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# AGRIVOLTAICS

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## A STAP background note

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STAP SCIENTIFIC AND TECHNICAL ADVISORY PANEL
*An independent group of scientists that advises the Global Environment Facility*

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## Executive summary

Agrivoltaics (AV)[1] is the simultaneous use of the same land for solar photovoltaic (PV) power generation and agricultural activities. It can provide an innovative and effective solution for addressing issues of land competition between food and energy. AV systems have been used for crop production and combined with livestock grazing, ecosystem protection, habitat restoration, and aquaculture. The deployment of AV solutions has grown significantly in recent years, from 5 megawatts of peak energy[2] in 2012 to 14 gigawatts in 2021. Countries currently leading in AV systems implementation include Japan, China, South Korea, Germany, Italy, and France, with the United States and India showing increasing interest in the technology.

Studies have identified potential benefits of AV systems application, including efficient renewable energy production with reduced greenhouse gas emissions and enhanced food production and land-use efficiency. AV systems can also help strengthen water use efficiency, prevent pollution, restore degraded lands, conserve terrestrial biodiversity and support adaptation and resilience to climate change. Furthermore, AV can diversify livelihood opportunities and revenue streams and contribute to other sustainable development objectives, such as poverty alleviation; food, water, and energy security; good health and well-being; decent work; economic growth; industrial and infrastructure development; and sustainable cities.

AV systems can provide good outcomes in regions with high sunlight levels, but possible tradeoffs should be considered. For example, these systems may need to prioritize either agricultural production (agriculture-centric) or solar energy output (solar-centric) since the same piece of land is used for the two activities. Also, some crops do better under AV systems than others. Studies indicate that crops already requiring protection against high temperatures (e.g. grapes, berries, vegetables, root crops, and nut-producing trees and shrubs) are good candidates for AV application, while those requiring high levels of sunlight (e.g. wheat, corn, rice, tomatoes, and peppers) have shown mixed results (i.e. lower, equal or higher yield), depending on growing season time and local climate. Additionally, AV systems could negatively impact soil quality if design and installation are not well-implemented. These findings highlight the importance of designing AV systems that first consider synergies and tradeoffs and then provide evidence for implementation approaches that can maximize benefits and minimize possible adverse impacts.

While AV systems present a clear opportunity to achieve environmental and socioeconomic objectives, their adoption and scaling face barriers. The primary barrier is the high initial investment cost, which is usually beyond the reach of local farmers. Due to increased costs associated with unique installation requirements and higher permitting, labor, and site investigation costs, AV systems are generally more expensive to construct than conventional ground-mounted solar PV systems. Cost increases can range from 4%–115%, depending on the type of agricultural activities and the AV system's structural configuration. Other barriers hindering adoption and scaling include a lack of technical capacity; economic and structural factors, such as the dominance of smallholder agriculture in the Global South, which makes obtaining loans difficult; a lack of supportive policies and regulations; and sociocultural factors, such as industry and societal apprehension due to inadequate awareness and concerns about compatibility with current practices.

Mapping AV systems benefits against the Global Environment Facility (GEF) and the Global Biodiversity Framework Fund (GBFF) focal area objectives shows that AV could help deliver global environmental benefits (GEBs) in biodiversity conservation, climate change mitigation, land degradation and international waters. AV could also contribute to achieving the objectives of the adaptation funds (Least Developed Countries Fund

[1] Several terms are used for agrivoltaics, including agrophotovoltaics (APV), agriphotovoltaics, agrovoltaics, agrisolar, or dual-use solar. Agrivoltaics (AV) is used throughout this paper.

[2] The size of a PV solar system is measured in wattage of energy produced, usually kilowatt peak (kWp–W x 1,000), megawatt peak (MWp–KWp x 1000), or gigawatt peak (KWp x 1,000,000), which represents the amount of power produced under standard laboratory test conditions and broadly equated to what will be produced under bright sunshine.

and Special Climate Change Fund). However, AV systems need to be implemented using a circular economy approach to avoid possible chemical pollution that could be associated with end-of-life PV panel disposal.

Adoption and scaling of AV systems, especially in the Global South, requires the following enablers:

- Adopting an integrated approach across relevant government ministries (e.g. agriculture, energy, water and finance); coordinating across multiple levels of government (e.g. national, state/province and local); and bringing together actors and stakeholders within the relevant sectors to address concerns and proffer synergistic solutions that address challenges and opportunities within the food, water and energy nexus.
- Developing supportive policies and creating a conducive regulatory environment, such as tax incentives and subsidies, risk and credit guarantees, land-use law clarification, fair energy pricing, feed-in tariffs, and quality standards and guidance.
- Implementing capacity-building initiatives to develop the necessary technical and management skills of conventional farmers.
- Developing business and financing models to address the high initial cost of AV systems and other economic and structural challenges hindering the adoption and scaling of AV systems.

Given the potential of AV systems to deliver GEBs and the need to overcome existing adoption barriers and challenges, the GEF could consider supporting countries in understanding the technological appropriateness for their specific context and helping them put in place the needed enablers for adoption and scaling. This support could be through investment in demonstration projects and fostering partnership and multistakeholder dialogue to promote technical assistance and capacity building, especially with countries leading in AV system implementation.

## 1.0. Background

Mitigating climate change, sustainably meeting global energy demands and achieving sustainable development goals (SDGs) require decoupling current production systems from fossil fuels by rapidly advancing renewable energy and improving energy use efficiency. All pathways to achieving the goals of the Paris Climate Agreement require significantly reducing dependence on fossil fuels and transitioning to renewable energy sources.[3]

However, selecting appropriate renewable energy solutions requires considering factors such as cost[4] and impacts on other socioeconomic and environmental objectives. For example, biomass energy options (e.g. wood and charcoal), utilized mainly in the Global South, can threaten natural forests, contribute to air pollution and negatively impact human health. Similarly, modern bioenergy applications (e.g. biomass and biogas for heating and power generation and liquid biofuels for transport) are laden with concerns about competition for land for food production versus crops for bioenergy.[5]

Solar photovoltaic (PV) is the least costly available renewable energy solution for electricity generation, and its adoption has increased significantly, according to the International Energy Agency.[6] Installed power capacity increased from less than 1% global share in 2010 to close to 15% in 2023 and is projected to increase to more than 22% by 2027.[7] However, with its rapid adoption due to increasing awareness, technological advancement, and cost reduction, concerns exist about land use competition with consequent economic and social conflicts, especially in areas with constraints on high-value agricultural land.[8]

Converting agricultural lands to solar farms with ground-mounted PV panels could threaten food security, underlining the challenge of addressing the interlinkages between energy and food production. Also, converting forest lands to solar farms can contribute to biodiversity loss by destroying native habitats. However, decoupling solar PV deployment from demand for limited land resources is possible through innovative win-win land sharing between solar PV systems and agricultural activities with an approach called agrivoltaics (AV).[9]

## 2.0. What is agrivoltaics?

Agrivoltaics is the combining of solar PV systems with agricultural production by using the same area of land for producing solar energy and agricultural products, thereby creating synergies between renewable energy and agricultural objectives.[10] It provides an effective, efficient, and innovative solution for addressing land competition while providing other environmental benefits and contributing to achieving other sustainability goals (see Figure 1).[11]

AV systems are similar to mixed agriculture systems, such as agroforestry (integrating crops and trees) and silvopastoral systems (integrating tree and livestock grazing). The primary difference being that AV substitutes trees with PV panels. AV systems can be compatible with regenerative agricultural practices, such as low- or zero-tillage farming in which PV installation restricts soil tillage and thereby minimizes soil disturbance, and conservation buffers in which the installed PVs can serve as buffers for windbreaks or habitats for beneficial biodiversity (i.e. native plants and organisms).[12]

