White Paper - ETIP PV Integrated PV Working Group

Agrivoltaics in European Countries and Happy Farmers

ETIP Photovoltaics

The European Technology
and Innovation Platform
for Photovoltaics

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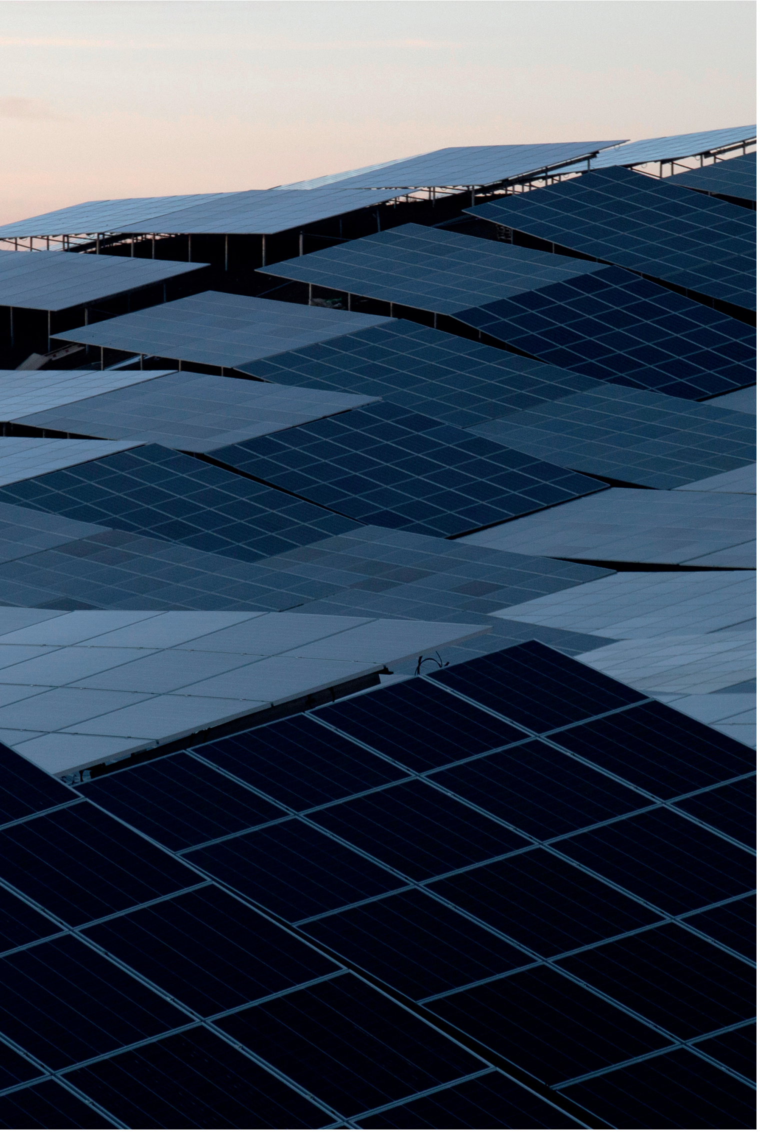

The European Technology & Innovation Platforms (ETIPs) have been created by the European Commission in the framework of the new Integrated Roadmap Strategic Energy Technology Plan (SET Plan) by bringing together EU countries, industry, and researchers in key areas. They promote the market uptake of key energy technologies by pooling funding, skills, and research facilities. The European Technology and Innovation Platform for Photovoltaics (ETIP PV) mobilizes all stakeholders sharing a long-term European vision for PV, helping to ensure that Europe maintains and improves its industrial position, in order to achieve a leadership position within the global PV market.

AgriPV systems, a novel synergistic dual use of the same plot of land for solar energy generation and agriculture production, aim to align renewable energy with sustainable agriculture goals. This research focuses on farmers' experiences with AgriPV systems, assessing the way those influence agricultural practices, resource use, and farming sustainability. Conducted by the ETIP PV Integrated PV Working Group, the survey explores farmers' reasons for adopting AgriPV, its practical effects, and changes in farming practices and resource management. It also examines the technicalities of AgriPV systems, farmer satisfaction, challenges encountered, and obstacles to broader adoption. The findings are summarized in a white paper, providing insights into AgriPV innovation from the farmers' perspective.

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1.
Introduction

Agri-PV, an expanding sector, incorporates a variety of technological solutions and agricultural meth- ods. This research is designed to capture the perspective of farmers, covering details about their farms, motivations for adopting solar panels, satisfaction with Agri-PV, system specifications, impacts on in- puts, changes in farming practices, environmental effects, and challenges faced. The primary objective is to gather insights that contribute to a comprehensive understanding from the viewpoint of a critical stakeholder—the farmer.

Agri-PV as a solution for dual-use cropland recognizes solar photovoltaic (PV) technologies for sup- plying renewable electricity and suggests a code of ethics to ensure the livelihoods of farmers and local communities while prioritizing crop production in Agri-PV systems [1]. Optimization of land use through Agri-PV systems examines the combination of soil-grown crops with photovoltaic panels installed above the ground, highlighting the system's ability to improve land productivity without negatively affecting crop yield [2]. The selection of solar panel technology and plant design in Agri-PV is influenced by local climate, agricultural practices, and specific project goals. Innovations in Agri-PV through spectrum separation introduce a novel agriculture photovoltaic system that combines concentration photovoltaic (CPV) and diffractive interference technology, allowing for cost-effective simultaneous agricultural use and electricity generation on the same land [3]. Machine Learning for Agri-PV Design describes a digital-twin and machine-learning framework to optimize solar power flow through Agri-PV systems, enabling rapid design and deployment of complex systems [4]. Economic and Environmental Assessment of Agri-PV Systems provides a thorough analysis of the environmental and economic performances of Agri-PV systems, emphasizing their potential to preserve agricultural land while generating renewable energy [5].

