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COMMENTARY

Greenhouse-integrated solar photovoltaics for sustainable future energy landscapes

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Driven by the urgent need to decarbonize the global economy and combat climate change, the energy sector is rapidly transitioning from fossil fuels to renewables. Low-carbon energy production is central to this shift, with solar photovoltaics (PV) emerging as a particularly dominant force. The global expansion of solar PV is evident, with installations now in hundreds of countries, reaching a cumulative capacity of 1.6 terawatts by 2023 (IEA, 2023). Indeed, solar energy is expected to become the premier renewable power source by 2050.[1] This swift growth is mainly driven by its cost-effectiveness, broad accessibility, and flexible installation options.[2] However, as PV system deployment continues to grow, conflicts with land use have become more pronounced. The significant area required for PV installations can interfere with existing land uses, including agriculture,[3] and may adversely affect biodiversity and ecosystem integrity. Recent research by Kruitwagen[4] indicates that a considerable portion of global PV installations is situated on agricultural land, raising concerns about potential compromises between food production and energy generation. Several countries, including Italy, Bulgaria, and the Netherlands, have explicitly restricted the deployment of PV systems on agricultural land. The core rationale behind such international bans on agricultural land-based PV lies in prioritizing food security and ecological balance.

In recent years, the practice of greenhouse cultivation has witnessed notable growth. A recent study employed both commercial and open-access satellite imagery in conjunction with advanced artificial intelligence methods to conduct a global evaluation of greenhouse coverage. The research successfully mapped roughly 1.3 million hectares of greenhouse infrastructures in 2019, underscoring the significant and worldwide expansion of greenhouse agriculture.[5] Retrofitting existing greenhouses with PV systems could achieve dual-purpose land use, maximize solar energy utilization, and generate clean energy while maintaining agricultural output. Agrivoltaic greenhouses are emerging as mainstream pathways to resolve land-use conflicts through technological innovation and efficient land-use practices. Agrivoltaic greenhouses achieve efficient collaborative utilization of solar energy resources by integrating PV modules on rooftops or in specific areas of greenhouses, rather than installing solar panels over open fields like agricultural land. This configuration simultaneously generates electricity while preserving suitable space below for crop production. Through the "electricity generation above, crop cultivation below" model, agrivoltaic greenhouses integrate clean energy with modern agriculture (Figure 1A).

Agrivoltaic greenhouses offer multiple advantages. The agrivoltaic greenhouses occupy no additional land resources and preserve the original soil properties, significantly improving comprehensive land-use efficiency. In addition, the solar power generated can supplement energy needs for greenhouse equipment, substantially lowering operational costs. Simultaneously, surplus electricity fed into the grid can qualify for financial subsidies. Further, by selecting PV panels with adjustable light transmittance, growers can dynamically regulate interior light intensity and temperature to meet crop needs, effectively supporting off-season cultivation. Agrivoltaic greenhouses boost productivity, income, rural revitalization, and renewable energy, yielding broad economic, social, and environmental benefits. Consequently, a growing number of countries are initiating pilot projects to install PV systems on greenhouse infrastructures, recognizing their dual potential for agriculture and sustainable energy production. In 2013, Shouguang, Shandong, China built 17 agrivoltaic greenhouses (1 MW) that produce 1.5 million kWh annually, support year-round vegetable growth, and double farmers' incomes.

