*Article*

# Exploring the benefits of photovoltaic non-optimal orientations in buildings

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**Featured Application: This work is intended to be used as a reference for designing photovoltaic installations in buildings which don't have architectural surfaces with optimal orientations or when it is required the use of several surfaces for maximizing total energy production.**

**Abstract:** As Solar Photovoltaics in buildings reaches maturity, grid integration and economic yield are topics of greater interest. The traditional design of photovoltaic installations has considered the optimal orientation of photovoltaic modules to be that which yields the maximum annual energy production. The influence of the consumption patterns and the hourly-variable electricity prices implies that this traditional optimal design might not be the most profitable. Using a full-year dataset for a residential installation, alternative installations using canopies and modules attached to the façades are simulated. Simulating the energy balances for different annual consumptions, it is found that the canopy and façade installations offer better self-consumption of the PV produced energy, reflected in a 9% higher self-consumption degree using modules on façades and a 5% using canopies. The economic evaluation under the new electricity tariffs in Spain shows a better profit for PV self-consumption, reducing by more than 2 years the time of return on investment. The analysis of different alternatives for an industrial PV has allowed us to identify several benefits for these orientations, such as an increase in annual energy production of up to 59% over the optimal-producing orientation, that are confirmed after several months of operation.

**Keywords:** Solar Photovoltaics, PV Self-consumption, Building-integrated photovoltaics (BIPV), Building-applied photovoltaics (BAPV), PV orientations, PV Grid-integration.

## 1. Introduction

The economic growth and the increase of the living standards generates a continuous increase in the energy demand; by 2050 it is expected that this growth will be responsible for an energy consumption approximately between 1.5 and 3 times that of today [1,2]. To meet this demand, renewable energies are presented as a viable alternative. There are estimations that by 2050 the amount of oil and coal in the energy mix will have been reduced by more than half from current levels, and the energy supply mix will be divided equally between renewable and non-renewable sources [3].

According to the latest report from the International Energy Agency [4], the share of renewable energies in electricity generation is expected to increase to almost 30% in 2021, being its highest share since the beginning of the Industrial Revolution. Wind and Solar energy will contribute approximately two-thirds of this growth in 2021. The great progress of solar energy is mainly due to the increase in its efficiency and the continuous costs reduction [5]. This has allowed the growth of the installed solar photovoltaic capacity from 580 GW in 2019 to 707 GW in 2020 [6], presenting an increase of approximately 22% in one year. The European landscape has a similar trend, according to the reported prospect of EU market of "Solar Power Europe" 16.7 GW of new photovoltaic installations has been incorporated in 2019, meaning an increase of 104% compared to 8.2 GW of 2018 [7], and installing more new solar capacity than any other power generation technology [8].

Several studies have focused on issues of economic and tech viability, sustainability, and applications of photovoltaic technology. A detailed analysis of the economic and financial feasibility of photovoltaic projects in [9] concludes that PV is one of the most secure investments. A technical, economic and geographic analysis points out the potential of PV to reduce CO2 emissions in the US to achieve its climate-change goals [10]. Results from a study using yearly horizontal irradiation data supports the feasibility of solar energy in Korea [11]. In general, grid-tied photovoltaic systems [12] present several economic benefits [13] and also have a satisfactory social acceptance [14,15].

In recent years the manufacturing of photovoltaic solar cells and photovoltaic modules has seen big advances [16], and installations on buildings are been increasingly accepted. There are two main ways to incorporate photovoltaic technology into a building, BAPV (photovoltaic applied or attached to the building) and BIPV (photovoltaic integrated into the building). In BAPV systems, photovoltaic modules are installed on the building's façade; in BIPV systems, photovoltaic modules are part of the building's façade [17]; that is, they serve as construction material in the envelope as multifunctional elements [18]. BIPV is considered one of the four essential key factors for the future success of PV, as is detailed in [19]. The power generation efficiency of BIPV systems is lower compared to standalone photovoltaic systems and compared to BIPV/T (Building Integrated Photovoltaic Thermal). However, it eliminates the additional space required for power generation and presents better aesthetics for the building structure [18]. It is shown that in 2 $km^2$ of urban area, the façades of the buildings provide almost three times the area of the roofs of the buildings; however, due to the non-optimal inclination and orientation, they receive only 41% of the total irradiation [20]. In another research [21], through a simulation with LiDAR data, it is found that the average annual irradiation per unit area on the façades is lower than that of the roofs, but that the much larger area means that a significant amount of energy reaches the vertical façades throughout the year. These research show that the annual irradiation in the vertical façades is lower than that of the most favorable surfaces such as roofs, but given that their coverage areas are huge, the solar potential of the façades is "relevant" for the general solar potential of a building and/or an urban area.