This comprehensive exploration of Agri-PV encompasses vital aspects, providing an in-depth understanding of this dynamic field. It explores system data, offering insights into geographical specifics while highlighting the benefits of utilizing land for both agriculture and solar energy. Statistical presentations using graphs and tables enhance the exploration, and a literature review sheds light on the diverse technologies involved in Agri-PV. The focus on PV panel technologies and agricultural machinery ensures a comprehensive grasp of the technological landscape. The detailed examination of system innovations, including design, mounting, and digital twin technologies, adds depth to this overview.

The inclusion of innovative case studies enriches the narrative, offering practical insights into diverse applications and successes within the Agri-PV domain. To understand the multifaceted impact of Agricultural Photovoltaics (Agri-PV) on the farming sector, our research focused on gathering and analyzing data directly from the agricultural community. Here are some expected findings based on the prepared survey which we designed to interview farmers from European countries, e.g. Austria, Germany, Italy, and the Netherlands.

Further details on the Agri-PV farms that the researchers in this study have engaged with or intend to engage with will be explored in the Preliminary Results and Discussions section. However, based on the interviews conducted thus far and the survey designed, the researchers in this work anticipate certain findings. These will be elaborated upon in the Preliminary Results and Discussions section, where the findings to date will also be detailed.

- **Farmer Perspectives and Adaptations to Agri-PV Systems:** The survey aimed to capture farmers' experiences with Agri-PV systems, exploring motivations for adoption and how these systems integrate with various farming practices. It examined the types of crops grown, the nature of farming operations, and specific geographical and soil characteristics. The survey also sought to understand farmers' satisfaction with Agri-PV, their willingness to recommend it to others, and any necessary adaptations in farm management due to these systems.

- **Impact of Agri-PV on Farming Practices and Resource Usage:** This part of the survey concentrated on the effects of Agri-PV systems on resource usage, such as water, fertilizer, and pesticides, and overall agricultural production. It aimed to gather empirical data on the environmental and economic impacts of Agri-PV, focusing on biodiversity, water management and saving, drought resilience, and crop damage mitigation during extreme weather events.

- **Challenges, Limitations, and Future Prospects of Agri-PV:** The survey addressed the less satisfactory elements of Agri-PV, identifying areas for improvement and challenges in integrating these systems with the local landscape structure and traditional farming. It explored barriers to wider Agri-PV adoption, gathering insights on misconceptions and limitations perceived by farmers.

2.
Country-Specific Developments

The EU's 2030 solar PV goal under REPowerEU aims to increase installed capacity to 720 GWp, four times the 2021 level. Already achieving over 211 GWp, the EU must raise the annual installation rate to over 100 GWp. Agri-PV, using just 1% of the EU's arable land, is crucial in this strategy, offering a more land-efficient alternative to biofuels and aligning with the EU's Solar Energy Strategy. The SolarPower Europe Best Practice Guidelines for Agri-PV support this sustainable initiative. In the following, we will briefly discuss recent actions taken by some European countries in this regard.

- **Italy** The Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) launched in 2021 the Task Force Sustainable Agrivoltaics (Agrivoltaicvo Sostenibile @ENEA), promoting the concept of sustainable Agri-PV systems: those aiming at synergies not only between energy and food but also within the landscape, ensuring public acceptance [6],[7]. In 2021, ENEA and ETA-Florence started the Italian Network Sustainable Agrivoltaics, whose aim was to share research questions and good practices within the development of sustainable Agri-PV systems. In November 2022 the Italian Association for Sustainable Agrivoltaics was established (AIAS). The concept of Sustainable Agrivoltaics had relevant impact on policy making and in June 2022 ENEA and other research institutions and key stakeholders were directly involved in the writing of the Environmental Ministry guidelines on the development of Agri-PV systems. Those introduced the category of "advanced Agri-PV systems", the only one currently admittible to public funds. Advanced Agri-PV are sustainable Agri-PV which guarantee a monitoring program on crops growth, water saving and soil quality enhancement. Italy is currently investing in experimental Agri-PV projects. In the Environmental Ministry Decree 14th February 2024, almost 1,1 billion euros public funds are currently attributed to Investment 1.1 (Agri-PV development) part of the Mission 2 (Green Revolution and Ecological Transition), Component 2 (Renewable Energy hydrogen, network and sustainable mobility), of the National Recovery and Resilience Plan funds. The aim is to develop 1.04 GW capacity, focusing on integrating Agri-PV systems in the existing Agri-environmental systems. On this capacity, 300 MW are exclusively dedicated to agriculture entrepreneurs, as defined by law, in individual or corporate forms for small scale Agri-PV systems (not exceeding 1 MW). The other 740 MW are accessible also to temporary business associations (investment funds) which include at least one agriculture entrepreneur for larger scale Agri-PV systems (without installed capacity limit) (DM 14th February 2024). Undoubtedly Italian legislation and funding schemes are strongly supporting Agri-PV systems as innovative and experimental tools for farming.

- **Germany** led in Agri-PV development with initial standards and solar tenders in 2022, but faces legal challenges as these systems are not fully integrated into the legal framework, necessitating further legal adjustments, as analyzed by [8]. Trommsdorff et al. (2021) evaluated the technical feasibility and design of Agri-PV systems in Germany, highlighting their ability to increase land productivity, especially during drought conditions [9]. Such an evolution of policy measures for photovoltaic technology is generally discussed within [10] that delineates the role played by Ger- many in fostering the most paramount FIT (feed-in tariff).

  It acquaints that this particular policy measure has proved to be quite effective enough in enhancing solar energy's growth, incorporating Agri-PV systems not only in Germany but also across the globe.

- **France** is the first-mover through European Agri-PV. France's approach is led by innovation tenders which shows a model for rapid expansion through the market. This country notably provides a clear definition of Agri-PV through ADEME (Agence de l'Environnement et de la Maîtrise de l'E´ nergie) in 2021, which sets up criteria for the PV system to be considered as such, for instance regarding contribution to agricultural production (e.g. protection of crops), limited or positive impact on yields, incidence on farmers revenues. This definition & the establishment of national standards allow for clearly defined Agri-PV systems and facilitate support to such installations under the Law on the acceleration of the production of renewable energy (LOI n° 2023-175 du 10 mars 2023). Regional criteria are considered for specific thresholds such as PV coverage or impact on yield to meet the needs of different agricultural productions in different climates.