This study assesses the theoretical global electricity output from PV systems integrated into greenhouse structures and investigates their potential role in facilitating decarbonization. The publicly accessible dataset on global 3-m greenhouse cultivation is available for viewing at https://rs-cph.projects.earthengine.app/view/greenhouse and can be downloaded from https://zenodo.org/records/10907151. To assess solar productivity, we utilize the PVOUT map provided by the Global Solar Atlas, which quantifies the long-term power generation per unit of installed PV capacity (kWh kWp^{-1}). The PVOUT metric is then transformed into power produced per unit land area using a predetermined constant C, set to 1.6 ha MW^{-1} based on previous studies. By multiplying this per-area power output by the total available land area, the annual PV power generation is determined (see Equation 1). Finally, CO_2 mitigation is assessed by linking the estimated generation with the lifecycle carbon dioxide-equivalent (CO_2e) emissions per kWh for greenhouse PV systems, as reported by the Intergovernmental Panel on Climate Change (IPCC).

$$\text{PV power generation} = \frac{\text{PVOUT}}{\text{C}} \times \text{S}, \tag{1}$$

where $\frac{\text{PVOUT}}{\text{C}}$ is the power generated per unit of land area (GWh) and S is the land area (km^2).

The theoretical capacity of PV installations across global greenhouse infrastructure (13,091.40 km^2) is estimated at 1431,494.92 GWh $year^{-1}$, approaching 87% the global PV electricity output of 1,641,577 GWh recorded in 2023 (Figure 1B). Asia (61.86%) and the Americas (16.53%) collectively dominate this potential, with major greenhouse-intensive nations—China (673,920.85 GWh), the United States (91,374.70 GWh), and Espana (78,900.26 GWh) leading the contributions. Notably, smaller countries such as Morocco (33,899.45 GWh) and South Korea (23,577.72 GWh) also exhibit substantial potential. This theoretical generation capacity, equivalent to powering 383 million people at the global average consumption rate (3,735 kWh $person^{-1}$ $year^{-1}$), would cover approximately 50% of the global unelectrified population (775 million in 2022; BP Statistics Review, 2024: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/energy-outlook/bp energy-outlook-2024.pdf). Sub-Saharan Africa bears a disproportionate burden in global energy poverty, home to roughly 80% of the world's unelectrified population. Implementing PV systems on greenhouses in this region could produce an estimated 56,359.05 GWh $year^{-1}$ of electricity, sufficient for nearly 15 million people. This development would significantly accelerate worldwide electrification efforts, aligning with the World Bank and African Development Bank's "Mission 300" objective to connect 300 million Africans to power by 2030. Beyond expanding electricity access, agrivoltaic greenhouses at scale could mitigate approximately 67.64 ± 10.37 million tons of CO_2 yearly (Figure 1C), corresponding to roughly 28.73 ± 4.4 million tons of standard coal savings. Such emission reductions constitute a material contribution to global efforts constraining temperature rise to 1.5°C under the Paris framework. In addition, we calculate the potential reduction in CO_2 emissions in each country achieved following the deployment of agrivoltaic greenhouses. For example,

