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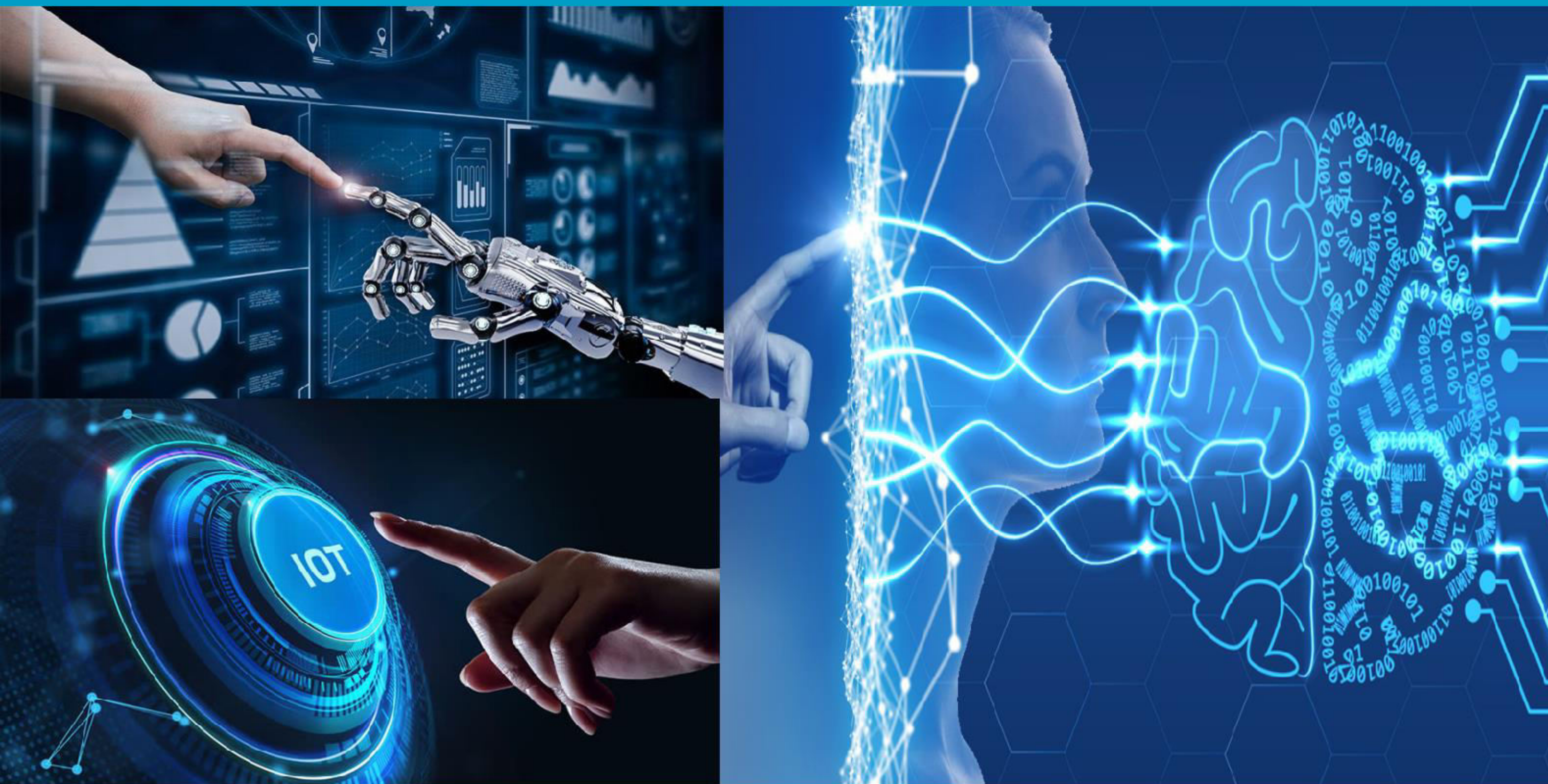

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Environmental Impact of Agrivoltaic Systems: Mitigating Climate Change and Promoting Biodiversity