- **The Netherlands** is aligning Agri-PV projects with its CAP Strategic Plan, ensuring PV installations complement agriculture. Smit et al. (2020) stress considering regional differences in the Netherlands' CAP NSP, highlighting the importance of strategies that balance agricultural and environmental concerns for successful Agri-PV integration [11]. In the Netherlands, farmers join Agri-environmental collectives for economic and environmental reasons, with such collectives enhancing cooperation and communication. This dual motivation is key to successfully integrating Agri-PV projects with environmental goals [12].

3.
Technology

Solar panel technologies employed in Agri-PV concepts are designed to integrate sustainable energy generation with agricultural practices, creating a synergistic and environmentally friendly approach to land use. The choice of solar panel technology and plant design in Agri-PV depends on factors such as local climate, agricultural practices, and the specific goals of the project.

3.1
Solar panels technologies

Several solar panel technologies are suitable for Agri-PV installations, each satisfying to specific requirements.

3.1.1
Standard Photovoltaic Modules

Traditional solar panels remain a popular choice for Agri-PV applications. These modules are mounted on elevated structures, providing shade for crops or livestock beneath while generating renewable energy. Illustrated in Figure 1, some Agri-PV projects incorporate specially designed solar modules that allow controlled light penetration for crops beneath. Customized designs aim to maintain optimal conditions for plant growth while maximizing solar energy production.

3.1.2
Bifacial Photovoltaic Modules

Bifacial solar panel technology is a cutting-edge approach to solar energy generation, revolutionizing efficiency by capturing sunlight from both the front and rear sides of the module by opening to rear side of tradition solar cell to absorb light.

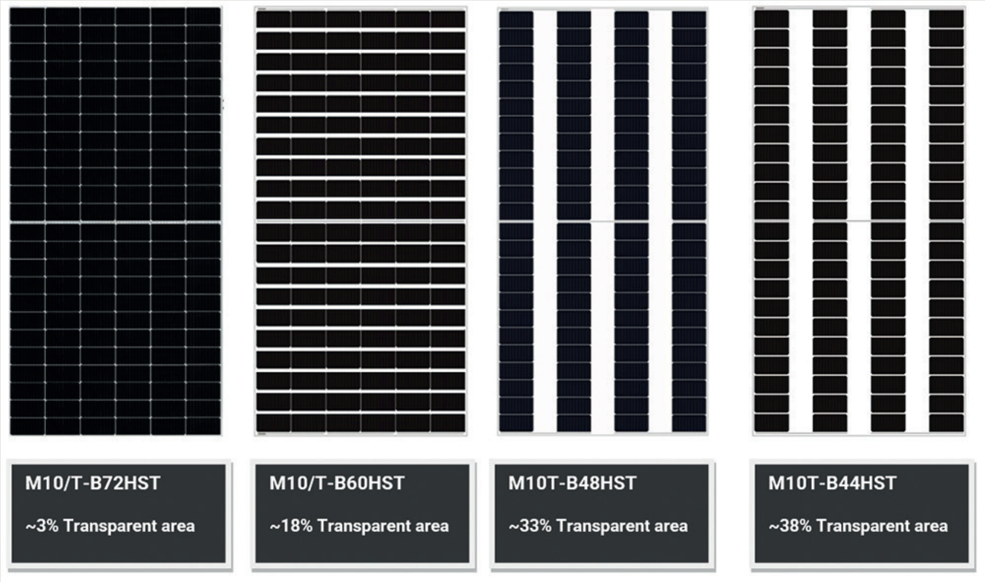

Figure 1:
Some examples of standards monocrystalline solar PV with different transparency [13].

In contrast to traditional monofacial panels that absorb sunlight solely from the front surface, bifacial modules utilize reflected light from surrounding surfaces, such as the ground or nearby structures. These panels feature transparent materials on both sides, allowing sunlight to pass through. This design significantly boosts energy yield, with improvements ranging from 5% to 30%, depending on factors like albedo and installation environment. Bifacial solar cells have demonstrated conversion efficiencies of 19.4% on the front and 18.1% on the rear under standard illumination conditions, indicating a promising potential to lower the costs of solar electricity compared to conventional monofacial solar cells [14]. More recent research showed that a bifacial SHJ cell with 25.6% cell efficiency creates a 144 half-cut module, 83×166 mm2 cells, with 470 Wp front and 415 Wp rear, e.g. bifaciality of 88% [15]. The albedo of surrounding surfaces, site-specific conditions, and panel tilt and elevation all influence the performance of bifacial panels [16].

Figure 2:
The Photovoltaic modules developed by Insolight, based at EPFL's Innovation Park

Lenses embedded in a thin glass layer focus sunlight on tiny, high-efficiency, space-grade solar cells below. However, Insolight dropped this approach and focused now on standard transparent bifacial panels [17].

3.1.3
Concentrating PV panels

Concentrating PV modules are well known for their high efficiency exceeding 40% and a very high cost. Optical lenses and protective glass can significantly enhance the efficiency of solar concentrators in Agrivoltaics systems by focusing sunlight onto photovoltaic cells while allowing for controlled light transmission to the crops below [18]. Shown in Figure 2a, a start-up company has developed translucent solar modules through a new design that allows cost reduction. Rather than covering the full module surface, the cells only cover 0.5% of the panel surface and are covered with protective glass and optical lenses to concentrate and direct sunlight onto them at around 100 times the intensity of standard solar glass reaching an efficiency of over 30% and purportedly let through up to 78% of sunlight. The cells are reportedly able to track the sun through horizontal movement. Luminescent Solar Concentrators (LSCs) offer a promising approach for Agri-PV systems, enabling simultaneous electricity generation and agricultural productivity. Recent advances focus on eco-friendly materials like carbon dots and quantum dots, which provide high luminescence with minimal environmental impact. Zdraˇ zil et al. demonstrated a carbon dot-based tandem LSC with significant optical efficiency and transparency, suitable for Agrivoltaic applications [19]. Bradshaw et al. highlighted doped nanocrystals' efficiency in reducing reabsorption losses, critical for LSC performance [20]. These developments highlight LSCs' potential in sustainable food and energy production.

