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Techno-Economic Viability of Agro-Photovoltaic Irrigated Arable Lands in the EU-Med Region: A Case-Study in Southwestern Spain

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Citation: Moreda, G.P.; Muñoz-García, M.A.; Alonso-García, M.C.; Hernández-Callejo, L. Techno-Economic Viability of Agro-Photovoltaic Irrigated Arable Lands in the EU-Med Region: A Case-Study in Southwestern Spain. *Agronomy* **2021**, *11*, 593. https://doi.org/10.3390/agronomy11030593

Academic Editor: Ajit Govind

Received: 1 February 2021
Accepted: 17 March 2021
Published: 20 March 2021

Abstract: Solar photovoltaic (PV) energy is positioned to play a major role in the electricity generation mix of Mediterranean countries. Nonetheless, substantial increase in ground-mounted PV installed capacity could lead to competition with the agricultural use of land. A way to avert the peril is the electricity-food dual use of land or agro-photovoltaics (APV). Here, the profitability of a hypothetical APV system deployed on irrigated arable lands of southwestern Spain is analyzed. The basic generator design, comprised of fixed-tilt opaque monofacial PV modules on a 5 m ground-clearance substructure, featured 555.5 kWp/ha. Two APV shed orientations, due south and due southwest, were compared. Two 4-year annual-crop rotations, cultivated beneath the heightened PV modules and with each rotation spanning 24 ha, were studied. One crop rotation was headed by early potato, while the other was headed by processing tomato. All 9 crops involved fulfilled the two-fold condition of being usually cultivated in the area and compatible with APV shed intermitent shading. Crop revenues under the partial shading of PV modules were derived from official average yields in the area, through the use of two alternative sets of coefficients generated for low and high crop-yield shade-induced penalty. Likewise, two irrigation water sources, surface and underground, were compared. Crop total production costs, PV system investment and operating costs and revenues from the sale of electricity, were calculated. The internal rates of return (IRRs) obtained ranged from a minimum of 3.8% for the combination of southwest orientation, early-potato rotation, groundwater and high shade-induced crop-yield penalty, to a maximum of 5.6% for the combination of south orientation, processing-tomato rotation, surface water and low shade-induced crop-yield penalty.

Keywords: agrophotovoltaic; agrivoltaic; dual-land use; solar sharing; solar photovoltaic energy; water–food–energy nexus

1. Introduction and Objectives

Nowadays, most countries worldwide are aware of the importance of preserving nature. Environment protection includes, amongst others, measures to limit the use of non-recyclable materials and to reduce the emission of greenhouse-effect gases (GHGs). Reduction in GHGs emission entails burning less fossil fuels and increasing the share of renewable energies in the electricity generation mix. The major renewable sources of electricity, wind and solar, intrinsically non-dispatchable due to the intermittency of their resource, could be backed-up by hydrogen fuel cells in the future. European Union (EU) member states are promoting increases in wind and solar installed capacity. Hereof, Spain and Italy planned national levels of 42% and 30%, respectively, of energy from renewable sources in their gross final energy consumption in 2030 [1,2].

Solar power plants produce electricity based on the photovoltaic (PV) effect or by concentrating solar energy onto a heat-transfer-fluid which produces the steam that drives a turbine-generator set. In many countries, ground-mounted solar PV power plants have become familiar in the rural landscape, being popularly known as solar farms. By the end of 2019, installed solar PV power capacity in Spain stood at 8913 MW, representing about 8% of the total installed power capacity in Spain [3].

Substantial further increase in ground-mounted PV power capacity could eventually lead to conflict of interest with the agricultural use of land. This could jeopardize the stability of agricultural produce prices, which should be carefully considered. In 1982, Goetzberger and Zastrow [4] analyzed the possibility of combining agricultural and electric-energy production in the same plot. This dual use of land was later coined in the literature as agrivoltaic or agrophotovoltaic. Here, we use the latter portmanteau, abbreviated as APV. The main differences between a conventional ground-mounted PV power plant and an APV system are:

i. the spacing between PV module rows in APV systems is greater, to let more irradiation pass through and hit the crop; in conventional ground-mounted PV power plants, row spacing is kept to the minimum compatible with tolerable row self-shading.
1. the PV modules in APV systems are substantially heightened above the ground, to decrease shade intensity and also to allow agricultural machinery operate beneath; thus, while in conventional ground-mounted PV power plants the vertical distance of the modules bottom edge to the ground is 0.5–1 m, in APV it is 5–6 m.

In 2010, a first APV prototype was erected by Dupraz et al. in Montpellier, France [5], using fixed-tilt PV modules. In their experiments, the main crop cultivated was lettuce [6]. Valle et al. [7] reported on the extension of the Montpellier 2010 prototype with sun-tracking PV modules. In 2016, a fixed-tilt 194.4 kWp APV array with bifacial PV modules and a ground clearance of 5 m was erected in Herdwangen, Germany [8]. The reason for using bifacial PV modules was two-fold: First, to harness snow reflectivity to produce more electricity; and second, to decrease crop shading, thanks to higher transparency of bifacial modules compared to monofacial counterpart. Schindele et al. [8] concluded that their system was profitable for potato but not for wheat. Dinesh and Pearce [9] concluded that PV installed capacity could be increased between 40 and 70 GW if lettuce cultivation alone were converted to APV systems in the United States of America. They recommended exploring the outputs for different crops and geographic areas, to determine the potential of APV farming worldwide. Recently, the consortium SolarPower Europe proposed to integrate a "European Agri-PV strategy" within the future Common Agricultural Policy (CAP) [10]. Hitherto, APV projects in Europe have been of limited acreage. To our knowledge, the largest APV complex, with 2.67 MW, spans 3.2 ha of raspberry near Arnhem, The Netherlands [11].

In APV systems, both the PV array and the understorey crop benefit mutually. For instance, in a watermelon field in the EU-Med region, the shade casted by the heightened PV modules could circumvent the need for anti-fruit-cracking solar protector spraying of the fruits. Apart from the economic saving for the farmer, this is beneficial for the environment. Another example of synergy is the soil moisture condition favored by APV sheds [12] that can save irrigation water. The latter is important for several reasons: First, environmental benefit; second, reduced cultivation cost; third, limited crop yield decrease in case of irrigation water allocation restricted due to drought; fourth, possibility of irrigating an acreage only slightly smaller than that of a non-drought year.

Albeit in Spain average yield per unit area of irrigated crops is 6.5 times greater than that of rainfed agriculture [13], drought episodes make granted water allocations not always deliverable. Irrigation blue water shortage is partly responsible for the difference between irrigable and irrigated area in many countries. Thus, in 2016 the share of irrigable and irrigated areas in the total Utilized Agricultural Area of Spain were of 15.7% and 13.2% respectively [14]. In the same year 2016, the corresponding shares were 32.6% and 20.2% for Italy and of 29.7% and 23.6% for Greece.

The objectives of this work were:

1. to design two irrigated annual crop rotations whereof crops are usually cultivated in the area of study and compatible with partial shading imposed by APV sheds.
2. to thoroughly determine the stream of expenditure and revenues for both agricultural and electricity production, with the final aim of analyzing the profitability of APV system for each combination of APV shed orientation (due south/ southwest), source of irrigation water (surface/underground), shade-induced crop yield penalty (low/ high) and crop rotation (early potato/processing tomato).

2. Materials and Methods

A hypothetical case-study was arranged with annual irrigated crops cultivated under APV sheds in the municipality of Brenes, close to the city of Seville, in southwestern Spain. The centroid of the site sits at 37°33′22′′ N and 5°50′8′′ W (Datum ETRS89), standing on average altitude of 40 m a.s.l. Some major woody and arable crops cultivated in the area are: Olive, citrus, almond, peach, alfalfa, early potato, maize, processing tomato, cotton and sunflower. Amongst the annual arable crops, we selected potato to be rotation-head, since under-shading yield data were found in the literature [15] for this crop. Based on agronomical considerations detailed in the next sub-section, a four-year rotation headed by early-potato was designed. Taking into account the 6 ha average size of the agricultural unit plot in Brenes, a total acreage of 24 ha was analyzed. Lettuce, a shade-tolerant crop with documented under-shade yield data, was disregarded in view of its limited cultivation in the area [16]. Conversely, cotton, a traditional local annual crop, was discarded because according to Weselek et al. [17] it does not thrive in shade. For the sake of universality, we considered as if land consolidation had not been implemented in the area of study. Thereby, the spatial distribution considered is fragmented, i.e., the four 6 ha plots are not adjacent to each other (Figure 1).

