ASSESSING THE ENERGY YIELD AND IRRADIATION DISTRIBUTION IN FIXED AND TRACKING AGRIVOLTAIC ORCHARDS

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ABSTRACT: Agrivoltaics (AV) plays a crucial role in mitigating land-use conflicts between photovoltaics and agriculture by enabling the simultaneous production of food and PV energy on the same land. While various models and simulation tools exist to predict the irradiation distribution and estimate the energy yield in AV systems, accurately simulating variations in the irradiation across different sections of the crop canopy remains a significant challenge. This difficulty arises from the complexity of modelling intricate crop shapes. This study proposes a modelling and simulation approach based on raytracing, to predict the irradiation variations in distinct sections (sky-facing and the top, middle, and bottom) of the external envelope of apple trees under fixed and single-axis tracking AV systems. For each AV topology, the irradiation on the apple trees directly under and between the PV arrays are analyzed. Findings show that for the trees directly under the PV modules in the fixed systems, the bottom receives the lowest irradiation followed by the middle and the top. The sky-facing part of the tree between the PV arrays receives higher irradiation than that of the tree directly under the PV arrays. Analysis of the shading losses during the flowering period show generally higher shading losses under tracking. Also, the shading losses for the east and west sides of the tree between the PV arrays is higher compared to the tree directly under the PV modules. The specific energy yield from the tracking system is 7% higher than the fixed systems. This research therefore indicates that there exists high variations in irradiation in AV orchards and at different sections of the same trees. Also, higher shading losses under tracking systems call for tracking algorithms which co-optimize crop and energy yields.

Keywords: Agrivoltaics, Irradiance modelling, Orchards, Raytracing, Shading loss

1 INTRODUCTION

Solar photovoltaic is a suitable technology to reduce the dependance on fossil fuels by producing clean and sustainable energy. The cumulative installed PV capacity exceeded 1.6 TW in 2023 [1]. However, the installation of PV creates competition with agriculture for the limited land resources. Agrivoltaic (AV) also known as agriphotovoltaic has been proposed as a suitable solution to alleviate this land-use competition by enabling the simultaneous production of food and PV energy on the same agricultural land. AV provides various synergistic benefits as crops susceptible to adverse weather conditions such as sunburn, hail, frost and wind could be grown under the protection of the PV panels. AV could also increase the economic value of farmers through the sale of extra energy generated [2] and the increased land-use productivity [3], [4]. For example, olive trees in an AV system in Spain had a land equivalent ratio of 1.71 [5] while a LER of 1.2 was reported for oats and potatoes grown in an AV set up in Sweden [6]. A land productivity increase of 50% was reported for blueberries [7] in USA. Also, a land use efficiency of 160% was reported for winter wheat, potatoes, celery, and grass/clover grown in an AV system in Heggelbach, Germany [8]. AV could also increase the water productivity on farmlands [9] as the PV panels reduce water loss from the soil (evaporation) and from the crops (transpiration) in the combined effect known as evapotranspiration. Up to 20% in irrigation water can be saved in an AV system [10]. An overview of existing AV systems and crop types across the world have been described [11].

In the classification of AV systems, and farming practices, orchards have been proposed as an option for the implementation of PV modules [8]. This is because the synergies from combining PV systems with permanent crops are expected to be higher [12]. This is due to possible integration of the PV modules into the existing orchard structures and cultivation in fixed rows for long periods without crop rotation [12]. Also, in orchard farms, these fruit trees are currently protected from hail and sunburn by nets, which could be replaced by the integrated structures of PV modules. Nevertheless, the implementation of PV modules above crops innately leads to shading which could be detrimental to crop growth and yields. To properly implement AV systems and more accurately predict the crop yields, the irradiation reaching the crops, and the shading losses need to be well simulated. Very few studies have assessed the irradiation distribution under different AV orchard systems to accurately predict the shading impact of the PV modules. Simulations of the irradiance on the canopy wall of pear trees under three PV configurations reported up to 70% light reduction with opaque PV modules, heterogenous distribution with checkerboard PV modules and a 28% light reduction for PV modules with 40% transparency [13]. The impact of light reduction during flower bud induction in fruit trees could be detrimental to fruit quality and quantity [14]. Therefore, accurate prediction of shading losses under AV orchard systems is essential to mitigate shading during critical periods and to ensure profitable crop yields. Also, the use of tracking systems could be a suitable option for a more dynamic management of shading losses.

