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ABSTRACT: This study focuses on the modelling and simulating of agrivoltaic (Agri-PV) systems, where solar photovoltaic (PV) and agriculture coexist. Systems aimed at orchards demonstrate land-efficient use and weather protection, whereas those aimed at vineyards improve wine quality through reduced solar exposure. LuciSun's LuSim, a specialized and detailed simulation and visualization tool, is used to analyze real Agri-PV projects in southern France, including orchards, vineyards, and berry fields. LuSim's high-resolution irradiance profiling reveals design parameter trade-offs, emphasizing the need for advanced modelling. Complexities surrounding PV module selection and 3D modelling are explored, along with initial investigations into the potential benefits of semi-transparent PV panels and light diffusers. This research underscores the significance of relying on specialized modelling tools when performing the critical task of optimizing projected Agri-PV systems.

Keywords: Agrivoltaics, light sharing, semi-transparent PV, GPU-based modelling, vineyards, orchards, berries

1 INTRODUCTION

Agrivoltaics (Agri-PV) is a novel application of solar photovoltaic (PV) power generation where the PV modules are installed in the same field as where crops are also cultivated. This is advantageous because this combines land use while keeping attractive productions from both agricultural crops and power generation.

Several configurations currently exist for these Agri-PV installations, including ground-mounted PV plants and PV installations on greenhouses. In recent years, the bifacial PV technology has experienced a swift increase in its share of the PV market, which opens the door to performance improvements, and even to new kinds of solutions.

For orchards, Agri-PV projects offer several important benefits, including increased land-use efficiency, reduced water stress, combined PV energy generation and crops harvest, crops protection from extreme weather conditions (such as hail or excessive sunlight), attenuated temperature extremes, extended growing seasons (by providing a more controlled microclimate), or income diversification for the farmer.

In the case of vineyards, Agri-PV projects have the same advantages, but additionally contribute to reducing the amount of solar irradiation received by the vines. This helps reduce the sugar content of the grapes, which in turn decreases the alcohol content in wine. This is increasingly important for winemakers in southern Europe because the increasing trend in the overall solar resource over the last few decades (known as "brightening") has led to the production of wine with excessive alcohol levels, which must be mitigated by other means. Reducing the amount of sunlight by controllable measures using Agri-PV technologies is therefore very attractive to that industry.

Regarding the production of berries, Agri-PV constitutes another very attractive possibility because they generally require a relatively low amount of solar radiation, and can thus tolerate high amounts of shading.

Finally, in most projects, the use of Agri-PV technologies also makes it possible to recoup the cost of the support structures for the nets that are used for protection against insects and birds.

All these reasons explain the recent surge in agrivoltaic applications and the increasing interest and popularity for this novel concept. However, in the current state-of-the-art PV simulation tools, the added complexity introduced by Agri-PV and bifacial technologies is still not fully covered. The associated solar projects include many complex structural elements that need to be accurately modeled so that the amount of light that reaches the crops can be accurately evaluated despite various sources of shading or light reflections from the plants to the backside of bifacial modules. Sunlight and skylight are partially transmitted through the glass of PV modules, semi-transparent modules, or diffusing materials, whose transmittance needs to be modeled accurately. Moreover, the shape and size of the crops can vary, which induces further complexity in the overall modelling.

This work presents the application of a novel simulation tool (LuciSun's LuSim) to the case of Agri-PV projects with bifacial PV modules installed above orchards (pear trees), vineyards, or berries. In particular, the role of several key variables that drive the irradiance received by the crops and reflected onto the backside of PV modules is discussed in detail. Overall, this work presents an overview of the direct experience gained from recent modelling exercises applied to several real-world case studies of light-sharing Agri-PV projects. In particular, several cases of Agri-PV applications in various types of farms (orchards, vineyards, and berries) located in southern France are explored, and the key findings from the modelling exercises are discussed.

2 METHODOLOGY OVERVIEW

The assessment of shading profiles affecting both vegetation and PV modules, along with the calculation of bifacial energy gain (BEG), is conducted using the LuSim simulation tool. This tool leverages cutting-edge 3D evaluation libraries integrated into the Graphic Processor Units (GPUs) found in modern computers. Although initially developed for the video game industry, these libraries offer several compelling advantages in the context of bifacial PV applications. The achievable spatial resolution rivals that of backward ray-tracing techniques but demands only a fraction of the latter's simulation time. The methodology followed to employ GPUs in solar energy applications has been detailed in previous contributions, such as for the assessment of intricate shading issues [1], bifacial irradiance [2], or the energy simulation of vertical bifacial PV systems in agrivoltaics [3]. The irradiance distribution profiles are assessed at high spatial resolution, either at the leaf scale or the PV cell level, and with a relatively high temporal resolution of 10 minutes. This study builds upon prior research involving light-sharing 3D modelling applied to Agri-PV applications within greenhouse environments [4]. In this context, a distinct 3D model is created for each configuration under investigation. The 3D view-field method is employed for the comprehensive evaluation of the irradiance field, both incident and reflected, that involves the ground and PV modules on a component-by-component basis. The incident irradiance profile for each PV cell comprising the PV system is obtained at 10-minute intervals throughout the year. Then, this irradiance data time series is transformed into electrical power using a PV simulation model that accounts for conversion losses within the entire system. In most cases, conventional simulation routines, such as those contained in pvlib [5], are sufficient to model these energy losses.

To assess the impact of the actual solar resource on crop yields, each configuration is compared to a reference model. The latter is intentionally designed to closely resemble the base case, where trees are planted in rows, and vertical structures support protective nets. However, in this base case, neither PV panels nor their supporting structures are present.