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[3] Rogelj et al., 2018; IRENA. 2022a.
[4] For example, expanding the national grid is a potential solution to the energy supply challenges prevalent in the Global South, but the prohibitive cost is a challenge, and most grids are based on fossil fuel energy sources.
[5] IRENA 2022b.
[6] IEA 2022
[7] IEA. 2023.
[8] Schindele et al. 2020; Willockx et al. 2020; Amaducci et al. 2018; Nonhebel, 2005
[9] Walston et al. 2022; Jain et al. 2021.
[10] See DOE. 2022; Jain et al. 2021. See also https://agrovoltaic.org/; https://www.iberdrola.com/innovation/agrovoltaics
[11] See: Dreves 2022. See also https://agrovoltaic.org/; https://www.iberdrola.com/innovation/agrovoltaics
[12] OYA Renewables 2023; ATTRA. 2022

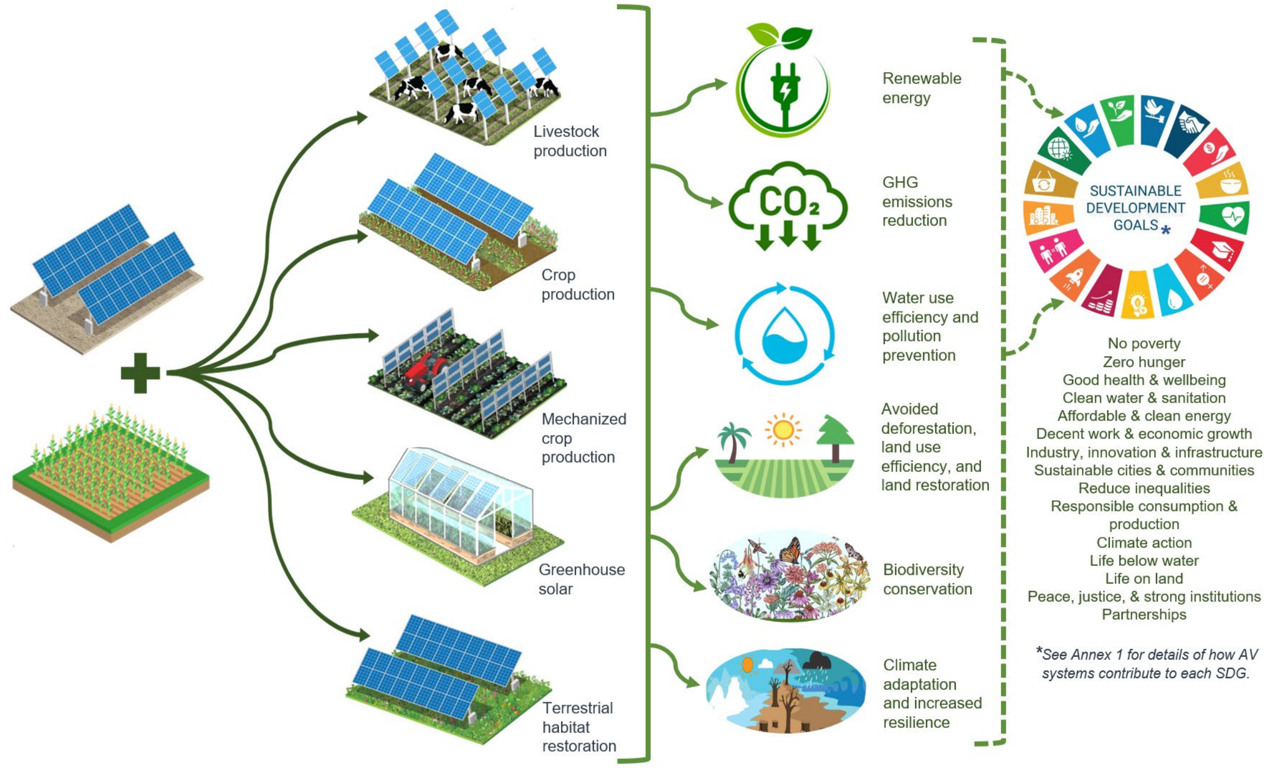


***Figure 1: Applications and benefits of AV systems.*** *Solar panels can be incorporated into agricultural systems and integrated with livestock and crop production. They can be used for grazing, livestock shelter, greenhouse roofs and terrestrial habitat restoration (left). Results can include additional renewable energy production, reduced greenhouse gas emissions, better water and land use efficiency, deforestation avoidance, biodiversity conservation, degraded land restoration, and climate change adaptation and resilience benefits (center). These applications and benefits all contribute to achieving the sustainable development goals (SDGs) discussed in section 3.0 (right).*

AV systems have different applications, including crop production, livestock shelter and grazing, ecosystem protection, and habitat restoration (see figure 1). They can be augmented with water-capturing mechanisms to meet freshwater and irrigation needs,[13] used in aquaculture,[14] and designed to either prioritize agricultural production (agriculture-centric) and solar output (solar-centric) or equally prioritize agricultural and solar production (co-location design).[15]

The AV approach has been explored under diverse climatic conditions and usually results in a win-win solution in regions with high solar irradiance.[16][17] However, prioritization (i.e. agriculture or solar-centric) could result in tradeoffs between crop production and energy generation, and some crops do better under AV systems than others (see section 5.1 for further discussion on technical considerations).

The deployment of AV solutions has grown significantly in recent years, with installed capacity increasing from 5 megawatts of peak energy[18] in 2012 to 14 gigawatts (GWp) in 2021.[19] The global AV market was valued at almost $4 billion USD in 2022 and is expected to exceed $11 billion USD by 2032.[20] First-mover

[13] Kolbeck-Urlacher, 2023; Walston et al. 2022
[14] Imani et al. 2023; NREL 2023; Pringle et al. 2017
[15] Brunswick and Marzillier. 2023.
[16] Solar irradiance is "the amount of solar energy that arrives at a specific area of a surface during a specific time interval. A typical unit is W/m$^2$." - https://www.nrel.gov/grid/solar-resource/solar-glossary.html#irradiance
[17] Adeh et al. 2019.
[18] The size of a PV solar system is measured in wattage of energy produced, usually kilowatt peak (kWp), which represents the amount of power produced under standard laboratory test conditions and broadly equates to bright sunshine.
[19] Gorjian et al. 2022; Fraunhofer ISE. 2022
[20] Precedence Research. 2022

countries implementing AV systems include Japan, China, South Korea, Germany, Italy and France.[21] The United States and India have shown increasing interest in AV technology.[22] While Japan has the largest number of AV farms in the world (>3,000 mostly small-scale systems),[23] China has the largest share of installed global capacity (12 GW peak energy as of 2021).[24] The largest AV system worldwide is located around the Gobi Desert, China and harness desert land for agricultural production. The site is used to farm goji berries while generating up to 1 GW of electricity annually.[25]

## 3.0. Benefits of AV systems

The literature highlights numerous benefits of AV systems implementation. This section summarizes the following eight benefits (see figure 1): (1) renewable energy production and efficiencies; (2) greenhouse gas emissions reduction; (3) food production, land-use efficiency and land restoration; (4) water-use efficiency and pollution prevention; (5) biodiversity conservation and habitat restoration; (6) climate change adaptation and increased resilience; (7) economic benefits and (8) other sustainable development benefits.

**Renewable energy production and efficiencies**. AV systems provide renewable energy solutions to meet on-farm, rural and other energy needs. Furthermore, because solar panel efficiency is influenced by the microclimate (e.g. air temperature, wind speed and relative humidity) of the system in which it is immersed,[26] AV systems can enhance the efficiency of solar PV systems. PV efficiencies decrease by 0.6% with a 1°C temperature increase at temperatures above 25°C.[27] Crops grown under a solar structure in an AV system help reduce the ambient air temperature by creating a cooler microclimate (reducing temperature by 1-2°C) through evapotranspiration.[28,29] A study found that the cooling effect due to evapotranspiration enhanced the efficiency of PV energy production by 10%.[30]

**Greenhouse gas emissions reduction**. AV systems provide renewable energy, avoiding fossil fuels and associated carbon emissions. A study mapping the potential for solar power production across different land cover types noted that deploying AV systems on just 1% of the ~1.6 billion hectares (ha)[31] of global arable lands could offset all the world's energy demand,[32] with consequent greenhouse gas emission reduction (although energy storage solutions will be required to ensure constant energy availability from PV systems). Also, decoupling the deployment of solar PVs and land clearance helps conserve carbon stocks. Furthermore, plants grown in AV systems have been shown to accumulate higher biomass than conventional agricultural systems, including in arid conditions,[33] with consequent increased soil carbon and sequestration benefits.