In this study, we propose a modelling approach to investigate the irradiation distribution on the external envelope of Guyot trained apple orchards under bifacial PV modules. Three AV systems are studied: fixed west-tilted and east-west wing, and single-axis tracking AV systems. This work is structured as follows: **section 2** describes the modelling approach. **Section 3** presents and discusses the results, focusing on the irradiation distribution and shading losses on different sections of selected apple trees. The specific energy yield for the different AV systems is also presented.

2 METHODOLOGY

2.1 Modelling framework

Agrivoltaic systems contain different complex structures such as the PV modules, the frames, the support structures, crops and ground which need to be accurately modelled. The modelling approach should therefore be robust and yet flexible to accurately predict the irradiance on the PV arrays and the crops, and the energy yield. To achieve this, imec's simulation framework [15], which is based on raytracing, and more specifically bifacial Radiance was used to model and simulate the different AV orchard systems. The modelling approach is divided into three stages: the geometric modelling, irradiance modelling and the energy yield modelling. The weather file used is based on a typical meteorological year (TMY) for Italy, Bolzano (46.344° N, 11.277° E). Figure 1 shows the simulation approach.

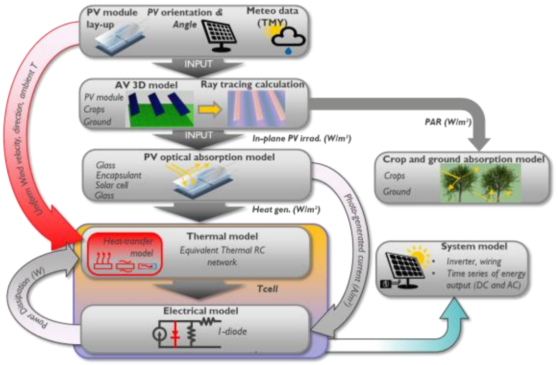

Figure 1: AV Modelling and simulation framework used in this work.

2.2 Geometric modelling of the AV apple orchards

The geometric modelling of the AV plant is divided into two parts: the PV array and the crops. AV systems generally contain different crop shapes which need to be accurately modelled to simulate the irradiation distribution and crop growths. Complex crop shapes generally lead to higher computational times due to the number of points per crop surface for which the irradiance needs to be accounted. Hence, simple shapes which represent the external envelope of the trees or crops need to be developed to bridge the gap between accuracy and computation time. For example, [13] modelled the canopy walls of pear tress using solid prisms meshed in equal points.

In this work, the external envelope of apple trees with Guyot training is modelled using SketchUp Pro 2023. In the Guyot system, the main tree axis is guided horizontally while the side shoots are extended vertically upwards to create slender fruit walls (narrow hedges) for ideal sunshine on all the fruits. This also offers ideal conditions for efficient cultivation measures and harvest [16]. For apple trees in north-south rows, two apple trees which represent a quarter of an orchard row and of length 6.8 m are considered in the modelling. Each tree has a height of 3.5 m, and the width of each row is 0.7 m. To assess the irradiation distribution on the apple trees, the east and west sides of each tree are divided into three equal sections: bottom, middle, and top. The sky-facing section of each tree is also considered for the irradiation distribution, giving seven sections per tree. The geometric model and sections the trees are shown in Figure 2. To address whether the synergistic benefits are maximized when the crops are either directly under or between the PV rows, the two scenarios were assessed for the total irradiation received.

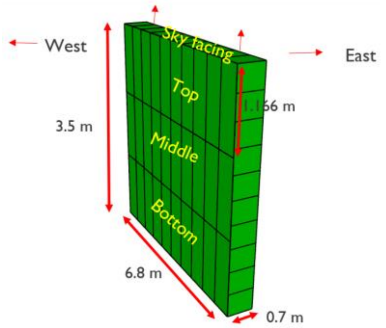

Figure 2: Geometric model of apple trees showing the sky-facing and the top, middle and bottom of the east and west tree sections. Model dimension is for two trees.

The geometric model of the PV modules was created in Python, and contains components such as the PV cells, the front and rear glass and the frames. From the PV modules, the PV arrays are then created to make up the AV system. In this work, fixed west (W)-tilted, fixed east-west (EW) wing and single-axis tracking AV systems are studied. The different AV orchard systems are shown in Figure 3.