A building with BAPV or BIPV reaches grid parity when photovoltaic electricity costs are equal to the retail electricity price, taking into account income, savings, implementation costs, maintenance costs, tax and depreciation [22]. Additionally, there is the influence of non-technical and uncontrollable factors that complicate reaching grid parity, such as investment costs, credit discount rate, and variations in the retail price of electricity, among others, which poses a scenario that requires economic incentives and supportive policies [22,23].

In some mature solar markets such as Germany and Italy, the low costs of PV systems implementation, low discount rates, and high retail electricity prices have facilitated reaching grid parity [24,25]. In the case of Germany, until 2012, there was a special bonus for self-consumed electricity. Still, when the FiT fell below the retail price of electricity, this bonus was removed because of self-consumption being profitable without additional incentives [26,27].

In most countries with self-consumption regulations, there are two main ways to compensate for the energy supplied to the electricity grid by the SFVs: net metering and net billing. Net metering is used to offset the photovoltaic production over a longer period of time against consumption; the production can be "stored" in the electricity grid and increase self-consumption; for example, the surplus during the summer months can be saved for the winter months [29]. In the net billing scheme, the energy fed into the grid is paid at a remuneration lower than the retail rate and can be indexed to the wholesale market prices [31]. A detailed comparison of the differences between net metering and net billing schemes can be found in [32].

In the analysis carried out in [28] HOMER software is used for the simulation of the 5 kW roof systems for the pilot provinces of Turkey under the current feed-in-tariff (FiT) and it is found that the discounted payback period ranges from 7.75 to 14.43 years. Another research of grid-connected PV system with Feed in Tariff and time of day tariff for New Delhi [29] concludes the economic viability of small PV grid-connected systems without battery storage. An environmental life cycle assessment of rooftop solar for Bangkok [30] found that the Energy Payback Time is 2.5 years and the Economic Payback Time is 7.4 years, concluding that on-site electricity consumption paired with net-metering is the best way for promoting PV.

In Spain, the recent approval of Royal Decree 244/2019 [33] made it possible to regulate the administrative, technical and economic conditions of Royal Decree-Law 15/2018 [34]. The new legislation introduces a simplified compensation mechanism in the electricity bill for consumers, offsetting their surplus of self-produced but not self-consumed energy [35]. The main changes in current regulations are:

- Energy produced from self-consumption facilities is completely exempt of tolls and charges. The charge known as "sun tax" is removed.
- The right to "collective self-consumption" is recognized.
- Administrative and technical procedures are simplified, especially for small power installations.
- The power limit for PV installations is removed. With the previous regulation, it was only possible to install a photovoltaic power equal to or less than the contracted power.
- It is possible to rent roofs and/or covers so that third parties can produce electricity.

The EU Directive on the energy performance of buildings states that by 31 December 2020, all new buildings must be Nearly Zero Energy Buildings (NZEB) [31]. This Directive is transposed to national regulations, and it is the main driver of self-consumption regulation in Spain and other EU countries. Based on this legal framework, it is important to consider the functionality of the BIPV systems and their implementation in the medium term to guarantee the construction of “Zero Energy Buildings”, as it is shown in [32].

Regardless of the photovoltaic strategy selected, the analysis carried out by [33] indicates through the description of some examples that there is a limit in the amount of energy that a photovoltaic collector can generate per square meter. This amount depends mainly on the efficiency, inclination and azimuth angles of the PV generator, latitude, and efficiency of the balance of the system.

