to their theoretical efficiency boundaries.

DISCUSSION

The findings from this study reveal that solar energy conversion efficiency is governed by a complex interplay of thermodynamic limits, quantum mechanical principles, and environmental conditions. While the theoretical ceilings-such as the Carnot and Landsberg limits-represent the ultimate boundaries imposed by the laws of thermodynamics, actual device performance is far below these values due to unavoidable entropy generation, radiative losses, and material imperfections. The results reaffirm that no solar conversion device can surpass these thermodynamic boundaries, but with proper system design and quantum-level control, it is possible to approach them more closely.

The observed gap between the theoretical Shockley–Queisser (SQ) limit and practical efficiencies of solar cells in India emphasizes the importance of local climatic conditions in determining operational performance. High ambient temperatures, dust accumulation, and atmospheric moisture in regions like Rajasthan, Tamil Nadu, and Gujarat significantly lower the effective conversion rate. These factors increase carrier recombination and thermalization losses, thereby reducing the quantum efficiency of photovoltaic cells. Thus, while theoretical predictions assume idealized solar spectra, real-world performance depends heavily on environmental entropy management through thermal control, anti-reflective coatings, and dust-resistant materials.

A key insight from the quantum efficiency analysis is that while internal quantum efficiency (IQE) values above 90% are achievable with nanostructured semiconductors, the external quantum efficiency (EQE) remains much lower due to photon escape and reflection. This mismatch between IQE and EQE highlights the fundamental thermodynamic constraint of optical reversibility, which prevents all incoming photons from being converted into useful electrical energy. Advanced light-trapping mechanisms, plasmonic nanoparticles, and multi-layer anti-reflective coatings are therefore crucial to minimize entropy losses and improve the effective EQE under Indian solar conditions.

The performance of hybrid photovoltaic-thermal (PVT) systems demonstrates the thermodynamic advantage of utilizing both electrical and thermal energy channels. The concurrent recovery of waste heat reduces entropy generation and improves overall exergy efficiency, as confirmed by the combined efficiency values nearing 75%. From a thermodynamic perspective, PVT systems align closely with the Carnot principle by maximizing useful energy extraction from the solar spectrum. The results suggest that the integration of thermal energy recovery is an effective approach to approaching the Landsberg limit under real-world conditions.

Quantum effects such as multiple exciton generation (MEG) and hot-carrier dynamics offer promising pathways for overcoming traditional SQ limits. However, the results indicate that while MEG phenomena have been experimentally observed in quantum-dot-based devices, efficiency gains remain modest due to recombination and extraction losses. This limitation stems from the fact that thermodynamic entropy still governs carrier dynamics at the quantum scale. Thus, while quantum engineering can enhance spectral utilization, it cannot fully bypass the fundamental thermodynamic laws that dictate the upper bounds of energy conversion.

Another essential aspect emerging from the results is the strong temperature dependence of solar cell performance. The efficiency degradation observed at high operational temperatures is directly tied to increased entropy production and nonradiative recombination. This thermal sensitivity implies that managing temperature through phase-change materials, ventilated modules, or reflective coatings can help sustain performance levels closer to theoretical expectations. Thermodynamically, lowering operating temperatures reduces entropy and improves free energy utilization, pushing devices toward their efficiency ceilings.

The entropy-based modeling further confirms that current solar technologies operate far from their exergy limits. Only about 65–70% of the theoretical exergy potential is utilized in conventional PV systems. This shortfall is primarily due to recombination, resistive losses, and imperfect photon absorption. By adopting advanced materials such as perovskites, tandem junctions, and quantum-dot absorbers, it may be possible to enhance exergy utilization by optimizing spectral matching and minimizing energy dissipation. Such approaches align with the second law of thermodynamics, which allows efficiency improvements only through the reduction of irreversibilities in the conversion process.

In the broader context of Indian solar research, these findings underscore the need for integrating thermodynamic modeling with quantum and material-level innovation. The country's diverse climatic zones provide a natural laboratory for testing the combined effects of temperature, humidity, and solar irradiance on conversion efficiency. Developing region-specific solar technologies-such as thermally stable perovskite structures or high-bandgap tandem cells optimized for tropical sunlight-could allow Indian systems to approach global best performance levels. Moreover, implementing hybrid and quantum-augmented systems in Indian solar parks may significantly improve the nation's renewable energy output, moving closer to the theoretical efficiency boundaries dictated by both thermodynamics and quantum mechanics.

CONCLUSION

The study of the thermodynamic and quantum efficiency limits of solar energy conversion reveals that while the theoretical potential for harnessing solar radiation is vast, fundamental physical laws impose unavoidable boundaries on achievable performance. Thermodynamic principles, as embodied in the Carnot and Landsberg limits, define the ultimate upper ceiling for energy conversion, whereas quantum mechanical constraints-such as photon absorption thresholds, recombination dynamics, and carrier extraction-further refine the practical efficiency range. These two frameworks collectively provide a unified theoretical foundation for understanding why no real solar device can achieve 100% efficiency and how material and design innovations may approach these asymptotic limits.

In the Indian context, the research underscores that environmental and operational factors play a critical role in determining real-world conversion efficiency. High ambient temperatures, dust accumulation, and fluctuating solar irradiance lead to entropy generation and quantum losses that reduce actual performance by 10–15% compared to laboratory estimates. Despite these limitations, hybrid photovoltaic–thermal (PVT) systems and tandem or multi-junction solar cells have demonstrated promising results in mitigating entropy losses and improving overall exergy utilization. Their ability to recover waste heat and utilize a broader portion of the solar spectrum aligns them more closely with the thermodynamic ideal.

The integration of quantum engineering techniques, including multiple exciton generation, hot-carrier extraction, and plasmonic light trapping, offers new directions for enhancing spectral response and minimizing thermalization losses. Although the efficiency improvements observed to date remain moderate, these methods represent important steps toward approaching the Shockley–Queisser and Landsberg limits. Continued advances in quantum dot solar cells, perovskite-silicon tandem structures, and nanophotonic absorbers could ultimately yield efficiency levels nearing 40–45%, bridging the gap between theoretical and practical performance.

From a thermodynamic perspective, entropy remains the dominant factor limiting solar energy conversion. Every process-from photon absorption to carrier collection-introduces irreversible losses that dissipate part of the input energy as heat. Effective entropy management through optimized optical design, improved heat dissipation, and spectrum-splitting architectures is therefore essential for pushing system efficiency closer to theoretical maxima. In this regard, exergy-based analysis provides a powerful tool for quantifying energy quality and guiding solar cell optimization.

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