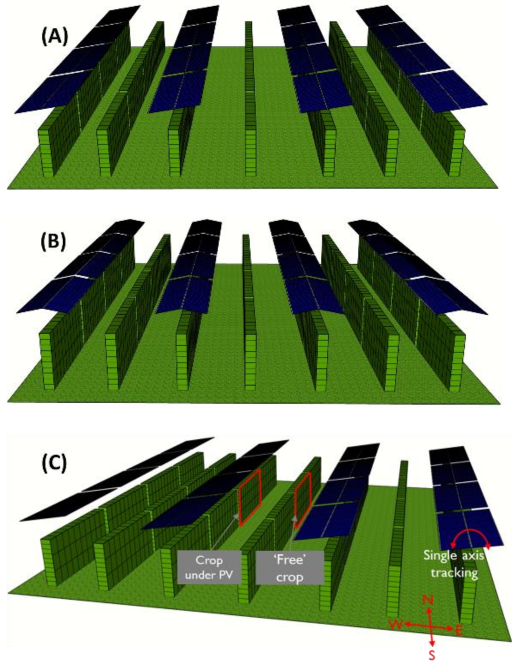

Figure 3: Geometric models of the different AV systems. (A) West-tilted, (B) EW wing and (C) single axis tracking. The models show the trees under and between ('free crop') the PV arrays assessed for the irradiation distribution.

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2.3 Irradiance modelling

The different components in the AV system are identified in Radiance by assigning material properties. The surfaces of interest include the front and rear of the PV modules, the ground and the trees. To properly identify the different materials based on their optical properties (reflectivity, transmissivity, emissivity...), the materials are given pre-defined Radiance properties. The amount of light reaching the rear of the PV modules is dependent on the ground albedo and the reflectance properties of the tree leaves. An albedo value of 0.22 was used. The shading loss on the seven faces of interest for the crop directly under the PV arrays and the "free crop" (crop between the PV arrays) is calculated based on equation (1)

$$Shading\ loss\ (\%) = \frac{G_{ref} - G_{AV}}{G_{ref}} X\ 100 \qquad (1)$$

Where G_{ref} is the irradiation in the reference system (open field) and G_{AV} is the irradiation in the AV setup.

2.4 Energy yield modelling

The energy yield modelling approach is a bottom-up physics-based method in which the PV modules are built in a hierarchical bottom-up approach, starting from the solar cells which can be interconnected to form modules and PV arrays. The coupled Electrical, Optical and Thermal (EOT) framework uses as main inputs the meteorological data (irradiance, ambient temperature, wind speed, wind direction), the material properties (optical, thermal and electrical constants, thicknesses of the different PV module layers), the PV cell and modules technology parameters (e.g., electrical behaviour of the cell, external quantum efficiency, temperature coefficients and the interconnection of the cells//modules). The coupled electrical and thermal model is obtained based on the net power absorbed in the solar cell which is given by the optical model. Some of the power extracted from the solar cell is computed from the single diode equation and is influenced by the actual operating point. Hence, the influence of factors such as temporal fluctuations (from changing weather conditions) and non-ideal conditions such as shading are accounted. The key parameters obtained from this simulation are the direct current (DC) output power at the Maximum Power Point (MPP). More detailed description of this modelling framework has been previously described [15], [17], [18].

The bifacial PV module used in this work consists of 108 half-cut cells, with a bifaciality factor of 80%. The losses used in the energy yield calculation are shown in Table 1.

Table 1: Different losses considered in the yearly energy yield calculation.

System losses considered	Value [%]
Soiling	2
Resistive (cabling)	1
Inverter	2

3 RESULTS AND DISCUSSIONS

3.1 Yearly irradiation on trees

The vertical sides (east and west) of the apple trees are prioritized in the irradiance calculations because they are more effective in the photosynthesis process. Also, each row of apple trees is considered long enough such that the contribution of the north and south faces in the photosynthesis process is considered negligible. Figure 4 shows the yearly integrated irradiation for the different AV systems.