3 3D MODELLING

Creating a 3D model for an agrivoltaic system can be a challenging task. It involves modelling several elements, including the PV modules, their support structures, racking elements, crops, the ground surface, and any other potential surrounding objects. Each object must be assigned specific optical properties such as albedo, transmittance, or optical porosity. As illustrated in Figure 1, the latter quantity is a crucial parameter when modelling agrivoltaic systems because it determines both the amount of sunlight that passes through a particular plant before potentially reaching another, as well as its impact on the irradiance that plant leaves can effectively collect and use for photosynthesis. For each type of crop, the optical porosity typically undergoes seasonal changes in direct relation with the growth and shedding of leaves. Using LuSim, this temporal evolution is modeled based on monthly values. This approach strikes a balance between simplicity and accuracy, while offering the advantage of using readily available monthly data inputs.

Figure 1: Illustration depicting the concept of optical porosity, which represents the fraction of sunlight that is transmitted through a canopy [6].

In LuSim, the 3D objects that constitute the scene can be imported from specialized CAD tools, such as SketchUp or AutoCAD, or from tools commonly used in the solar energy industry, such as PVcase. Subsequently, each object is assigned a texture containing its optical properties. A mesh associated with these textures defines the spatial resolution used in irradiance modelling.

Figure 2 illustrates a 3D model of an Agri-PV pear-tree orchard. Two types of trellises are included in the model: T-mode and V-mode, resulting in distinct shapes for pear trees. The modelling process accounts for light interception by structures and PV modules at every point of the trees, considering each trellis mode and PV module installation geometry.

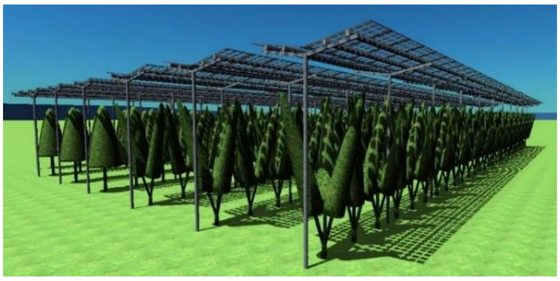

Figure 2: Example of 3D modelling of an agrivoltaic pear-tree orchard with T-mode and V-mode trellises.

When assessing plant growth, the incident irradiation must be integrated separately for specific plant zones. In the realm of 3D modelling, several key questions arise regarding how to best represent plants and define these zones of interest. For plant shapes, it is possible to select either simple shapes, which approximate the outer boundaries of the crops, or more intricate shapes, which attempt to faithfully replicate the geometry of plant organs and leaves in detail. Basic geometric shapes, such as parallelepipeds, cylinders, spheres, or cones, can be employed to represent the outer envelopes, whereas shapes of varying complexity between the simplest and most detailed forms are also viable options. Each approach comes with its own set of advantages and disadvantages.

Complex geometries attempt to realistically represent the shape of crops. They facilitate the utilization of more intricate models used to evaluate crop photosynthesis and good estimates of the 3D optical porosity (see Section 5).

However, this approach demands significantly higher computational resources because of the concomitant substantial increase in required spatial resolution and of the number of points where irradiance must be assessed. It also restricts the use of simpler agronomic models that have been developed based on a preliminary evaluation of the irradiance incident on the external canopy envelope.

In contrast, the use of basic shapes that depict the external envelope of crops reduces the computational complexity significantly by reducing the number of points where irradiance calculations are necessary. This approach also facilitates the direct utilization of parametric models that assess photosynthesis in the canopy based on the solar radiation reaching its outer envelope. When employing these straightforward models, optical properties—including optical porosity—cannot be directly modeled, but must be incorporated through a parametric model attached to the object's texture.

In most agrivoltaic applications modeled using LuSim, experience has favored the use of basic geometric shapes alongside parameterized optical properties. If necessary, the optical porosity can be initially modeled using a high-resolution 3D representation of the plant under scrutiny, and the results can then be applied to all simple shapes employed in modelling the entire agrivoltaic system.

Figure 3 shows a simple geometric shape used to represent the external envelope of a pear tree in an orchard with T-mode trellises. The subdivisions used for the modelling of the incident light are also indicated.

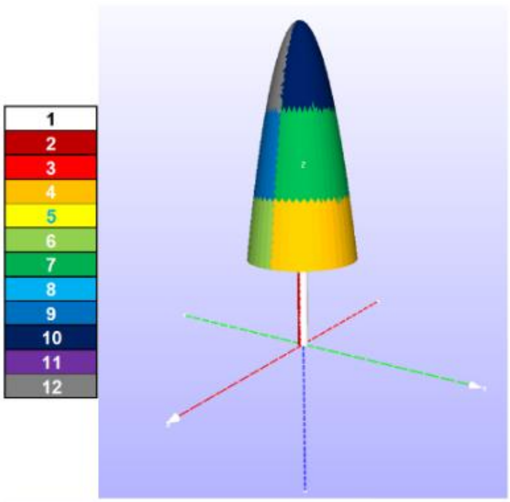

Figure 3: External envelope used for pear-tree orchards with T-mode trellises. The twelve subdivisions used for the modelling of the incident light are indicated.

Figure 4 illustrates the use of a parallelepiped to model a vineyard. The height of the plant is separated into three equal zones per side, for which the irradiance incident on the plants is calculated. Additionally, the horizontal upper face constitutes a seventh zone.