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ABSTRACT: Agrivoltaic (AV) systems integrate the production of agricultural crops and electric power on the same land area through the installation of solar panels several meters above the soil surface. It has been demonstrated that AV can increase land productivity and contribute to the expansion of renewable energy production. Its utilization is expected to affect crop production by altering microclimatic conditions but has so far hardly been investigated. The present study aimed to determine for the first time how changes in microclimatic conditions through AV affect selected agricultural crops within an organic crop rotation. For this purpose, an AV research plant was installed near Lake Constance in south-west Germany in 2016. A field experiment was established with four crops (celeriac, winter wheat, potato and grass-clover) cultivated both underneath the AV system and on an adjacent reference site without solar panels. Microclimatic parameters, crop development and harvestable yields were monitored in 2017 and 2018. Overall, an alteration in microclimatic conditions and crop production under AV was confirmed. Photosynthetic active radiation was on average reduced by about 30% under AV. During summertime, soil temperature was decreased under AV in both years. Furthermore, reduced soil moisture and air temperatures as well as an altered rain distribution have been found under AV. In both years, plant height of all crops was increased under AV. In 2017 and 2018, yield ranges of the crops cultivated under AV compared to the reference site were −19 to +3% for winter wheat, −20 to +11% for potato and −8 to −5% for grass-clover. In the hot, dry summer 2018, crop yields of winter wheat and potato were increased by AV by 2.7% and 11%, respectively. These findings show that yield reductions under AV are likely, but under hot and dry weather conditions, growing conditions can become favorable.

KEYWORDS-agrivoltaics, climate, mitigating, biodiversity, environmental

I.INTRODUCTION

Climate change has become a severe threat to humanity. If concentrations of greenhouse gases in the atmosphere continue to rise, the risks facing humanity and the Earth in general will increase significantly [1]. Many countries have agreed to limit global warming to 1.5 °C compared to pre-industrial levels [2]. Consequently, the Dutch government aims to reduce greenhouse gas emissions in the Netherlands by 55% compared to 1990 [3]. In addition to climate change, global population growth also increases the demand for energy and food [3]. One of the solutions to mitigate the challenges posed by climate change and food security is agrivoltaics [4].

'Agrivoltaics' refers to the combination of electricity production, using photovoltaics (PV) and agriculture on the same area of land [5]. While monofunctional solar power plants (SPP) are often criticised for creating land use competition with food production [6], agrivoltaics is considered to be multifunctional [7]. Globally, agrivoltaics have grown exponentially in terms of installed capacity in recent years, reaching 2800 MW in 2020 from an initial 5 MW in 2012 [8]. Multiple classifications for agrivoltaics have emerged in recent years. Willocks et al. [9] have proposed that the way land is used beneath the PV arrays can be used as a defining parameter for the classification of agrivoltaics. Accordingly, they distinguish between 'rangevoltaics' (PV arrays with livestock beneath) and 'agrovoltaics' (PV arrays with crops beneath). Another classification has been proposed by Sekiyama & Nagashima [10], dividing agrivoltaics into three classes: (1) conventional stilt-mounted systems, (2) PV arrays placed between the agricultural rows and (3) greenhouses with PV arrays placed on the roofs. Another classification is the Deutsches Institut für Normung standard with number DIN SPEC 91434:2021–05 [11]. Classes are first defined according to the type of agricultural production and, second, to energy production. This research combines the definitions for agrivoltaics provided by the Deutsches Institut für Normung standard [11] and Willockx et al. [9]. The agrivoltaic systems considered in this study are installations that consist of PV arrays installed over crops designated for food production. Agrivoltaics with livestock beneath are included if the agrivoltaic power plant (AVPP) is designated for grazing with economic revenue. In this research, 'agrivoltaic system' is defined as the technical hardware installation with PV arrays and an AVPP as the ensemble of agrivoltaic system and the land underneath and in-between PV arrays.[1,2,3]

The primary focus of the growing body of literature on agrivoltaics is on optimising the synergy between agricultural yield and electricity production [12]. At the same time, societal considerations on circularity are starting to influence policy and research agendas for agriculture [13], and issues related to landscape change and experience those agendas of SPP [14]. However, in the field of agrivoltaics – the combination of agriculture and solar power plants– little scientific attention is thus far being paid to circularity and landscape experience. Both circularity and landscape experience have the potential to become significant factors in the public acceptance of agrivoltaics and, consequently, the timely implementation of local projects.