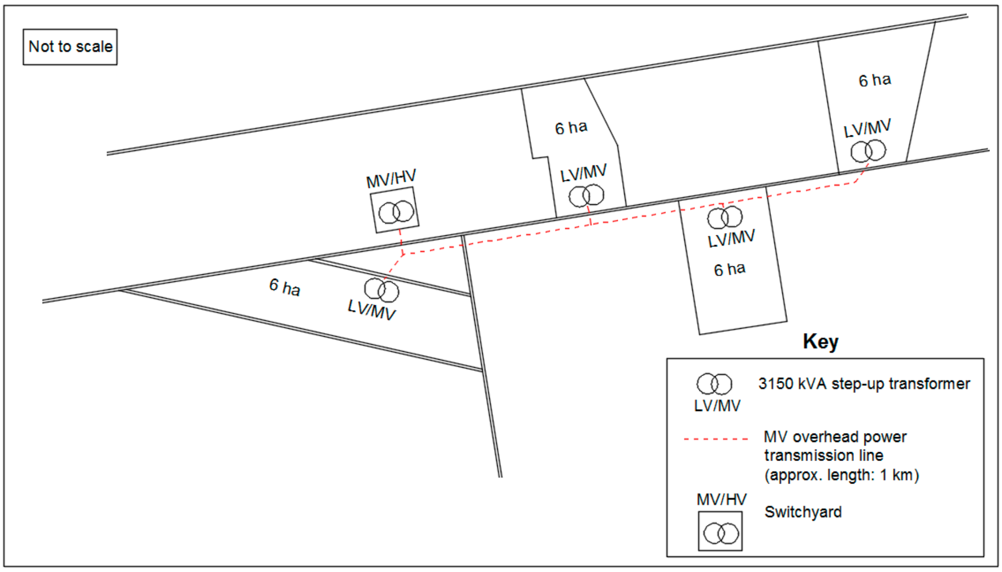

Figure 1. Spatial distribution of the four plots totalizing 24 ha, the medium voltage power transmission line budgeted and the pre-existing grid-connection switchyard.

2.1. PV System

The basic APV shed considered consisted of 22 non-tracking and heightened supporting structures aligned in two parallel swaths of 11 supporting structures each Figure 2. The PV modules are arranged in groups of 24 modules on each supporting structure. The fixed-tilt angle is of 27° (the local latitude minus 10°). The PV module considered was the opaque-monofacial-polycrystalline CSP290-60, of 290 Wp [18]. The dimensions of this module are 1640 mm × 992 mm and it weighs 18.2 kg. The supporting structures are equispaced 9.5 m. The mechanical configuration of the basic APV shed, including lateral (Northeast-Southwest direction for the due SW shed orientation depicted) lattice bracing that leave a ground-clearance of 5 m, is similar to the one reported by Schindele et al. [8]. This substructure is of known cost and would be valid for the location of Seville, where snow and wind loads are less or equal than in Herdwangen. The pillars of the substructure are fixed to the ground by means of a so-called spider-shaped anchor made of an anchoring bush plate with long threaded rods assembled in a circular fashion [19].

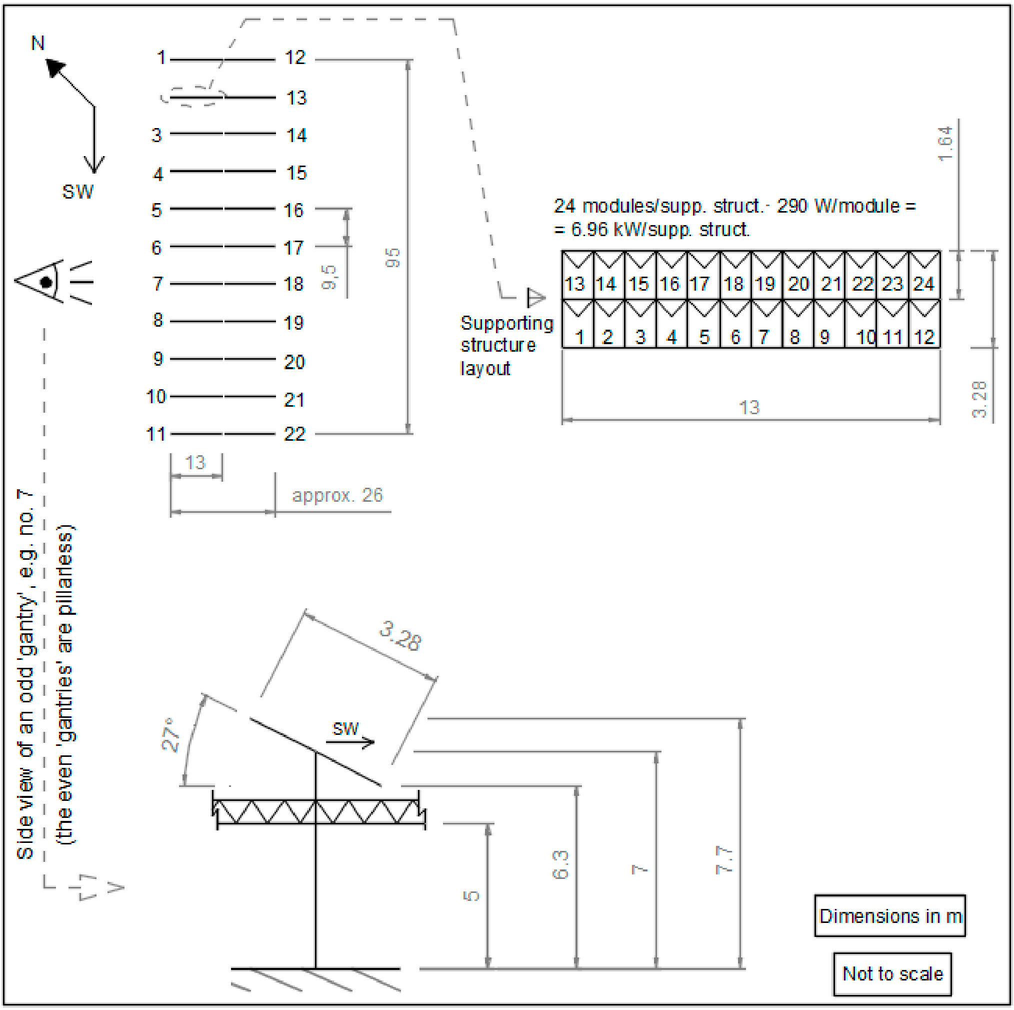

Figure 2. Basic Southwest-oriented agrophotovoltaic shed featuring an installed PV capacity of 153.1 kWp and connected to a 150 kW inverter.

With regard to the PV modules azimuthal angle, two orientations were compared: due southwest and due south. Although the latter is the one that maximizes electric production in the northern hemisphere, Beck et al. [20] concluded that either southeast or southwest is preferable for the crop cultivated beneath the APV shed, since ground radiation distribution is more uniform. The increased radiation uniformity favors crop plants isochronous ripening, which is particularly important for arable crops, usually harvested in mechanized or semi-mechanized one-single pass. Here, we used SAM 3D scene shade calculator [21] to compare due South (Figure A1, Appendix A) and due Southwest (Figure A2) orientations.

The number of PV modules in the basic APV shed is

$$24\frac{\text{PV modules}}{\text{Supporting structure}}\cdot 22\frac{\text{Supporting structures}}{\text{Basic APV shed}} = 528\ \text{PV modules/Basic APV shed}$$

The corresponding peak power is

$$528\ \frac{\text{PV modules}}{\text{Basic APV shed}} \cdot 290 \frac{\text{Wp}}{\text{PV module}} = \text{ 153120 Wp } \cong \text{ 153.1 kWp/Basic APV shed}$$

To calculate the ground area covered by the basic APV shed, we have to multiply its overall width (26 m (Figure 2)) by its overall length. The latter, in turn, is the sum of 95 m (10 × 9.5 m, Figure 2) plus 1.5 m (the horizontal projection of the last module row cantilever 1.64 m to an angle of 27°) plus 9.5 m, i.e., 106 m. Hence,

$$26\ \text{m} \times 106\ \text{m} = 2756\ \text{m}^2 = 0.2756\ \text{ha}$$

To calculate the ground coverage ratio (GCR), the overall module surface area has to be first computed as:

$$528\ \text{PV modules} \cdot \frac{1.68\ \text{m} \cdot 0.992\ \text{m}}{\text{PV module}} = 880\ \text{m}^2$$

Then, the GCR is

$$\frac{880\ \text{m}^2}{2756\ \text{m}^2} = 32\%$$

Power density is

$$\frac{153.1\ \text{kWp}}{0.2756\ \text{ha}} \cong 555.5\ \text{kWp/ha}$$

Considering an effective land area of 5.7 ha, obtained by reducing by 5% the size of the agricultural unit plot to account for mismatch between plot legal boundaries and APV shed orientation, the PV capacity installed in each of the four 6 ha plots is

$$555.5 \frac{\text{kWp}}{\text{ha}} \cdot 5.7\ \frac{\text{ha}}{\text{plot}} = 3166\ \text{kWp/plot}$$

The inverter considered is the SMA SHP Peak 3, which features a nominal AC power of 150 kW [22]. The number of inverters in the agricultural unit plot would be

$$\frac{3166\ \text{kWp /agricutural unit plot}}{153.1\ \text{kWp/inverter}} \cong 21\ \text{inverters /agricultural unit plot}$$

The lifespan considered for the APV system is 25 years, the conventional lifespan of the PV modules. The service life assigned to the inverters is 13 years, which entails inverters replacement in the year 14. Module degradation was computed by means of a degradation coefficient, assigned a value of 1 until year 11 and annually decreased by 0.5% from the year 12 onwards. A simulation was run to estimate annual income from the sale of the energy generated by the PV system. Simulation was done using SISIFO [23], an online free simulation tool for the quality and bankability of PV systems. Table 1 presents a compilation of the main data fed to the SISIFO PV simulator.

