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Spectral Splitting for Full-Spectrum Solar Utilization: From Efficiency Improvement to Spectral Intelligence

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Dear Editor,

Among various renewable resources, solar energy stands out for its vast availability, predictable diurnal cycle, and broad spectral coverage, offering extraordinary potential for sustainable power generation. Photovoltaic (PV) innovations are changing from focusing on device-level efficiency improvements to the next frontier lies in spectral intelligence — the ability to actively manage, distribute, and utilize photons according to their energy grade. Spectral splitting technology, which optically or materially separates sunlight into targeted wavelength bands, not only addresses the intrinsic limitations of single-junction solar cells but also enables hierarchical, multi-energy system integration. This paper provides a perspective on the scientific principles, technological routes, and systemic implications of spectral splitting, highlighting key challenges, overlooked opportunities, and its potential to redefine future renewable energy architectures.

INTRODUCTION

Solar energy, the most abundant energy source on Earth, has been harnessed since ancient times — from drying food and clothing to the designedly generation of electricity and heat with modern PV and solar thermal systems. This long-standing evolution reflects humankind's persistent exploration and innovation in solar utilization, underscoring its central role in the future global energy landscape.

Despite remarkable advances, conventional Si-based PV systems remain constrained by the Shockley–Queisser limit (~30%) due to spectral mismatch: high-energy photons undergo thermalization losses, while low-energy photons remain unabsorbed.[1] While studies emphasize incremental device-level improvements, many researchers posit that the next transformative step will be shifting from maximizing single-device efficiency to orchestrating energy flows across multiple spectral bands and energy forms. Spectral splitting offers this pathway, representing a conceptual leap from device optimization to system-level energy intelligence.

By optically decomposing sunlight into multiple wavelength bands and directing photons to the most suitable conversion modules — PV, photothermal, or photochemical — spectral intelligence enables hierarchical and cascaded energy utilization. Viewed from this standpoint, the concept represents not just a technical enhancement but a shift in how solar energy can be conceived, allocated, and functionally deployed. This perspective therefore examines spectral intelligence from its physical basis to its current technological pathways and system-level manifestations, and further outlines potential future directions shaped by this framework.

SPECTRAL SPLITTING FROM THE PERSPECTIVE OF ENERGY QUALITY

A central advantage of spectral splitting lies in its capacity for energy-quality matching. Solar radiation spans 280–2500 nm, encompassing ultraviolet, visible, and near-infrared light, with photon energies differing by over an order of magnitude. Conventional PV devices cannot simultaneously utilize both high- and low-energy photons efficiently, resulting in fundamental exergy losses.[2]

From an energy-science perspective, high-grade photons should be allocated to high-grade processes (electricity generation, photochemical reactions), while low-grade photons are better suited for heating or thermal storage. Spectral splitting achieves this stratification, directing short-wavelength photons to PV or photochemical modules, mid-band photons to photocatalysis or cooling, and long-wavelength infrared photons to heating or storage.[3]

Many current efforts focus on maximizing PV efficiency within a narrow band, while the spectral splitting argues that maximizing system exergy across the spectrum is a more consequential goal, potentially transforming solar energy from an electricity resource into a multi-energy hub.

TECHNOLOGICAL FRAMEWORK AND CURRENT STATUS OF SPECTRAL SPLITTING

Spectral splitting techniques aim to match the solar spectrum with potential energy conversion devices more effectively, enhancing overall efficiency by directing photons to the most suitable process.

Material-based approaches exploit the intrinsic absorption and emission properties of advanced materials. For instance, nanofluids containing plasmonic nanoparticles or bandgap-tuned perovskite thin films can selectively absorb visible light while transmitting near-infrared radiation, enabling simultaneous electricity generation and thermal harvesting. Quantum dots and down-conversion materials[4] further extend this concept by converting high-energy photons into lower-energy ones, reducing thermalization losses and improving photovoltaic stability.

Optical splitting approaches, in contrast, separate sunlight spatially through reflection, refraction, or diffraction. One-dimensional photonic crystals[5] and cold/hot mirrors provide precise wavelength-dependent routing, redirecting short-wavelength photons toward photovoltaic cells while guiding longer-wavelength light to thermal receivers. Advanced diffractive or holographic elements,[6] especially when combined with adaptive materials, offer dynamic spectrum control, allowing real-time optimization of energy distribution under varying solar conditions.