With regard to circularity, circularity and circular economy are concepts that lead towards sustainable systems. Circular economy aims to generate economic and social prosperity and protect the environment by preventing pollution and facilitating sustainable development [15]. There are 114 definitions for 'circular economy' [16]; the concept is both vague and wide-reaching [17]. The circularity of food production systems is commonly denoted as circular agriculture [15]. 'Circular agriculture' is used for analysis in this research. It assists in ensuring four goals: (1) economic sustainability, (2) the conservation of biodiversity, (3) environmental sustainability and (4) social sustainability (i.e. providing food security, eradicating poverty and improving health and living conditions) [15]. These four goals form part of the ten indicators of circular agriculture (CPICA) introduced by Dagevos & de Lauwere that are used in this study [18].

With regard to landscape experience, AVPPs, similarly to 'conventional' SPPs, change the landscape, and this is often met with low public acceptance [19]. A 'landscape' is defined as: "an area, as perceived by people, whose character is the result of the action and interaction of natural and/or human factors." [20]. The implementation of agrivoltaics affects how users (e.g. inhabitants, farmers, tourists) experience a landscape. Different from conventional SPPs, agrivoltaic systems often use higher elevated structures to allow access for agricultural machinery. Although the land use combination of agriculture and PV may be favourable in terms of the public acceptance of agrivoltaics, these elevated and often permanent structures may affect landscape experience and, consequently, detract public acceptance [21]. Landscape change, the accompanying landscape experiences and low public acceptance may restrain the application of agrivoltaics [5]. Several studies have investigated agrivoltaics and its effects on the environment and landscape. Gomez-Casanovas et al. [22] studied the benefits of agrivoltaics for mitigating climate change. Other papers investigated the shading properties of agrivoltaics on crop production (for example [23]) and rain water harvesting in agrivoltaic systems [24]. Mamun et al. [4] investigated microclimate conditions underneath PV arrays. However, there is an overall lack of studies that examine the landscape experience of agrivoltaics (4,5,6]
Public acceptance of agrivoltaics can be influenced by their circularity and effects on landscape experience, but these factors have hardly been studied before. This research therefore aims to explore how circularity and landscape experience are addressed in agrivoltaics, supported by an overview of agrivoltaic cases from around the world and a more detailed study of cases in the Netherlands.

II.DISCUSSION

Photovoltaic (PV) solar panels seem to be appearing everywhere: on homes, in the countryside, and even as art murals in Texas.Photovoltaic (PV) solar panels seem to be appearing everywhere: on homes, in the countryside, and even as art murals in Texas.
It's all part of the nation's drive to reduce greenhouse gas emissions and boost clean energy production. Indeed, the U.S. Department of Energy's dream is to have 40% of its electricity generated by solar power by 2035.
Yet solar farms and home solar arrays account for only 3.4% of the country's energy production. By 2050, some 0.5% of the contiguous American surface area may need to be given to large-scale solar farms.
That's 15,600 square miles or 10 million acres bigger than the states of Maryland, Vermont, New Hampshire, Massachusetts and New Jersey and more than all the land available in Hawaii, Connecticut, Delaware, and Rhode Island combined.
So how will all these photovoltaic panels fit and how will they affect the countryside? Agrivoltaics is one tool that attempts to find a balance between supporting our energy systems and agricultural production.
Agrivoltaic Systems
Agrivoltaics is the use of one piece of land for two purposes. Energy producers install solar photovoltaic systems on agricultural land that farmers or communities then also use for food production, grazing, or growing wild.
These set-ups are known as agriphotovoltaics, agrivoltaics, agrisolar, or dual-use solar.
The idea is that solar PV panels help local ecosystems and promote sustainability by providing shade during the day. In return, crops or livestock can keep solar panels operating more efficiently and save on maintenance costs. Agrivoltaic systems also increase a land's usefulness.
For example, a hectare of land may be used to produce wheat or it could have solar panels installed to generate renewable energy. That hectare's production efficiency could increase by 60% through agrivoltaics. [7,8,9]

Well, growing wheat between a solar array could result in that hectare producing 80% of its maximum wheat yield plus 80% of its total possible renewable energy. Add those together, and the field is working at 160% of its capacity compared to dedicating it to just one of wheat or solar energy.

Agrivoltaics Work

There are several ways solar projects can harness this synergy.

