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Renewable Energy COMMENTARY

Leverage the solar photovoltaic potential of coastal aquaculture areas: Promote the regional clean energy transition

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Received: November 24, 2025; Accepted: January 12, 2026; https://doi.org/10.59717/j.xinn-energy.2026.100138

Citation: Xu N., Sun K., Ou Y., et al. (2026). Leverage the solar photovoltaic potential of coastal aquaculture areas: Promote the regional clean energy transition. *The Innovation Energy* **3**:100138.

Against the accelerating global energy transition, solar photovoltaic (PV) technology continues to expand as a critical renewable energy solution, yet large-scale ground-mounted installations face inherent conflicts with agricultural land use and ecological conservation.[1-3] Concurrently, coastal aquaculture has formed high-density industrial belts worldwide, including shallow-water ponds and intertidal zones in East and Southeast Asia, deep-water net-pen systems in Northern Europe, and tropical shrimp farms in Latin America, occupying vast underutilized aquatic spaces. This geographic distribution creates unique opportunities for aquavoltaics (PV-aquaculture synergy), where solar arrays can be deployed on pylons or floating platforms above aquaculture waters to achieve efficient spatial resource utilization.[4] The core advantages fundamentally resolve land-use competition while generating co-benefits: solar shading improves aquatic habitats, and clean electricity powers aquaculture equipment to reduce operational costs. Governments worldwide are advancing specialized policies to promote this model within blue economy and low-carbon agriculture frameworks. By activating the PV potential within global aquaculture zones, this integrated approach emerges as an innovative convergence strategy for balancing energy security, food production, and ecological sustainability.

The development of photovoltaic power in coastal aquaculture areas has significant geographical advantages: (1) Aquaculture areas are widely distributed and close to demand centers. The world's major aquaculture areas are mostly concentrated in densely populated and economically active coastal regions (such as the coasts of East Asia, Southeast Asia, Northern Europe, and North America etc.). This means that by deploying photovoltaic power in these areas, the electricity generated can be transmitted nearby to towns and industrial zones with high power demand, greatly shortening the transmission distance, reducing grid losses, and infrastructure construction costs. (2) There is huge potential for the development of photovoltaic space resources in coastal aquaculture areas. The water surface (or tidal flats) in coastal aquaculture areas is vast, and they often already have a certain foundation for road and power access. By making use of the space resources above it to install floating photovoltaic systems, ground-mounted photovoltaic systems can be installed on the embankment and management area of the pond, effectively achieving "dual use of one land (water)" without occupying additional precious land.[5] (3). There is a synergy effect. The "fishery and photovoltaic complementary" model has been proven to have potential synergy benefits. Moderate coverage of photovoltaic panels can provide shade for some aquatic products and improve the local microclimate. Photovoltaic projects can provide stable power for livestock farms and support the operation of equipment such as oxygenation and temperature control. Meanwhile, the project rent or dividends can increase the income of farmers raising livestock. The research results indicate a theoretical upper limit under conservative coverage assumptions, not the complete or unconditional utilization of aquaculture areas. Consequently, photovoltaic deployment should be a selective, context-dependent, and integrated endeavor, rather than a universal solution.

As shown in Figure 1, theoretical modeling indicates that global aquavoltaic deployment across coastal aquaculture zones, spanning 357.56 km2 of underutilized water surfaces, could generate approximately 10,607 GWh/year. This equates to 0.66% the global PV output in 2023. The default PV system coverage rate is 30% of the power generation potential. Geospatial analysis reveals Asia (85.3%) and the Americas (9.9%) as dominant contributors, led by China (6,209 GWh), Indonesia (791 GWh), and Vietnam (485 GWh), with high area-to-output efficiency in Chile, Peru, and Norway. Based on global per capita electricity consumption of 3,735 kWh per person per year, this theoretical capacity could supply electricity to 2.83 million people, representing nearly 0.4% of the estimated 775 million global individuals without electricity access in 2022 according to Guidebook for Improved Electricity Access Statistics (https://www.iea.org/, accessed in 2025). Concurrently, annual carbon reductions would reach 6.22 million tons, equivalent to removing 1.34 million gasoline vehicles, thereby accelerating national climate commitments. Examples include China's reduction of 3.61 million tons, covering 0.24% of its coastal industrial emissions per year, and Vietnam' s progress toward NDC targets. By integrating blue carbon enhancement with distributed renewables, aquavoltaics emerges as a nexus solution for SDG 7, by expanding electricity access for coastal populations; SDG 13, through climate mitigation; and SDG 14, by curbing marine eutrophication via PV shading. This approach aligns the UN Ocean Decade goals with just energy transitions.