Taking these considerations, the main strategy for increasing the electricity production of photovoltaic self-consumption systems (PVSC hereinafter) is to place photovoltaic modules in suitable façades; for example,  it is showed [33] that the photovoltaic modules installed on a façade facing west are best suited to residential applications, where electricity consumption tends to peak in the afternoon. For buildings with administrative or office uses, an installation facing southeast provides a better fit for electricity consumption, which is higher in the morning [34]. This presents us with scenarios where installing solar panels in non-optimal orientations is possible to obtain a potential benefit. These scenarios would produce lower amounts of energy, but their hourly production profiles could shift beyond noon, allowing them to better meet demand [35].

The main objective of the presented research is to analyze the technical and economic potential of the integration of PVSC in non-optimal orientations in Spain, using reference installations with real consumption and PV production data and the hourly-varying electricity prices. For reaching this goal, the analysis of two case studies is carried out on a residential PVSC and an industrial PVSC. Based on one full year of real operational data for the residential PVSC, the operation of several alternative PV arrangements suitable for the building using different orientations are simulated and an energy and economic analysis is done considering past and new residential tariffs in Spain. For the investigation on industrial PVSC, the reference case is a mid-size installation of 169 kW using orientations different from the South. It is shown the analysis of different layouts for the PV modules prior to the project that led to the use of this orientations. Due to the recent construction of this PVSC, preliminary results are presented.

This paper is divided into five sections. After the Introduction, Section 2 describes the case studies, with a description of Spanish residential tariffs and the methods used in the energy and economic analysis of energy consumption and production for each case study. The results are presented in Section 3, with an economic analysis for the different configurations evaluated in the residential PVSC and considering the past and new residential tariffs. In Section 4 the results are discussed, and the conclusions are presented in the final Section 5.

The main findings of our study are that non-optimal orientations show fair economic performance in residential PVSC despite their lower energy production. For one alternative installation using canopies the economic savings are close to the optimal energy producing and for another installation using modules attached to the façade the economic benefit is only a 14% lower. The new electricity tariffs in Spain will have a positive impact on residential PVSC economic performance, calculated in a 12% better. For industrial applications, these orientations have the potential of installing more PV power, resulting in an increased energy production of 9% for the case study.

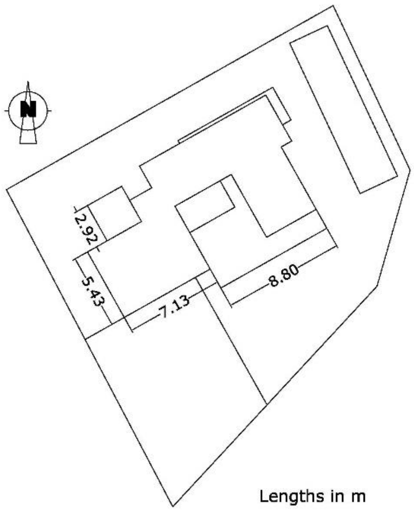
## 2. Materials and Methods

This work is based on two PVSC installations, one residential, and the other industrial. The residential PVSC is a single-family detached home with the solar modules aligned with the building in near optimum orientation. For this PVSC, alternative PV configurations in non-optimum orientations are proposed and an energy and an economic analysis are carried out. The industrial PVSC is configured in non-optimal orientations, and it is compared with South and East-West configurations.

### *2.1. Case study #1: Residential PVSC*

The residential PVSC is a single-home building located in the Madrid metropolitan area. It is a two-stories detached building equipped with heating and ventilation air conditioned (HVAC), shown in Figure 1. The climate in Madrid is the continental-mediterranean, with cold winters and hot summers. Hence, the yearly consumption is high, 14,189 kWh for the full year under study. The installation has a peak power of 3.85 kW and uses 10 Canadian Solar Ku Max CS3U-385MS monocrystalline PERC PV modules with power optimizers and a 4 kW SolarEdge inverter. The modules are installed in the roof, with a southeast orientation aligned with the building and with an inclination of 30°.