2.2. Irrigated Crops

In the EU-Med countries, irrigation water use represents an average 70% of total water withdrawals [24]. On the other hand, more than 80% of the irrigated land-acreage in Spain, involving $7 \cdot 10^5$ irrigators and $2 \cdot 10^6$-hectare, is serviced by an irrigation district [25]. According to Masia et al. [26], surface water from reservoirs represents most of the water stewardshipped and distributed by irrigation districts in the EU-Med region. Concurrently, underground water abstractions in Spain irrigate over one-third of the country irrigable area [27]. Our study is on the arable lands of the Guadalquivir river valley near Seville, where the climate is Mediterranean-oceanic [28]. According to the site coordinates, water would be served by the Comunidad de Regantes del Valle Inferior del Guadalquivir irrigation district, hereinafter abbreviated as Valle Inferior Irrigation District (VIID). Their irrigation scheme provides surface water with a pressure head (p_h) of 441 kPa of water measured at the pumping station [29].

Table 1. Input data for PV simulation of a 5.7 ha agro-photovoltaic plant oriented due Southwest, in Brenes (Seville, Spain).

SISIFO Simulator Input Data	
Site Geographical Latitude	37.557351° N
Site geographical longitude	5.834142° W
Local altitude (m)	40
Meteorological data type	TMY [(a)]
PV system peak power (kWp)	3166
PV system peak power per inverter (kWp)	153.1
Inverter nominal power (kW)	150
Real power/peak power (dimensionless)	0.98
PV system peak power per transformer (kWp)	3166
Generator inclination or PV modules tilt angle (°)	27
Generator orient. or azimuth angle (°)	–45
Generator height at supporting structure center (m)	7
Separation among structures (dimensionless)	3 [(b)]
PV generator width (dimensionless)	8 [(c)]
Deviation of back structure (dimensionless)	0 [(d)]
LV/MV transformer power (kVA)	3150
LV/MV transformer iron losses (kW)	32
LV/MV transformer copper losses (kW)	32
DC wiring losses (% of peak power)	2.0
AC wiring losses between inverter and LV/MV transformer (% of peak power)	2.0
Soiling impact (%)	1.0

[(a)] Typical meteorological year. [(b)] 9.5 m/3.28 m ≈ 3. [(c)] 26 m/3.28 m ≈ 8. [(d)] 0 m/26 m = 0.

Instead of continuous mono-cropping, a crop rotation was designed to submit to the principles of sustainable farming. The crop selected as rotation head was early-potato. To do the study more comprehensive, we extended it to an alternative four-year crop rotation. The head-of-rotation in this case was processing-tomato, which in the last years competes with early-potato in local farmers preferences. It is worthy of note that processing-tomato is also mainstream in other EU-Med countries such Italy. The main difference between the two crop rotations is that the early-potato rotation is symmetrical, unlike the processing-tomato counterpart. The latter is asymmetrical because tomato withstands well—or indeed "'prefers'"—to be cultivated up to thrice on the same plot, whereas potato is required to be cultivated in a different plot each year.

The crops included in the early-potato rotation, apart from the potato (Solanum tuberosum L.) itself, were: Canola (*Brassica napus*), onion (*Allium cepa* L.), faba bean (*Vicia faba* L.) and forage maize (*Zea mays* L.). The latter two are cultivated on the same plot one after the other in the same year, practice known as sequential cropping or double cropping (Table 2). This scheduling was designed following the sustainable agriculture principles of: (i) avoid cultivating two demanding crops one after the other in the same plot; and (ii) for every plot, avoid repeating the botanic family of the previous year.

Table 2. The early-potato rotation designed, wherein potato returns to each plot every four years.

Year	Plot 1	Plot 2	Plot 3	Plot 4
1	FB-FM [(a)]	Canola	Potato	Onion
2	Canola	Potato	Onion	FB-FM
3	Potato	Onion	FB-FM	Canola
4	Onion	FB-FM	Canola	Potato

[(a)] Sequential cropping of faba bean (FB) in first harvest and forage maize (FM) in second harvest.

The crops comprising the processing-tomato rotation (Table 3), apart from tomato (*Lycopersicum esculentum* or *Solanum lycopersicum*) itself, were: Melon (*Cucumis melo* L.), carrot (*Daucus carota* L.), onion and dry peas (*Pisum sativum* L.). Due to the asymmetry of this rotation, its full 25-year scheduling derivation is tedious and is relegated to Table A1 (Appendix B).

Table 3. Tomato rotation designed, wherein processing-tomato is cultivated in the same plot for three consecutive years.

Year	Plot 1	Plot 2	Plot 3	Plot 4
1	Melon	Onion	Carrot	Tomato
2	Onion	Carrot	Melon	Tomato
3	Carrot	Melon	Onion	Tomato
4	Tomato	Onion	Pea	Melon

2.3. Profitability Analysis

From an entrepreneurship point of view, an APV farm is a business comprised of two activities, namely crop production and electric power generation. To determine the profitability of an APV system, the stream of annual income and expenditure during the project lifetime has to be computed. Expenditure comprise initial investment cost (ascribed to the PV activity, since all the crops considered are annual), plus annual operation and maintenance costs (due to both agricultural and electric energy generation activities). Revenues originate from both activities and go from the second year onwards, since the first year is unproductive and carries only investment costs.

With regard to the APV system investment cost or capital expenditure (CapEx), the main items are the acquisition and installation of the substructure and mounting structures, PV modules, inverters, transformer and the so-called balance-of-system (cables, switch-boards, etc.). Table A2 (Appendix C) includes a breakdown of the cost items involved. With regard to the operating expenditures (OpEx), they can be split in two: First, the annual PV OpEx. Second, the annual costs incurred for crop cultivation beneath APV sheds. Table 4 includes estimated crop production costs under the partial shading of an APV shed.

Table 4. Crop production cost under full sunlight and under APV partial shading (in both cases assuming irrigation with surface water).

	Crop Production Cost [(a)] under Full Sunlight (€/ha)	Savings Due to Synergetic APV Partial Shading				Crop Production Cost under APV Partial Shading (€/ha)
		Irrigation Water Saving (%)	Fertilization Saving (%)	Hail in Surance Saving (%)	Fruit Solar Protector Saving (%)	
Canola	934	11.5 [(b)]	–	–	–	931
Carrot	8978	11.5 [(b)]	–	–	–	8964
Forage maize	1826	11.5 [(b)]	–	–	–	1813
Dry faba bean	544	11.5 [(b)]	–	–	–	541
Melon	7725	14.0 [(c)]	–	2.5	1.5	7697
Onion	7899	11.5 [(b)]	–	–	–	7885
Dry pea	631	11.5 [(b)]	–	–	–	628
Early potato	4701	9.0 [(d)]	–	–	–	4694
Processing tomato	4430	9.0 [(d)]	2.0 [(e)]	2.5	–	4403

[(a)] See Table A4 (Appendix D) for details. [(b)] Due to scarcity of bibliographic data on water saving for some crops under shade, they are assigned the mean between 14% (c) and 9% (d). [(c)] Assimilated to cucumber as both melon and cucumber belong to the botanical family of *Cucurbitaceae*; data for cucumber available at [30]. [(d)] Data for cherry tomato available at [31]. In addition, processing-tomato, the same value is assigned to early-potato, since the latter belongs to the same botanical family as tomato, namely, *Solanaceae*. [(e)] [32].

The irrigation district is liable for pressurizing the pipeline network. Therefore, the electricity generated by the APV system would not be partially self-consumed by a pump station, but entirely sold in the electricity wholesale market. Hence, the management of electricity binomial tariff cost items (contracted power, energy consumption, capacity charge, meter-gauge leasing, irrigators partially exempted electric tax, etc.) is on the irrigation district behalf.

Following the recommendations/prescriptions of the EU Water Framework Directive, many irrigation districts have abandoned the traditional per-hectare flat-rate pricing. The installation of volumetric metering valves has enabled irrigation districts to change to binomial tariffs. These consist of a fixed per-hectare component that is proportional to the area with irrigation rights and a variable or volumetric component that is proportional to the volume of water used [33,34].

The irrigation district determines the volumetric component, based on energy cost. This cost depends on the p_h of the irrigation network, the acreage irrigated and the type of crop, since the required hydraulic power is equal to the p_h multiplied by the flow rate (in turn, p_h depends on whether the water source is underground or surface, the irrigated area topography (plot elevations, size and shape) and the irrigation system service pressure, e.g., sprinklers demand more pressure than drippers) For the VIID, current energy cost is of 0.012 EUR/m^3 [35]. Rodríguez-Díaz et al. [36] measured energy consumption and power required per unit of irrigated area for several surface-water irrigation districts in southern Spain. One of them, the Bembézar Margen Derecha (BMDID), featured a p_h of 461 kPa, almost identical to the VIID p_h of 441 kPa. The crops irrigated are similar in both irrigation districts and similar to those of our study. In a sequel work, Fernández-García et al. [37] reported an energy cost of 0.02 EUR/m^3 and a total irrigation cost of 283 EUR/ha for the BMDID. Here, we took the energy cost of 0.02 EUR/m^3 [37] instead of the lower 0.012 EUR/m^3 [35]. Total irrigation cost in sites where underground water is used is usually two-fold (600 EUR/ha) and sometimes it can reach 900 EUR/ha [38].