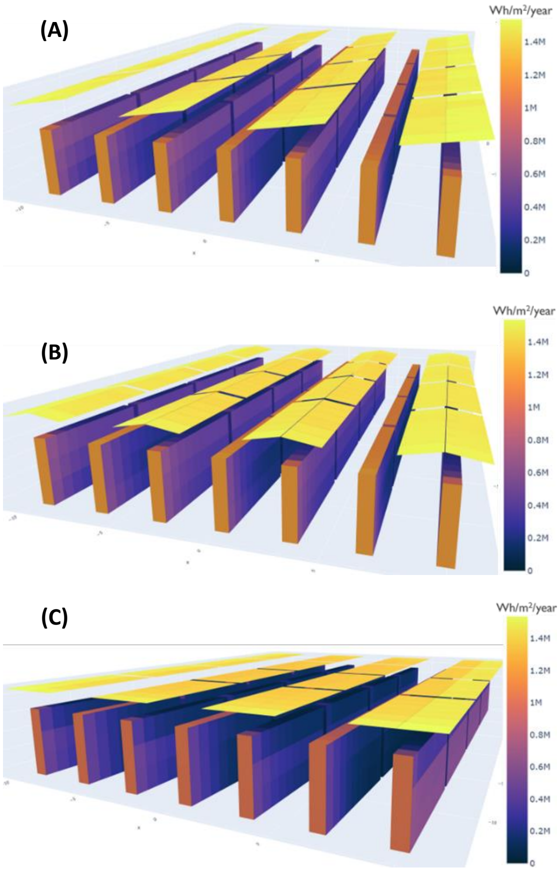
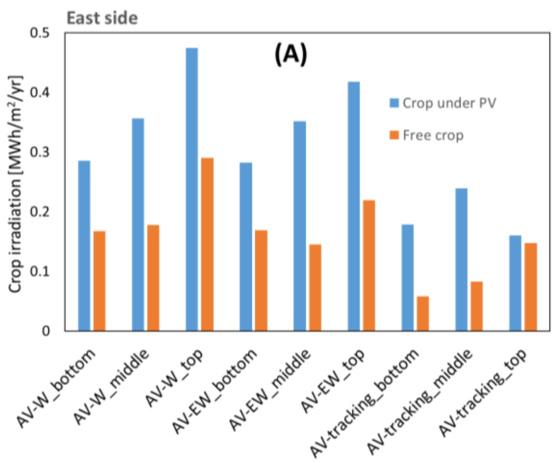


Figure 4: Yearly integrated irradiation for the (A) West-tilted, (B) EW wing and (C) single axis tracking systems.

The calculated yearly irradiation values on the east, west and sky-facing sides of the trees for the AV systems are shown in Figure 5.



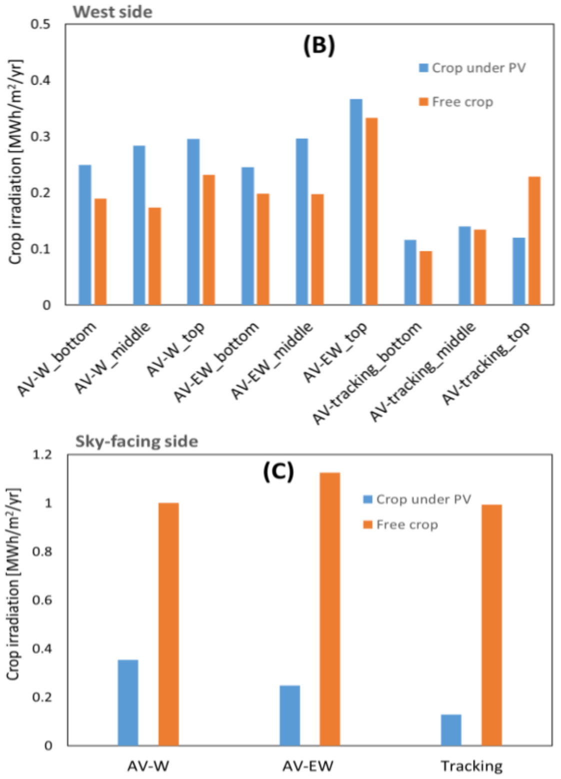


Figure 5: Yearly integrated irradiation on the (A) East (B) west and (C) sky-facing sides of the tree directly under the PV array and the tree between the PV arrays ('free crop') for the three AV systems.