- Solar PV and grazing: Sheep, cattle, or even rabbits graze around solar panels, keeping the arrays debris-free and removing the need for mowing. This helps farmers reduce their water use, with animals using the shade to stay cool during hot weather, meaning they drink less. Some farmers use solar panels as fences.
- Greenhouse agrivoltaics: Semi-transparent solar modules provide partial shade, protecting plants from harsh weather like intense sunlight, hail, and rain. These “solar gardens” create a microclimate that reduces evaporation and water use and increases yields. Some call this orchard or horticulture farming.
- Pollinator habitats: Solar panels lifted to certain heights can support biodiversity by allowing pollinator plants to grow underneath.

Farmers can install solar panels at a desired height, high enough to drive tractors underneath or low enough to provide shelter for sheep. Solar arrays twist and tilt to follow the sun’s rays to maximize electricity generation. This dual land use generates renewable energy while boosting crop production, a win-win for those involved.

Need Agrivoltaics

Climate change affects every global citizen. Extreme weather events can ruin crops, wash away topsoil, and kill livestock, all of which majorly disrupt the food production chain.

Countries are moving to net-zero emissions by 2050, reducing dependence on fossil fuels like coal, natural gas, and oil. Solar energy will be a big part of the puzzle. However, the sheer land requirement for large-scale solar farms will have an impact on American food production.

For that reason, a dual-use approach is required to benefit both sides: the farmers and communities where solar farms exist and the energy producers installing them. This helps reduce land competition between food growers and the demand for clean energy.

Advantages of Agrivoltaics

There are several advantages to agrivoltaics. These include:

- Saving water by reducing evaporation
- Preserving soil moisture
- Increased crop productivity and crop yield
- Generating renewable energy
- Reducing depends on fossil fuels
- Cutting greenhouse gas emissions
- Developing new income streams
- Preserving agricultural land
- Protecting biodiversity

Positives of Agrivoltaics

Plants naturally reach a light saturation point where more sun cannot increase their photosynthesis. The solar panels protect crops by acting as a shield, protecting them from the intense sun, which they may not require, as well as storm winds and torrential downpours. [10,11,12]

A whopping 85% of all human water consumption goes into agriculture. Water scarcity will only increase as the global population grows from today's 7.6 billion people to a predicted 9.8 billion in 2050.

A 2019 study by the University of Arizona's Greg Barron-Gafford showed that tomatoes and jalapeños used water more efficiently when grown under solar panels. Solar modules also reduce evaporation, helping save another precious commodity, water, of particular importance in arid and semi-arid regions. A pilot agrivoltaics project in Kenya saw irrigation requirements drop by 47% and produced cabbages 24% bigger.

Solar panels can lose 10% of their efficiency on hot days. Fortunately, the plants underneath panels produce a cooling microclimate that studies have shown increases solar PV efficiency by up to 10%.

Agrivoltaics is also about sustainability, mitigating climate change by reducing emissions and promoting sustainable farming techniques. Biodiversity can be encouraged beneath solar panels, further reducing the impact of installing solar panels on rural land.

And finally, there are benefits to farmers who can sell the electricity they generate back into the grid or reduce their own energy bills. They may also make money by leasing their land out for a solar farm while continuing to use it for agricultural purposes.

Businesses behind solar installations can lower their operational costs thanks to grazing livestock that remove the need for maintenance like regular mowing.

Problems with Agrivoltaics

Agrivoltaics is a nascent industry, with a lot of research going into best practices. Disadvantages associated with agrivoltaics include the following:

- High upfront capital costs mean agrivoltaics are more expensive to install than traditional solar developments.
- Some agrivoltaic solar arrays require deeper foundations, increasing the project's greenhouse gas emissions footprint through extra construction processes.
- Different states and counties have varying rules and regulations surrounding solar developments, acting as a barrier to some solar developers and farmers. These may include environmental impact assessments.
- Growing crops requires maintenance and associated costs. Farmers will also need to learn how to look after solar arrays and understand how to maximize crop yields.
- Collaboration between multiple stakeholders, from farmers to communities to energy companies, can be a long and drawn-out process.

Crops Work Best with Agrivoltaics

There are many crops suitable for growing alongside a solar development. These include beets, potatoes, radishes, tomatoes, peppers, and carrots. Leafy greens like spinach and lettuce do well, and berries like strawberries, blueberries, lingonberries, and raspberries are also considered apt for agrivoltaics. Conversely, taller crops like sunflowers, corn, and apple trees have not performed better with agrivoltaics.