(a)




(b)

**Figure 1.** Residential building under study before PV installation. (a) Satellite image (Google Earth) (b) Floorplan with basic dimensions and orientation.

2.1.1. Energy balances

The PVSC was installed in February 2020, so there is data for a full year starting in March 2020. As electricity prices are rising in 2021, the period under study is selected from August 2020 to July 2021. The monitoring system provides data of the PV-produced electricity $E_{PV}$, consumed electricity $E$, self-consumed PV electricity $E_{sc}$ and the exchanges with the grid (energy imported: $E_{in}$, exported: $E_{srpl}$) every fifteen minutes. The relationships between these energies are expressed in equations (1) and (2).

$$E = E_{in} + E_{PV} - E_{srpl} \tag{1}$$

$$\begin{aligned} E_{sc} &= E_{PV} \; if \; E > E_{PV} \\ E_{sc} &= \mathrm{E} \; if \; E < E_{PV} \end{aligned} \tag{2}$$

These data will serve as a reference for comparison with simulations of alternative installations with the modules in different orientations suitable with the building. The alternative PVSC are simulated using PVSYST 7.1 software. The meteorological database used is the Meteonorm 7.3 and the models for the PV modules and the SolarEdge P405 power optimizers and SE4000H inverter are provided with the software. Thermal parameters, mismatch, and incidence angle are selected by default. No ageing degradation is used in the simulations because a 0.8% linear degradation is assumed in the financial analysis. The simulations are performed using the detailed electrical model considering the design of the module.

The simulated energy production $E_{PV}$ is processed with the measured consumption profile $E$, and using (1) and (2) there are computed the PV self-consumed energy $E_{sc}$, the surplus energy $E_{srpl}$ fed into the grid and the energy imported from the grid. In addition, the self-consumption and self-sufficiency degrees are calculated as defined in [26] and expressed in equations (3) and (4).

$$SCD = Self - consumption = \frac{E_{PV} - E_{srpl}}{E_{PV}} \tag{3}$$

$$SSD = Self - sufficiency = \frac{E_{PV} - E_{srpl}}{E_{in} + E_{PV} - E_{srpl}} \tag{4}$$

Once the energy balances are calculated, the next step is the calculation of the economic balances. The energy costs saved will be the valuation of the self-consumed PV energy at the hourly retail price of electricity. The surplus energy is valuated at a price slightly lower than the wholesale electricity market hourly price.

Regarding the electricity prices, the Spanish electrical grid operator Red Eléctrica de España (REE) provides real-time information about electricity pricing and valuation of surplus electricity for PVSC plants in its webpage ESIOS [36]. With the processed data, it is possible to compute the economic savings under Spanish self-consumption regulation [37] and the residential pricing of electricity, which will be addressed in the next subsection.

2.1.2. Residential tariffs in Spain

Before performing the economic evaluation is required to look at the residential tariffs for electricity in Spain. These tariffs are composed of three parts: a part based on the nominal contracted power (named access charge), a variable part for the energy consumed (energy charge) and taxes (a 5.11% of electricity tax and 21% VAT, resulting in a total of 27.50%). The final price of the electricity for the consumer depends on the electricity marketer company and the consumer can freely choose among a variety of commercial offers in the free market and in the regulated marked.

The electricity tariffs support not only the costs of the production, transport, and distribution of the electricity. The costs of producing electricity exhibit in the wholesale electricity market prices. In Spain, the overall costs of the electrical system are called tolls and charges. Tolls includes the electricity transport and distribution costs and are established by the CNMC (National Commission for Markets and Competition). Charges is a concept including other costs such as renewable energy retribution (mainly the FiT for wind and solar power generation, overcharges of the Balearic and Canary Island electrical systems, tariff deficit and other costs). The charges are established by the National Government. Part of these costs are included in the access charge and part in the energy charge. For residential tariffs there are no other charges such as reactive power and maximum demand penalties. The maximum power demanded for these consumers is controlled by the ICP, that is a switch that turns off the electricity supply if the maximum contracted power is exceeded in a 15-minute period. So, the installation of a self-consumption system does not allow to diminish the contracted power for the residential case. A more comprehensive description of the Spanish tariffs is available in [39].