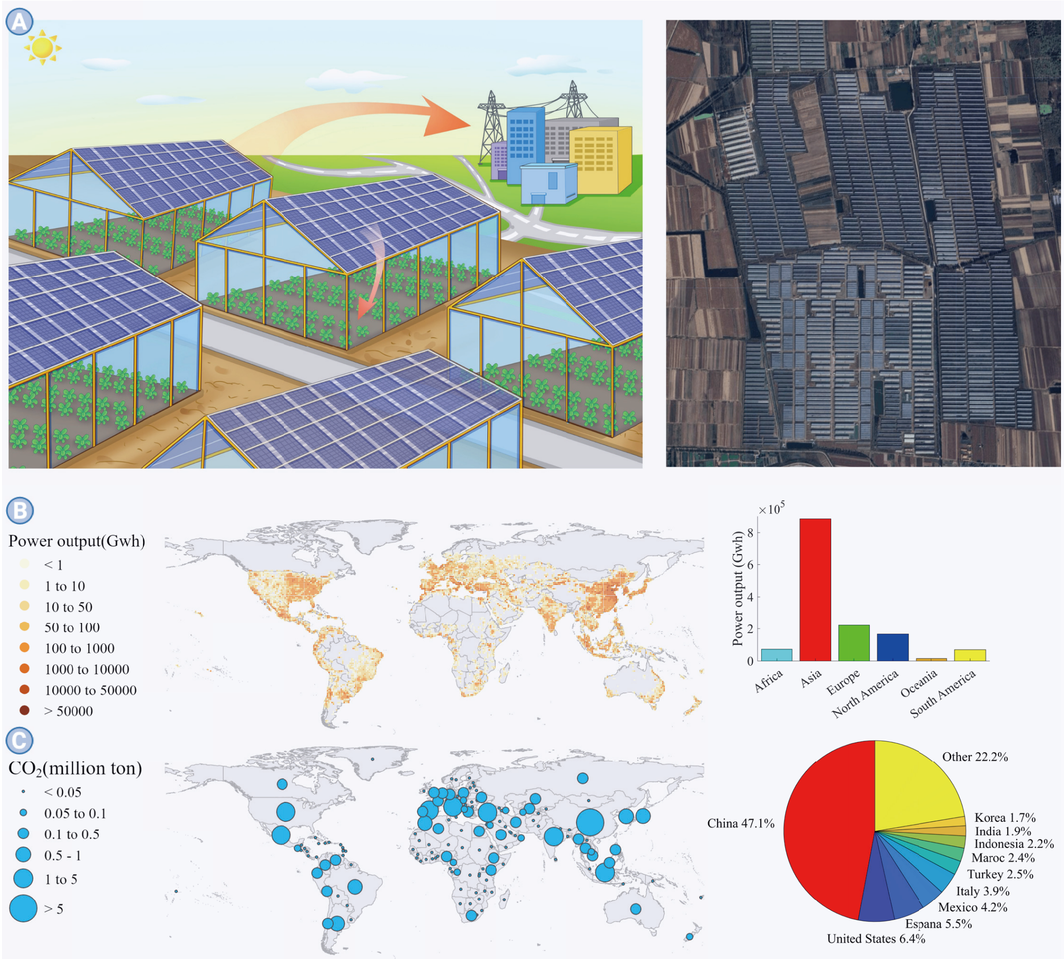

Figure 1. Potential for integrating PV systems on greenhouse infrastructures (A) Agrivoltaic greenhouse concept: PV electricity generation above, crop cultivation below. (B) Simulated total annual power output of agrivoltaic greenhouses. (C) Simulated annual CO_2 emission reduction of agrivoltaic greenhouses.

we estimate an annual decrease of 27.63 million tons of CO_2 in China and 3.75 million tons of CO_2 in the United States, two of the world's largest emitters. In addition, greenhouses-rich nations like Espana (decrease 3.23 million tons CO_2) Mexico (2.49 million tons CO_2) and Italy (2.27 million tons CO_2), could significantly reduce their carbon footprints through such initiatives, reinforcing national commitments to global climate goals.

Agrivoltaic greenhouses combine crop cultivation with electricity generation but face several challenges. First, integrating PV technology with farming is complex and requires careful component selection, system design, and environmental adaptation. Second, high initial costs create financial strain, particularly for small-scale farmers, despite promising long-term returns. Third, insufficient and inconsistent policy support further dampens investor confidence. Fourth, PV components installed inside the greenhouse may affect crop growth as different crops have varying light requirements. Therefore, the light transmittance of agrivoltaic greenhouses should be appropriately configured based on the growth characteristics of specific crops.

The construction of agrivoltaic greenhouses not only enhances agricultural production efficiency but also provides farmers with significant economic benefits. Despite facing numerous challenges during construction, these issues can be effectively addressed by introducing specialized technologies to enhance quality and efficiency, implementing phased investments to overcome funding barriers, and securing policy support to mitigate risks. This paves the way for integrating agriculture with photovoltaics. As technology continues to advance and policies gradually improve, agrivoltaic greenhouses are poised to play an increasingly vital role in future agricultural production.

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DECLARATION OF INTERESTS

The authors declare no competing interests.