Apart from the energy cost, irrigation cost includes water as a fixed-cost levied upon the land. The fixed per-hectare component in turn splits in two: The royalty of the River Basin Organism (Confederación Hidrográfica del Guadalquivir), a public incumbrance for upstream public civil works that allow water disposal to irrigation schemes (42.47 EUR/ha·annum); and the irrigation district fee, for management and maintenance of downstream irrigation district proprietary pipeline network and facilities (63.23 EUR/ha·annum in the case of the VIID [35]). The sum of both amounts equals 105.8 EUR/ha·annum. Further, VIID subscribers are currently, subjected to surcharge disbursement of 84.30 EUR/ha·annum in concept of amortization of pipeline, reservoirs and pumping stations upgrading works commissioned in 2008. Herein, this cost item is not included, since the expected remaining surcharge payment period is shorter than our study lifespan. In addition, regarding water use, Table 5 compiles the volumetric component and the total irrigation cost under full sunlight for the 9 crops considered.

With regard to annual revenues, the main entries are: First, the income from the sale of electricity generated by the PV modules; and second, the income originated from the sale of agricultural produce. With regard to the first, the two variables that intervene are: The annual specific energy yield (kWh/kWp) and the price perceived for the energy generated (EUR/kWh). The annual yield will decrease from year 12 onwards, due to the module degradation coefficient abovementioned. With regard to the wholesale electricity market price perceived for the energy sold, we proceeded as follows: From the future solar contracts due 2026 (FTS YR-26) published in the OMIP 2019 sessions market bulletins [42], one day per month of the year 2019 was selected for averaging. The mean of the 12 prices was 45.02 EUR/MWh (specifically, we took the 11th day of every month, except for May and August, where the 13th and 12th day, respectively, were picked, to skip the eventual Sunday effect). We deliberately dropped the 2020 sessions of the future solar market, because concerns arose about the prices thereof being convoluted with the COVID-19 effect. Afterwards, we divided the 25-year lifespan into three periods: The first one encompassing the first 9 years, while the second and third period spanning the following eight-year each. Finally, we assigned the OMIP FTS mean price previously calculated, 45.02 EUR/MWh, to the first period of 9 years; a price diminished by 5% to the second period (0.95·45.02 = 42.77 EUR/MWh); and a price diminished by 10% to the last 8-year period (0.90·45.02 = 40.52 EUR/MWh). The reason to assign the foregoing reduced prices to the second and third period is that foreseeably—and unfortunately for generators—increasing solar PV capacity installed in the forthcoming years will lead to decline of wholesale electricity prices [43].

Table 5. Irrigation costs under full sunlight.

		Surface Water		Groundwater	
	Water Use (m^3/ha)	**Energy Cost [(b)] (EUR/ha)**	**Total Irrigation Cost [(c)] (EUR/ha)**	**Energy Cost [(e)] (EUR/ha)**	**Total Irrigation Cost [(f)] (EUR/ha)**
Canola	1200	24	130	48	291
Carrot	6000	120	226	240	483
Maize	5600	112	165 [(d)]	224	346
Faba bean	1300	26	79 [(d)]	52	174
Melon	4300	86	192	172	415
Onion	5900	118	224	236	479
Pea	1300 [(a)]	26	132	52	295
Potato	4000	80	186	160	403
Tomato	4951	99	205	198	441

[(a)] Following Karkanis et al. [39] and ITACYL [40]. [(b)] Energy cost translates into a volumetric component of 0.02 EUR/m^3 [37]. [(c)] Fixed component: The sum of the River Basin Organism royalty plus the irrigation district fee equals 105.8 EUR/ha [35]. [(d)] The fixed cost is halved because faba bean and forage maize share the same field in one year. [(e)] Assuming a well depth of 100 m, energy cost translates into a volumetric component of 0.04 EUR/m^3 [41]. [(f)] The fixed component is related to the capacity factor charged to the irrigation district (ID) by the electric utility; in turn, the ID apportions this charge to irrigators. It is estimated as 2.3 × 105.8 ≅ 243 EUR/ha; with 105.8 EUR/ha taken from this same table footnote (c) as representative of a surface water ID. The rationale behind the 2.3 coefficient is that, as a rule of thumb, more powerful pumps are required in groundwater IDs compared to surface water IDs; this has a direct effect on the capacity factor charge.

Table 6 is a compilation of estimated decreases in crop yield due to APV shed shading compared to full-sunlight cultivation. In Table 7, values are five-year (2014–2018) averages calculated from official data of Spain Department of Agriculture [16] compiles crop yields (kg/ha) and prices (EUR/t) under full sunlight.

Table 6. Crop yield variation under APV partial shading with respect to full sunlight.

	Crop Yield Variation under Shading [(a)], High Crop-Yield Penalty (%)	**Source [(b)]**	**Crop Yield Variation under Shading [(c)], Low Crop-Yield Penalty (%)**
Canola	–20	[44]	–5
Carrot	–10	[45]	+5
Maize	–7	[46]	+8
Faba bean	0	[47]	+15
Melon	–17	[48]	–2
Onion	–6	[49]	+9
Pea	–15	[50]	0
Potato	–23	[15]	–8
Tomato	–5	[32]	+10

[(a)] Rounded to the closest integer. [(b)] See Appendix E for details on the *uncertainty factors* applied. [(c)] Assumption: Δ+15% over the values in the second column.

Table 7. Crop revenues under full sunlight conditions.

	Crop Yield under Full Sunlight (t/ha) [(a)]	Produce Price Paid to the Farmer (EUR/t)	Farmer Income from Produce Sale under Full Sunlight (EUR/ha)	EU-CAP Direct Payment to the Farmer (EUR/ha) [(b)]	Total Income under Full Sunlight (EUR/ha)
Canola	3.10	326.9	1013	35	1048
Carrot	49.22	303.4	14,933	NA	14,933
Forage maize	59.37	41.3	2452	NA	2452
Dry faba bean	1.79	223.6	400	45	445
Melon	34.60	337.7	11,684	NA	11,684
Onion	44.74	211.4	9458	NA	9458
Dry pea	1.79	220.6	395	45	440
Potato	30.98	246.2	7627	NA	7627
Processing tomato	85.00	72.5	6162	200	6362

[(a)] Values calculated as 5-year (2014–2018) averages from [16]. [(b)] NA: Not applicable.

3. Results

A well-established metric to assess the performance of dual-land use systems like agroforestry [51] and also APV, is the land equivalent ratio (LER). However, the LER exclusively accounts system revenues and not the expenditure. On the other hand, the benchmark yardstick for energy generation systems, the levelized cost of electricity (LCoE), computes cost relative to electricity yield, but does not incorporate the crop production activity. Here, the indicator wherethrough profitability was evaluated was the internal rate of return (IRR). Once income and expenditure from both agricultural and energy generation activity were accounted, their aggregation to obtain the IRR was straightforward.

Figure 3 shows the annual specific yield of 1628 kWh/kWp predicted by the PV simulator for the southwest-oriented APV shed. This value was introduced in Table 8 to compute annual PV income throughout the foreseen lifespan. Likewise, the annual specific yield was introduced in Table A3 to compute the annual PV OpEx. After the entire flow of APV income and expenditure was computed, the IRR was calculated for both early-potato and processing-tomato rotation. The same procedure was followed with the annual specific yield of 1786 kWh/kWp predicted by the SISIFO PV simulator for the south-oriented APV shed.

Unlike Beck et al. [20], we did not find substantial differences between the two orientations. A mean shade factor of 30.6% was calculated for due south orientation (Figure A3), while the counterpart for due SW was of 29.2% (Figure A4). The small difference between both values prevented from matching orientation and shade-induced crop yield penalty. Therefore, we determined that in our case-study APV shed orientation only affects electricity production. With the dichotomist sources of variation considered, namely, crop rotation (potato/tomato), source of irrigation water (surface/underground), level of shade-induced crop yield penalty (low/high) and APV shed orientation (SW/S), the number of combinations analyzed was of 2^4.

The formula for the IRR is given by (Equation (1)):

$$0 = \sum_{t=1}^{26} \frac{C_t}{(1 + \mathrm{IRR})^t} - \mathrm{CapEx} \tag{1}$$

where C_t = net cash flow during the year t (calculated as the sum of annual income from electricity sale—Table 8 plus annual income from the sale of agricultural produce harvested, with subtraction of annual PV-OpEx—Table A3 and annual crop production cost; for the early-potato rotation, annual agricultural flow is constant throughout the 25-year lifespan, due to rotation symmetry, whereas in the case of the processing-tomato rotation, the annual agricultural flows vary according to the pattern shown in Table A1); CapEx = total initial investment cost (calculated as 562770 EUR/ha in Table A2 multiplied by 22.8 ha, giving 12,831,156 EUR).