Despite its significant potential and clear advantages, the practical implementation of this approach still encounters challenges. Aquaculture areas are usually located in remote or rural regions, and rural power grids may not be able to accept and utilize these photovoltaic power generation, which is the main constraint in practice. Excessively high coverage ratios of photovoltaic panels can reduce light penetration into the water body, thereby affecting the growth of primary producers such as algae and potentially triggering a chain reaction within the aquaculture ecosystem. The introduction of engineering structures like mounting brackets and floating platforms may alter water exchange and flow patterns locally, impacting water quality renewal. Furthermore, the construction and routine operation and maintenance of photovoltaic systems may cause periodic disturbances to both aquaculture activities and the aquatic environment. Under extreme weather conditions, such as typhoons and storm surges, the photovoltaic infrastructure also faces risks to its structural safety and operational stability. Given these uncertainties, this paper explicitly identifies these potential impacts as key foci for future research, requiring evaluation through field observations and long-term monitoring. Currently, quantitative evidence remains limited and must be substantiated through future systematic empirical studies. Subsequent research should combine field monitoring with controlled experiments to systematically assess changes in light availability, water temperature, water quality, primary productivity, and aquaculture yield under varying photovoltaic coverage ratios, installation designs, and aquaculture types. This will provide the empirical foundation needed to ensure the ecological safety and