At UC Santa Cruz, innovative research greenhouses have incorporated luminescent solar concentrators (LSCs) into their design, creating a dual-purpose environment that supports both agriculture and renewable energy generation, illustrated in Figure 3, [21]. These LSCs are designed to control the sunlight from spectral regions that are less critical for plant growth, converting it into electricity without compromising the health of the crops. As a result, vegetables such as tomatoes and cucumbers flourish within these spaces, just as robustly as they would under traditional agricultural conditions.

Figure 3:
Luminescent Solar Concentrator (LSC) PV integration for greenhouse

3.1.4
Thin-Film panels

Thin-film solar panels are becoming increasingly popular in agriculture due to their flexibility, lightweight design, and easy integration into various environments. Constructed from materials like amorphous silicon (a-Si), cadmium telluride (CdTe), or copper indium gallium selenide (CIGS), these panels offer specific advantages for agricultural settings. Advantages include their flexibility, making them suitable for uneven surfaces and integration into existing structures. Their lightweight nature reduces structural loads, benefiting structures like agricultural roofs. Thin-film panels excel in diffuse or low-light conditions, making them ideal for areas with partial shading. Additionally, their cost-effective production contributes to overall project savings.

Considerations involve lower efficiency compared to crystalline silicon panels, emphasizing the importance of evaluating available space and energy requirements. Understanding potential degradation over time is crucial for estimating long-term performance, and the need for more space due to lower efficiency should be carefully assessed. Different thin-film technologies (a-Si, CdTe, CIGS) offer unique characteristics, emphasizing the need for tailored technology choices based on specific agricultural project requirements. A comprehensive assessment of specific needs, available space, and environmental conditions is crucial when considering thin-film solar panels for agricultural applications.

Based on CIGS technology, an innovative module concept was designed by TubeSolar AG. An encapsulated glass tube contains a thin film CIGS cells inside. 40 PV tubes are combined to form a system module. There is a gap between the tubes so that the module is permeable to the sun and water. This results in extremely robust, weatherproof, and at the same time translucent solar modules that can be used to combine protection function and power generation. The company is currently investigating the potential of Perovskite as an alternative technology to CIGS.

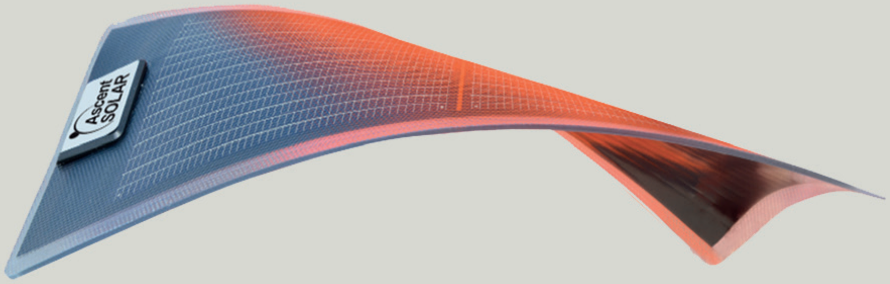

Figure 4:
Flexible thin film solar module by Ascent Solar (ascentsolar.com)

(a)

(b)

Figure 5:
Integration of thin film solar panel for Agri-PV by TubeSolar AG

The integration of semi-transparent organic solar cells (ST-OSC) into greenhouse operations presents a promising synergy between sustainable agriculture and renewable energy production. Research focusing on the cultivation of red leaf lettuce under these modified conditions has demonstrated that the incorporation of ST-OSC technology does not adversely affect plant growth, yield, or nutrient content [22]. These findings are significant as they suggest that greenhouses can maintain high-intensity agricultural production while also functioning as solar energy generators. As illustrated in Figure 6 The reported power conversion efficiency of these organic solar cells ranges from 6% to 12%, indicating a substantial potential for on-site energy production. The economic implications of such a dual-system approach are favorable, providing a model for agricultural operations that minimize energy costs and reliance on non-renewable power sources, without compromising crop output.

3.2
Mounting structure types and designs in Agri-PV

When establishing an Agrivoltaic facility, it is essential to account for its impact on agricultural operations and address specific requirements. The design and construction phases should carefully consider potential issues like soil compaction and changes in water circulation, as these factors can adversely affect the quality of agricultural land. Additionally, the installation of solar panels must consider the dimensions, width, and rotational radius of agricultural equipment used for crop maintenance. Attention should also be devoted to the proper provision and protection of external cables, including the depth of buried cables, taking into consideration the presence of personnel, agricultural machinery, or animals in the vicinity. The integration of photovoltaic (PV) systems with crop cultivation is a dynamic and evolving field marked by a lack of standardization in designs and applications. Various innovative approaches are currently under exploration, reflecting the dynamic nature of these systems.

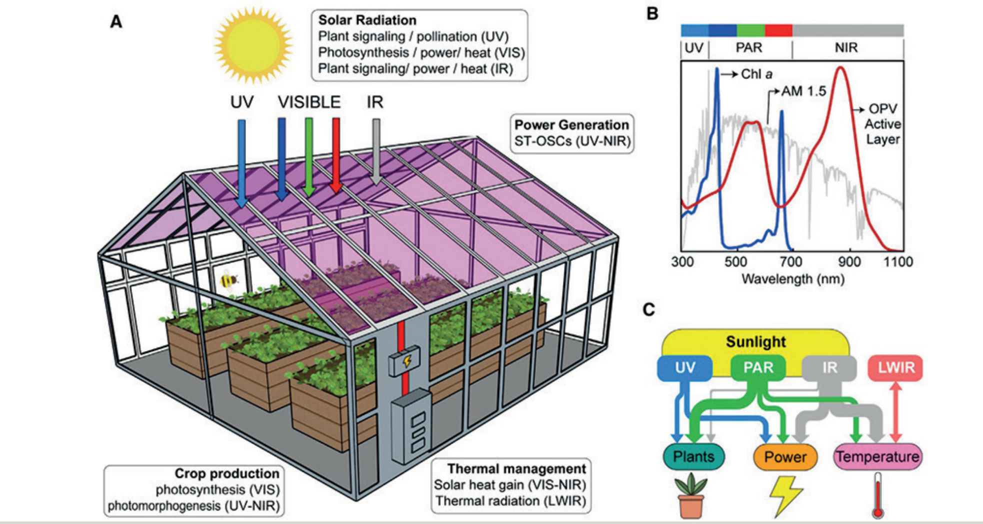

Figure 6:
Balancing crop production and energy harvesting in organic solar-powered greenhouses [22].