Leads the World in Agrovoltaics

China leads the way with more than 1.9 GW of the world's 2.9 GW of agrivoltaics in place as of 2020. It's also home to the most extensive agrivoltaics system in the world. Situated in the Ningxia desert, it covers 215 million square feet (20 million square meters), just shy of 5,000 acres.

The European Union is promoting agrivoltaics to its member countries. France is the main player in Europe, with 2.4 GW of agrivoltaics under development. Italy has a 70-megawatt (MW) facility under construction at Latina and a 48

MW agrivoltaics solar project in the pipeline for Lazio. Germany, the Netherlands, Austria, and many other countries are all also committed to developing the technology.

Agrivoltaic Sites in the United States

In America, the United States Department of Agriculture (USDA) has 22 agrivoltaic projects bubbling away. The Foundational Agrivoltaic Research for Megawatt Scale (FARMS) looks at how to scale up agrivoltaics to benefit stakeholders. Then there is the Innovative Solar Practices Integrated with Rural Economies and Ecosystems (InSPIRE) program, whose role is to protect the interests of the solar industry and farmers and preserve landscapes.

New Jersey has recently sanctioned a 200 MW agrivoltaics program on farmland. Colorado is putting money into agrivoltaics research. One fascinating site is called Jack's Solar Garden. A third-generation hay-producing farm is now America's largest agrivoltaics research facility, powering 300 homes and growing vegetables, herbs, and berries.

Install Agrivoltaics at Home

Most people fix solar panels on their rooftops rather than on the ground. However, in theory, anyone with a ground-mounted system could develop a miniature agrivoltaics scheme.

Assuming it's a small system, a great start is to not mow the area and let a biodiverse ecosystem develop for pollinators. Small herb gardens or salad plants may like growing in and around the solar panels; experimentation will be required to see which plants thrive.[13,14,15]

Other ideas include community solar gardens. Solar panels generating electricity for the neighborhood could be arranged to allow space for stakeholders to set up a community allotment. Participants can grow fruits and vegetables for themselves or local charities and get people involved in learning about the food cycle.

Texas a Good Place for Agrivoltaics

The wide-open spaces of Texas—America's second-largest state—coupled with its superb solar energy potential make the Lone Star state a prime candidate for agrivoltaics.

Texas is already the second-largest solar power producer in the country. Joining two of the state's primary assets, land and sunshine, means Texas is an excellent option for agrivoltaic projects.

For now, agrivoltaics remains very much in its development stage. But it would be interesting to see how solar panel installers could keep the famous Texas Longhorn cattle's horns from damaging solar modules.

Agrivoltaics Could Be a Win-Win for Farming and Solar Energy

On the surface, agrivoltaics looks like good land-keeping. They bring together money-making and clean energy to provide solar panels that boost crop yields, save water, and protect delicate ecosystems.

What agrivoltaics does is give farmers and energy producers a potentially valuable tool to help battle climate change while increasing food production for an ever-growing population. Rural communities and economies can benefit from methods that reduce competition for land and water, which are becoming scarcer.

This win-win, best-of-both-worlds approach requires planning and cooperation between several parties to come to fruition. Not every crop suits life alongside a solar panel, and not every farmer wants to turn their land to generate electricity.

Of course, research continues into the efficiency of this industry. Like most businesses, the bottom line will be as important as the process. But if crop yields can increase, livestock enjoy more comfortable living conditions in the field, and natural resources are better cared for, the effort is rewarded.

Texas is well set to take advantage of any developments in agrivoltaics with vast swathes of land and plentiful sunshine. Success also depends on the ability of many parties to come together to make agrivoltaics work. Farmers, government, businesses, and communities will need to see tangible benefits to this mixed land use.

Agrivoltaics is symbolic of the whole battle against climate change. There must be adaptation and goodwill from many elements to make it work because the win-win possibilities over the fundamental cornerstones of life are at stake: water, food, and energy.

III.RESULTS

Agrivoltaics is considered a viable solution when addressing the challenges of sustainable food production and renewable energy generation as it enables the dual use of the arable land.

In the era of climate change, crop cultivation is becoming increasingly demanding due to unexpected and extreme weather changes, making the benefits of presence of panels over the crops even more important.

Agrivoltaic systems can leverage a microclimate created by vegetation beneath solar panels. Crops reduce temperatures through transpiration and shading, potentially enhancing PV module efficiency. Additionally, this approach minimizes potential land-use conflicts, allowing farmers to generate energy on the same land used for agriculture, thereby reducing competition for land resources.