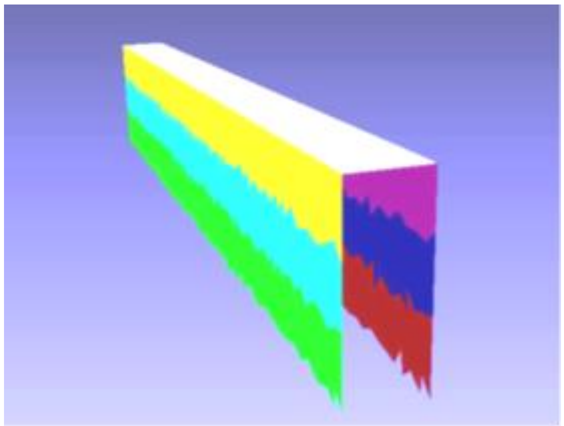

Figure 4: Zones of study of the light incident on vines (7 zones).

Figure 5 shows the shadows cast by the PV system and its structure at one specific moment and on one specific part of a pear-tree agrivoltaic system with T-trellises. The mesh adopted here for the trees is made visible on one of them.

Figure 5: Shadows cast on a pear-tree agrivoltaic system, showing the mesh on one of the trees.

4 IRRADIANCE MODELLING

Once the 3D mesh model of the agrivoltaic system has been completed, the irradiance simulations are carried out at each instant and for each radiation component (direct, isotropic sky diffuse, circumsolar sky diffuse, and ground reflected). For instance, Figure 6 illustrates the evaluation of the direct irradiance component reaching the agrivoltaic system at 3 PM during a clear summer day. The irradiance values are then aggregated into areas of interest within the 3D scenario, as well as over periods of time that are relevant to the crop yield to be evaluated. Those periods depend on the type of crop and the corresponding growth and harvest seasons. These integrations are typically done on a daily, monthly, or yearly basis, depending on what needs to be evaluated. As an example, Figure 7 shows the results of the temporal integration of the direct irradiance over one whole year. Similarly, Figure 8 shows the yearly-integrated isotropic diffuse irradiation, and Figure 9 shows the yearly-integrated global irradiation.

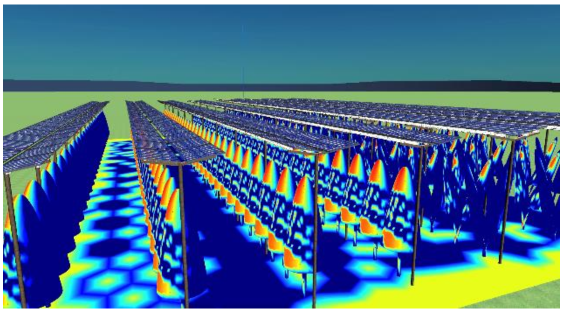
Figure 6: Evaluation of the direct irradiance reaching the agrivoltaic system during a clear summer day.

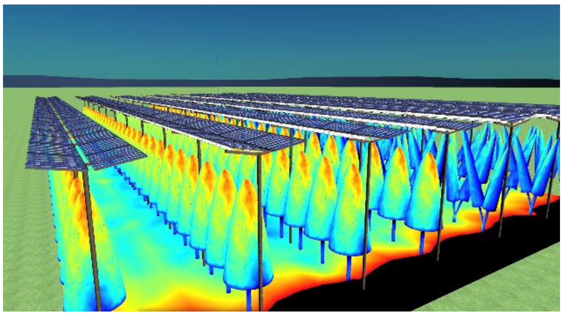
Figure 7: Yearly-integrated direct irradiation.

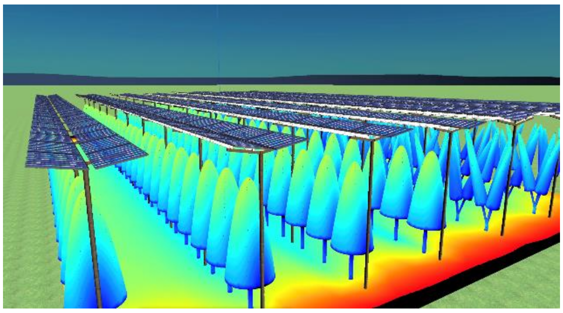
Figure 8: Yearly-integrated isotropic diffuse irradiation.

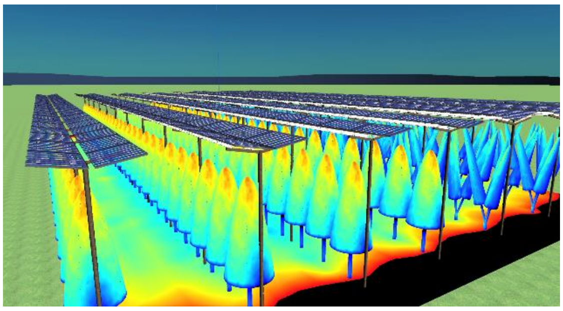
Figure 9: Yearly-integrated global irradiation.

5 REFERENCE SCENARIOS FOR CROP YIELD

The assessment of the solar resource's impact on photosynthesis can be approached in various ways. The scientific literature has introduced agronomic models tailored to specific plants, varying in complexity from basic agronomic models to intricate Functional Structural Plant Models (FSPMs). In agrivoltaic system modelling, simple agronomic models often suffice, offering the advantage of wider applicability across plant types.

The modeled irradiance incident on trees is not directly usable for agronomic interpretation because it strongly depends on the 3D model used. In particular, the surface area of the tree's outer envelope increases when the complexity of the 3D shape model also increases. Hence, complex shapes lead to larger areas, whereas simple shapes lead to smaller areas. In reality, however, the total solar irradiation (in Wh) that truly reaches a tree is relatively independent from the complexity of its actual shape. Consequently, using a complex 3D tree geometry induces a smaller irradiation per unit area (in Wh/m^2), since the total irradiation is intercepted by a larger surface. Carrying out the agronomic interpretation relatively to a base-case scenario is thus more reliable. In the LuSim framework, this is done by comparing a reference case (without PV panels) to each of the configurations under scrutiny, always using the same 3D tree models. This normalizes most of the model-induced irradiation variations noted above, thus providing more robust results.

