AQUILA CAPITAL

Whitepaper

AGRIVOLTAICS – THE FUTURE OF AGRICULTURE?

Introduction

A RISING PHENOMENON IN THE RENEWABLE ENERGY SECTOR is the increasing adoption of agrivoltaic systems, also known as APV. These constitute the dual and mutually beneficial use of land for agricultural purposes and photovoltaic (PV) power generation.

The expansion of large-scale PV plants is an essential component of global efforts to mitigate climate change. The International Energy Agency's (IEA) World Energy Outlook 2022 calls for a near quadrupling of investment in clean energy this decade to stay on a pathway to net-zero carbon emissions by 2050.[1] However, a constraint to achieving these targets is the extensive space requirements of solar parks, complicated by global food demands that are expected to increase by 50 % by 2050, and rising competition for land exacerbated by persistent population growth, anticipated to grow to nearly 10 billion people.[2] Thus, the integration of crop production and PV power generation could help solve this land economy dilemma, while meeting future energy and food demands.

Growing public opposition over the loss of farmland and natural areas to solar parks is a key driver of APV expansion worldwide. Its adoption eliminates the mutually exclusive nature of competition for scarce land resources, preserving arable land for food production while meeting the need for greater renewable electricity generation. Additionally, the financial upside of energy self-generation of an APV system could incentivise farmers to target marginal productivity lands that are not currently being farmed.

Climate change is also disrupting the global hydrologic cycle, causing chronic water scarcity in many major food-producing regions. Even if net-zero carbon emission targets are achieved by 2050, a major portion of the world will become drier and much more susceptible to extreme droughts before the end of the century. Significantly, the most favourable regions for solar energy, characterised by high irradiation and level land, are also some of the best places to grow food crops. Multiple combinations of solar PV and agriculture are in use, depending on the cultivated crop, ranging from overhead and interspace solar arrays with varying elevations and tilt angles to PV greenhouses.

These types of integration systems can help boost electricity production, raise food yields, and reduce water consumption. This win-win condition for both the farmer and the PV operator can be attributed to particular plants benefiting from shading and solar panels gaining power conversion efficiency and greater longevity thanks to the plants' evapotranspiration, which cools the surrounding air. The co-location optimises the microclimate and lowers the surface temperature of PV modules, whilst also shading the plants and thus reducing their transpiration rate, helping them retain more water.

1 IEA, "World Energy Outlook: executive summary" (October, 2022). Available at: *https://www.iea.org/reports/world-energy-outlook-2022/executive-summary*.
2 World Resources Institute, "World Resources Report: Creating a Sustainable Food Future" (July, 2019). Available at: *Creating a Sustainable Food Future | World Resources Report (wri.org)*.

CONTENTS

1. Agrivoltaic system designs

Three key combinations of solar PV and agriculture are in use: overhead solar arrays situated above crops, interspace modules with space between for crops and greenhouse solar modules. All three systems benefit from a multitude of variables used to maximize solar energy absorbed in both panels and crops, including the tilt angle of the solar panels, the type of crops cultivated, panel heights, solar irradiance, and the climate of the area.

1.1 Categories

The Fraunhofer Institute categorises overhead solar arrays as those with vertical clearance over 2,1 metres and interspace PVs as those with vertical clearance under 2,1 metres, according to a recent German standard for APVs (DIN SPEC 91434). Various tilt angles are applied for permanent and multi-year crops (fruits and viticulture), single-year and long-term crops (arable crops and vegetables), and commercial grassland for mowing or pasture.[3] The clearance elevation of overhead structures can vary widely according to the cultivated crop in question. APVs with high ground clearance, about 4-6 metres, are sometimes applied to arable crops so as to allow the passage of agricultural vehicles in the space below the modules, whereas those relating to permanent and multi-year crops have lower mounting structures of about 2-3 metres. However, these designs are more capex intensive and thus more circumstantial in their application.[4]

More widely used and preferable designs for developers involve spacing in-between rows of modules, with Aquila Clean Energy's APV project developments mostly having clearance distance between rows of 7–9 meters, depending on terrain, thus allowing the free movement of tractors between the rows. These interspace PV systems have a typical design in which the rows of modules are oriented according to an east-west direction and the modules look south with a tilt angle equal to the latitude minus 10 degrees. The rows are spaced so as not to generate mutual shading except in a limited number of hours and the minimum height of the modules from the ground is such that they are not frequently shaded by plants that grow spontaneously around them. This pattern, optimised on the assumptions of maximising energy and economic performance in terms of electricity production, varies in the case of an agrivoltaic plant so as to leave space for agricultural activities and benefit plant growth.[5]

3 Fraunhofer ISE, "Agrivoltaics: Opportunities for Agriculture and the Energy Transition – A Guideline for Germany" (April, 2022), p. 12.
4 Ministero della Transizione Ecologica (MITE), "Linee Guida in materia di Impianti Agrivoltaici" (June, 2022), p. 32.
5 Ibid., p. 18.