At Greenvolt Power, our unwavering commitment to biodiversity is at the heart of our mission. In our Biodiversity Strategy we committed to promote partnerships to develop biodiversity management, conservation and restoration projects by 2030. Through collaborations with key stakeholders—local authorities, scientists, universities, NGOs, and local communities—we actively contribute to the realization of this Strategy.

An exemplary manifestation of this commitment is our current partnership with Warsaw University of Life Sciences (SGGW) to reintroduce agricultural land use on an operating photovoltaic farm. This initiative not only aligns with our Biodiversity Strategy but also demonstrates our dedication to innovative solutions and continuous learning, with the ultimate goal of optimizing benefits for both agriculture and solar energy generation.

As we are responsible for renewable projects in development, construction and operational phase of, we are not solely focused on innovating system designs for our new projects in development, but also on efficient asset management.

Therefore, we are seeking smart and simple solutions to enable dual land use on our operating PV farms without interfering with the existing infrastructure.

This can be achieved by optimizing crop choices and management practices on operating PV farms. One of our goals has been to assess the potential of individual plant species for cultivation on photovoltaic farms.

After nearly a year of field research conducted in cooperation with WULS Faculty of Agriculture and Horticulture, we have obtained the first results of our research.

Second year will be crucial in terms of collecting data and drawing final conclusions but even after such a short time of observations, we can see that:

The shading effect of panels has a definitively positive influence on crops;

specific species do have the potential to be effectively cultivated on a solar farm;

It is possible to reintroduce agricultural land use on an operating photovoltaic farm without significant financial outlays;

In the upcoming year of our research, our plan involves evaluating the potential of specific plant species to improve the productivity of PV installations. We aim to achieve this by studying their positive effects on the microclimate and by increasing the albedo of the area beneath the photovoltaic panels.

We have been living in the world of diminishing resources and I personally view agrivoltaics as a promising strategy that will allow us to face the interconnected challenges of sustainable food cultivation and the generation of renewable energy.

Having said that, we are still in the preliminary stage of introducing and popularizing agrivoltaics, even though according to SolarPower Europe, if agrivoltaics was introduced on just 1% of Europe's arable land, its technical capacity would amount to more than 900GW, more than six times the current installed PV capacity in the whole of the EU. The fact that we are still at the beginning of the road stems from several reasons.

First, there is a need for continuous research to be carried out, so we can collect data that will allow us to make informed decisions and spread awareness. Secondly, there is still no legislation in place to support the development of agrivoltaics in Poland. Needless to say – without it, we won't be able to take next steps. Finally, agrivoltaics requires technology that will fully take advantage of its potential, which boils down to savy and precise crop cultivation and sustainable agriculture. This will not be possible without the support and participation of farmers. The RE industry needs to prioritise collaboration that aims for educating crop producers and sharing best practices of how solar and farming can go hand in hand, benefitting not only the renewable energy sector and food production sector, but most importantly the communities and the environment.

Agrivoltaics, which combines food production with solar photovoltaics, can have an impact on biodiversity. The installation of photovoltaic panels above farmland can create shade, limiting the amount of solar radiation reaching the ground and potentially affecting crop productivity.[16,17,18]

IV.CONCLUSION

The word agrivoltaics describes the use of land both to produce photovoltaic energy through the installation of solar panels and also to carry out pastoral and crop farming activities.

Renewable energy sources, sustainable use of land, protection of biodiversity – agrivoltaics encompasses all of this: it's an innovative approach that enables solar energy generation and agricultural practices to coexist and interact in a mutually beneficial way, thereby fostering the creation of shared value with the local area and communities within which the plants are located.

Thanks to our collaboration with agronomists, agricultural enterprises, universities, research centers, non-profit organizations and startups – all of whom understand the characteristics of the local area and can bring substantial added value to the individual projects – we have started to promote and experiment with this type of model in many of our plants around the world.[19]

As a result, we have new opportunities for joint ventures which highlight how the worlds of energy and agriculture are not pitted against each other but rather are part of a shared, sustainable journey.

There are also numerous benefits in terms of nature conservation and the protection of ecosystem services, as can be seen in the projects we have launched to attract and protect pollinating insects – in particular, bees.[20]

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