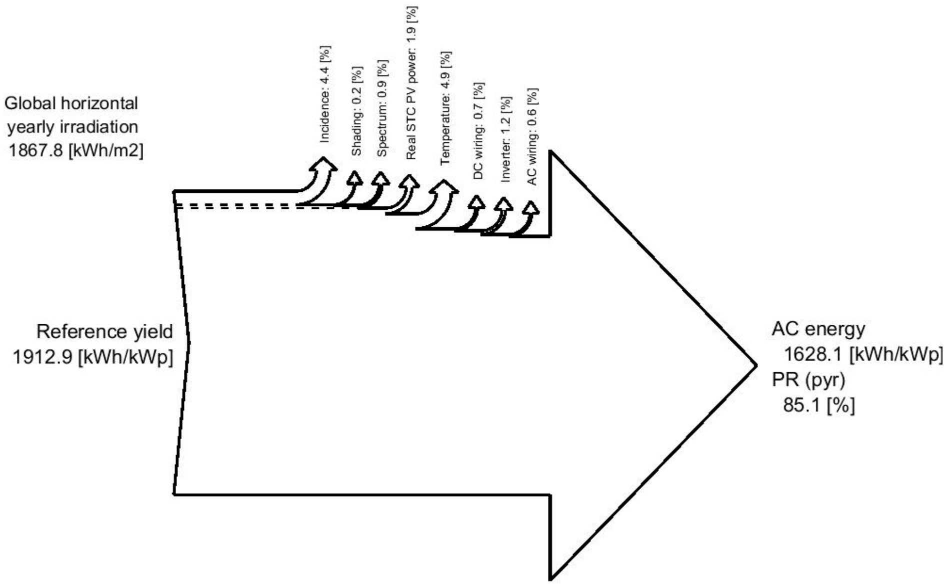

Figure 3. Annual AC energy output as predicted by PV simulator SISIFO [23] for the southwest-oriented APV system in Brenes, Seville, Spain.

Table 8. Annual PV income for 24 ha and due SW orientation, assuming a 5% loss as to PV productive land, due to plot dead corners (PV productive land of 22.8 ha).

Year	PV Module Degrad. Coeff.	Specific Yield (kWh/kWp)	(kWh/ha) [(a)]	Total Yield (kWh) [(b)]	(cEUR/kWh)	Energy Sale Income (EUR)	Total PV Income [(c)] (EUR)
1		0	0	0		0	0
2	1	1628	904,354	20,619,271	4.502	928,280	928,280
3	1	1628	904,354	20,619,271	4.502	928,280	928,280
4	1	1628	904,354	20,619,271	4.502	928,280	928,280
5	1	1628	904,354	20,619,271	4.502	928,280	928,280
6	1	1628	904,354	20,619,271	4.502	928,280	928,280
7	1	1628	904,354	20,619,271	4.502	928,280	928,280
8	1	1628	904,354	20,619,271	4.502	928,280	928,280
9	1	1628	904,354	20,619,271	4.502	928,280	928,280
10	1	1628	904,354	20,619,271	4.502	928,280	928,280
11	1	1628	904,354	20,619,271	4.277	881,886	881,886
12	0.995	1620	899,832	20,516,175	4.277	877,477	877,477
13	0.990	1612	895,310	20,413,078	4.277	873,067	873,067
14	0.985	1604	890,789	20,309,982	4.277	868,658	910,861
15	0.980	1595	886,267	20,206,886	4.277	864,249	864,249
16	0.975	1587	881,745	20,103,789	4.277	859,839	859,839
17	0.970	1579	877,223	20,000,693	4.277	855,430	855,430
18	0.965	1571	872,702	19,897,597	4.277	851,020	851,020
19	0.960	1563	868,180	19,794,500	4.052	802,073	802,073
20	0.955	1555	863,658	19,691,404	4.052	797,896	797,896
21	0.950	1547	859,136	19,588,308	4.052	793,718	793,718
22	0.945	1538	854,615	19,485,211	4.052	789,541	789,541
23	0.940	1530	850,093	19,382,115	4.052	785,363	785,363
24	0.935	1522	845,571	19,279,019	4.052	781,186	781,186
25	0.930	1514	841,049	19,175,922	4.052	777,008	777,008
26	0.925	1506	836,527	19,072,826	4.052	772,831	772,831

[(a)] (x kWh/kWp)·(555.5 kWp/ha) = y kWh/ha. [(b)] 0.95·24 ha = 22.8 ha; (y kWh/ha)·(22.8 ha) = z kWh. [(c)] Values in this column are equal to values in the adjacent-left column except for the due year of inverters replacement (year 14), where an income of 10% of inverter purchase price (18,505 EUR/ha, Table A2) is added in concept of old inverters residual value. Hence, the income added in the year 14 is of: 0.1·18,505·22.8 = 42,191 EUR.

Since the IRR is not explicit in Equation (1), it has to be solved by an iterative method, like the ad hoc function of Microsoft Excel®. Table 9 is a compilation of the IRR for each of the 2^4 combinations, wherein the minimum and maximum IRR are highlighted.

Table 9. Internal rate of return for the 16 combinations generated.

		IRR (%)			
		Due-Southwest Orientation		Due-South Orientation	
		Low Shade-InduceD Crop Yield Penalty	High Shade-InduceD Crop Yield Penalty	Low Shade-InduceD Crop Yield Penalty	High Shade-InduceD Crop Yield Penalty
Potato rotation	Surface Water	4.1	3.9	5.1	4.8
	Ground Water	4.0	3.8	5.0	4.8
Tomato rotation	Surface Water	4.7	4.3	5.6	5.2
	Ground Water	4.6	4.2	5.6	5.2

To elucidate the profitability associated to the foregoing IRRs, they were confronted with the private investor expected remuneration or annual cost of equity (r_e). According to Guaita-Pradas and Blasco-Ruiz [52], the cost of equity can be estimated through the capital asset pricing model, (Equation (2)):

$$r_e = r_f + (r_m - r_f)\cdot \quad (2)$$

where r_e = annual cost of equity, i.e.,demanded rate of return on equity; r_f = annual risk-free rate of return; r_m = annual stock-exchange market rate of return; β = coefficient that reflects the sensitivity of the sector to market fluctuations.

A good representative for r_f in Spain is the interest rate of the 30-year maturity Public Treasury bonds, 1.31% [53]. Current market profitability, r_m, is of 4.5% [54]. In strict sense, in our case β would be somehow compounded, since the project economic activity sector is not only electric generation but also agricultural production. For the sake of simplicity, we took a PV β of 1.10 [55]. Substituting in (Equation (2)):

$$r_e = 0.0131 + (0.045 - 0.0131) \cdot 1.10 = 0.04819$$

Therefore, the threshold of profitability is 4.8%. The IRRs compiled in Table 9 indicate that some combinations would be profitable from the perspective of a private investor, whereas others would be not.

4. Discussion

Following the mainstream APV philosophy of prioritizing agricultural over power production and based on Beck et al. [20] conclusion, we initially performed calculations for a SW-oriented APV shed. Finally, a comparative shaded-fraction analysis between southwest and south orientation was undertaken. The small difference found (abovementioned values of 29.2% and 30.6%), together with the shape of histograms Figures A3 and A4 suggest little difference between both orientations. Perhaps the subtle difference in ground radiation uniformity in our case was due to the TMY data used. Edge effects could also play a role. This issue deserves more attention and should be further analyzed in a future work.

The result obtained for the early-potato rotation when the APV shed is oriented due Southwest is in line with Trommsdorff [56], who, for organic potatoes cultivated beneath the APV shed described by Schindele et al. [8], obtained an IRR 1.6% lower than WACC. In a broader sense, López Prol et al. [43] wondered if renewable energy generators like PV would ever be competitive considering the faster decline of the wholesale market price compared to the LCoE. From the inception of our study, it was envisaged that a negative factor for APV system profitability would be the high CapEx compared to conventional ground-mounted PV power plants. To restrain APV system CapEx, fixed-tilt PV modules were selected instead of single-axis trackers, which are 7% more expensive in average [57]. Here, the reason to select fixed-tilt PV generator was three-fold: First, to restrain system cost; second, to utilize the substructure described by Schindele et al. [8], which is of known cost; and third, to cast less shading on the understorey crop canopy. With regard to the latter, in an early stage a set of simulations was performed with the dual-use shading analysis tool, an on-line simulator promoted by the Massachusetts government to analyze the technical viability of APV layouts. Results indicated that single-axis tracking casted more shading, in w% per square meter than fixed-tilt. On the other hand, Amaducci et al. [58] concluded that reduction of global radiation beneath their APV shed was more affected by PV module array GCR than by tilt angle management (fixed tilt/sun-tracking).

In the case that in one of the 6 ha APV plots there existed an authorized underground water well equipped with a submersible pump, a reservoir to store the water abstracted by the well pump and a horizontal-axis pump to pressurize the whole 24 ha farmer irrigation network, the following management strategy could be analyzed: During PV productive hours, a small fraction of the energy produced would be self-consumed by the well pump to replenish the reservoir. To irrigate, i.e., to pressurize the irrigation network preferably during nocturnal hours, energy would be consumed from the grid, through the same HV power transmission line wherethrough PV production is injected. The energy consumed would be registered, for billing purposes, by a bi-directional metering gauge. This management strategy would remove the cost of water delivery charged by the irrigation district. Concurrently, the income from the sale of electricity would be diminished in the amount of the energy self-consumed—and therefore, not sold—by the well pump. Likewise, the farmer would incur in the cost of the nocturnal energy consumed from the grid by the irrigation pump. According to IDAE [59], average installed power pump for pressurized irrigation in Spain is of 2 kW/ha. For a flat topography like the area of study, assuming low pressure drip irrigation and for moderate water depth in the well, the share of installed power could be e.g., 70% for the submersible well pump and 30% for the irrigation pump (the well pump share would increase with increasing depth). Therefore, this results in 0.3 2 kW/ha = 0.6 kW/ha and 0.6 kW/ha 24 ha = 14.4 kW. This is significantly smaller than 450 kW, the minimum contracted power to benefit from the cheapest nocturnal electricity period of the Spanish tariff 6.1.