PV greenhouses are an increasingly adopted combination type, thanks to their capacity to generate electricity for greenhouse environmental control systems such as ventilation, irrigation, heating and cooling; thus, protecting crops from excessive sunlight and temperatures and reducing their water consumption.[6]

1.2 Core requirements

Core requirements according to typical standards for agrivoltaics include: the guarantee of the agricultural use of the land, a maximum land loss after installation of PV systems of no more than 10 % for overhead PVs or 15 % for interspace PVs, verified light availability, light homogeneity and water availability, the adaption to agricultural needs, the avoidance of soil erosion and damage, the option to dismantle without soil degradation, and an agricultural yield of at least 66 % of the reference yield.[7] Various studies have highlighted the growth patterns and yields of crops subjected to reductions in light radiation following the integration of APV. Plants with an elevated need for light, for which even modest shading densities determine a strong reduction in yield, such as wheat and fruit trees, were deemed to be unsuitable unless optimisation in terms of tilt angles and elevation was applied. Crops where moderate shading has almost no impact on yields, such as rye, barley, oats, were considered suitable. High suitability crops, such as potatoes and hops, were those for which shading had positive effects on yields.[8]

2. Developments in Europe

There have been several exemplary developments of APV in Europe that illustrate its potential scalability and its technical and economic feasibility in many countries with varying climates and irradiation levels. In the south of Germany, vertical bifacial solar panels were installed by China's Jolywood, a leading solar manufacturer that has announced a 700-watt 'N-type', bifacial solar panel called 'Niwa Max'. These panels capture between 21.7 % and 22.5 % of the sun's irradiation compared to the 17 % to 19 % panel average and are placed vertically, so as to provide wind protection and ensure crops receive full sunlight.[9]

In the Netherlands, agrivoltaic projects with special monocrystalline solar panels with different transparency levels have been shown to boost crop yield and quality for five types of crops, including blueberries, red currants, raspberries, strawberries, and blackberries. The transparency of the panels is designed to ensure sufficient light can reach the plants below, while also creating a protective cover from direct sunlight, rain, hail and frost. The modules are set up in such a way that air can pass through them, ensuring that the air under the plants is cooler than ambient conditions, and much cooler than standard foil coverings.[10] In Greece, nanostructure-coated solar cells which filter out unwanted UV rays entirely cover a 1,000 square metre greenhouse for a vineyard, ensuring that nearly all its energy needs are met whilst being carbon-neutral.[11]

2.1 Developments in Italy

In Italy, the potential for agrivoltaic systems is perhaps the most significant, given the country's high solar radiation levels and its substantial agricultural sector. While the country still has very convoluted planning laws and permitting procedures for farm-based solar systems, its government has devoted €1.1 billion to establishing 2 GW of new agrivoltaic generation capacity this decade as part of its EU-funded post-Covid National Recovery and Resilience Plan.

The country's 'National Agency for New Technologies, Energy and Sustainable Economic Development' (ENEA) has launched a national network for sustainable agrivoltaic systems, with the objective of increasing installed solar power by 30 GW. Significantly, according to ENEA, in order to reach 50 % of the objectives of the national energy plan, only 0.32 % of Italian agricultural fields would have to integrate PV systems.[12]

6 Fraunhofer, "Agrivoltaics" (April, 2022), p. 11.
7 Ibid., p. 12.
8 MITE, "Linee Guida" (June, 2022), p. 19.
9 13D Research & Strategy, "What I Learned This Week: Agrivoltaic Disruption: Produce more food with less water while generating enough clean electricity to power the world" (October, 2021). Available at: *13D Research & Strategy*.
10 Bellini, E., "Special solar panels for agrivoltaics", PV Magazine (July, 2020). Available at: *Special solar panels for agrivoltaics – pv magazine International (pv-magazine.com)*.
11 Klenske, N., "To feed a growing population, farmers look to the Sun", European Commission (January, 2022). Available at: *To feed a growing population, farmers look to the Sun | Research and Innovation (europa.eu)*.
12 HT, "Agrivoltaics: what is it and how does it work?" (November, 2021). Available at: *Agrivoltaics: What is it and How does it Work? (ht-apps.eu)*.