The base-case scenario needs critical attention because the PV yield directly depends on it. Hence, it has to accurately represent the canopy and other objects in the absence of any specific PV structure, including support bars and mounting racks. For instance, Figure 10 depicts the reference scenario for the pear-tree orchards discussed earlier. This scenario consists of the canopy and supporting structures for the nets that are typically used to protect the crops from insects and birds. For standard nets used in agriculture, a typical constant transmittance (90%) is applied to estimate their impact on the entire sky view.

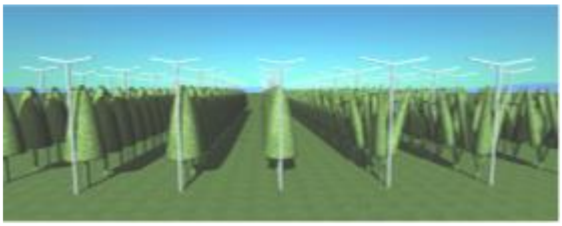
Figure 10: Reference scenario corresponding to the pear-tree orchards shown in Figure 5.

6 PV MODULE SEMI-TRANSPARENCY

The use of semi-transparent PV modules is becoming increasingly popular in agrivoltaic projects because of several potentially important advantages. These include (i) the possibility to install PV modules above the plants without much change with respect to the common installation practices in standard PV projects, and (ii) the desirable outcome of a more homogeneous distribution of light around the crop. PV modules offering various semi-transparency attributes are available on the market, thus offering more flexibility to adapt to the needs of each specific project. However, the use of semi-transparent PV modules also conveys some important disadvantages, including a higher price per nameplate power. This is because the manufacturing costs of such PV modules are not proportional to the amount of PV cells but also depend on the balance of materials, which is roughly dependent on the total surface of the PV modules, and can be relatively more expensive than PV cells.

This section explores some key observations gathered while using LuSim in the context of simulating the pear-tree Agri-PV systems introduced earlier, for which semi-transparent modules are considered as an option. This experience might provide guidance on the main parameters to consider, and help decide whether this kind of module is suitable or not for similar agrivoltaic projects.

Different configurations are tested here, with a combination of design parameters including PV modules with semi-transparency of either 27% or 51%, the installation of PV modules in portrait or landscape mode, and the installation of either one or two PV modules per row. Figure 11 shows the 3D model from the top side of the PV installation, where the semi-transparency of the PV modules is visualized.

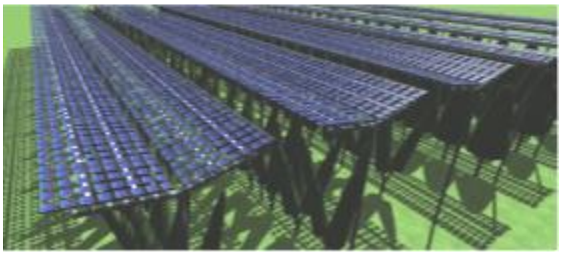

Figure 11: Semi-transparent PV installation above a pear-tree Agri-PV system.

Figure 12 shows the pear trees with the panel support structures in portrait mode. Clearly, the structures intercept a significant fraction of the trees' field of view. This shading is caused by the width of the bars, particularly for the bars that are just above the chosen viewpoint, but, even more so, by their depth. This is observed for the bars that are above the neighboring tree rows because these bars block a significant part of the sky, including the light rays that arrive obliquely.

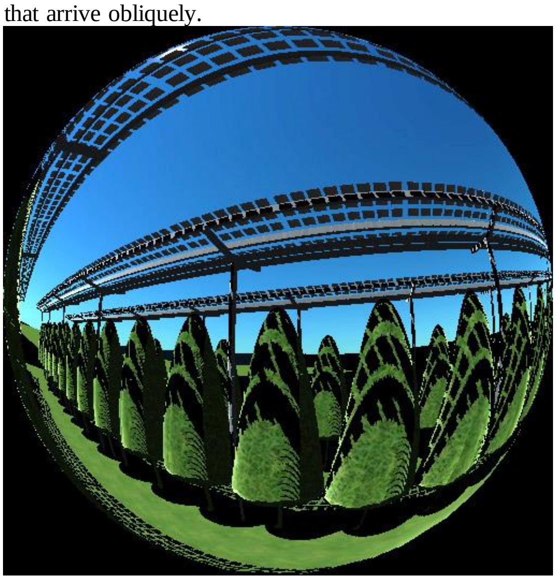

Figure 12: Trees with T-mode trellis using panel support structures in portrait mode.

Figure 13 shows an example of incident light profile for a specific Agri-PV configuration over the course of a clear summer day. The blue curve represents the simplest configuration where only *one* tree is present and only the vertical support structures are included. This case obviously corresponds to the highest solar resource that can be captured by that tree. The second configuration (orange curve) corresponds to the presence of *all* trees and vertical structures, but still with no PV panels or support bars. In summer, this configuration results in a resource almost as high as that for a single tree. The third configuration (green curve) corresponds to the case of panels installed in portrait mode, with a semi-transparency factor of 27%. Finally, the last configuration (red curve) corresponds to panels installed in landscape mode, with a semi-transparency factor of 51%. Interestingly, a more dramatic reduction in transmitted light is noticeable in landscape mode compared to portrait mode, mainly caused by the presence of 4 support bars rather than 2. The curves also show a trend with two peaks separated by a trough around local noon, which corresponds to the passage of the sun over the PV panels. The green curve shows a slight asymmetry, which is caused by the panels being tilted towards the west. Conversely, the installation in landscape mode (red curve) shows relative symmetry, because half of the panels are tilted towards the east and the other half are facing west.