With regard to the possibility of reducing the 5 m clearance height of APV shed substructure and accordingly save in system CapEx, the following has to be considered: In our study, one head of rotation was first-early potato, planted in late December–January and harvested in late May–early June. In Spain, this type of potato is not harvested with the bulky and tall potato harvester, but with much smaller and shorter machines, namely, potato lifters and windrowers. These machines just dig-up and expose the tubers so that they can be afterwards hand-picked by manual workers. The reason to discard the potato harvester is to preserve tuber quality, since hand-picking is less aggressive. In other parts of Spain, where half-season potatoes are grown, the tubers spend more time within the ground, resulting in a thicker skin that withstands better the abrasions and impacts that occur inside potato harvester. Attending to the potato harvesting machinery used in the area, one could think of saving in substructure height, at least in the case of the early-potato rotation. However, a two-fold reason dissuade from this: First, canola and faba bean, two of the potato "partners" in the eponymous rotation, are harvested with the bulky combine harvester. Second, the main interest of a high substructure is not only to allow agricultural machinery work beneath, but to provide homogenous light distribution for the crop, casting shade of lower intensity. Analogous considerations apply for the processing-tomato rotation, whereinto processing tomato is harvested with a bulky-tall machine, similar in dimensions to both the potato and combine harvesters.

Among the circumstances that would yield lower IRR are: (i) APV plots remoteness from the grid-connection switchyard (distance higher than the 1 km assumed in Figure 1; (ii) re-activation of Spanish Law 15/2012, under which electricity generators must satisfy a tax of 7% on the value of the energy injected to the grid -this law was challenged before the Constitutional Court of Spain and the final judgment is pending [60].

Among the circumstances that could render higher IRR are: (i) Higher electricity yield due to favorable microclimate condition. Thus, the SISIFO PV simulator used here is not APV-specific but computes yield from site TMY climate data. Cooler temperatures on the back side of the modules, induced by the irrigated understory crop, would improve PV performance, especially in the summer months. (ii) Modification of the PV system electrical design: considering that while the peak power (153.1 kWp) to nominal power (150 kWp) ratio is of approximately 1.02 Wp/Wn; stronger oversizing of the PV array with respect to inverter is recommended [61].

Here, only the quantitative effect of shading on produce yield (t/ha) was considered. More research is needed to investigate the effect of APV shading on produce quality that ultimately affects revenues or even could be a limiting factor for the spread of APV. Nishizawa et al. [62] concluded that severe levels of shading negatively affected melon fruit firmness. Hernández et al. [32] measured not only higher concentration of lycopene, but also lower concentration of vitamin C and phenolic compounds, in tomatoes grown under partial shade compared to the full-sunlight counterpart.

In the authors' opinion, the lack of profitability in some of the combinations of the case-study analyzed herein does not tarnish the potential profitability of APV systems. Higher IRR is envisaged for specialty crops, thanks to extended synergies between the food generator—agricultural crop—and energy generator—PV modules. Savings in fruit orchard hail and bird netting allowed by APV sheds paddle in this direction [63]. Likewise, the utilization of semi-transparent PV modules could increase crop intercepted light without the need for the expensive 5 m ground-clearance substructure that supports conventional opaque PV modules. The fragility of specialties such as raspberry, blackberry and blueberry advises against their mechanized harvesting, contributing to the technical viability of cost-effective limited-height sheds and the subsequent increased profitability of APV systems.

5. Conclusions

In correspondence with objectives (1) and (2) indicated in Section 1, the following conclusions can be drawn:

1. two crop rotations, one of them headed by early-potato partnered with canola, faba bean, forage-maize and onion, and the other one headed by processing-tomato partnered with onion, dry-pea, carrot and melon were designed;
2. the stream of expenditure and revenues for both agricultural and electric energy production was determined for a lifespan of 25 years. The internal rates of return obtained ranged from a minimum of 3.8% for the combination of southwest orientation, early-potato rotation, groundwater and high shade-induced crop-yield penalty to a maximum of 5.6% for the combination of South orientation, processing-tomato rotation, surface water and low shade-induced crop-yield penalty.

Author Contributions: Conceptualization, M.A.M.-G., G.P.M. and M.C.A.-G.; methodology, G.P.M., M.A.M.-G. and M.C.A.-G.; validation, G.P.M., M.A.M.-G., M.C.A.-G. and L.H.-C.; formal analysis, G.P.M., L.H.-C. and M.C.A.-G.; investigation, G.P.M., M.A.M.-G., M.C.A.-G. and L.H.-C.; data curation, G.P.M.; writing—original draft preparation, G.P.M., M.A.M.-G. and M.C.A.-G.; writing—review and editing, G.P.M., M.A.M.-G., M.C.A.-G. and L.H.-C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors wish to acknowledge the reviewers for their valuable comments.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

a.s.l.	Above sea level
CapEx	Capital expenditures (investment cost)
Med	Mediterranean
OpEx	Operating expenditures
AC	Alternating current
APV	Agrophotovoltaic
BMDID	*Bembézar Margen Derecha* Irrigation District
CAP	European Union Common Agricultural Policy
DC	Direct current
EU	European Union
FB	Faba bean
FM	Forage maize
FTS	Future solar contract
GCR	Ground coverage ratio
GHG	Greenhouse-effect gas
HV	High voltage
ID	Irrigation district
IRR	Internal rate of return
LCoE	Levelized cost of –electric- energy
LER	Land equivalent ratio
LV	Low voltage
MV	Medium voltage
PE	Polyethylene
PV	Photovoltaic
SW	Southwest
TMY	Typical meteorological year
VIID	*Valle Inferior* Irrigation District
Symbols	
p_h	Pressure head
r_e	Cost of equity (demanded rate of return on equity)
r_f	Risk-free rate of return
r_m	Stock market rate of return
C_t	Cash flow in the year t

Appendix A

Comparison between due south and due southwest orientation of APV shed.

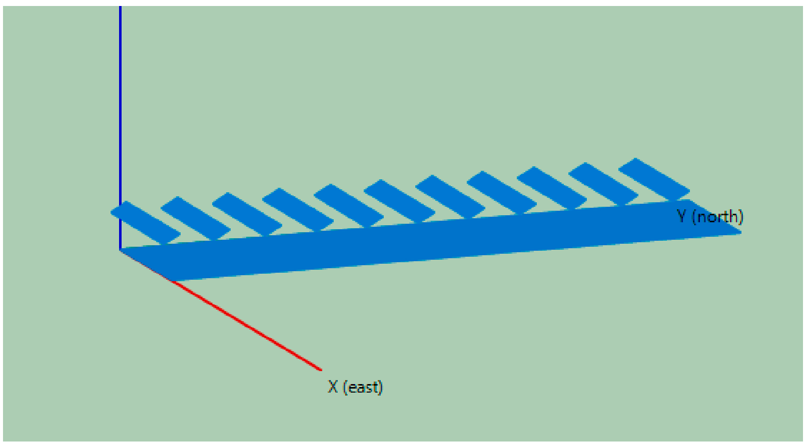

Figure A1. Due south APV shed. Ground area: 26 m × 106 m. Dimensions and number of PV module supporting structures: 26 m × 3.28 m × 11. Equidistance between supporting structures axes: 9.5 m, as in Figure 2.

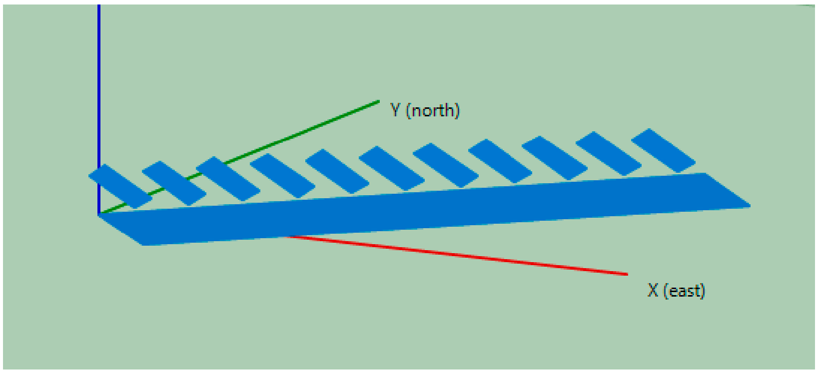

Figure A2. Due southwest APV shed.