The Italian government's 2021 'Simplification Decree' has also been a major breakthrough in the implementation of PVs in agriculture, listing integrated solutions that do not compromise the continuity of agricultural activities.[13]

2.2 Innovations throughout Europe

Major market participants in Europe have developed innovative projects at sites in Spain, Greece and Italy, with companies experimenting with the cultivation of species of plants beneath and between panels without radically altering the layout of the PV projects.[14] The crops that reaped the most benefits from the synergy were of limited height, such as forage crops (corn, barley, oats), herbs, vegetables and short fruit-bearing plants, with tests indicating increases in agricultural yields of between 20 % and 60 % and a reduction of up to 15-20 % of water consumption for crops. The integration of livestock farming and PVs has also been successfully tested.[15] Other market participants are developing APV projects in the region of Campania, Italy, where bifacial solar arrays built 2 metres above ground with vertical tilt trackers are integrated with livestock, horticulture and vertical farming, as well as battery energy storage systems.[16]

2.3 APV and Aquila Clean Energy

Aquila Clean Energy, the clean energy platform of Aquila Group, is developing a substantial solar PV portfolio in Italy of ca. 2.6 GW, of which the vast majority will be APV systems fully compliant with national agrivoltaic guidelines with an average production of 1.700 MWh / MWp / year. More than 70 projects are being developed in multiple regions, placing Aquila Clean Energy at the forefront of the country's APV market. Its office in Milan, Italy, opened in March 2021 and has since then expanded rapidly to include 20 employees, of which half constitute the Clean Energy Development and Construction team, giving great impetus to future expansion in the country. It should be noted that Aquila Clean Energy does not target APV projects just to have a higher likelihood of getting a project on agricultural land permitted. Indeed, considering the ambitiousness of build-out targets for renewables as part of the 'European Green Deal' and the 'Next Generation EU' packages, industrial and urban areas are not sufficient for all envisaged development; hence the need to integrate PV into agricultural land as a compromise towards achieving the energy transition. APV system designs are thus optimised to limit hindrance to continued agricultural use as much as possible. Hence, agrivoltaics are likely to become an essential part in boosting renewable investment and strengthening domestic energy production, whilst ensuring the resilience and security of Europe's energy supply.

13 Ibid.
14 Enel Group, "Energy: agreement between Enel Green Power and ENEA for an innovative agrivoltaic pilot plant (May, 2021). Available at: *Energy: agreement between Enel Green Power and ENEA for an innovative agrivoltaic pilot plant | Enel Green Power*; Enel Group, "Agrivoltaics: Enel Green Power's campaign bears its first fruits" (June, 2022). Available at: *A new Agrivoltaic model | Enel Green Power*.
15 Enel Group, "All the benefits of agrivoltaics" (March, 2023). Available at: *Agrivoltaics: benefits of agriculture and solar energy | Enel Green Power*.
16 PV Europe, "Land of the Sun project in Italy" (2023). Available at: *https://www.pveurope.eu/agriculture/agrivoltaics-land-sun-project-italy*.

3. Opportunities

3.1 Rapid expansion over the years

APV systems hold significant potential for sustainable energy production and food security. According to Fraunhofer ISE, installed APV power has expanded exponentially from ca. 5 MWp in 2012 to ca. 2.9 GWp in 2018 to over 14 GWp as of 2021. While Japan has more than 3,000 smaller systems installed, China remains the undisputed APV leader with an estimated 12 GWp of installed capacity (as of July 2021).[17]

3.2 Solving the land economy dilemma

APV has the capacity to meet the world's entire electricity needs on less than 1 % of the world's croplands. Assuming the integration of APV to only 10 % of total greenhouse space in European Mediterranean countries, a potential capacity of around 15 GWp could be exploited. In Germany alone – which had around 59 GWp of installed PV capacity in 2021 – a target of expanding PV capacity to 215 GWp by 2030 and overall power demands of 300-450 GWp, highlight the significant potential for agrivoltaics to accommodate for the planned expansion's vast area requirements without the loss of agricultural land and minimal conflicts and acceptance problems.[18]