**Food production, land-use efficiency and land restoration**. AV systems provide an efficient way of producing food with limited resources. Research shows that AV systems could drive land use efficiency up to around 180%.[34] PV systems help create a microclimate that enhances crop yield,[35] although excessive shading can reduce the productivity of shade-intolerant crops.[36] A study indicated that AV systems achieved a land equivalent ratio of 1.7, meaning 1 ha of farmland under AV systems produced as much food and electricity

[21] IISD. 2023a; DOE. 2022.
[22] DiGangi 2023; IGEF-SO. 2023; DOE. 2022.
[23] Fraunhofer ISE. 2022. See also https://agrivoltaicatlas.com/asia.html
[24] Fraunhofer ISE. 2022
[25] Schoeck, 2023; Fraunhofer ISE. 2022; Williams 2022; Bellini, 2020. See also: https://www.chinadaily.com.cn/a/202211/26/WS6382140ca31057c47eba13e7.html;
[26] Adeh et al. 2019.
[27] Barron-Gafford et al. 2019.
[28] Evapotranspiration is the process through which water moves from the soil through a plant and is evaporated to the atmosphere from aerial parts, such as leaves, stems and flowers. Increased plant transpiration rate usually leads to increased water use.
[29] Waghmare *et al.* 2023; Williams et al., 2023; Patel et al. 2019; Sekiyama et al. 2019; Othman et al. 2017
[30] See: https://agsci.oregonstate.edu/newsroom/sustainable-farm-agrivoltaic; https://engineering.oregonstate.edu/all-stories/crops-and-killowatts-agrivoltaics-project-will-harvest-solar-energy-farmland
[31] Value of total arable land from Our World in Data. https://ourworldindata.org/land-use
[32] Adeh et al. 2019
[33] Jamil and Pearce. 2023; Adeh et al., 2018.
[34] Ketzer et al. 2020.
[35] For example, Edouard et al., 2023; Amaducci et al. 2018
[36] Weselek et al. 2019

as when a 1.7 ha farm is shared between food and electricity production.[37] Furthermore, AV systems are being used to reclaim degraded, contaminated, or abandoned agricultural lands,[38] as AV can enhance native plant growth (for more information, see "Biodiversity conservation and habitat restoration" benefit and case study 1).

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**Case study 1: Using AV to enhance ecological, economic and socioeconomic benefits on degraded land in Jiangshan, China.[39]**

The agrivoltaic park in Jiangshan, China, is a privately-owned commercial-scale, 200 MW PV on-grid power plant with a total area of 4.2 $km^2$ installed on degraded farmlands by Astronergy/Chint Solar Co. Ltd. The project's upfront cost was $312 million USD. The park, which represents a practical model of using AV systems to address land degradation, is located on land that has become barren due to soil erosion. Unlike conventional PV, which involves difficult-to-get approval due to land-use change laws, the fact that the land was used for crops (the original designated use for the land) and energy made approval easier.

The systems address land degradation, agricultural profitability, and PV industry development in an integrated manner using a business model that fuses power generation, agriculture and ecotourism. It employs a multilayer PV installation (e.g. high, medium and low layers of PVs) and crop-planting approach (with shade-tolerant crops under the PV panels and non-shade-tolerant crops between the PV panels) to improve land-use efficiency while also promoting mixed cropping and associated agricultural productivity and biological diversity benefits.[40] Large areas of ornamental herbs and flowers were also planted to form colorful scenery in all seasons, providing ecotourism opportunities. The microclimate created by the shading effect of the solar panels and plants results in increased soil water storage, which ensured vegetation growth from 1% before AV system installation to 90% after, thus mitigating soil erosion and increasing soil fertility.

***The agrivoltaics park in Jiangshan, China, before(left) and after (center, right) installation. Source: Xiao and others.[39]***

One project implementation challenge involved the one-off Farmland Occupation Tax, which is levied when agricultural lands are used for nonagricultural activities. The one-off tax was levied on the AV system ($145,863 USD at $5.47 USD/$m^2$) even though the land was degraded and still used for agriculture. This highlights the need to clarify regulations to differentiate conventional ground-mounted PV installation from AV systems, as discussed in Section 5.2. The project was able to overcome the challenge by the profitability of the business model that incorporates multiple revenue sources from the same piece of land, supported by feed-in-tariff policies that guaranteed revenue from generated electricity (see Section 5.3).

The Jiangshan AV park is expected to operate for 25 years and generate 4.9 billion kWh of power. The generated power will meet the annual electricity demand of 100,000 households in Jiangshan City. The project has created employment for 120 to 150 locals, benefitted nearly 1,000 farmers, and sustained local economic development. The park is expected to achieve an emission reduction of about 4.5 million tons of carbon dioxide and provide air quality benefits by preventing emission of 140,000 tons of sulfur dioxide and about 70,000 tons of nitrogen oxides.

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**Water-use efficiency and pollution prevention**. AV systems provide shade that helps reduce plant transpiration rates and increases soil moisture content, thereby enhancing water-use efficiency.[41] PV panels may require regular washing to maintain their radiation efficiency and the reuse of the cleaning water for crop irrigation[42] could be an additional way AV systems support more efficient water use. Studies also show that rearing livestock in an AV system can reduce water consumption compared to open pastures.[43]

[37] Dupraz et al. 2011
[38] Li et al. 2023; Xiao et al. 2022; Pedron et al., 2021; Tajima and Iida 2020
[39] Xiao et al. 2022. See also https://www.linkedin.com/pulse/splendid-pv-global-footprint-jiangshan-200mw-agri-solar-park-/
[40] Jones et al., 2021; Lizarazo et al. 2020; Moss et al. 2020
[41] Walstonet al. 2022; Barron-Gafford et al. 2019; Adeh et al. 2018
[42] Proctor et al. 2021; Weselek et al. 2019
[43] DOE. 2022; Andrew et al. 2021.

Furthermore, rainwater harvesting systems could be installed with AV systems to support irrigation, PV cleaning and other water uses (see case study 2).[44] Rainwater harvesting and/or shade provided by PV panels may also prevent excessive nutrient runoff, reducing water pollution. Also, shades have been shown to increase nutrient uptake (e.g. nitrogen and phosphorus),[45] which reduces nutrient pollution of water bodies. In addition, the energy generated through the PV systems could be used to power water pumps or water treatment solutions (e.g. desalination in coastal areas[46]). Ultimately, AV systems provide an integrated solution to food, water and energy security challenges.

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**Case study 2: Harvesting the Sun Twice: an agrivoltaic pilot project in Tanzania[47]**

Faced with significant energy security challenges, several East African countries have developed decentralized, small-scale mini-grid solar systems to tackle the problem. However, since the installing mini-grid solar systems involve land clearance, current electrification strategies lead to ecosystem degradation. Funded through the United Kingdom Research and Innovation-Global Challenges Research Fund (£1.3 million GBP), the Harvesting the Sun Twice project was designed to test the application and adaptation of AV systems in the East Africa region. The project sought to investigate the potential of AV technology to improve access to energy, increase household incomes by enabling the production of higher-value crops and identify barriers to AV adoption in the semi-arid regions of East Africa.

***The off-grid AV system used in the Harvesting the Sun Project improved access to electricity, generated higher crop yields, and reduced irrigated water use. Source: Dr Richard Randle-Boggis, University of Sheffield.***

As part of the project, a 35 kWp off-grid AV system, which includes rainwater harvesting and battery storage systems, was installed at the Sustainable Agriculture Tanzania agricultural training center in the Morogoro Tropical Savannah region. Several benefits were identified: (1) improved access to electricity[48]; (2) higher crop yields for beans, Swiss chard and maize compared to those under conventional production systems and (3) a 13.8% reduction in the quantity of irrigation water applied. The bean crop showed about 60% higher survival rate under AV than conventional production, suggesting that the AV system provided a protective environment that enhanced crop resilience to high temperatures, highlighting AV climate change adaptation benefits. A land equivalent ratio of 1.86 was observed, indicating 86% higher land productivity for AV systems. Results suggest the possibility of meeting energy and food security needs with fewer land resources.