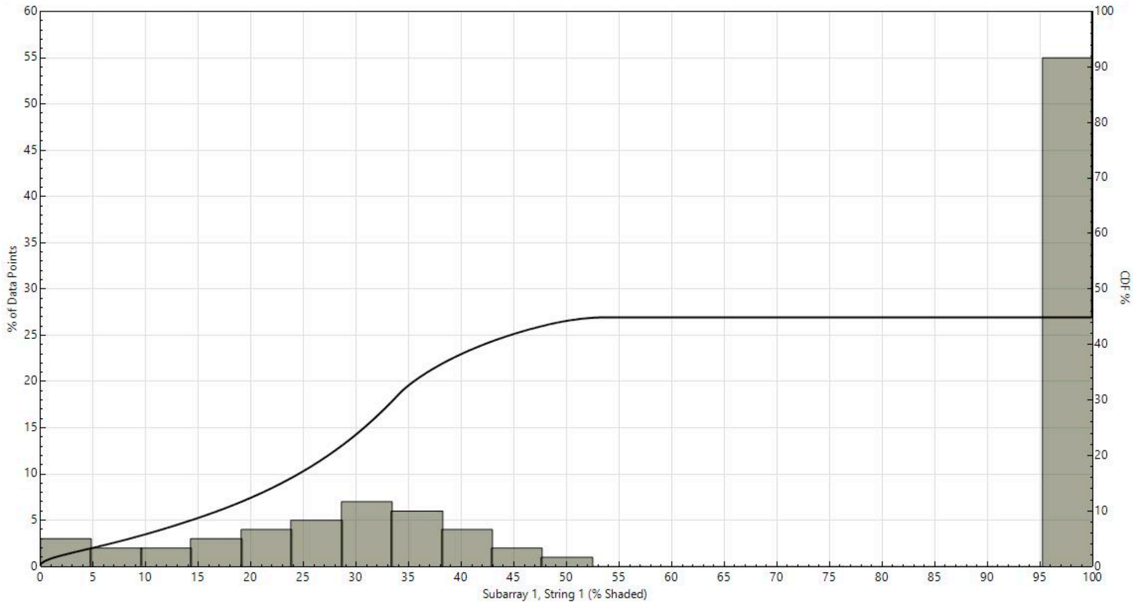

Figure A3. Time series (1 min step) shaded fraction histogram (zero values excluded) for due south orientation.

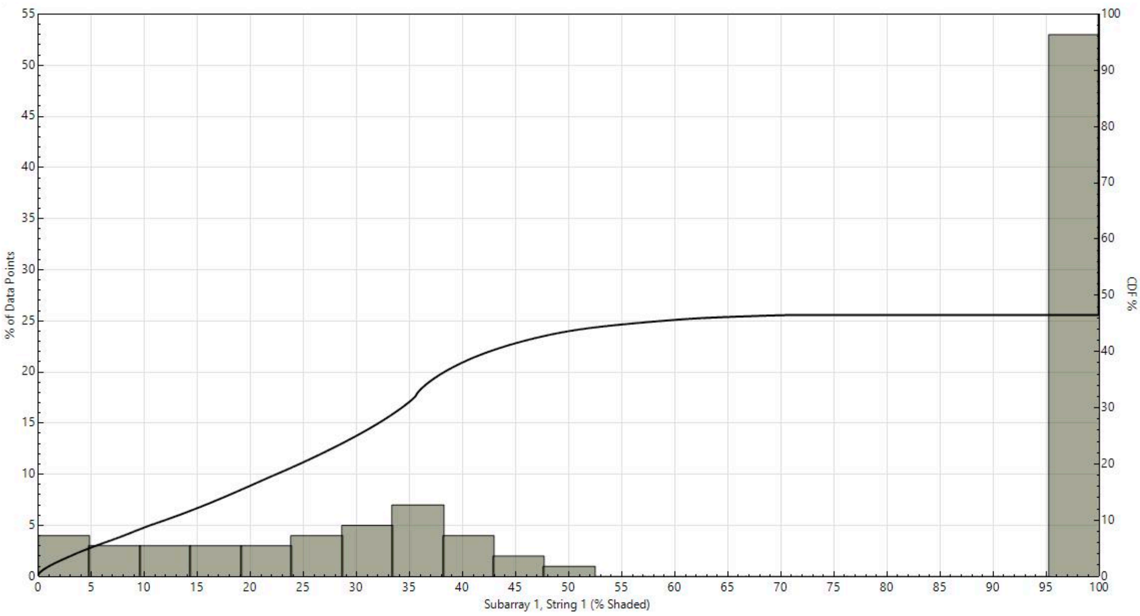

Figure A4. Time series (1 min step) shaded fraction histogram (zero-values excluded) for due southwest orientation.

Appendix B

Table A1. Processing-tomato rotation scheduling for 25-year lifespan.

Year	Plot 1	Plot 2	Plot 3	Plot 4
2	Melon	Onion	Carrot	Tomato
3	Onion	Carrot	Melon	Tomato
4	Carrot	Melon	Onion	Tomato
5	Tomato	Onion	Pea	Melon
6	Tomato	Onion	Onion	Onion
7	Tomato	Carrot	Carrot	Carrot
8	Melon	Tomato	Melon	Melon
9	Carrot	Tomato	Onion	Onion
10	Melon	Tomato	Carrot	Carrot
11	Onion	Melon	Tomato	Melon
12	Pea	Onion	Tomato	Onion
13	Onion	Carrot	Tomato	Pea
14	Carrot	Melon	Melon	Tomato
15	Melon	Onion	Onion	Tomato
16	Onion	Carrot	Carrot	Tomato
17	Tomato	Melon	Melon	Melon
18	Tomato	Onion	Onion	Onion
19	Tomato	Pea	Carrot	Carrot
20	Melon	Tomato	Melon	Melon
21	Onion	Tomato	Onion	Onion
22	Carrot	Tomato	Pea	Carrot
23	Melon	Melon	Tomato	Melon
24	Onion	Onion	Tomato	Onion
25	Carrot	Carrot	Tomato	Pea
26	Melon	Melon	Melon	Tomato

Appendix C

Table A2. APV system initial investment cost or capital expenditure, CapEx (the delayed CapEx item of inverters replacement incurred in year 14 is included in Table A3).

	EUR/unit	EUR/kWp	EUR/ha [(a)]	No. Units Per ag. Plot of 6(5.7) ha
(1) PV modules	60.9	210.0 [(b)]	116,655	10,919 [(c)]
(2) Galvanized steel mounting structure		378.6 [(d)]	210,312	
(3) Earthing		0.6 [(e)]	333	
(4) Lightning protection system			9000 [(f)]	
(5) DC switchboards (combiner boxes)	584.0 [(g)]	3.8	2111	21
(6) DC cables		35.0 [(h)]	19,443	
(7) Inverters	5100.0 [(i)]	33.3 [(j)]	18,505	21
(8) AC low voltage cables		18.4 [(e)]	10,221	
(9) LV/MV Transformer	80,500.0 [(e)]	25.4 [(k)]	14,124	1
(10) MV overhead power transmission line		1.9 [(l)]	1055	
(11) Monitoring and communications		0.9 [(e)]	500	
(12) Security		2.1 [(e)]	1167	
(13) Installation works			132,490 [(m)]	
(14) Subtotal 1 {=Σ(1) . . . (13)}			535,916	
(15) Administration costs (1%)			5359	
(16) Designer and construction manager fees (4%)			21,437	
(17) Subtotal 2 {= (14) + (15) + (16)}			562,712	
(18) Subsoiling			58 [(n)]	
(19) **TOTAL** {=(17) + (18)}			**562,770**	

[(a)] (x EUR/kWp)·(555.5 kWp/ha) = y EUR/ha. [(b)] [64]. [(c)] (528 modules/153.1 kWp)·3166 kWp = 10,919 modules. [(d)] Calclated from [8]. [(e)] Calculated from [65]. [(f)] Adapted from [66]. [(g)] From [67], (531 £)·(1.10 EUR/£) ≅ 584 EUR. [(h)] From [68] with consideration of 1000 VDC inverter wire section saving. [(i)] From [69], (0.034 EUR/W_{AC})·(150 kW_{AC}) = 5100 EUR. [(j)] 5100 EUR/153.1 kWp ≅ 33.3 EUR/kWp. [(k)] 80500 EUR/3166 kWp ≅ 25.4 EUR/kWp. [(l)] Calculated from [70]. [(m)] Calculated by introducing 155,241 EUR/ha [8] in the following breakdown model: Construction work, 65% of the installation works cost; electrical installation work, 35% of the installation works cost; labor share within construction work, 40%; labor share within electrical installation work, 70%; ancillary equipment (cranes, welding machines, tools, etc.) share within construction work, 60%; ancillary equipment share within electrical installation work, 30%. Price of construction labor in Spain relative to Germany: 54%; price of electrician labor in Spain relative to Germany: 89% [71]. [(n)] [72].

Table A3. Twenty-four hectare (22.8 ha effective) due SW-oriented PV system annual operating expenditure, OpEx, plus the delayed CapEx of inverters replacement in the year 14.