3.2.1
Mounting structures

Various design options are available, ranging from configurations with bifacial vertical panels that incorporate crops between them or serve as fencing for crops or livestock. Alternatively, more conventional PV system structures can be used, where crops are planted exclusively between the panels. Elevated structures, facilitating the passage of harvesting machinery beneath the panels, contribute to this diversity. These include" stilt-mounted" designs with thin posts at a lower density of PV panels designed to enhance light penetration, and traditional reinforced and elevated PV structures.

(a) Overhead with vertical clearance

(b) Vertical clearance

(c) Interspace PV with clearance

Figure 7:
Various design options for Mounting systems

3.2.2
Shade optimization

To avoid modules shading too much and degrading agricultural yield, enhancing shade control efficiency with automatic panel movement using IoT sensors could be integrated, see Figure 8. These sensors measure crucial factors such as plant type, soil moisture, sun radiation, and microclimate. By leveraging real-time data, this system optimizes the positioning of panels to create an ideal environment for plant growth, ensuring a smart and responsive approach to agricultural shading.

Retractable, passive shades are a standard in controlled environment agriculture (greenhouses) to protect crops from excessive sunlight. A startup company is replacing passive shades with photovoltaically augmented screens to harness the blocked sunlight. The photovoltaic area can be tailored to deliver typical shading levels between 40% and 70%, depending on the region and type of crops. High- efficiency silicon solar cells are embedded in lightweight encapsulation materials to allow for a drop-in replacement of passive shade cloths. As shown in Figure 9, like conventional shades, the photovoltaic screens can be retracted and expanded on demand allowing for flexible light management and ideal shading conditions for the crops.

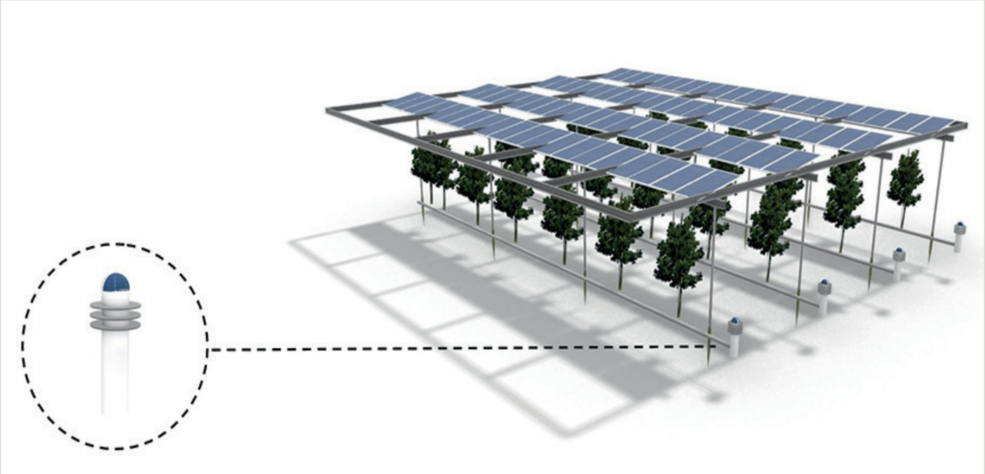

Figure 8:
Shade optimization implementing IoT sensors

3.2.3
Rainfall and water management

In the event of intense rainfall, the strong runoff generated by PV modules may result in soil erosion and the creation of gullies. It is essential to consider specific technical designs of the installation features aimed at enhancing rain distribution or effectively collecting runoff from the panels. Thus, in Agri-PV systems, rainwater harvesting becomes an integral part of the water management strategy. By placing rainwater collection systems, such as gutters and storage tanks, farmers can capture and store rainwater runoff from both the solar panels and adjacent agricultural areas. This harvested rainwater can then be utilized for irrigation during dry periods, reducing reliance on external water sources and promoting water sustainability. The integration of rainwater harvesting into Agri-PV aligns with the principles of circular agriculture, where resources are efficiently recycled within the system.

Photo: Luca, Unsplash.com

4.
Results and Discussions

Although our interviewing process with farmers is ongoing and has been somewhat slow due to delays in scheduling meetings with these stakeholders, we will present our preliminary findings from seven selected farms, which are to be thoroughly analyzed and formally presented at a later stage.

In Italy, researchers conducted interviews at two distinctive farms that have integrated Agricultural Photovoltaic (Agri-PV) systems into their operations, each addressing the unique challenges and opportunities of their regional agricultural practices. The first farm, located in the Po Valley near Piacenza in the Emilia-Romagna region, specializes in growing grains and corn. It utilizes an advanced Agri-PV system featuring bi-axial trackers mounted on structures four meters high. This setup not only facilitates increased crop yield but also supports sustainable farming practices through minimal soil disturbance and innovative sub-irrigation systems, which have proven beneficial particularly in clay soils. Despite the loss of 20 percent of arable land due to the installation of PV structures, the farm has seen a net positive impact, including a 4 percent increase in dry matter corn production as monitored over three years by the Catholic University in Piacenza.

The second farm is situated in Gioia del Colle, close to Bari in the Apulia region. This farm diversifies its agricultural production by cultivating wine grapes alongside grains. Its Agri-PV system consists of fixed panels installed 2.9 meters above the ground, enabling dual land use for both energy generation and viticulture. The strategic placement of these panels allows for delayed grape harvesting by four to six weeks, enhancing the quality of the wine and even enabling the production of sparkling wine—a novelty in southern Italy made possible by the moderated microclimate under the panels. The system also collects rainwater, helping to maintain a balance in the hydro-climatic conditions of the area, reducing the risk of pests and diseases, and shielding the crops from extreme weather.