However, onion, kale, sweet pepper and eggplant performed poorly under AV compared to conventional production systems. The observed yield reductions of these crop types may make AV unattractive for some farmers and thus constitute a barrier to AV adoption. These findings highlight the need to consider crop types and the specific local context when considering AV adoption (see section 5.1).

During the stakeholder consultation process, representatives from public and private sectors expressed interest in creating a conducive environment to support AV systems scaling. Energy provision through AV mini-grid systems is more attractive than expanding the national grid, as the former results in reduced energy transmission costs and losses. In addition, combining energy and crop production makes rural electrification possible without adversely impacting social cohesion, which could happen if land were taken from farmers for conventional solar farms. Amongst farmers, an appetite to adopt AV systems was expressed, but there was recognition that initial investment costs would be prohibitive for resource-constrained communities. Innovative financing mechanisms or business models would be needed to make AV adoption possible (see section 5.3).

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[44] Al-Agele et al. 2021; Jain et al. 2021; Al-Saidi et al. 2019; Mekhilef et al. 2013
[45] Díaz-Pérez 2013
[46] For example, Dhonde et al. 2022
[47] Randle-Boggis et al. 2023. See also: https://www.sei.org/projects/harvesting-the-sun-twice/; https://gtr.ukri.org/projects?ref=ES%2FT006293%2F1#/tabOverview; https://www.sheffield.ac.uk/research/harvesting-sun-twice
[48] The project generated $137 USD of electrical power per month that was used to power lighting, refrigerators, computers, and charging points for laptops and devices.

**Biodiversity conservation and habitat restoration**. The simultaneous use of land for agricultural activities and renewable energy production reduces the need for new lands, protecting terrestrial ecosystems and habitats and their associated biodiversity. Beyond that, AV systems can improve native habitats and conserve existing biodiversity, resulting in increased soil carbon accumulation, improved soil stabilization, erosion resilience, reduced water runoff, and biodiversity restoration.[49] Also, AV systems can be used to create pollinator-friendly habitats that help improve pollinator populations and safeguard or enhance the ecosystem services that they provide.[50]

**Climate change adaptation and increased resilience.** The microclimate created in an AV system can help crops and livestock adapt to climate change-induced conditions and events, especially increasing temperature (see case studies 2 and 3).[51] Studies also indicate that AV systems create shadings and barriers that protect crops against extreme weather events, such as heat waves, drought, heavy rain and hailstorms,[52] which are expected to occur more frequently and with increased intensity in the future due to climate change.[53] Thus, AV systems reduce weather-related financial risk for farmers.[54] The shade also protects farm workers, livestock and other animals during heat waves and droughts.[55]

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**Case study 3: AV systems and smallholder farmers in Sitapur, India.[56]**

***Source: OneEarth.org***

Sitapur, a town in northern India, is characterized by a humid subtropical climate with dry winters. The region has been experiencing significant reductions in crop yields, partially due to poor rain distribution and high temperatures. Extreme weather events have reduced farm productivity and increased local food prices. Awareness about an AV project implemented by the Central Arid Zone Research Institute (CAZRI) elsewhere inspired Sitapur farmers to consider AV as a potential solution to their multiple challenges.

Some Sitapur farmers worked with CAZRI to install small-scale AV systems using savings from rural government subsidies. One wheat farmer generated enough electricity to power three night lamps and increase yields of seven more wheat tillers per square meter compared to the parts of the field without AV systems. The small-scale AV systems gave farmers an understanding of the benefits in the region, but they noted that scaling would require more financial and technical support, such as access to low-cost credits and knowledge and data sharing across AV systems in India to inform improved management in new and existing AV installations.

AV systems adoption has been expanding in India, and the country is a leading Global South nation with several experimental and a few commercial-scale projects for irrigation and aquaculture.[57] The expansion has led to the creation of the India Agrivoltaics Alliance, an organization that brings together stakeholders across the value chain in the solar and agricultural sectors to coordinate stakeholder inputs, promote AV practices across the country, and develop policy recommendations that can help generate a comprehensive policy framework for AV. Stakeholders include industry associations, research institutes, financial institutions, think tanks, civil societies and farmer producer organizations. This type of multistakeholder dialogue among relevant actors within the sector is essential for exchanging knowledge, building capacity, facilitating access to finance, and developing solutions that address tradeoffs and maximize benefits.

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[49] Walston et al. 2021; Yang et al. 2019; Schulte et al. 2017
[50] Kolbeck-Urlacher, 2023; ENEL. 2022; Mouw 2022; Walston et al. 2022; Dolezal et al. 2021; Hernandez et al. 2019; Hernandez et al. 2014
[51] Barron-Gafford et al. 2019; Weselek et al. 2019.
[52] Willockx et al 2024; Schweiger and Pataczek. 2023; Bellini 2021a
[53] IPCC 2021.
[54] Cuppari et al. 2021
[55] Barron-Gafford et al. 2019
[56] See: https://www.oneearth.org/town-in-india-using-solar-panels-to-protect-crops/ and https://www.mercomindia.com/agrivoltaics-solve-land-scarcity-problem-solar-installations
[57] IGEF-SO. 2023.

**Economic benefits**. Using the same land for agricultural activities and energy generation creates diversified livelihood opportunities and revenue streams for farmers[58] and reduces revenue volatility.[59] In addition to the potentially higher yields under AV systems, energy access enables farmers to adequately store and process their produce. This results in better market timing and increased value and income, which are particularly relevant in many Global South countries where storage and processing are major challenges in agricultural value chains.[60] Also, AV systems reduce farm operation costs by increasing water use efficiencies and the availability of self-generated electricity. Furthermore, AV farmers can become energy entrepreneurs and generate income by selling excess power to national or local mini-grids in countries with supporting policies. A study investigating the economic benefits of an AV system in the United States found a 30% increase in economic value compared to conventional agriculture.[61] Another study in China found that AV systems produced a 9%–20% annual return on investments, depending on crop type.[62]

**Other sustainable development objectives**. Studies have shown that implementing AV systems could directly or indirectly bring other socioeconomic co-benefits and contribute to achieving SDGs related to poverty alleviation; food, water and energy security; good health and wellbeing; decent work; economic growth, industry, innovation and infrastructure; reduced inequities and sustainable cities.[63] The Annex maps how AV systems can directly or indirectly contribute to at least 15 of the 17 SDGs.

## 4.0. AV and GEF objectives

The Global Environment Facility (GEF) supports countries in addressing the drivers of environmental degradation. It aims to deliver global environmental benefits (GEBs) across its focal areas: biodiversity, chemicals and waste, climate change mitigation, climate change adaptation, international waters and land degradation. AV presents an innovative solution through which GEBs could be delivered across multiple work areas covered by GEF-administered funds.[64]

The potential contribution of AV systems to the core indicators of the GEF-8 Result Measurement Framework[65] is illustrated in figure 2. AV systems implementation could positively contribute to core indicators across the biodiversity, climate change mitigation, land degradation and international waters focal areas of the GEF Trust Fund. AV systems would also contribute to achieving some of the core indicators of the Least Developed Countries Fund and the Special Climate Change Fund, as noted in the GEF-8 Programming Strategy on Adaptation.[66]

However, if AV systems are not well-designed using a lifecycle approach, they could negatively impact the objectives of the GEF chemicals and waste focal area. This is because the components of PV systems (e.g. solar panels, inverters and batteries) may contain toxic and hazardous substances that could cause chemical pollution when not properly disposed of at the end of life. However, this issue is not specific to AV systems. Rather, it is a general concern regarding solar PV panel technology that can be alleviated by adopting a circular economy approach in designing, using and decommissioning AV systems. The STAP report titled "The circular economy and climate mitigation"[67] describes how the circular economy can be applied to renewable energy transition. Options described in the report include designing solar PVs and other renewable energy infrastructure for longevity, ease of reuse, repurposing, repair, and recycling through methods like modular