In general, the east and west sides of the tree between the PV arrays received less light than those of the tree directly under the PV array. This is due to higher shading from the adjacent rows of PV modules. However, the sky-facing side of the tree between the PV arrays received more irradiation than that of the tree directly under the PV arrays. For the respective sides of the apple trees, the irradiation was lowest under the single-axis tracking system. Also, for the crop directly under the fixed PV arrays, the bottom of the trees received the lowest irradiation followed by the middle and the top parts. For the tree between the PV rows, no clear trend was visible for bottom and middle sections, though the top part received the highest irradiation.

3.2 Shading losses during the flowering period

The shading loss for the different sections of the apple trees during the flowering period was also assessed in this work. The flowering period of apples and pears which usually lasts between April and May is crucial for fruit production (in terms of number and quality) [13], [19]. For example, shading during the flowering phase of an AV pear orchard resulted in 16.4% reduction in pear yield [13]. The shading losses for the seven tree sections during the flowering period are shown in Figure 6.

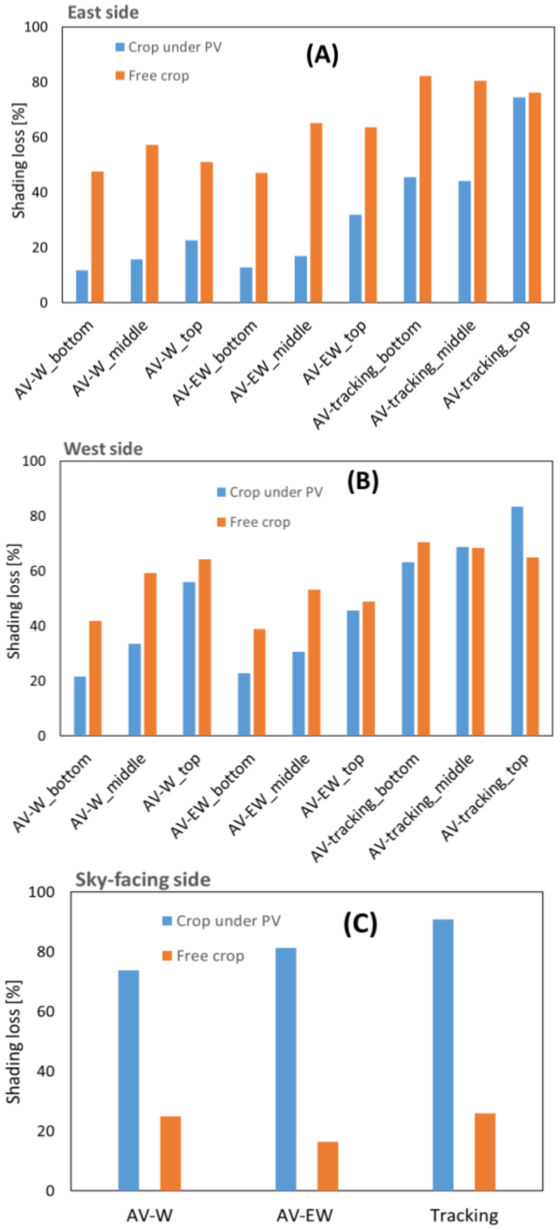


Figure 6: Shading losses during the flowering period (April - May) of apple trees for the (A) East side, (B) west side and the (C) sky-facing sides of the tree under the PV array and the tree between the PV array ('free crop').

The shading loss on the east and west sides of the tree between the PV arrays was generally higher than that of the tree directly under the PV arrays. Under the different AV systems and for the east and west sides, the minimum shading loss for the 'free crop' was 39%. There was up to 90% shading loss (with tracking) for the sky-facing part of the tree under the PV module. For all the sides of the apple trees, the shading loss was higher under the single-axis tracking system.

Therefore, contrary to expectations, the sides of the trees located between the PV rows experience higher shading compared to those of the tree directly under the PV modules. Though a higher shading percent does not necessary imply lower yields, the design of AV orchards must nevertheless consider shade mitigation strategies such as the use of semitransparent PV modules, higher row distances or tracking algorithms which co-optimize crop and energy yields. Such tracking systems are desired to help mitigate the high shading losses recorded on the top and sky-facing sections of the trees directly under the PV modules.

3.3 Specific energy yield

The simulated yearly specific energy yield for the different AV systems given the different losses (see Table 1) is shown in Figure 7. The maximum specific energy yield was obtained for the single axis tracking system followed by the west-tilted system. Up to 7% gain in energy was obtained with the tracker compared to the fixed systems.