Formerly, there were three main residential tariffs of choice in the regulated market or PVPC (voluntary price for the small consumer).

- Time constant tariff: the price of electricity is indexed to the pool market by a fixed toll that includes part of the electrical system costs and is added to the hourly pool market price and other costs, including commercial profit.
- Two-period tariffs: the price of electricity is indexed to the pool market, but the toll has two different values depending on the hour of the day. There were the former 2.0DHA and the 2.0VE for electric vehicles.

New tariffs in Spain have become effective in June 2021. The new residential tariff 2.0TD is a three pricing period structure that replace all the 2.x tariffs [38] (see Table 1). This regulatory change establishes higher prices on periods of higher consumption to promote demand shift management habits in the customers. In Figure 2 the demand profiles for the whole Spanish electrical system in representative days of winter and spring are plotted and it is clear the selection of peak periods in accordance with the two periods of maximum electricity demand in the Spanish electrical system.

**Table 1.** Hourly distribution and comparison with horizontal solar irradiation for tariff 2.0.

| Hour | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Winter Solstice irradiation (Wh/m²) [1] | | | | | | | | | 6 | 42 | 94 | 119 | 300 | 422 | 314 | 186 | 92 | 8 | | | | | | |
| 2.0A | "FLAT" | | | | | | | | | | | | | | | | | | | | | | | |
| 2.0DHA | "VALLEY" | | | | | | | | | | | | "PEAK" | | | | | | | | | | | |
| 2.0VE | "VALLEY" | | | | | | | | | | | | | "PEAK" | | | | | | | | | | |
| Equinox irradiation (Wh/m²) [1] | | | | | | | | 3 | 75 | 272 | 472 | 639 | 761 | 831 | 836 | 761 | 633 | 475 | 272 | 75 | | | | |
| NEW 2.0TD[2] | "VALLEY 2.0" | | | | | | | | | | "PEAK 2.0" | | | | "FLAT 2.0" | | | | | | | | | |
| Summer Solstice irradiation (Wh/m²) [1] | | | | | | | | 125 | 308 | 503 | 681 | 608 | 947 | 1031 | 744 | 583 | 900 | 678 | 422 | 336 | 153 | 14 | | |

[1.] Data corresponding to Madrid. Source AEMET. [2.]"Valley" on weekends and public holidays.

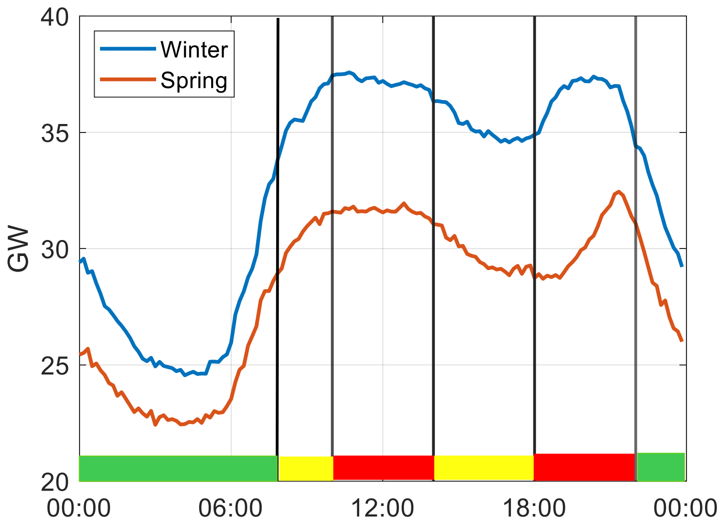



**Figure 2.** Load profile of Spanish electrical system on representative days (2021/01/21, 2021/04/21). The different pricing periods in tariff 2.0TD are highlighted, with the peak periods correlated with daily maximum electricity demand periods.