[58] DOE. 2022; Cuppari et al. 2021; Horowitz et al. 2020; Sekiyama and Nagashima 2019
[59] Cuppari et al. 2021
[60] For example, Balakrishnan 2023; Bisheko and Rejikumar 2023; Goyal et al. 2023
[61] Dinesh and Pearce 2016
[62] Li et al. 2017
[63] Walston et al. 2022; Agostini et al. 2021
[64] These funds include the GEF Trust Fund, the Global Biodiversity Framework Funds (GBFF), the Special Climate Change Fund (SCCF), and the Least Developed Countries Fund (LDCF)
[65] GEF 2022a
[66] GEF 2022b
[67] Ali and Leonard 2021

design. The International Energy Agency and International Renewable Energy Agency report on end-of-life management of solar PV panels[68] also highlights actions that can address this concern. Actions include developing solar PV panel end-of-life management regulations and standards, coordinating between energy and waste sectors to support solar PV panel end-of-life management, expanding waste management infrastructure, and continuing innovation on value creation from PV end-of-life panels through a circular economy approach.

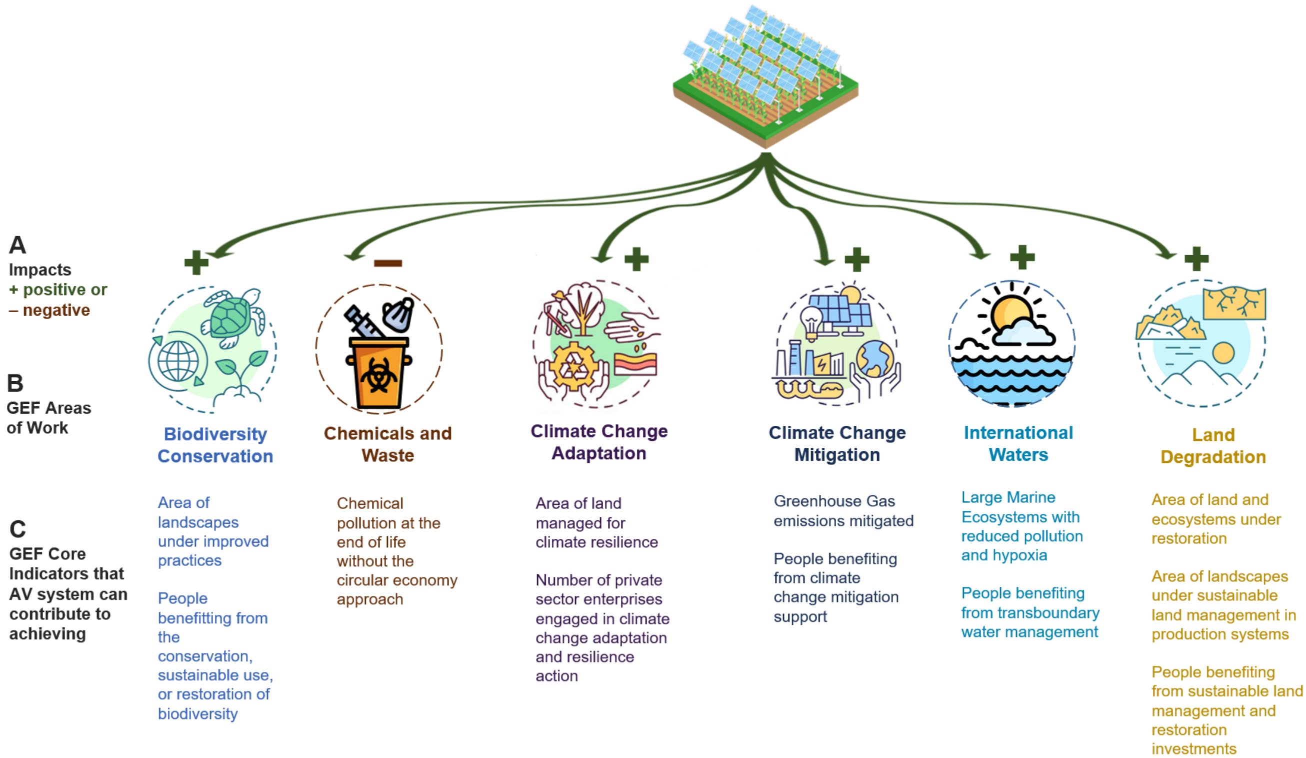


***Figure 2: AV systems can contribute to the GEF-8 result measurement framework***. *Impacts (A) of implementing AV systems on GEF work areas (B). Implementing an AV system can contribute positively (+) to all focal areas except chemicals and waste (-). Specific GEF-8 core indicators that AV systems can contribute to are noted (C).*

## 5.0. Implementing and scaling AV systems

This section discusses technical considerations, barriers to adoption and the enablers needed for successful implementation and scaling of AV systems.

### 5.1. Technical considerations

AV systems may not be technically effective in all agricultural settings, so AV design must be carefully considered to maximize benefits and reduce tradeoffs. The following factors should be considered before adopting AV systems.

**Crop type.** Crops that are usually planted in rows (e.g. fruits like grapes and berries, vegetables, or nut-producing trees and shrubs) are generally aligned with AV systems, as it is easy to mount the panels between rows. Also, many of these crop types already require protection against extreme weather conditions, which the AV system can provide.[69] Crops requiring high levels of sunlight, like wheat, corn and rice, have shown

[68] IRENA and IEA-PVPS. 2016
[69] DOE 2022

mixed yields depending on growing season.[70] In contrast, leafy greens like lettuce and spinach and root crops like potatoes, radishes, beets and carrots have shown promising results (i.e. increased yields). A good performance summary of different crop types in AV systems is available in Weselek and others (2019),[71] Fraunhofer ISE (2022)[72] and Sarr and others (2023).[73] Several adjustments or innovations could help mitigate crop yield penalties for shade-intolerant plants. These include decreasing the density of PV modules to reduce the shading,[74] using novel semi-transparent PV panels that allow solar radiation transmission, using automated AV systems that minimize shading based on the crop growth stage and photosynthetic light demands, and adopting spectral-splitting concentrator PVs.[75]

**Land type and local climates.**[76] One study shows that crops such as barley and other grasses worked well in the U.S. Pacific Northwest, but tomatoes and peppers did not perform well as the AV systems shade reduced the hot temperatures they required for growth.[77] Generally, AV systems have shown significant benefits in arid and semi-arid climate zones and regions with relatively hot climates,[78] although they have been implemented across diverse climatic zones. Studies also indicate that the top three land classes for AV systems are croplands, grasslands and wetlands.[79]

**AV systems mounting structures.** The mounting structures for AV systems must be adjusted to the requirements of the agricultural activity type and are generally taller than those of standard ground-mounted PV systems to accommodate crops or animals and facilitate agricultural machinery use.[80] This requirement may necessitate a tradeoff between agricultural and energy production associated with possible land loss due to dual land use.[81] However, overall land-use efficiency and returns are higher, as discussed earlier. Examples of existing mounting structures and layouts include raking, high elevation, canopy, vertical and sunlight tracker.[82]

**AV systems installation methods.** Installation methods must avoid possible negative impacts on soil quality. AV system and installation method design must ensure minimal soil compaction that does not diminish soil quality. Construction must not degrade the topsoil or change essential soil properties, such as infiltration rates, micronutrients, bulk density, texture and conductivity. Utilizing low-impact site preparation practices that avoid heavy machinery, leave existing vegetation intact or work the natural land contour into AV system design and configuration[83] can help achieve this goal. Moreover, soil preservation can also be achieved by deploying innovative installation methods that use software to model preconstruction needs to minimize grading, compaction, and erosion risks and implementing soil decompaction measures after PV installation.[84]