Hybrid approaches integrate both material and optical strategies to maximize spectral utilization. For example, volumetric PV/thermal (PV/T) receivers or semi-transparent perovskite–nanofluid devices[7] can simultaneously channel high-energy photons to PV cells and long-wavelength radiation to heat transfer media, achieving remarkably high combined

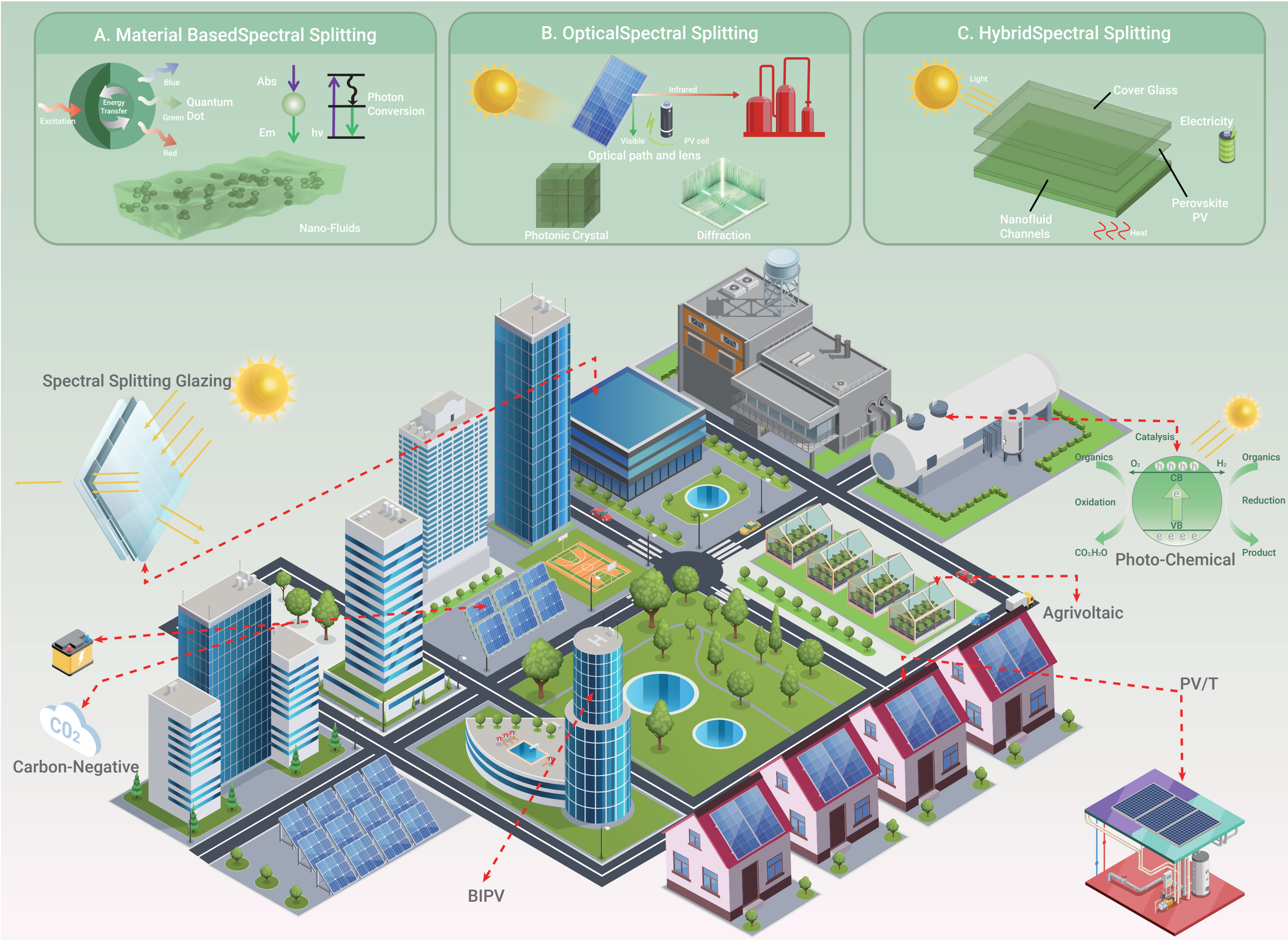

Figure 1. Technological Framework and Multi-Energy System Architecture Based on Spectral Splitting

electricity–heat efficiencies. By uniting the strengths of material selectivity and optical precision, hybrid spectral splitting reveals an achievable route toward full-spectrum solar energy harvesting.