3.3 APV incentive programs

Furthermore, Europe also has a number of APV incentive programs, including 1.1 bn EUR in funding under the European Green Deal. Countries including France, Italy and Germany have their own incentive programs and various new APV sites are being installed primarily for fruit, berries and vineyards, since APV systems present additional benefits in the protection of delicate crops from hail, heavy rain, sunburn, drought and frost. National APV funding programmes have been in effect in Japan since 2013, China since 2014, France since 2017, the USA since 2018 and more recently in South Korea, are encouraging signs suggesting continued expansion in APV capacities.[19]

3.4 Crop synergies

Alternative combinations of agriculture with PV arrays, depending on the cultivated crop, such as solar panels elevated 2-4 metres above farm fields, have been shown to help food crops grow with less water, while making panels produce up to 10 % more energy. The integration of APVs allows for the shading of plants around or below the modules at particular intervals during the day. Since all plants have a limit on daily levels of sunlight needed for photosynthesis, any excess light beyond this light-saturation point causes plants to increase their water usage. Shading from APV systems can help protect plants from excess sunlight, while using it to generate electricity. Whilst in areas with lower irradiation this can reduce crop yield and quality, bifacial solar panels that capture sunlight on either side can be placed vertically, allowing crops to receive full sunlight in addition to providing wind cover.[20]

A study in *Nature Sustainability* reported that shaded crops such as chiltepin peppers and cherry tomatoes grown under solar panels doubled their yields compared to a traditional growing environment. The plants reduced their water loss 65 % on average, and the soil retained more water, reducing irrigation needs.[21]

3.5 Solar PV synergies

A recent microclimate study in Applied Energy has also demonstrated that placing solar modules 4 metres above a soybean farm resulted in a reduction of up to 10°C in solar panel surface temperature compared to a standard PV module mounted half a metre above ground, contributing to increased solar module power conversion efficiency, lower panel heat stress and greater longevity. The study attributes these effects to greater passive

17 13D Research & Strategy (October, 2021); Fraunhofer, "Agrivoltaics" (April, 2022), p. 21.
18 Fraunhofer ISE, "Tapping the potential of APV – definitions, standards and classification" (May, 2022); Fraunhofer, "Agrivoltaics" (April, 2022), p. 8.
19 13D Research & Strategy, "Agrivoltaic Disruption" (October, 2021); Fraunhofer ISE, "Integrated photovoltaics" (April, 2023). Available at: *Agrivoltaics - Fraunhofer ISE*.
20 13D Research & Strategy, "Agrivoltaic Disruption" (October, 2021).
21 Barron-Gafford et al., "Agrivoltaics provide mutual benefits across food-energy-water nexus in drylands", Nature Sustainability, vol. 2 (July, 2019), p. 848.

cooling thanks to taller panel heights, more reflective ground cover and higher evapotranspiration from plants.[22] The scalability of the study shows promise in the potential for agrivoltaics to generate more food and energy, whilst also reducing water consumption and relaxing land-use competition.

3.6 Agricultural business synergies

In addition, the use of renewable energy to power a farm's operations, including lighting, heating and cooling, PV greenhouses and the sale of surplus electricity, can all help agricultural businesses raise additional revenue. Additionally, the electrification of agricultural facilities, such as solar-powered irrigation systems, has been shown to increase the resale value of land.[23]

The synergistic potential of agrivoltaics is thus self-evident thanks to the operational efficiency and the proven technical and economic viability of such systems.

4. Challenges

Key challenges to widespread implementation of agrivoltaic systems include the need for international standardisation, the removal of regulatory hurdles, effective incentive systems, even more comprehensive monitoring and the greater involvement of farmers, as well as further improvements in economic efficiency.[24]

4.1 Regulatory hurdles

Arguably the greatest impediment to realising the full potential of APV is the current regulatory framework. In Germany, there is yet no dual land use of photovoltaics and agriculture for the same area in the country´s land development plan. Hence, this has been a source of considerable dispute as municipalities are compelled to consider in their planning which land areas are to be allocated for solar PV development and which for agricultural land use. Dual use of the same area is not foreseen yet, requiring closer cooperation with the municipalities and more detailed planning from the start of any development.