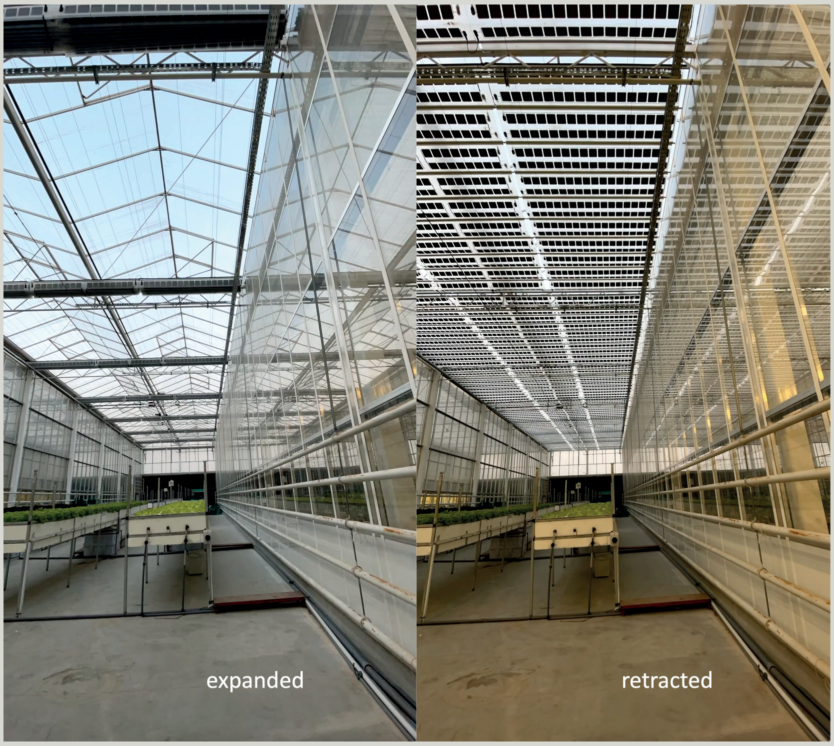

Figure 9:
The Photovoltaic screens can be retracted and expanded

Figure 10:
Proof of concept for the rainfall collection beside an Agri-PV system

Both farms illustrate the tangible benefits of Agri-PV systems in enhancing agricultural productivity and sustainability. However, they also reflect the inherent challenges such as the uncertainties related to crop growth under new technologies, the impact on land usage, and economic factors like fluctuating production costs and market stability. Despite these challenges, both farmers expressed a positive overall experience with the Agri-PV systems, noting significant improvements in crop management and yield, and would recommend the adoption of such systems to other farmers seeking to innovate and sustain their agricultural practices in the face of climate change and economic pressures.

Moving to the Netherlands, the focus of interviews with farmers was to delve into their motivations for setting up pilot Agri-PV systems, their satisfaction with the outcomes, and their perspectives on why wider adoption has not yet taken hold.

Two farmers grow soft fruit under raised PV systems, with the rows of plants below long, narrow rows of PV panels. The third is a dairy farmer with rows of vertical panels on grassland, which is grazed and harvested. Where one of the fruit farmers has mechanized a large part of its labour, the other has more traditional methods. The fact that these three enterprises have such varying operations illustrates how each Agri-PV system must be tailor-made. But despite the different agricultural practices, there is a large overlap in their opinions on (their) agri-PV systems. Overall, the farmers were very positive about how it impacted their activities. The main benefits mentioned were improvement of labour conditions by the microclimate below the panels for the fruit farmers. Also, the PV system reduces or even removes the need for netting, which saves a lot of labour and replacement costs. Sheep are often found in the shadows of the vertical modules.

The dairy farmer is satisfied with the growth conditions of the grass and the way the animals are using the shade or ignoring the PV panels. As the land is extensively farmed there was and is no usage of pesticides and irrigation water. Only fertiliser originating on the farm is applied. Both fruit farmers indicate that under the solar panels less water, via drip irrigation in pots, is needed, values around 30-40% are mentioned. No significant changes in usage of pesticides, except that fungicides are somewhat less applied under the PV panels. There is also less damaged fruit due to high direct sun conditions under the PV systems, but total yield is also reduced.

Have things changed since converting the agricultural land to an Agri-PV field? There has been no significant change in the Way of working.

For the dairy farm the same machines are used, but the farmer is conscience of the damages that stones or cows could inflict on the PV system. The PV systems above soft fruit do not restrict the way of working on the fruit. It even improves the working conditions. There is the potential to (directly) collect rainwater. Because less light reaches the ground under the fruit Agri-PV, the grass between the rows grows less. This has the advantage that the grass cover extracts less nutrients from the soil, but on the other hand the water retention is lower.

No impact on biodiversity has been measured, but one farmer mentions that mammals are more often seen below the panels. Also, one farmer indicates that the system and the visual integration in the (agricultural) landscape are not so good.

All farmers indicate that they would like to benefit themselves (more) from the generated electricity and use some of the energy directly on the farm. Farmers do not profit from the ¿100% land use efficiency that Agri-PV provide, since both legal and financial systems regard Agri-PV as two separate entities, which perform less well compared to single-use farms or single-use solar parks. As Agri-PV systems are still under development, government support would be appreciated particularly tackling the additional burdens of Agri-PV: the higher CAPEX, e.g. mounting structures, more (expensive) cabling, for the PV project developer, the uncertain classification of the land use for the farmer and the project developer and larger, financial benefits for the farmers and landowners. The latter could be achieved by Agri-PV stimulating subsidies or smart ways to use part of the electricity directly on the farm. One farmer also mentioned that Agri-PV produce could and should be marketed as a positive choice.

Neighbours are interested, but care about their traditional way of working. The additional benefits are not enough for widespread adaptation yet. The Agri-PV farmers are keen to show their colleagues their systems, but they also indicate the risks.