At present, spectral splitting technologies have progressed from laboratory concepts to prototype validation, showing promising applications in building-integrated photovoltaics (BIPV), agrivoltaics systems, and solar-fuel production.

MULTI-ENERGY SYSTEM INTEGRATION BY SPECTRAL SPLITTING

Beyond merely enhancing solar utilization efficiency, spectral splitting offers a paradigm shift in how solar energy can be harnessed, enabling the orchestrated utilization of multiple energy forms and redefining the design of future solar energy systems. By strategically directing specific wavelengths to execute the most effective tasks, the spectral splitting systems unlock performance and functionality that low-carbon photovoltaic systems cannot achieve, laying the groundwork for multi-functional, high-efficiency, and even negative-carbon energy infrastructures.

(1) Redefining Photovoltaic–Thermal Systems:

Traditional photovoltaic systems face intrinsic limits due to spectral mismatch, but spectral splitting transforms this challenge into an opportunity. In PV/T systems, visible light can be directed to PV modules for electricity generation while near-infrared radiation is captured thermally, pushing total energy utilization beyond 80%. At higher concentration levels, concentrated PV/T systems can further exploit infrared photons to drive endothermic chemical reactions, such as methane dry reforming, enabling simultaneous production of electricity and solar fuels. This coordinated allocation of solar radiation highlights how spectral splitting moves beyond single-purpose energy conversion toward multi-output wavelength-specific strategies.

(2) Integrating Energy and Biology in Agrivoltaics:

Spectral splitting is also reshaping the interface between energy systems and biological productivity. By using selective-transmission films that transmit photosynthetically active light (400–700 nm) while redirecting the remaining spectrum to electricity or thermal management, agrivoltaics systems achieve a remarkable synergy: crop leaf area indices can rise by ~8%, energy consumption in greenhouses can drop by ~30%, and both yield a quality improve. Such examples suggest that spectral splitting is not merely a technical enhancement, but a design principle that balances ecological and energy objectives.[8]

(3) Optimizing Photochemical and Solar Fuel Production:

For photochemical and hydrogen-generation applications, wavelength-specific task allocation is critical. Shortwave photons are best suited for photocatalytic oxidation, mid-wave for photoelectrochemical hydrogen production, and longwave infrared for thermochemical reactions. Coordinated three-band systems demonstrate solar-to-hydrogen efficiencies of 28–30%,[9] emphasizing that spectral splitting allows precise alignment of photon energy with chemical task requirements—a principle that could redefine solar fuel production.

(4) Advancing Building-Integrated and Urban Energy Systems:

In urban contexts, spectral-splitting glazing and semi-transparent PV windows illustrate how architectural design can be directly informed by spectral management. These systems simultaneously provide natural daylighting and electricity generation, reducing lighting energy consumption by up to 42% and decreasing cooling loads. They can also achieve economic payback periods of about 2–6 years, highlighting the practical feasibility of such integrated building solutions.[10] This demonstrates that spectral splitting can guide the evolution of energy-conscious, human-centered building design.

(5) Enabling Carbon-Negative Pathways:

Finally, spectral splitting can synergize with biological carbon capture. Manipulating excess light to microalgae photobioreactors enhances photosynthetic CO_2 fixation and biomass production, creating an integrated route for electricity generation, carbon sequestration, and energy storage. Such coupling positions spectral splitting at the frontier of carbon-negative energy technologies, bridging the gap between renewable energy production and active carbon mitigation.

Spectral splitting is more than an efficiency improvement, which is a new design philosophy. By aligning the energy "quality" of photons with specific tasks across electricity, heat, chemical, and biological domains, it allows energy systems to operate with unprecedented efficiency and multifunctionality. The challenge moving forward lies in developing materials, optical architectures, and integrated systems that can fully exploit this potential. If successful, spectral splitting could catalyze a transformation in how solar energy being captured, converted, and utilized, from single-function PV panels to holistic, carbon-negative, and bio-integrated energy infrastructures.

DEVELOPMENT STRATEGIES AND FUTURE OUTLOOK FOR FULL-SPECTRUM SOLAR UTILIZATION

Successful advancement and widespread implementation of spectral splitting demand integrated efforts across technological, systemic, and policy domains. In light of this, the following recommendations are offered.