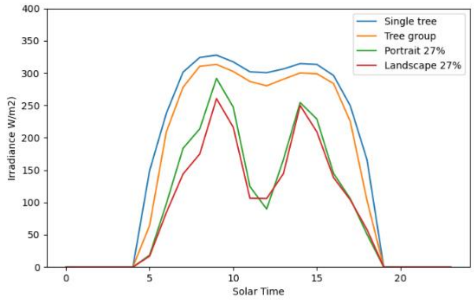

Figure 13: Solar irradiance on trees for different Agri-PV configurations, during a clear summer day.

Figure 14 presents the comparison of the solar resource evaluated for different scenarios: the base-case reference (no PV, blue curve), PV with overall panel transparencies of either 51% or 27%, and PV modules installed in either portrait or landscape mode. The solar resource decreases as expected depending on the transparency factor of the modules. Remarkably, it is found that the landscape configuration with 51% transparency leads to a slightly lower resource than the portrait configuration with 27% transparency. This is caused by the high impact of the modules' support bars, which are twice as many in landscape than in portrait configuration.

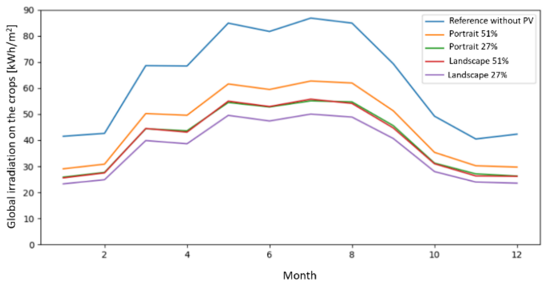

Figure 14: Comparison of the resource evaluated for the reference scenario, panel transparencies of 51% or 27%, and PV modules installed in portrait or landscape mode.

These modelling exercises have shown that the shading caused by panel support bars plays a major role in reducing the resource. The relative impact of semi-transparency is therefore reduced compared to what it would be without the presence of the support bars. On the other hand, these simulations assume that a reduction of ≈6% in the transmittance of glass-glass PV modules is caused by soiling. This might be a relatively optimistic scenario if the practice of spraying calcined kaolinite clay as a protective measure against insects is carried out in the standard way.

Overall, the present results suggest that the use of semi-transparent modules might not be optimal, at least for some agrivoltaic projects, and that rather relying on conventional PV modules could lead to a better technical-economic optimum. If semi-transparent modules are used, then a detailed design optimization of the supporting structures, and in particular the module fixing bars, should be carried out to reduce their impact on the incident light.

7 EVALUATION OF THE CROP YIELD

Photosynthetic efficiency can be described by the well-known irradiance-photosynthesis function, which expresses the ability of plants to respond linearly to low irradiance levels, and to rather saturate at high irradiance. This property can be advantageously used to drastically improve the productivity of some appropriate crops under PV shades because the irradiation magnitude drops drastically when affected by the shadows created by the panels and structure.

Obtaining a good homogeneity in the photosynthetic irradiance field (i.e., highly scattered light) around the plants is important to maximize the crop yields because this helps the plant limit the need to translocate metabolites towards the fruits located in the shaded zones. For the pear-tree agrivoltaic system under scrutiny, the analysis of this homogeneity is done at two tree levels, and its results appear in Table 1 for the month of April. This period is key for the tree development, and ultimately for the crop yield. In general, the presence of projected shadows from the modules and structure improves the light distribution homogeneity by reducing the resource more in the upper part of the trees than in their lower part.

Table 1: Irradiation received per unit area at two tree levels, for the T-shaped trellises.

Monthly effective solar irradiation on pear trees with T-shaped trellises			
	TMY April [kWh/m²]		
	Bottom of pear trees	Top of pear trees	Difference vs average
Control scenario	21.8	27.6	23%
Portrait 51	21.0	26.5	23%
Landscape 51	18.4	23.1	23%
Portrait 27	18.6	23.2	22%
Landscape 27	16.6	20.6	21%

In the case of pear trees, the simulations show that irradiance reductions caused by the presence of PV-induced shadows (i.e., by the modules and their supporting structure) do not present a major risk for the agricultural production in the planned implantation area. In fact, measurements made with an Agri-PV prototype for apple trees in France have shown that an average irradiation reduction of 50–55% does not significantly impact the quality of the harvest [7]. In parallel, simulations made for raspberry shrubs show very favorable results under most possible configurations. Raspberry is an understorey plant found in temperate and cold regions that is particularly well adapted to low light levels. In its natural environment, it is actually able to maintain itself under very low light levels. For instance, the results in [8] attest to the presence of raspberry plants at residual irradiance levels of only 7% of the photosynthetic flux density above the canopy. Raspberry bushes remain abundant above the level of 25% residual irradiance and even increase their vigour by up to 40%. This illustrates the raspberry's great adaptability to a wide range of solar illumination levels. Such analyses leave no doubt as to the feasibility of growing raspberries with a satisfactory yield and quality when their cultivation is combined with an Agri-PV system. Various geometric configurations and panel types offer multiple combinations. The remarkable adaptation of the raspberry plant to the available solar resource means that it is probably possible to take advantage of most, if not all, proposed configurations.

For vineyards, the modelling exercises carried out with LuSim for various PV configurations show that, for the typical climate of southern France, it is important to use relatively modest Ground Cover Ratios (GCRs), typically under 30%, to maintain an optimum yield for the crops. Changing the panel size, or using semi-transparency PV modules, only alters the frequency of the irradiance modulation. In parallel, introducing diffusing components between the PV cells or modules can greatly contribute to homogenize the amount of sunlight received by each part of the plant at any time, leading to the beneficial phenomenon called “even lighting”. From that standpoint, the potential benefits offered by light diffusers are further discussed in the next section.