Year	Total Annual Yield [(a)] (MWh)	Grid Access Toll [(b)] (EUR)	Brokerage P.W.M. Agent [(c)] (EUR)	Maintenance and Repair [(d)] (EUR)	Insurance and Video-Surv. [(e)] (EUR)	Internet Fee [(f)] (EUR)	TOTAL (EUR)
1	0	0	0	0	0	0	0
2	20,619	10,310	4124	26,597	22,798	10,132	73,961
3	20,619	10,310	4124	26,597	22,798	10,132	73,961
4	20,619	10,310	4124	26,597	22,798	10,132	73,961
5	20,619	10,310	4124	26,597	22,798	10,132	73,961
6	20,619	10,310	4124	26,597	22,798	10,132	73,961
7	20,619	10,310	4124	26,597	22,798	10,132	73,961
8	20,619	10,310	4124	26,597	22,798	10,132	73,961
9	20,619	10,310	4124	26,597	22,798	10,132	73,961
10	20,619	10,310	4124	26,597	22,798	10,132	73,961
11	20,619	10,310	4124	26,597	22,798	10,132	73,961
12	20,516	10,258	4103	26,597	22,798	10,132	73,889
13	20,413	10,207	4083	26,597	22,798	10,132	73,817
14	20,310	10,155	4062	26,597	22,798	10,132	474,562 [(g)]
15	20,207	10,103	4041	26,597	22,798	10,132	73,672
16	20,104	10,052	4021	26,597	22,798	10,132	73,600
17	20,001	10,000	4000	26,597	22,798	10,132	73,528
18	19,898	9949	3980	26,597	22,798	10,132	73,456
19	19,795	9897	3959	26,597	22,798	10,132	73,384
20	19,691	9846	2954	19,948	17,099	7599	57,445
21	19,588	9794	2938	19,948	17,099	7599	57,378
22	19,485	9743	2923	19,948	17,099	7599	57,311
23	19,382	9691	2907	19,948	17,099	7599	57,244
24	19,279	9640	2892	19,948	17,099	7599	57,177
25	19,176	9588	2876	19,948	17,099	7599	57,110
26	19,073	9536	2861	19,948	17,099	7599	57,043

[(a)] From Table 8. [(b)] 0.5 EUR/MWh [73]. [(c)] p.w.m., power whosale market. Brokerage fee applied: 0.2 EUR/MWh [74], years 2 through 19; years 20 through 26: assumption of 25% price decrease applied [69], resulting in 0.15 EUR/MWh. [(d)] Years 2 through 19, (2.1 EUR/kWp)·(555.5 kWp/ha)·(22.8 ha) = 26,597 EUR; years 20 through 26: assumption of 25% price decrease applied [32], $0.75 \times 26{,}597 = 19{,}948$ EUR. [(e)] Years 2 through 19, (1.8 EUR/kWp)·(555.5 kWp/ha)·(22.8 ha) = 22,798 EUR; years 20 through 26: assumption of 25% price decrease applied [32], $0.75 \times 22{,}798 = 17{,}099$ EUR. [(f)] Years 2 through 19, (0.8 EUR/kWp)·(555.5 kWp/ha)·(22.8 ha) = 10,132 EUR; years 20 through 26: assumption of 25% price decrease applied [32], $0.75 \times 10{,}132 = 7599$ EUR. [(g)] Inverter's replacement cost included ($0.95 \times 18{,}505$ EUR/ha $\times$ 22.8 ha = 400,818 EUR; a 5% price decrease is assumed with respect to the year zero; 18505 EUR/ha taken from Table A2).

Appendix D

Table A4. Annual production costs for the 9 crops under full sunlight. Values adapted from [75,76].

Costs in EUR/ha	Canola	Carrot	Forage Maize	Dry Faba Bean	Melon	Onion	Dry Pea	Early Potato	ProCessing Tomato
Seed	60	3900	170	60	3000	3925	55	1400	820
Fertilizer	205	860	610	10	800	750	10	600	590
Plant Protection products	115	650	50	60	505	230	60	250	510
Externalized works (mechanized harvest, etc.)	67	1390	85	55	80	75	55	110	850
Tractor fuel	60	420	120	60	330	180	60	105	110
Tractor & mach. Repair & Maint.	45	230	106	40	110	105	40	80	80
Tractor & mach. Shed costs	30	60	45	30	60	60	30	55	60
Amortization of tractor & mach.	20	170	105	17	150	145	17	120	140
Hired labor (manual harvest)	0	0	0	0	1125 (a)	1035 (b)	0	900 (c)	0
Soc. Sec. contrib.for hired labor (25%)	0	0	0	0	281	259	0	225	0
Own labor	65	480	200	50	500	350	50	290	580
Soc. Sec. contrib.for own labor (25%)	16	120	50	13	125	88	13	73	145
Insurances (crop, tractor)	15	57	15	15	100	100	15	57	100
Land property tax	70	70	35 (d)	35 (d)	70	70	70	70	70
Irrigation total cost	130	226	165 (d)	79 (d)	192	224	132	186	205
Subtotal	898	8633	1756	524					4260
Working capital interest (4%)	36	345	70	21					170
Total	**934**	**8978**	**1826**	**544**	**7725**	**7899**	**631**	**4701**	**4430**

(a) Considering a required harvest labor of 25 *labor units*/ha and a *labor unit* regulated price of 45 EUR/labor unit [77]; *labor unit* represents the work done by one worker in one day. (b) Considering a required harvest labor of 23 *labor units*/ha and a *labor unit* regulated price of 45 EUR/ labor unit. (c) Considering a required harvest labor of 20 *labor units*/ha and a *labor unit* regulated price of 45 EUR/ labor unit. (d) Since faba bean and forage maize are cultivated in sequential cropping, they are each ascribed with half the cost of land-property-tax and half the fixed component of irrigation cost.

Appendix E

Uncertainty factors applied on literature references to obtain percentage yield variation under shading for each crop (high crop yield penalty).

Appendix E.1. Canola

We took -20% yield value straightforwardly from Figure 1 [44], as the average of their experiments shading at flowering (2011) and shading at pod filling (2011). We disregarded yield value of shading at flowering (2010) because that year was extremely dry and we are analyzing irrigation farming.

Appendix E.2. Carrot

We pay attention to the marketable yield column of Table 2 [45]. From the different shading nets listed there, we select white polyethylene (PE) as the closer to our APV-shed configuration (at first glance, one could think that due to monofaciality of our PV modules, black PE would be more similar, but the shading intensity decrease due to modules height plays a role). With respect to no-shade, the variation is of 9.6%, which we rounded to 10%.

Appendix E.3. Maize

We paid attention to Table 2 [46], biomass of corn stover and Table 3, grain yield. To be conservative, for both tables we focused on the higher PV GCR. We took data from both tables because forage maize crop harvest is a mix of chopped stover, ears and grains. From Table 2 [46], we obtained -3% under shading, whereas from Table 3 [46], we obtained -3.6%. The average of both values is 3.3%. To be conservative, we applied an uncertainty factor of 2, which multiplied by 3.3 equals 6.6%, and finally, rounded to 7%. The reason underlying the uncertainty factor of 2 is that Sekiyama and Nagashima [46] experiments were conducted at latitude 35 °N, while our latitude is higher (37 °N).

Appendix E.4. Faba Bean

Table 2 [47] shows higher yield under shading than under full sunlight. To be conservative, we assume zero variation with respect to full sunlight.

Appendix E.5. Melon

In Figure A3 [48], we took marketable yields corresponding to control (full sunlight) and aluminet shading net, which to our understanding is more similar to our APV shading than the other two types of shading net categorized in Figure 3 [48]. The difference between them is approximately 8.4 t/ha, which divided by the control equals 16.5%, which we rounded to 17%.

Appendix E.6. Onion

From Table 7 [49], we calculated an average yield variation of 2.3% between full sunlight and shading conditions. Then, we applied an uncertainty factor of 2.5, for a three-fold reason: First, the latitude of Khan et al. [49] experiment was tropical, unlike ours; second, their shade was not generated by an inert artificial screen, but by a plant canopy which entails a competition not only for sunlight, but also for soil nutrients. In third place, the onion yield (t/ha) reported [49] are much lower than the common in our area, most probably because spacing between plants was rather large. Finally, we calculated $2.3\% \cdot 2.5 = 5.8\%$, which we rounded to 6%.

Appendix E.7. Pea

In Table 2 [50], we took the yield values of *lighter shading*—one layer of screen—which, to our understanding, reflects better the light conditions under our APV shed and compare them to the no-shade conditions. For the year 1973, we obtained 19.4%, whereas for 1974 we obtained 10.5%. The average of both is approximately 14.9%, which we rounded to 15%.

Appendix E.8. Potato

We took years 2015 and 2017 from Figure 3 [15]. To be conservative, we assumed an average shading level of 38%, the mean of 26% and 50%, two of the shading intensities shown in Figure 3 [15]. Reading in the graph the pertinent values and calculating, a shading level of 38% delivered an average tuber yield variation of 23.4%, which we rounded to 23%. We decided to apply no further uncertainty factor due to the following: although, with respect to the availability of the solar resource, our latitude of Seville is more advantageous than the latitude of Germany [15], this is cancelled-out by the fact that our early potato crop season is shifted towards winter.

Appendix E.9. Tomato

The data compiled in Table 1 [32] indicate no tomato yield variation between full-sunlight and shade (60% light). To be conservative, we considered a -5% in yield, to account for the fact that Hernández et al.'s experiment [32], although at the same latitude than ours, was conducted inside a greenhouse.

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