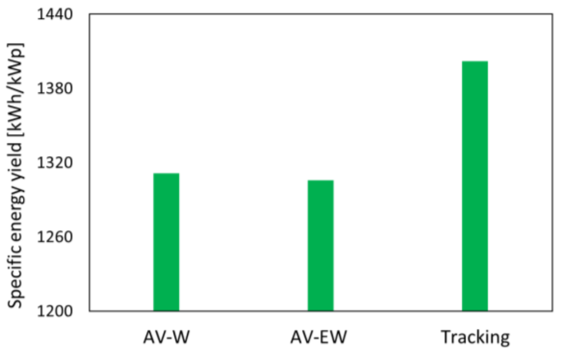


Figure 7: Yearly specific energy yield for the west, EW and tracking systems.

Also, analysis of the power output behavior for the fixed and tracking systems on a clear sky day (Figure 8) showed that the higher output power for the tracker was recorded in the morning and evening while the output profile remained constant around midday. The west and EW wing systems showed similar power output profiles with the west-tilted reaching peak power slightly later than the EW wing.

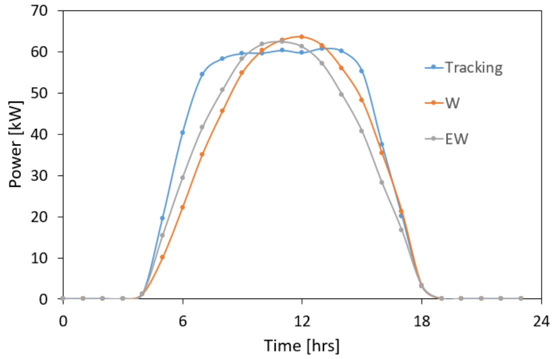


Figure 8: Power output behavior for the fixed and tracking AV systems on a clear-sky day in summer (July 18th).

4 CONCLUSION

Agrivoltaics is considered a suitable solution for sustainable energy and crop production. Orchard farms provide a suitable option for the implementation of PV modules as the PV panels can replace the nets and plastics currently used to protect the crops from hail and sunburn. However, to maximize the land-use efficiency and productivity of AV orchard systems, more accurate prediction of the variation in irradiation on the trees is needed. This work modelled the external envelope of apple trees and assessed the irradiation distribution and shading loss on the sky-facing and the top, middle and bottom of the east and west sides of the apple trees in fixed and single axis tracking PV modules. The findings showed that:

- During the flowering period, the shading losses on the east and west sides of the tree between the PV arrays ('free crop') were generally higher compared to the tree directly under the PV array. As the east and west sides of the trees are more efficient in the photosynthesis conversion process, placing the PV panels directly above the trees might be more suitable for more light availability on the crop walls while offering crop protection around noon.
- The shading losses of the sky-facing part of the tree under the PV modules were higher than that of the trees between the PV array.
- Shading losses were generally higher under the tracking system compared to the fixed systems.
- Under the fixed PV arrays, the bottom of the trees received the lowest irradiation followed by the middle and top sections.
- The specific energy yield under tracking was 7% higher than the fixed systems.

This research therefore indicates that in AV orchards, there are huge variations across different trees and across different sections of the same trees. Also, tracking algorithms should prioritize crop light requirements especially during key periods such as flowering, as higher shading levels could negatively impact crop yield in quantity and quality.

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6 REFERENCES

[1] "Snapshot of Global PV Markets 2024", Accessed: May 23, 2024. [Online]. Available: www.iea-pvps.org

[2] H. Dinesh and J. M. Pearce, "The potential of agrivoltaic systems," Feb. 01, 2016, *Elsevier Ltd*. doi: 10.1016/j.rser.2015.10.024.

[3] B. Valle *et al.*, "Increasing the total productivity of a land by combining mobile photovoltaic panels and food crops," *Appl Energy*, vol. 206, pp. 1495–1507, Nov. 2017, doi: 10.1016/j.apenergy.2017.09.113.