(1) Technological Strategies

Research should prioritize the development of high-stability, low-loss spectral materials, including phase-change oxides (e.g., VO_2), low-refractive-index metal–organic framework (MOF) films, and lead-free perovskites. In parallel, advancing quantum-dot up/down-conversion mechanisms is essential for dynamic spectral management and long-term environmental resilience.

(2) System-Level Integration

Future systems should seamlessly couple spectral splitting modules with energy storage, hydrogen production, and carbon capture technologies. Leveraging artificial intelligence and multiphysics modeling can enable real-time optimization of light–heat–electricity–chemical energy flows, ultimately creating a "spectral-energy hub" that intelligently coordinates multiple energy forms.

(3) Policy and Standardization

Spectral splitting technologies should be incorporated into green building and renewable energy standards, supported by new metrics such as "full-spectrum energy efficiency" (share of solar energy converted to useful electricity, heat, chemical, or biological energy, etc.) and "carbon-benefit index" (annual net CO_2 avoided per unit area or energy, accounting for embodied emissions). Integration with carbon trading mechanisms would not only incentivize adoption but also enhance investment returns and market competitiveness.

CONCLUSION

Spectral splitting transforms solar energy from single electricity generation to multi-energy synergy, bridging PV, photothermal, photochemical, and carbon-capture technologies. From an energy-science perspective, it embodies spectral intelligence, enabling dynamic orchestration of photons according to energy grade and system demand. The next revolution in solar energy will not be determined solely by device efficiency, but by the ability to intelligently orchestrate energy flows across multiple forms. By embracing spectral intelligence, researchers can move beyond incremental improvements toward holistic, system-oriented, low-carbon energy architectures.

REFERENCES

1. Lee Y.H. (2024). Beyond the Shockley–Queisser limit: Exploring new frontiers in solar energy harvest. *Science* **383**:eado4308. DOI:10.1126/science.ado4308
2. Lüer L., Müller A., Schmidt T., et al. (2024). Bypassing the single-junction limit with advanced photovoltaic architectures. *Adv. Mater.* **36**:2308578. DOI:10.1002/adma.202308578
3. Huang G., Curt S.R., Wang K., et al. (2020). Challenges and opportunities for nanomaterials in spectral splitting for high-performance hybrid solar photovoltaic–thermal applications: A review. *Nano Mater. Sci.* **2**:183−203. DOI:10.1016/j.nanoms.2020.03.008
4. Azam A., Khan M., Li X., et al. (2025). Quantum dots-enabled downshifting and downconversion strategies for enhanced photovoltaics. *ACS Nano* **19**:28969−28991. DOI:10.1021/acsnano.5c04988
5. Wei D., Zhang Y., Liu H., et al. (2021). Enhanced spectral splitting in a novel solar spectrum optical splitter based on one-dimensional photonic crystal heterostructure. *J. Materiomics* **7**:648−655. DOI:10.1016/j.jmat.2020.10.014
6. Hu Y., Li P., Yao Y., et al. (2025). Numerical analysis and performance investigation of holographic spectrum-splitting concentrated photovoltaic–thermoelectric hybrid system with phase change material. *Energy Convers. Manag.* **328**:119571. DOI:10.1016/j.enconman.2025.119571
7. Liang H., Zhao J., Chen X., et al. (2022). A novel spectral beam-splitting photovoltaic/thermal hybrid system based on semi-transparent solar cell with serrated groove structure for co-generation of electricity and high-grade thermal energy. *Energy Convers. Manag.* **252**:115049. DOI:10.1016/j.enconman.2021.115049
8. Lu S.M., Zhang Y., Wang L., et al. (2024). Wavelength-selective solar photovoltaic systems to enhance spectral sharing of sunlight in agrivoltaics. *Joule* **8**:2483−2522. DOI:10.1016/j.joule.2024.08.006
9. Jia J., Seitz L.C., Benck J.D., et al. (2016). Solar water splitting by photovoltaic–electrolysis with a solar-to-hydrogen efficiency over 30%. *Nat. Commun.* **7**:13237. DOI:10.1038/ncomms13237
10. Wheeler V.M., DeWolf S., Benson N., et al. (2022). Photovoltaic windows cut energy use and CO_2 emissions by 40% in highly glazed buildings. *One Earth* **5**:1271−1285. DOI:10.1016/j.oneear.2022.10.014

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DECLARATION OF INTERESTS

The authors declare no competing interests.