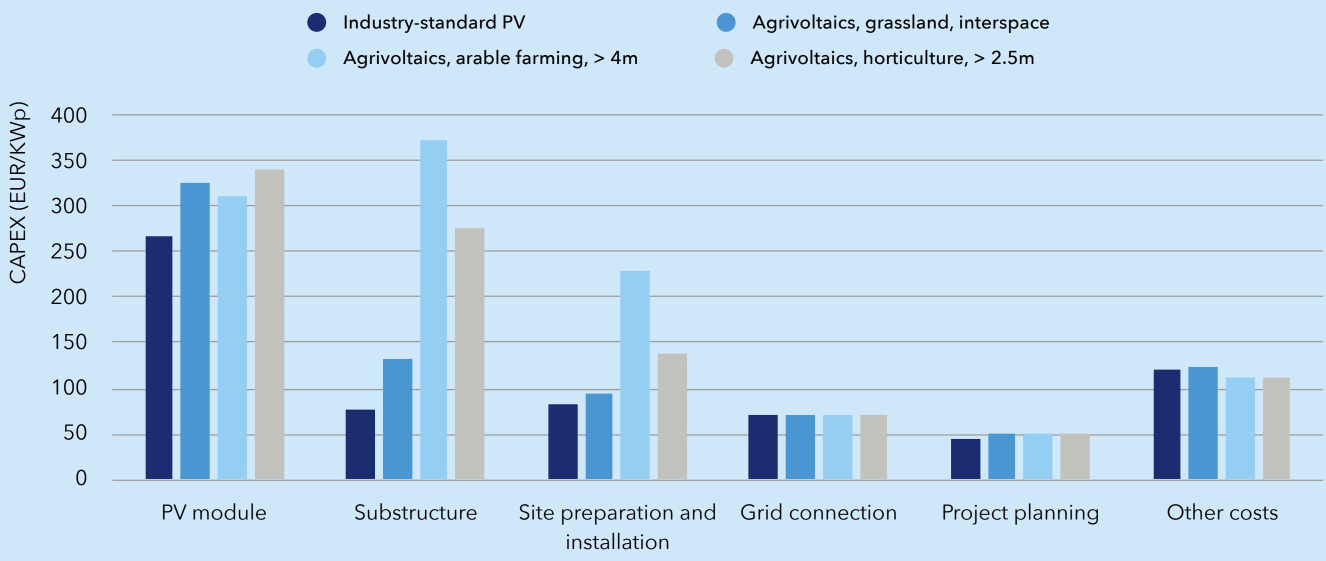
Furthermore, another regulatory obstacle is that the EEG does not permit own consumption of energy produced by APV systems for the farms themselves but must deliver it to a third party or feed it all into the electricity grid. Integrating APV to meet a farm's own demand for electricity also vastly increases the economic viability of the systems, especially for smaller systems which benefit the most from savings on grid charges, as self-consumption accounts for a major share of the electricity produced. Thus, self-consumption should be permitted and EU-wide or global APV standards are needed to ensure widespread implementation of the technology within the agricultural sector, especially for permitting where new land categories and greater legal clarity are required.

4.2 Incentive systems

In Germany, current incentive systems, such as the Renewable Energy Sources Act (EEG), do not offer adequate remuneration. Germany is subsidizing APVs as so-called "special solar power systems" in its Innovation Tenders Ordinance for projects up to 150 MWp as of June 2021. The limitation of this subsidy is its conditioning of the tender to a system combining solar PV to either battery storage or an additional renewable energy system, adding another hurdle to agrivoltaic plants. Moreover, interspace agrivoltaic systems allowing crops to be grown between the PV module rows are far more competitive, due to their less complex substructure, than overhead systems allowing crops to be grown between the PV module rows, reducing the latter's likelihood of being awarded funding. This is detrimental as overhead systems are more conducive to efficient land use and protection against climate change.

22 Williams et al., "The potential for agrivoltaics to enhance solar farm cooling", Applied Energy, vol. 332 (February, 2023). Available at: *The potential for agrivoltaics to enhance solar farm cooling - ScienceDirect*.
23 R.R. David, "Agrivoltaic systems, a promising experience", Energy Industry Review (April, 2021). Available at: *https://energyindustryreview.com/analysis/agrivoltaic-systems-a-promising-experience/*.
24 All information in this section is derived from data for German agrivoltaic systems analysed in Fraunhofer ISE, "Agrivoltaics" (April, 2022), pp. 32-35, 60-63.