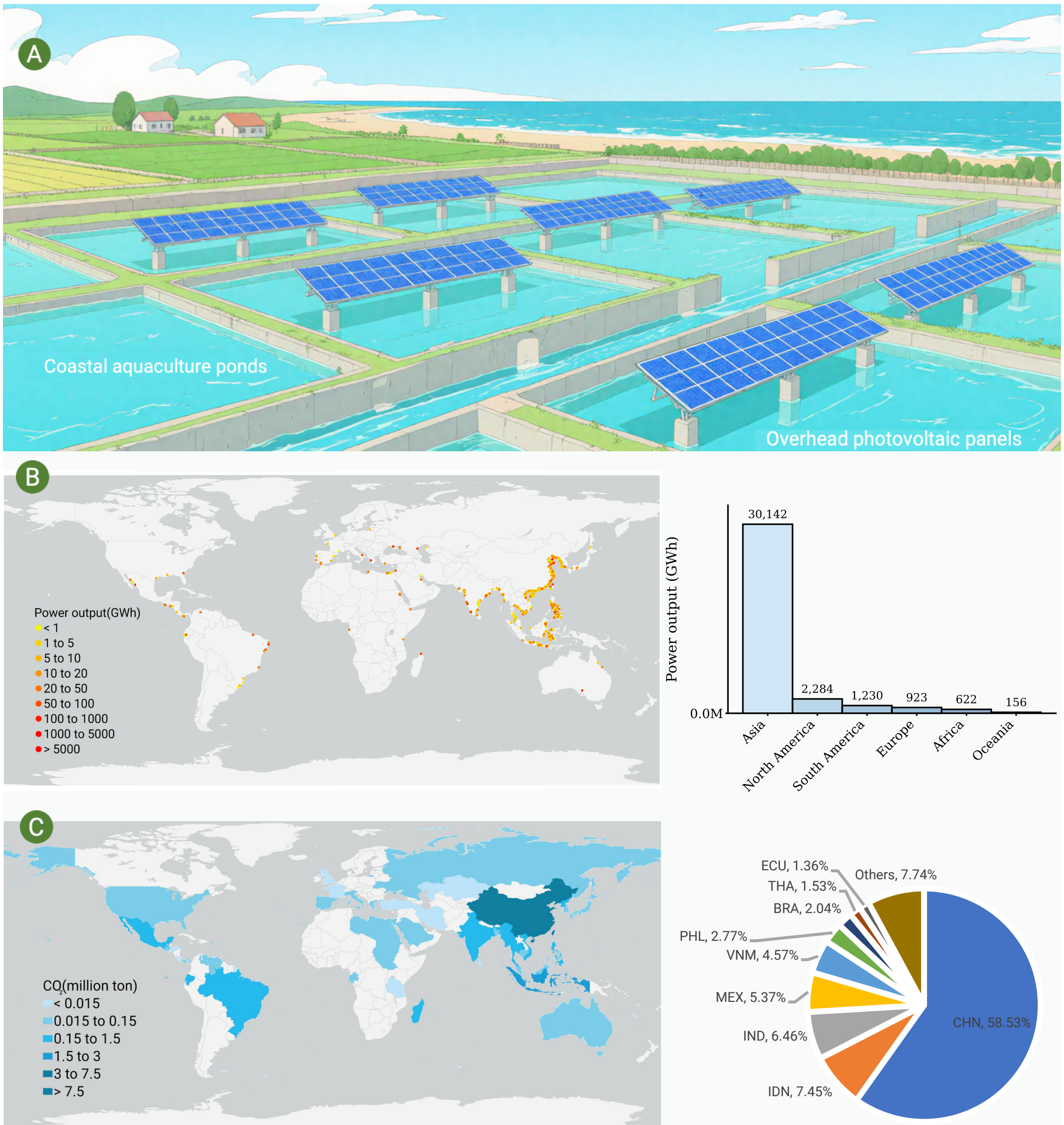

Figure 1. Solar photovoltaic potential in global coastal aquaculture zones (A) Conceptual framework illustrating the synergistic integration of photovoltaic (PV) systems within coastal aquaculture landscapes for transforming working waters into multi-functional sustainability nexuses. (B) Global potential for PV power generation across coastal aquaculture zones. (C) Estimated potential for global CO_2 emissions reduction through PV systems installation on coastal aquaculture zones.

guide the engineering optimization of the "photovoltaic + marine aquaculture" model.

The integration of photovoltaic systems with coastal aquaculture, a geographically strategic sector spanning densely populated regions, constitutes a transformative pathway to resolve land-energy conflicts inherent in clean energy transitions. This aquavoltaic symbiosis transcends mere coexistence, actively catalyzing coastal sustainability through three mutually reinforcing mechanisms: 1) Spatial Decoupling by repurposing underutilized aquatic domains such as aquaculture ponds and tidal flats, thereby alleviating terrestrial ecosystem pressures; 2) Metabolic Synergy where solar shading regulates aquatic habitats while onsite renewables slash operational energy burdens; and 3) Risk Diffusion via distributed infrastructure that buffers communities against energy-water-food nexus shocks.

Collectively, these attributes reconfigure coastal landscapes into integrated socio-ecological production systems. Their implementation crystallizes a paradigm shift from fragmented sectoral interventions toward regenerative stewardship, simultaneously fulfilling SDG 7 (Energy Access) through localized clean power and SDG 14 (Marine Conservation) via ecosystem-sensitive deployment. When scaled across global aquaculture corridors, this model establishes a replicable blueprint for planetary boundaries governance, where energy transition becomes an accelerator rather than competitor of ecological integrity.

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FUNDING AND ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China (42101343, 42571378), Scientific Foundation for Youth Scholars of Shenzhen University (868-000001033431), and European Commission Horizon 2020-Marie Skłodowska-Curie Actions Fellowship Programme (CECECDW-101204687).

DECLARATION OF INTERESTS

The authors declare no competing interests.