The results from Austria confirm these findings. The interviewee has a vertical PV system in combination with the production of hay or silage. The installation does not affect the normal operation

of the farmland, the farmer is satisfied with the PV system, but sees the administration involved in the permitting and grid connection as long and tiresome procedures as bottlenecks for fast implementation. The final interview was conducted with a German farmer, growing cash crops like grains and clover with two PV installations. The first-built PV system consists of horizontal single-axis trackers that are atypically having the rotation axis running East-West, with the panels rotating between horizontal and south-facing. The second is more standard North-South oriented with alternatingly rows having bifacial and monofacial modules, with the panels rotating from east-facing via horizontal to west-facing. Again, overall satisfied with the combination of farming and generating solar electricity. Also, there is some additional protection against hail and heavy rain. Some points of attention are the shading that occurs a few weeks before the harvest when growing corn. Also, the GPS driven machinery drives a bit slower. Estimation is an additional worker-hour per year per hectare. The farmer stresses the lack of knowledge on Agri-PV among fellow farmers, but also that agricultural yield should be leading.

We have simulated the photon sharing between photovoltaics and photosynthesis for the Agri-PV systems of the interviewed farmers. The distribution of the incoming irradiance is shown in 11 for seven Agri-PV systems, located in the Netherlands, Germany and Austria. The soft fruit Agri-PV systems show a 50:50 division of the irradiance. We note that the distribution of irradiance on ground level for these systems is very homogeneous.

This is partly due to the partial transparency of the applied PV panels and partly because the system is rather high above ground level compared to the dimensions of the PV tables and gaps between them. In contrast, the tracker and vertical system show more variation in relative irradiance on soil level. Although we reported the distribution of irradiance over PV and agriculture, we would like to stress that these systems respond rather differently to light intensity. In the first approximation, the power conversion in a solar park is linear with the light intensity. Minor deviations occur at very low light intensity when the voltage decreases fast; resistive losses are quadratic with current and will cause a less than linear increase in power with irradiance at very high intensities; with increasing irradiance the panels also heat up, again causing a small decrease in power. In contrast, photosynthesis is highly non-linear. With increasing PAR light intensity, the carbon fixation rate increases with decreasing pace. Depending on conditions, there is either a maximum carbon fixation rate or this rate even decreases in full (summer) sun conditions. In crop growth with some water stress, a decrease in light intensity could lead to a much smaller decrease in crop production. At higher water or temperature stresses, crop production might even increase due to the lower irradiance and milder conditions.

For tracked systems, the area directly below the PV panels and mounting structure has the lowest irradiance. These areas could contribute to biodiversity and natural pest control as the irradiance level and accessibility for farming vehicles prevents agricultural but will allow significant photosynthesis for a biodiverse zone. The area between the trackers shows a high level of irradiance with some variations. The transition from the high-irradiance zone suitable for agriculture and the low-irradiance zone takes place within a metre. Depending on choice of crops and machinery, these transition zones could either add gradients to the biodiverse zone or additional crop-productive area.

For vertical systems that have a gap between ground level and the bottom of the system, the irradiance will be lowest in a zone next to the solar fences. The region in between will have a fairly high irradiance that is also rather homogeneous. Any gap between panels and mounting structure would add to the soil/crop irradiance and improve homogeneity, refer to Figure 11.

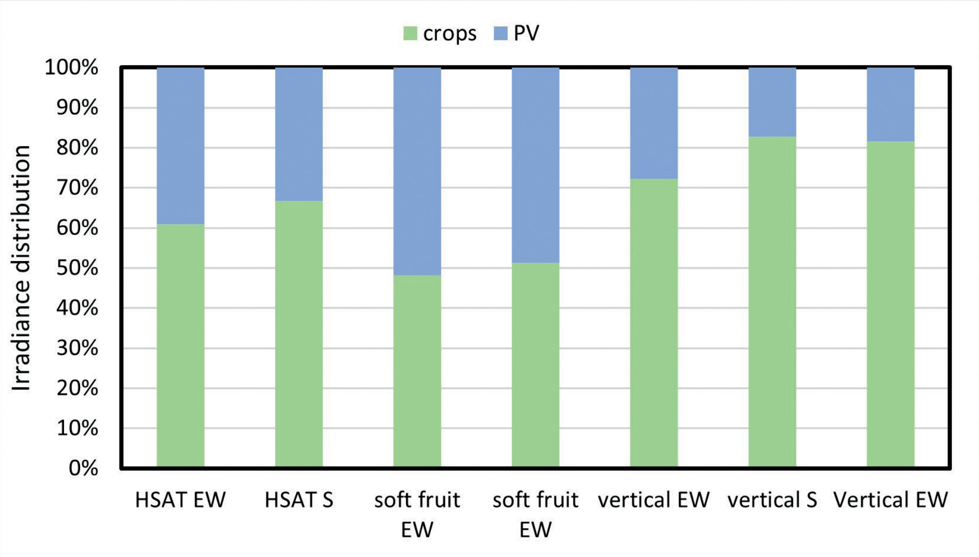

Figure 11:
Soil irradiance for the Agri-PV systems of the respondents in DE, AU and NL.

Country	Farm Description	Main Benefits	Challenges	Farmer Feed-back
Italy	In Monticelli d'Ongina, Emilia Romagna, this farm grows winter and summer cereals under 4-meter-high structures. The Agri-PV, not owned by the farmer, provides additional income through surface rights.	It leads to increased income and a 4% boost in corn production, monitored over three years by the Catholic University in Piacenza. Additionally, it enhances farming sustainability system, particularly beneficial for clay soil.	The main challenge is the loss of 20% of arable land	The final balance is positive and the farmer would recommend it to other farmers.
Italy	Located in Gioia del Colle, Apulia, this farm uses a 2.5-hectare Agri-PV system with 2.9-meter-high fixed panels for cultivating cereals and vineyards in dry conditions. The system, owned by the farmer, supports both agriculture and solar energy production.	The Agri-PV system allows for delayed grape harvesting by 4-6 weeks and enables the production of sparkling wine in southern Italy. It also improves the hydro-climatic balance, reduces pest risks, and shields crops from extreme weather, while collecting rainwater for irrigation.	Challenges include uncertainties in harvest revenue, climate, and rising production costs, which Agri-PV systems can alleviate. Additionally, specific challenges relate to the system's innovative, handcrafted nature, like uncertainty in long-term vineyard growth without extensive observational data.	The final balance is positive and the farmer would recommend it to other farmers.
The Netherlands	Soft fruit under raised PV systems	Improved labor conditions, less water via drip irrigation (30-40%), less fungicide Need for netting reduced, saving labor and costs	visual integration in the (agricultural) landscape are not so good	Very positive, no significant change in working methods
The Netherlands	Soft fruit under raised PV systems (Traditional methods)	Improved labor conditions, less water via drip irrigation (30-40%), less fungicide Need for netting reduced, saving labor and costs	Not specified	Very positive, no significant change in working methods
Austria	Hay/silage with vertical PV system	Not specified	Long and tiresome permitting and grid connection procedures	Satisfied, but administrative burden noted
Germany	Grains and clover with horizontal single-axis trackers & bifacial/monofacial modules	Additional protection against hail/strong rain, less shading before harvest	Slow GPS machinery, additional labor hour per hectare/year	Satisfied, but points out lack of knowledge among peers and marginal agricultural yield impact