[4] C. Dupraz *et al.*, "To mix or not to mix : evidences for the unexpected high productivity of new complex agrivoltaic and agroforestry systems," Sep. 2011. Accessed: Jul. 26, 2023. [Online]. Available: https://www.researchgate.net/publication/230675951_To_mix_or_not_to_mix_evidences_for_the_unexpected_high_productivity_of_new_complex_agrivoltaic_and_agroforestry_systems

[5] E. Mouhib *et al.*, "Enhancing land use: Integrating bifacial PV and olive trees in agrivoltaic

systems," *Appl Energy*, vol. 359, Apr. 2024, doi: 10.1016/j.apenergy.2024.122660.
[6] P. E. Campana, B. Stridh, S. Amaducci, and M. Colauzzi, "Optimisation of vertically mounted agrivoltaic systems," *J Clean Prod*, vol. 325, Nov. 2021, doi: 10.1016/j.jclepro.2021.129091.
[7] O. A. Katsikogiannis, H. Ziar, and O. Isabella, "Integration of bifacial photovoltaics in agrivoltaic systems: A synergistic design approach," *Appl Energy*, vol. 309, Mar. 2022, doi: 10.1016/j.apenergy.2021.118475.
[8] M. Trommsdorff *et al.*, "Agrivoltaics: Opportunities for Agri-culture and the Energy Transition", Accessed: Apr. 27, 2023. [Online]. Available: https://www.ise.fraunhofer.de/content/dam/ise/en/documents/publications/studies/APV-Guideline.pdf
[9] Y. Elamri, B. Cheviron, A. Mange, C. Dejean, F. Liron, and G. Belaud, "Rain concentration and sheltering effect of solar panels on cultivated plots," *Hydrol Earth Syst Sci*, vol. 22, no. 2, pp. 1285–1298, Feb. 2018, doi: 10.5194/HESS-22-1285-2018.
[10] H. Marrou, L. Dufour, and J. Wery, "How does a shelter of solar panels influence water flows in a soil–crop system?," *European Journal of Agronomy*, vol. 50, pp. 38–51, Oct. 2013, doi: 10.1016/J.EJA.2013.05.004.
[11] S. Asa'a *et al.*, "A multidisciplinary view on agrivoltaics: Future of energy and agriculture," *Renewable and Sustainable Energy Reviews*, vol. 200, p. 114515, Aug. 2024, doi: 10.1016/J.RSER.2024.114515.
[12] B. Willockx, B. Herteleer, and J. Cappelle, "Techno-economic study of agrovoltaic systems focusing on orchard crops".
[13] B. Willockx, T. Reher, C. Lavaert, B. Herteleer, B. Van de Poel, and J. Cappelle, "Design and evaluation of an agrivoltaic system for a pear orchard," *Appl Energy*, vol. 353, Jan. 2024, doi: 10.1016/j.apenergy.2023.122166.
[14] S. S. Miller, C. Hott, and T. Tworkoski, "Shade effects on growth, flowering and fruit of apple," *Journal of Applied Horticulture*, vol. 17, no. 2, pp. 101–105, May 2015, doi: 10.37855/JAH.2015.V17I02.20.
[15] I. T. Horváth *et al.*, "Photovoltaic energy yield modelling under desert and moderate climates: What-if exploration of different cell technologies," *Solar Energy*, vol. 173, pp. 728–739, Oct. 2018, doi: 10.1016/j.solener.2018.07.079.
[16] "(PDF) Guyot training: a new system for producing apples and pears." Accessed: Sep. 20, 2024. [Online]. Available: https://www.researchgate.net/publication/338595250_Guyot_training_a_new_system_for_producing_apples_and_pears
[17] H. Goverde, J. Govaerts, K. Baert, F. Catthoor, J. Driesen, and J. Poortmans, "Optical-thermal-electrical model for a single cell PV module in non-steady-state and non-uniform conditions build in SPICE," *28th European Photovoltaic Solar Energy Conference and Exhibition - EUPVSEC* , vol. 4, no. 1, pp. 3291–3295, Jan. 2013, doi: 10.11648/j.ijefm.20160401.14.
[18] H. Goverde *et al.*, "Energy yield prediction model for PV modules including spatial and temporal effects," *IIOimport*, 2014, Accessed: Feb. 21, 2024. [Online]. Available: https://imec-publications.be/handle/20.500.12860/23873
[19] "Gallery: Lifecycle of an Apple, From Bud to Blossom to Fruit | Orchard Notes." Accessed: Feb. 09, 2024. [Online]. Available: https://orchardnotes.com/2023/03/28/lifecycle-apple-bud-blossom-fruit/