## 5.2. Barriers to adopting and scaling AV systems

Commercial-scale AV systems exist in Japan, China, South Korea, Germany, Italy, France and India, but many existing systems are in the experimental stage.[85] The successful adoption and scaling of AV systems in these countries can be attributed to factors such as limited arable land and the consequent need to maximize

[70] For example, Pataczek et al. 2023; Prakash et al. 2023; Sarr et al. 2023; Jain et al. 2021; Weselek et al. 2021; Schindele et al. 2020.
[71] Weselek et al. 2019
[72] Fraunhofer ISE. 2022.
[73] Sarr et al. 2023
[74] Prakash et al. 2023; Reasoner and Ghosh 2022
[75] A spectral-splitting concentrator PV harvests photosynthetically excess light energy for photovoltaic power without compromising crop productivity. This system transmits a selected light spectrum for plant growth while reflecting the remaining spectrum for electricity generation (Zhang et al., 2023)
[76] Fraunhofer ISE. 2022; Macknick et al. 2022
[77] Adeh et al. 2019; Barron-Gafford et al. 2019
[78] IISD. 2023a; Randle-Boggis et al. 2021. See also https://www.pveurope.eu/solar-modules/agrophotovoltaics-land-use-efficiency-186-percent
[79] Adeh et al. 2019
[80] DOE. 2022
[81] Jain et al. 2021.
[82] Sarr et al. 2023; DOE. 2022; Toledo and Scognamiglio 2021; Weselek et al 2019
[83] See InSPIRE website: https://openei.org/wiki/InSPIRE/Primer
[84] Macknick et al. 2022
[85] Weselek et al. 2019; See also https://energyindustryreview.com/analysis/agrivoltaism-a-win-win-system/; https://www.treehugger.com/what-is-agrivoltaics-5705794; https://www.treehugger.com/agrivoltaics-jacks-solar-garden-clean-energy-5205559

available land (e.g. in Japan), access to finance, availability and willingness of private investors, and the existence of supportive policies. Many Global South countries lack such resources and are faced with other factors that act as barriers to AV adoption and scaling. These barriers are discussed below.

**High initial investment costs.** Despite the potential benefits, technical innovations, and market competition that have reduced the cost of solar PVs, the initial capital expenditure costs of installing AV systems are still substantially high and generally beyond the reach of most global farmers, particularly in resource-constrained communities in the Global South. The cost of AV systems is highly individually variable depending on factors such as the size or capacity of the system, type of agricultural activities, and types of PV modules and their positioning.[86] Generally, the unique installation requirements of AV systems (e.g. high distance from the ground and special mounting structures) and high permitting, labor, and site investigation costs due to additional design efforts and stakeholder engagement make them more expensive than conventional ground-mounted PV systems. In addition, PV panel cleaning requires operational expenses for dust removal to maintain high electricity outputs. Cleaning panels with irrigation water and guttering AV systems to harvest rainwater may improve water-use efficiency and reduce maintenance costs.

Several studies have noted the higher cost implications of AV systems. A study by the U.S. National Renewable Energy Laboratory (NREL)[87] found that AV systems have higher installation costs ranging from \$0.07–\$0.80 USD per watt of generated electricity, which is between 4%–52% higher than conventional ground-mounted PV solar installation of equal watts of energy production. The cost variation depends on application type (e.g. crop production, animal grazing or habitat restoration) and the system's structural configuration. Additionally, a German study found that the installation cost of AV systems was €0.12–€0.62 EUR per watt of peak energy production, which is 20%–115% higher than conventional ground-mounted PV systems.[88] Another German study noted the cost of AV systems as 11%–50% higher than conventional ground-mounted solar PV, depending on whether the AV system was used for grassland, arable farming or horticulture.[89] A commercial AV systems project in India reported a higher cost of ₹3 million–₹15 million rupees per megawatt of electricity produced than a conventional ground-mounted PV system, depending on the configuration of the system and the type of solar panels (e.g. bifacial or non-bifacial panels).[90] Further, a study on the price of using AV systems for blueberry cultivation in Chile found that the capital cost of AV systems was \$1.10 USD per watt of peak energy produced compared to \$0.90 USD per watt for conventional solar PVs.[91] Generally, total capital and operating costs are usually cheaper when AV systems are used for livestock grazing than other agricultural activities, such as crop production and horticulture.[92]

However, it is essential to note that these findings mainly focus on the installation and operating costs of AV systems. As pointed out in the NREL study, other factors like crop yield, crop type, water use efficiency, and effects of PV panel shading on microclimates, along with installation, operation, and maintenance costs, need to be considered to assess AV systems' lifetime cost and value proposition. The revenue and profitability analysis of the Indian commercial system noted above shows that AV systems have higher profitability than conventional ground-mounted PV systems due to dual revenue streams. It further noted that profitability can be enhanced by growing high-value crops such as grapes, cherry tomatoes and colored capsicums.[93,94] Also, AV systems can be more economically advantageous compared to ground-mounted PVs in areas where land availability is a significant constraint (as AV improves land-use efficiency) or on degraded lands (as it

86 Fraunhofer ISE. 2022.
87 Horowitz et al. 2020.
88 Bellini 2021; Scharf et al. 2021
89 Fraunhofer ISE. 2022
90 REGLOBAL 2022
91 Jung and Salmon. 2022
92 Fraunhofer ISE. 2022; Bellini 2021b; Scharf et al. 2021; Horowitz et al. 2020
93 This conclusion is supported by the techno-economic analysis by Alam et al. 2022
94 REGLOBAL 2022

helps bring unused lands into productivity with financial returns from both energy generation and crop or animal production)[95] (see case study 1).

**Economic and structural factors**. Smallholder farmers with limited resource access dominate agriculture in many Global South countries.[96] Where access to financing is available, the predominantly high interest rate of commercial loans[97] makes borrowing unattractive or unfeasible. Also, small farms are less suited to a farming system requiring significant investments and changes to farming practices. Additionally, smallholder farmers may be constrained by the lack of technical capacity and skills to implement and maintain AV systems and may find it challenging to access required training (see case study 3). For example, a lack of PV experts and technicians to design and maintain the technology has been identified as a major constraint to renewable energy expansion in Africa.[98]

**Sociocultural challenges.** Because of the relative newness of AV, government officials, farmers, and the public lack a general awareness of the opportunities and benefits it provides.[99] AV installations have faced opposition from local governments and the public in the United States and Austria, for example,[100] and varied levels of acceptance are held by the public and even within the industry in Germany, Belgium, Denmark and the United States.[101] A U.S. study noted lack of certainty about continued land productivity, market potential uncertainty, and compatibility with existing agricultural practices as hindrances to farmers' adoption of AV systems.[102] A study focusing on Mali, Africa, noted concerns about how to govern AV systems and its effects on traditional ways of living as reasons for societal apprehension to AV adoption.[103] These studies highlight the importance of incorporating behavioral change measures in AV projects to encourage adoption and scaling of AV solutions.

**Lack of supportive policies and regulations**. Because AV is relatively new, many countries do not have policies, regulations or standards to support or guide its adoption and implementation.[104] Current land tenure and use legislation and energy policies do not consider AV systems and may require clarification to be more supportive.[105] For example, existing regulations restrict the installation of clean energy structures on agricultural lands in some countries.[106] In this context, regulations need to be clarified to differentiate between conventional ground-mounted PV installations, which compete with agriculture for land, and AV systems that involve synergistic energy and agricultural production.[107] Further, specific regulations and standards are needed to guide unique design and installation constraints, including addressing potential health and safety concerns. Additionally, supportive policies are needed to incentivize AV adoption and ensure its profitability. Examples include changing complex permitting and regulations and enacting policies that allow AV-generated electricity to be sold to the grid (e.g. via feed-in tariffs) or used in decentralized/distributed energy or mini- or micro-grids systems. Also needed are policies and incentives to help cushion risks associated with renewable energy projects and provide a stable and favorable environment to attract investment, including from the private sector.