decreasing pace. Depending on conditions, there is either a maximum carbon fixation rate or this rate even decreases in full (summer) sun conditions. In crop growth with some water stress, a decrease in light intensity could lead to a much smaller decrease in crop production. At higher water or temperature stresses, crop production might even increase due to the lower irradiance and milder conditions.

For tracked systems, the area directly below the PV panels and mounting structure has the lowest irradiance. These areas could contribute to biodiversity and natural pest control as the irradiance level and accessibility for farming vehicles prevents agricultural but will allow significant photosynthesis for a biodiverse zone. The area between the trackers shows a high level of irradiance with some variations. The transition from the high-irradiance zone suitable for agriculture and the low-irradiance zone takes place within a metre. Depending on choice of crops and machinery, these transition zones could either add gradients to the biodiverse zone or additional crop-productive area.

For vertical systems that have a gap between ground level and the bottom of the system, the irradiance will be lowest in a zone next to the solar fences. The region in between will have a fairly high irradiance that is also rather homogeneous. Any gap between panels and mounting structure would add to the soil/crop irradiance and improve homogeneity, refer to Figure 11.

Photo: Raphael Cruz, Unsplash.com

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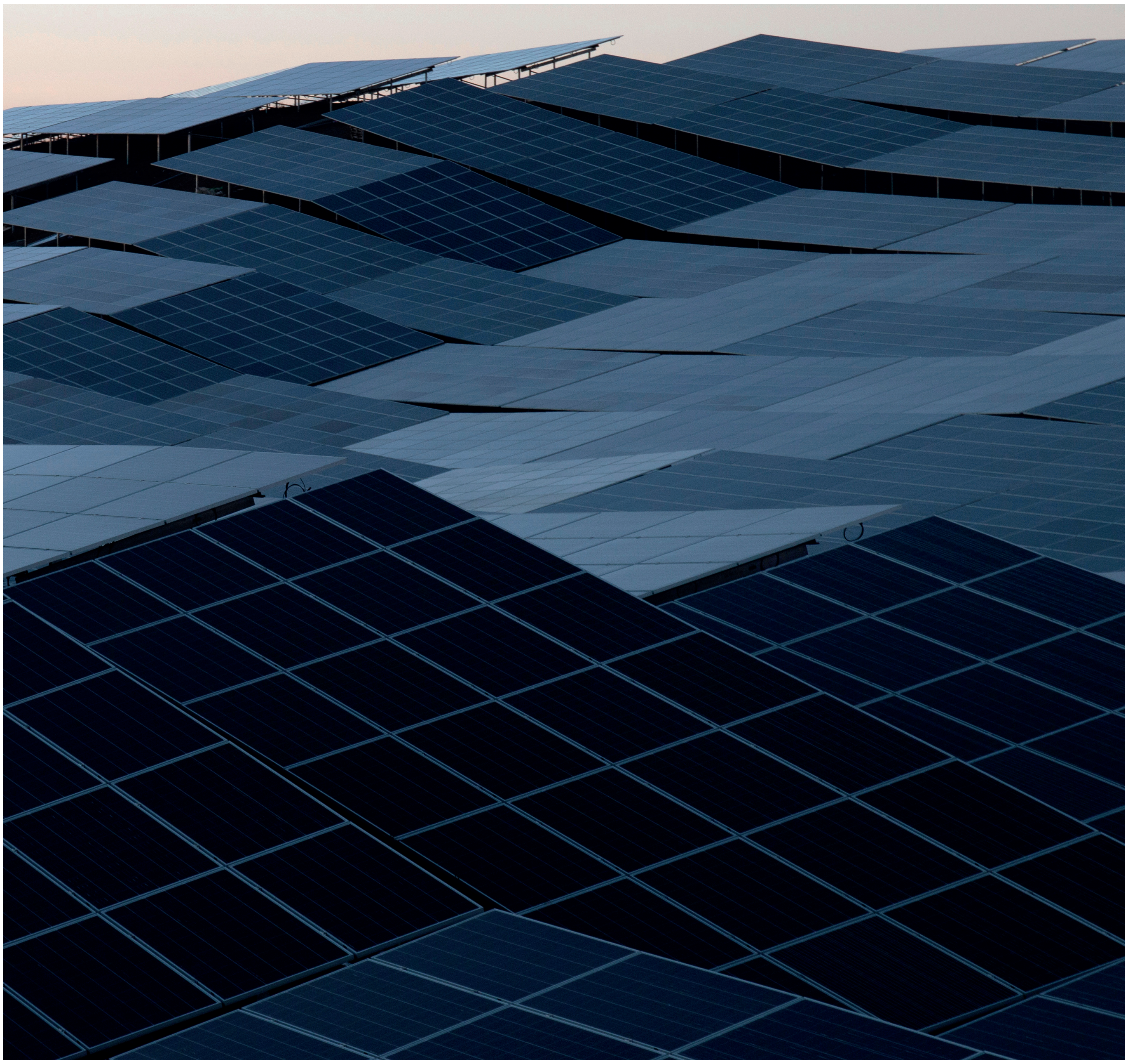

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