8 POTENTIAL ADVANTAGES OF LIGHT DIFFUSERS

The crops’ need for light is a major constraint in many agrivoltaic projects. The design of such a system is tedious because finding the optimal balance between PV array density and crop yield is difficult to achieve. This stems from the fact that the shadows cast by the solar panels reduce the light available to the plants for several hours a day on sunny days, which are precisely the days that determine growth, most usually. Conversely, during hours of high irradiance, the light received by plants might be far beyond their photosynthetic saturation threshold (particularly in summer). This excess light does not contribute to plant growth. To the contrary, it reduces growth through the phenomena known as “photoinhibition” and “stomatal closure”, possibly combined with episodes of water stress. In this context, agrivoltaic systems could greatly benefit from the introduction of light diffusing elements between the PV cells or modules, by redistributing the light more evenly over all the crops. Several approaches are possible, including quasi-isotropic diffusing surfaces or partially diffusing materials. More elaborate solutions also exist, such as lenticular diffuser sheets that are specially designed to maintain photosynthesis to its virtually unchanged potential—a concept known as “even-lighting agrivoltaics”. These novel solutions remain largely unexplored, but at least this work presents some first results modeled for one specific agrivoltaic system.

9 BORDER EFFECTS

For Agri-PV projects, LuSim is an appropriate tool to simulate the irradiance’s field inhomogeneity around plants as a function of their location relative to the PV system. This leads to the precise quantification of edge effects in the spatial light resource. As above, these edge effects are easier to assess and visualise in relative terms, i.e., by comparison with a no-PV base-case scenario.

Figure 16 illustrates the results of one modelling exercise that is representative of typical agrivoltaic projects involving orchards, vineyards, or berries (e.g., an agrivoltaic system similar to the ones shown in Figures 2 and 17). Figure 16 displays the normalised annual irradiance received by each plant, in relation with the minimum overall irradiance. The x-axis represents the distance in an east-west (E-W) direction, and the y-axis represents the distance in a north-south (N-S) direction. The LuSim results show that the overall resource available to the plants located in the centre of the installation is about a quarter of what would be available in the absence of the agrivoltaic system.

From the standpoint of pure agricultural yield, it is pragmatically considered that an edge effect occurs when the solar resource available at one point of an Agri_PV project is more than 10% greater than the resource available at its centre. According to this definition and the typical system under scrutiny, an edge effect occurs when plants are located less than 5–6 m from the east or west edges, or less than 3–4 m from the north or south edges. In simplified terms, significant edge effects occur wherever the distance from the edges is less than ≈5 m. Such results provide a critical estimate of the radiation field's overall homogeneity, as well as some guidance on the minimum size that an agrivoltaic demonstration plant would need to have so that its results can be statistically meaningful.

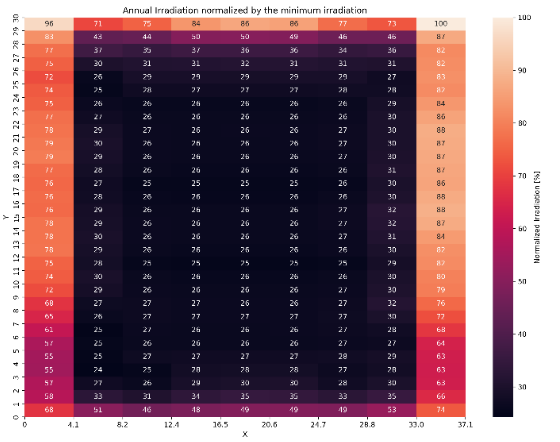

Figure 16: Example of border effects in an Agri-PV system, represented through the annual received irradiation normalized by the minimum irradiation. The red color indicates strong border effects.

10 DESIGN OPTIMIZATION: A CASE STUDY

Considering the lack of appropriate design tools for Agri-PV systems, it is desirable to investigate LuSim's capabilities in terms of design optimization. To that effect, a modelling exercise is conducted here to evaluate the respective merits of several possible configurations for an agrivoltaic system to be installed in a vineyard:
0) Reference (E-W and N-S): Trees alone without structures or panels.
1) E-W panels: Standard (full) PV panels
2) E-W panels: PV panels with 50% semi-transparency.
3) E-W panels: Standard PV panels on the west side alternating with a row of diffusing translucent polycarbonate panels on the east side.
4) E-W panels: Alternating standard panels and diffusing polycarbonate panels (1 standard PV panel, 1 polycarbonate panel) of the same panel size (alternating on the N-S axis). The west modules are staggered in relation to the east modules.
5) N-S panels: Standard PV panels on the south alternating with a row of polycarbonate panels on the north.

Figure 17 shows the scenario corresponding to the PV installation case with semi-transparent panels.

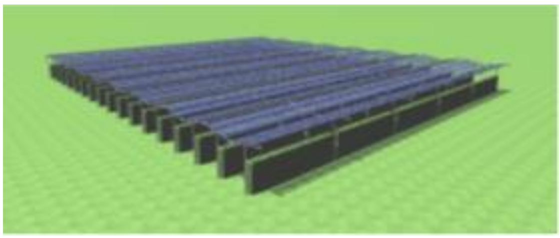

Figure 17: PV installation using semi-transparent panels.

Similarly, Figure 18 shows the scenario corresponding to a PV installation with alternating standard PV panels and light-diffusing panels.