[95] Francia and Cupo. 2023.
[96] Savoy 2022; Foster and Rosenzweig 2022; Goldman et al. 2016
[97] Yieke 2023; Spiegel and Schwank 2022
[98] Abdelrazik et al. 2022
[99] Brunswick and Marzillier 2023
[100] Brunswick and Marzillier 2023; Ivanova 2022; Jossi 2022
[101] Brunswick and Marzillier 2023; Torma and Aschemann-Witzel. 2023; Pascaris et al. 2022; Pascaris et al. 2021
[102] Pascaris et al. 2020
[103] Cheo et al. 2022
[104] Taylor et al. 2023; Randle-Boggis et al. 2021
[105] Krishnamurthy and Serpell 2021
[106] For example, Kolbeck-Urlacher 2023; Bloomberg News. 2022; Gabbatiss et al. 2022
[107] Weselek et al. 2019

## 5.3. Enablers needed for AV adoption and scaling

The following enablers are needed to accelerate adoption and scaling of AV systems, especially in the Global South.

**An integrated approach.** As previously noted, AV systems provide an opportunity to address different socio-economic and development issues concurrently and, therefore, require adopting an integrated approach that promotes a whole-of-government or whole-of-society approach to synergistically address the challenges and opportunities within the food, water and energy nexus. This means bringing together actors and stakeholders (e.g. farmers, energy industry, investors, nonprofits and community organizations) and coordinating among multiple levels of government (e.g. national, state/province and local) to address concerns and proffer common solutions (e.g. regulations, standards and incentives) that maximize benefits and manage tradeoffs.[108]

An integrated approach that explicitly targets local communities can help manage conflicts and address power dynamics between energy industries and local communities over land rights.[109] Such an approach would also help raise awareness of the requirements, benefits and drawbacks of AV systems. It would also provide opportunities to identify and link intersectoral priorities and socioeconomic concerns (e.g. food security, poverty alleviation, human health and wellbeing, and water and sanitation infrastructure development) with AV and drive its adoption and scaling. An integrated approach can also help facilitate coordination with financial institutions, development finance and other funding sources to address the challenges of low financial capacity, especially among smallholder farmers.[110]

**Supportive policies and guidance.** As noted earlier, for AV to thrive and move to commercial scale, supportive policies need to be enacted and conducive regulatory environments created to encourage farmers and attract private investors and development partners. Examples of policy instruments that could facilitate the adoption and scaling of AV systems[111] include:

- Land tenure and use legislation that facilitates simultaneous and synergistic land use for energy, agriculture and other developmental objectives. Legislation could also support the strategic use of AV systems for restoring abandoned or contaminated lands.
- Tax incentives and subsidies, partial risk and credit guarantees, and credit enhancement instruments to reduce initial investment costs, financial barriers and potential risks of AV adoption.
- Policies and legislation to support feed-in-tariffs and explicitly target the sale of AV-generated electricity to the grid or facilitate its use in decentralized/distributed energy or mini- or micro-grid systems.
- Renewable energy portfolio standards that specifically target AV-generated energy, requiring electricity suppliers to incorporate a certain percentage into their supply.
- Market mechanisms, including policies and legislation promoting fair energy prices[112] that will make renewable energy competitive and AV systems attractive to farmers and investors. Examples include implementing innovative tariff structures,[113] avoiding subsidies for energy sources that harm the environment and human health, and enacting carbon taxes to account for the negative externalities of nonrenewable energy sources.[114]

[108] Pascaris 2021
[109] Blaine 2021
[110] IISD 2023b
[111] See, for example, Bingwa 2023; Brunswick and Marzillier. 2023; Kolbeck-Urlacher 2023; IISD 2023a; IISD 2023b; NREL 2022; UNDP 2022; IGEF-SO. 2021; Pascaris 2021
[112] Fair energy pricing addresses the concern that the price paid for energy may not appropriately reflect the actual production cost due to incentives such as government subsidies for fossil fuel and the lack of consideration for the externalities (e.g. the negative health impacts of fossil fuels.) Considering these factors when determining energy prices can not only increase fairness to government and consumers but also minimize environmental degradation associated with non-renewable energy sources.
[113] This could include alternative tariff-setting approaches focusing on the energy source or granting access to developers to sell power directly to consumers at a mutually agreed rate (IISD 2023b).
[114] UNDP. 2022

- Quality standards and guidance for implementing AV systems to provide clear definitions of what AV systems entail (e.g. the minimum percentage of land that must be used for agriculture in an AV system) and address topics like procedures and conditions for permitting agricultural land conversion for AV systems, technical requirements (see Section 5.1), impact assessment and health and safety concerns during installation and operation. Such standards and guidance are needed to provide a shared understanding among project developers, governments and financing institutions and is essential for AV policy development and effective administering of incentives.

**Infrastructure to facilitate AV adoption**. To maximize the benefits of AV systems, critical infrastructure investment may be needed. For example, existing grids in some countries may require upgrading to enable feed-in of energy generated via AV systems (this is similarly required for other renewable energy systems). Using AV systems for mini-grids would also require quality infrastructure, including comprehensive standards, testing, certification and accreditation, inspection and monitoring, and metrology components, which are needed to ensure performance and efficiency.[115] Furthermore, for farmers to fully enjoy the economic benefits of AV in the Global South, critical infrastructure (e.g. roads) may be required to improve access to viable agricultural produce markets.

**Capacity-building initiatives.** This include developing programs that build technical skills among conventional farmers on the requirements of AV systems. Furthermore, AV systems may involve resource co-management in cases where programs are co-owned (e.g. between farmers and energy industries) and may require developing farmers' managerial skills to avoid miscoordination that can compromise efficiency.[116] (For additional details, see the next sub-section titled "Viable business and financing models"). Also, given that the benefits and tradeoffs of AV systems depend on context-specific factors, adoption and scaling depend on continuous research on maximizing gains, reducing adverse impacts, and facilitating peer learning, e.g. through international collaboration with leading institutions and countries (see case study 4).

**Viable business and financing models.** To address the high investment cost and economic and structural challenges facing AV adoption, it is essential to develop innovative and creative business and financing models for specific contexts (e.g. smallholder farmers in the Global South). Some possible business/financing models that have been proposed for AV systems[117] include:

- ***Publicly owned business model***, in which governments fund projects and bear operational and maintenance costs. A publicly owned energy company assumes a developer role. The government could carry out agricultural activities on the land or lease it to farmers based on agreed terms.
- ***Developer-owned business model***, in which a private developer funds the installation, operation and maintenance of the system (i.e., agriculture and energy operations), with a power purchase agreement between the developer and an anchor client (e.g. the national grid, energy companies or distributors, or rural households).
- ***Farmer/agricultural cooperatives business model***, in which several farmers, including smallholders, aggregate land through farmer unions or cooperatives. The cooperatives could aggregate funds, including through credit from financial institutions, to install the PV system. Excess energy generated could be sold to an anchor client (e.g. the national grid, energy companies or distributors, or rural households).
- ***Shared ownership between developers and farmer/agricultural cooperatives***, in which farmers and private or public developers work collectively to install, operate and maintain AV systems. The land is leased to the developer by the farmer and the associated costs and benefits are shared based on a mutually agreed stake.

[115] IRENA 2020
[116] IISD. 2023a; IGEF-SO. 2021
[117] CSTEP 2023; IISD 2023a; IISD 2023b; Weaver 2022; Randle-Boggis et al., 2021; Fraunhofer ISE. 2022

- ***Purchase agreement with a PV company***, in which farmers (small-, medium-, or large-scale) purchase or lease PV systems from the PV supplier, usually backed by a financial institution loan). Depending on system size, the farmer could sell energy to an anchor client (e.g. the national grid, energy companies or distributors, or rural households) or use it locally.
- ***Shepherd partnership business model***, in which large solar farm developers engage shepherds to graze their livestock on the land. This model is unique to livestock/animal husbandry applications. It provides mutual benefits with livestock grazing reducing the cost of regular mowing of solar farms and solar farms providing vegetation for animal grazing.