FIGURE 1: **ESTIMATED CAPEX FOR INDUSTRY-STANDARD PV AND AGRIVOLTAIC SYSTEMS**



Source: Approximate data from Fraunhofer, "Agrivoltaics" (April, 2022), p. 33.

4.3 Development challenges

There are also challenges in the development, construction and operational phases of an agrivoltaic system. In the development phase, there is still uncertainty over the number of lease agreements required to coordinate and combine the differing interests of the agricultural and PV operators. Moreover, it is unclear who the main lessee would be and whether there could be double lessees on one site. Significant uncertainty also remains regarding the agricultural licensing that the power plant operator would have to acquire to operate APVs and also the compliance requirements needed for APVs to access EU and national agricultural incentives. There are also obstacles in permitting, which would depend on the local municipality.

4.4 Construction challenges

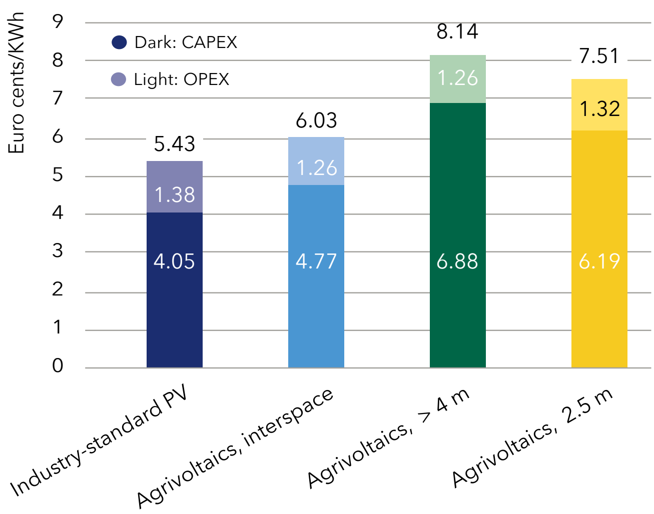
In the construction phase, higher capex assumptions are to be considered depending on the technology utilised (bi-facial modules, tracker, etc.). Moreover, the higher the height of plants, the higher the PV mounting system needed, thus increasing capex (see Figure 1). Furthermore, coordination with the farmer is necessary as the construction of the PV plant should not collide with agricultural activities such as tilling and harvesting.

4.5 Operational challenges

Conversely, in the operational phase, the costs of APV systems are more variable, with the possibility of there being potential savings on operating expenses, unlike on capital expenditure, compared to ground-mounted PV systems (see Figure 2). This can be attributed to the equal division of land lease costs among the farm and the APV operator and the elimination of PV operator land management costs due to regular agricultural use. However, costs of cleaning or repairing the PV modules are likely to be higher due to the work being carried out at greater elevation, for example using lifting platforms.[25]

FIGURE 2: **ESTIMATED LEVELISED COSTS OF ELECTRICITY**

by capex and opex of industry-standard PV and agrivoltaic systems



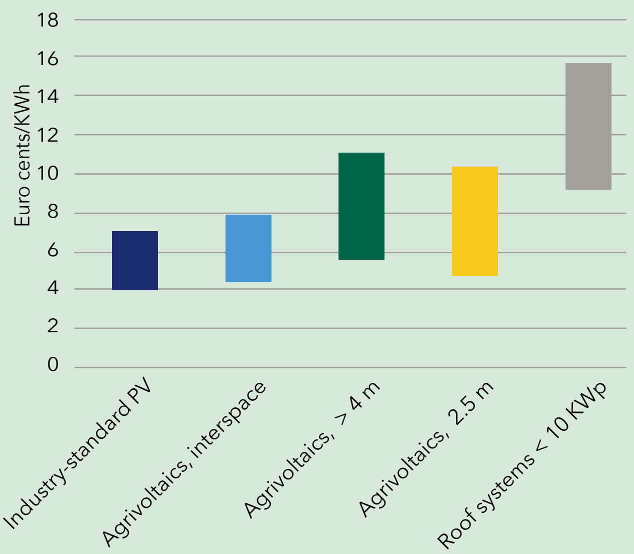
Source: Approximate data from Fraunhofer, "Agrivoltaics" (April, 2022), p. 34