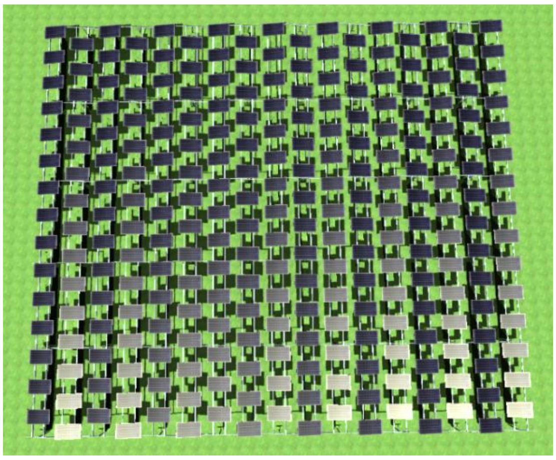

Figure 18: PV installation with alternating standard panels and light-diffusing panels.

Figure 19 shows views from above and below in the case of Scenario 2 with semi-transparent panels. They provide the plants with a better view to the sky than Scenario 1.

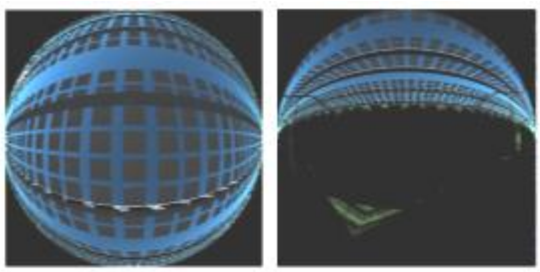

Figure 19: Hemispherical view from above (left) and from the side of the plant (right) for Scenario 2 (semi-transparent panels).

Scenarios 3 and 5 are simulated for two different possible positions of the trees: either beneath a row of PV panels or under a diffusing polycarbonate sheet. The upper face of the plant receives significantly more diffuse irradiance in the latter case than in the former case, since a significant portion of the light is intercepted by the PV panels. Conversely, on vertical crop surfaces, more light is received when neighboring rows of plants are covered by a diffuser rather than a row of PV panels. However, the vertical faces of the plants receive less irradiance when they are positioned just below a diffuser, because then the adjacent rows are under the panels, resulting in a reduction in the diagonal light reaching the plants. Additionally, to study the effect of structures, these scenarios are also simulated both with and without diffuser support structures.

As mentioned just above, Scenarios 3 and 5 are simulated in different ways, firstly to evaluate how the position of the tree impacts the results, and secondly to study the effects of the diffuser's supporting structure. Figure 20 shows the fraction of the sky seen from the top of the plant as a function of the position of the tree.

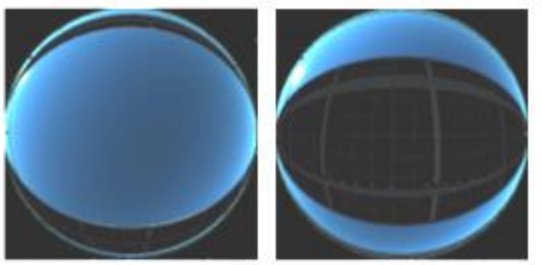

Figure 20: Spherical views of the top of the plant, for Scenario 3, with the plant under either the diffuser (left) or the row of modules (right).

To complement this information, Figure 21 shows the spherical views from a vertical face of the plant. The general finding is that the irradiance received by the different zones of the plants (see Figure 4) is significantly different depending on the row in which they are located. More specifically, the vertical plant faces that see the largest fraction of the sky are those located under the row of PV panels.

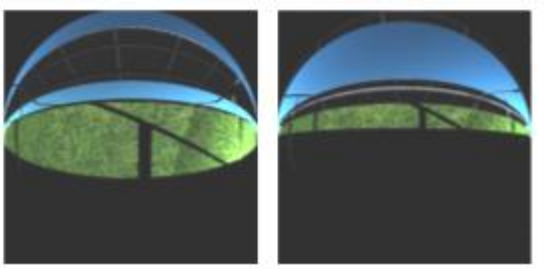

Figure 21: Spherical views of the plant, for Scenario 3 with the plant under either the diffuser (left) or the row of modules (right).

The presence of supporting structures also affects the results because of their shadowing effect. Figure 22 shows the spherical views of the side of the plant either with or without support structure. The structures intercept a non-negligible fraction of the field of view perceived from any point on a plant. This interception is partly caused by the width of the bars and, even more so, by their depth. Overall, these bars block a significant proportion of the light rays that arrive obliquely onto the plant.

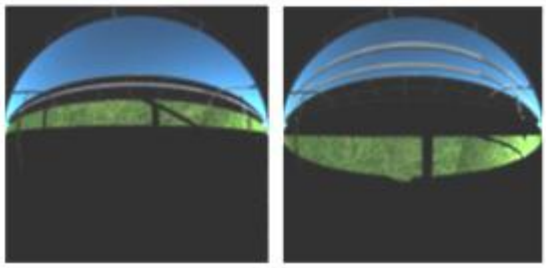

Figure 22: Spherical views of the plant, for Scenario 3 with the plant under a diffuser either without structure (left), or with structure (right) to support it.

Simulations made with LuSim evaluate the direct and diffuse components of the irradiance reaching each of the plant's seven zones (from Figure 4) at hourly temporal resolution or better. These results are then aggregated on a monthly basis, but also at the level of the complete plant by integrating the results from the 7 zones.

Figure 23 provides a general overview of the irradiance received by the plant (averaged across zones 1–6, with contributions from zone 7 neglected) on a clear spring day for all 5 scenarios. The global horizontal irradiance (GHI) that is incident above the crops is significantly reduced in all scenarios, primarily because of its transposition onto the tree's vertical sides, and also because of the nearby sources of shading from neighboring trees, structures, and rows of PV panels. Additionally, this reduction accounts for the optical porosity of the trees (the fraction of light passing through vegetation or not available for photosynthesis) and the effective fraction of irradiance that can be utilized by the plants for photosynthesis.