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**Case study 4: The experimental and educational AV system at UNAM, Mexico[118]**

The Sustainable and Educational Agrivoltaic Platform is Mexico's first AV system installation. Funded by the Ministry of Education, Science, Technology and Innovation and implemented by the Renewable Energies Institute of the Universidad Nacional Autónoma de México (UNAM), the experimental and educational platform aims to increase the quantity and enhance the quality of agricultural products, produce renewable energy, reduce freshwater consumption, create awareness, and build capacity for new technologies among agricultural producers. The AV system, which is part of an international consortium comprising research and educational institutions working on AV from France, Morocco, Israel, Kenya, Mexico and the United States, will produce biomass for animal husbandry and food for human consumption. The AV installation covers an area of about 350 $m^2$ with 72 solar panels positioned three meters above the ground. The generated power is expected to meet a significant portion of the center's energy needs. The AV system includes rainwater harvesting with a storage tank of 145 $m^3$ capacity and a drip irrigation system. The system also incorporates solar dehydrators for crop processing and preservation. The system will strengthen teaching and learning in several disciplines, including engineering, mathematics and animal and crop production. Installing an AV system at a university campus could facilitate use of the platform for cross-disciplinary education. This type of partnership, supporting knowledge curation, sharing, and learning between first movers and countries interested in AV systems, is essential for understanding AV fitness in each country's unique context and can help facilitate adoption, replication and scaling.

***The experimental AV platform funded by the Ministry of Education, Science, Technology and Innovation of Mexico City and implemented by UNAM's Renewable Energies Institute. Source: UNAM.***

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## 6.0. What the GEF can do

Our review of AV and its applications shows that deploying the technology could help the GEF deliver GEBs across several work areas, including mitigating and adapting to climate change, reducing land degradation, conserving biodiversity, and protecting international waters. However, AV systems need to be implemented using a circular economy approach to prevent chemical pollution associated with PV panel disposal at the end of life.

For AV systems to be effectively deployed and scaled up in some of the countries supported by the GEF, enablers need to be in place to overcome barriers such as finance (i.e. chiefly, the high installation costs), societal apprehension and structural factors (e.g. dominance of smallholder agriculture, inadequate capacity and lack of awareness). Enablers include supportive regulations and policies, financial incentives, capacity building and technical assistance initiatives, awareness raising, and developing viable business models.

[118] Hernandez 2023.

Given the potential of AV systems to deliver GEBs, the GEF could consider supporting countries in understanding the fitness of the technology for their specific context and implementing needed enablers to overcome barriers and challenges, where applicable. This could be accomplished by considering AV as a potential intervention option in relevant GEF work areas and investing in projects that apply AV technology, such as other climate funds already do.[119] For example, AV systems could be a good candidate for GEF blended finance projects, which typically help address financial barriers or provide mitigation measures for risks associated with emerging technologies.

The GEF could also help foster multistakeholder dialogue and partnership to promote technical assistance, capacity building, and knowledge exchange, especially with countries leading in AV system implementation. For example, Japan provides a good model for deploying small-scale AV systems (see case study 5). Lessons from Japan's experience could help several GEF countries where small-scale agriculture dominates. The GEF could also facilitate South-South cooperation and knowledge exchange between GEF countries leading in AV implementation (e.g. China and India) and others interested the technology.

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**Case study 5: Agrivoltaics development in Japan.**[120]

***AV systems at Chiba Ecological Energy in Japan. Image: Toru Hanai. Credit: Bloomberg.***

Japan boasts more than 3,000 small-scale agrivoltaics (AV) systems generating up to 600,000 megawatt hours of power annually, each occupying less than 0.1 hectare. A significant driver of adoption is the need for efficient land use due to limited arable land. In addition, government policies, such as subsidies and incentives to farmers, crop performance benefits, and opportunities for additional revenues, have encouraged widespread adoption. Regulations on land conversion have been clarified and provide an advantage to AV over conventional ground-mounted solar PVs. The introduction of feed-in tariffs in 2012 also facilitated quick adoption, and a 2020 amendment to the feed-in tariff law preferentially favors AV systems over conventional PVs. AV systems are being positioned as a means of revitalizing Japanese agriculture, specifically for reclaiming degraded or abandoned farmlands. A notable barrier is the reluctance of elderly farmers to make the high investments needed, mainly because they do not have successors to take over their agricultural businesses.

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Lastly, any GEF-funded AV project should include strong monitoring and evaluation, as well as knowledge management and learning components to help capture lessons and data to fill gaps related to AV systems implementation such as costs, crop types, optimization, unintended impacts (e.g. on soil quality), business and financing models, and regulatory and governance frameworks.

[119] The Green Climate Fund funded a 4 MW AV system (with battery storage) project in Fiji. The project, approved in 2020, will provide technical assistance to strengthen the capacity of local communities while also establishing a climate project financing facility within Fiji's Development Bank (FDB). The Adaptation Fund is currently considering a proposal submitted by Armenia that aims to implement AV systems in communities adjacent to arid zones and forest-protected areas of the country. The project aims to reduce climate risk vulnerability by promoting sustainable and climate-resilient agricultural practices in degraded areas and buffer zones while sustaining protected areas.

[120] Nakata and Ogata 2023; Fraunhofer ISE. 2022; Graham 2022; Oda 2022; Bellini 2021b. Tajima and Iida. 2020

# Annex: Alignment of AV systems with sustainable development goals[121]

| Goal | AV type[a] | Alignment with agrivoltaic systems |
|---|---|---|
| SDG 1: No poverty | All | All AV systems could have positive impacts on poor rural communities in terms of energy and economic security and improve social equity |
| SDG 2: Zero hunger | AV-animal; AV-cropping | AV systems increases land productivity and can be used to increase food production |
| SDG 3: Good health and wellbeing | All | AV systems reduce GHG emissions and other air pollutants in comparison to other energy systems |
| SDG 4: Quality education | — | — |
| SDG 5: Gender equality | — | — |
| SDG 6: Clean water and sanitation | AV-cropping; AV-habitat | AV systems improve the site's water use efficiency by either (a) repurposing water used for cleaning panels for irrigating crops or (b) reducing plant transpiration due to shading from PV panels |
| SDG 7: Affordable and clean energy | All | As solar PV developments, AV systems produce affordable and clean energy |
| SDG 8: Decent work and economic growth | All | AV systems contribute to economic growth by providing job opportunities and other sources of revenue in rural areas |
| SDG 9: Industry, innovation, and Infrastructure | All | AV systems help promote inclusive and sustainable industrialization of rural and developing areas |
| SDG 10: Reduced inequalities | All | AV systems may help reduce inequalities between industrialized and rural communities by contributing to economic development in rural areas |
| SDG 11: Sustainable cities and communities | AV-animal; AV-cropping | AV systems may be developed close to cities and villages, providing these areas with more sustainable access to food and clean energy |
| SDG 12: Responsible consumption and production | All | AV systems work to minimize inputs for energy and food production and biodiversity conservation, thereby exemplifying responsible consumption of resources |
| SDG 13: Climate action | AV-habitat | AV systems contribute in both reducing climate change by reducing GHG emissions compared to other energy systems and improving the site's carbon sequestration potential through on-site habitat restoration (e.g., solar-pollinator habitat) |
| SDG 14: Life below water | All | In comparison to other energy sources, AV systems may support aquatic biodiversity by reducing GHG emissions and other pollutants that may impact waterbodies |
| SDG 15: Life on land | All | AV systems support terrestrial biodiversity by minimizing the cumulative land disturbance for energy and agricultural production and through on-site habitat restoration (e.g., solar-pollinator habitat) |
| SDG 16: Peace, justice, and strong institutions | All | AV systems can provide peace and justice to poor communities and developing countries by alleviating conflicts for energy sources |
| SDG 17: Partnerships | All | Large scale AV systems will leverage important partnerships between solar developers, site operators, and members of the agricultural and natural resource management communities |

Refer to this table for references on the ecosystem services of agrivoltaic systems that support these alignments.
[a] AV-Cropping: AV Systems co-located with crop production; AV-Animal: AV systems co-located with animal husbandry; AV-Habitat: AV systems co-located with habitat restoration.

[121] Taken from Walston et al. 2022

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