25 Schindele et al., "Implementation of agrophotovoltaics: Techno-economic analysis of the price-performance ratio and its policy implications", Applied Energy, vol. 265 (May, 2020). Available at: *Implementation of agrophotovoltaics: Techno-economic analysis of the price-performance ratio and its policy implications - ScienceDirect.*

4.6 Overall challenges

Overall, APV systems have a higher capital-cost-per-watt generated than solar parks due to the cost of the racking system used to elevate the panels and wider spacing between them. However, total costs for APV systems are lower on average than those for roof-mounted PVs and, thanks to a dual revenue stream, can be feasibly recovered within five to twelve years. Moreover, it should be noted that for permanent grassland, electricity generation costs have been shown to be only slightly higher than those of a ground-mounted PV system (see Figure 3).

FIGURE 3: **ESTIMATED LEVELISED COSTS OF ELECTRICITY (LCOE)**
for industry-standard PV and agrivoltaic systems



Source: Approximate data from Fraunhofer, "Agrivoltaics" (April, 2022), p. 35.

5. Outlook

5.1 Solar PV capacity growth

APV stands to benefit substantially from exponential growth in projected global and European solar PV generation in the coming decades. The technology increased generation by 22 % in 2021 to exceed 1,000 TWh worldwide. It is also becoming the lowest-cost option for new electricity generation globally and, in order to meet the Net Zero Emissions by 2050 Scenario, solar PV is expected to grow by an annual average of 25 % in the period 2022-2030 to approximately 7,400 TWh worldwide, a more than threefold increase in annual capacity deployment until 2030. In Europe alone, generation capacity is projected to increase markedly from 198 TWh in 2021 to 688 TWh by 2030 to 1,184 TWh by 2050.[26]

5.2 European climate policies

In its objective of reducing net greenhouse gas emissions by at least 55 % by 2030 and becoming climate neutral by 2050, as well as rapidly reduce dependence on Russian fossil fuels, the European Commission's REPowerEU plan aims to have renewable energy sources account for at least 45 % of the EU's overall energy mix by 2030. The plan's three pillars of increasing energy efficiency, scaling up renewables in power generation and diversifying the EU's energy supplies will be instrumental in driving investment into solar PV and wider support mechanisms, accelerating capacity growth.[27]

5.3 Lower capital costs

EU solar PV capital costs are also expected to fall considerably from 810 USD/KW in 2021 to 530 USD/KW in 2030 to 410 USD/KW in 2050 thanks to scale effects, technology advances, more widespread technical knowhow, improved regulatory environments and increases in targeted concessional public finance.[28] Moreover, potentially lower capex, thanks to lower ceiling costs, and opex, due to self-consumption of power, are key financial benefits to PV greenhouse operators. Overall, total costs for APV systems are also lower than those for roof-mounted PVs.[29]

5.4 Resolution of land-use competition

Arguably the greatest benefit of agrivoltaics is its resolution of land-use competition and conflict. APVs boost multi-functional land-use on pastureland, benefiting the PV operator but also the farmer in increasing animal welfare due to shading in dry and hot summer months. Overhead or interspace PVs ensure the continued agricultural use of fertile arable land.

5.5 APV's synergistic potential

Agrivoltaic systems thus hold significant potential for sustainable energy production and food security. By combining solar energy generation with agricultural production, these systems offer a range of benefits including increased land use efficiency, improved crop yields, reduced water consumption, lower soil erosion, greater shading, lower evaporation, greater solar module efficiency, income diversification for the farmer and a clean and renewable energy source.

As technology and research continue to evolve, it is likely that agrivoltaic systems will become more efficient, scalable, and accessible, making them a key solution for addressing the challenges of the land economy dilemma whilst meeting ambitious global, European and national renewable energy targets.

26 IEA, "World Energy Outlook: executive summary" (October, 2022); IEA, "Solar PV" (September, 2022). Available at: *Solar PV – Analysis - IEA*.
27 EU Commission, "Renewable energy targets" (April, 2023). Available at: *Renewable energy targets (europa.eu)*.
28 IEA, "World Energy Outlook: executive summary" (October, 2022).
29 Fraunhofer, "Agrivoltaics" (April, 2022), p. 35.

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