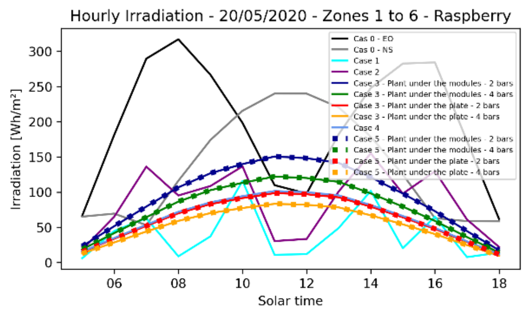

Figure 23: Irradiance received and useable by plants on a clear spring day for all scenarios.

The irradiance received by the tree sides is higher in the cases of the reference scenarios with trees alone without structures or solar panels, as could be expected. The scenario with the lowest irradiance values is Scenario 1, i.e., with standard PV modules. Scenario 2, with semi-transparent modules, provides more light to the plants. It is relatively difficult to distinguish between Scenarios 3 and 5 for the same position of the tree and the same number of bars, because the only difference between these two scenarios is the orientation of the agrivoltaic system. Moreover, the polycarbonate diffuser is assumed to transform all the direct component into isotropic diffuse, which therefore makes the results not very sensitive to orientation. Scenarios 3, 4, and 5 also show the smoothest irradiance curves, thanks to the polycarbonate sheet acting as a pure diffuser.

In contrast, Scenario 2, with semi-transparent modules, has the roughest irradiance curve because of the absence of a diffuser, unlike the other scenarios. In addition to being associated with irradiance variations that are not smooth over the day, Scenario 2 provides the least homogeneous light to the plants, again compared with Scenarios 3, 4, and 5 with diffusers.

For still the same clear day in spring, the most favorable cases for the plants correspond to Scenarios 3 and 5, which are somewhat ideal because there are no supporting structures for the diffusers. The scenarios in which the trees are located under the row of panels offer more interesting results than when they are located under the diffuser. That is because the vertical surfaces of the crops capture most of the solar irradiation, and the light reaches them mainly obliquely.

The monthly analyses provide a more general and meaningful comparison of the results in terms of solar potential and crop yield. Figure 24 represents the monthly irradiation received and useable by the plant (after integration of the incident irradiance on zones 1 to 6 only) for each of the scenarios.

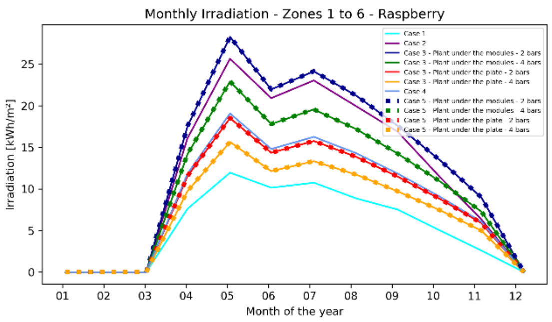

Figure 24: Monthly irradiation received and useable by plants for all scenarios.

Whereas the incident GHI above the canopy is always non-zero, the monthly irradiance received and useable by plants is zero for different scenarios in January, February, March, and December. This is because the trees cannot make use of the solar irradiation to grow or generate fruits in the absence of foliage. Moreover, the reference cases labelled E-W and N-S are the scenarios that offer plants the most irradiation, thanks to the absence of structures and PV panels.

Scenario 1 with standard PV modules is the least favourable case for plant growth. This is simply because the panels do not let any light through, and the installation is almost entirely covered with PV.

The simulation results also show the significant reduction in irradiance received by the plants and through the diffusing panels for Scenarios 3 and 5, when a support structure is considered for the diffusers (indicated by “4 bars” in the legend) compared with the scenarios without a support structure (compare the blue curve and the green curve, or the red curve and the orange curve). As already observed in the analysis of hourly irradiances, Scenarios 3 and 5 without supporting structures and with the trees located under the row of panels (blue curve) provide the plant with the largest monthly irradiance.

Scenario 2 with semi-transparent modules (violet curve) provides only slightly less monthly irradiance to the plant than the most optimal case. However, its irradiance is more uneven, which is less favourable for the crop.

In scenarios where plants are placed alternately between rows of panels and diffuser plates, one row out of two receives a larger solar irradiance, whereas the other row receives less. This difference, depending on the strategy adopted in terms of crop layout and harvesting method, could result in either an advantage or a disadvantage; hence, a more in-depth study would be necessary to provide a more definitive answer.

11 CONCLUSION

This investigation has consisted of a succession of modelling exercises carried out in the context of several agrivoltaic projects related to applications for orchards, vineyards, and berries in southern France. Various configurations of the PV systems were considered, leading to various comparisons of both their electric output and their effects on the crops growth and yield. The results have shown that the modelling of such Agri-PV systems leads to several important challenges that are difficult to tackle with conventional modelling tools. The use of LuSim has made it possible to model the irradiance profiles on the crops with a high spatial resolution, and subsequently to investigate the trade-offs between the main design parameters of Agri-PV systems and their implications on the solar radiation field’s homogeneity and the yield of the crops.

The study’s results have also demonstrated that many important questions deserve further investigation, such as whether the design of semi-transparent PV modules can be optimized depending on each crop’s requirements, or whether standard PV modules with sufficiently low GCR can be used to maintain the solar resource at a high-enough level to preserve or even improve the yield of the crops underneath.

Details of the 3D modelling of the agri-PV system have also been discussed, including the application of the optical porosity approach, the specific crop modelling, and the mutual interaction between the different model parts. A major finding is that simple crop models possess many important advantages over more elaborate ones. Finally, the potential beneficial role of light diffusers has been explored through a preliminary study, showing that they might not be advantageous in all situations, contrary to expectations. Hence, further analyses should be undertaken to expand the present results and obtain more specific recommendations.

ACKNOWLEDGMENTS

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