2.1.3. Economic balance

The economic balance it is calculated on an hourly basis using the prices of electricity published by the Spanish TSO Red Eléctrica de España in its webpage ESIOS [36] and the energy balances calculated with equations (1) and (2). The economic savings $S$ are composed of two parts: the cost of self-consumed PV-produced energy $A$ (not imported from the grid), calculated according to equation (5); and the value of the surplus energy (PV-produced and not self-consumed) compensated with the grid $C$.

$$A = \sum_{i=1}^{n} \left(E_{PV}^{i} - E_{srpl}^{i}\right) \cdot Pr_{ret}^{i}$$
$$being\ i\ the\ i^{th}\ hour\ of\ the\ month \quad (5)$$
$$Pr_{ret}^{i}\ the\ retail\ price\ of\ electricity\ on\ the\ i^{th} hour$$

The surplus compensation mechanism states that the surplus energy fed into the distribution grid is valuated at a price indexed to the wholesale market price (slightly lower) and that the final balance (the energy term in the monthly bill) cannot be negative. Thus, the value of compensated surplus energy can be expressed in equation (6).

$$C = \sum_{i=1}^{n} E_{srpl}^{i} \cdot Pr_{srpl}^{i}\ \forall \sum_{i=1}^{n} \left(E_{in}^{i} \cdot Pr_{ret}^{i} - E_{srpl}^{i} \cdot Pr_{srpl}^{i}\right) \geq 0 \quad (6)$$

$$C = \sum_{i=1}^{n} E_{in}^{i} \cdot Pr_{ret}^{i} \quad \forall \sum_{i=1}^{n} \left(E_{in}^{i} \cdot Pr_{ret}^{i} - E_{srpl}^{i} \cdot Pr_{srpl}^{i}\right) < 0$$

$being\ Pr_{srpl}^{i}\ \ the\ price\ of surplus\ electricity\ on\ the\ i^{th} hour.$

So, the monthly economic savings are:

$$S = A + C \tag{7}$$

And the monthly cost of the electricity taken from the grid

$$M = \sum_{i=1}^{n} E_{in}^{i} \cdot Pr_{ret}^{i} \tag{8}$$

The hourly prices for the new tariff 2.0TD before June 2021 and for the old tariff 20A after May 2021 are calculated accordingly to the tolls of both tariffs. The yearly balances for the reference PVSC and old and new tariffs are presented in Table 2. From the yearly sums of the cost of the imported energy $\sum M$, the savings of self-consumed PV energy $\sum A$, and of the compensated energy $\sum C$, there are calculated the yearly sum of the energy term in the electricity bill without PVSC and with PVSC, and the total savings (yearly cashflow for the financial study). For this consumer without PVSC, the yearly bill with the new tariff 2.0TD is almost equal to with the former tariff 2.0A. Regarding the bill with PVSC, the new tariff 2.0TD is an 6.4% lower than the 2.0A. For the cashflow (total savings), there is an increment of 12% of the new 2.0TD over the 2.0A. These higher economic savings for the PV self-consumed electricity are due to the highest electricity prices from 10 a.m. to 2 p.m. in this new tariff. The cashflow will be used for the calculation of the levelized cost of electricity (LCOE), net present value (NPV) and the internal rate of return (IRR).

**Table 2.** Economic performance of the PVSC installation for a full year (August 2020 to July 2021) comparing the former tariff 2.0A and with the new 2.0TD tariff. Taxes are included.

| **Tariff** | $\sum M$ **Imported** | $\sum A$ **Self-cons.** | $\sum C$ **Surplus** | **Bill w/o PV**[1.] | **Bill with PV**[1.] | **Total savings (Cashflow)** |
|---|---|---|---|---|---|---|
| 2.0A | -1,559.48 € | 441.08 € | 217.83 € | -2,000.56 € | -1,341.65 € | 658.91 € |
| 2.0TD | -1,473.52 € | 520.55 € | 217.83 € | -1,994.08 € | -1,255.69 € | 738.38 € |

1 Energy term in the electricity bill.

The study incorporates the Time of Return On Investment (TROI) as the first economic measure. TROI is one of the most widely used methods for comparing the benefits of a programme with the same costs per unit, per person or aggregated for the programme as a whole. The TROI is selected because it is a cost-benefit oriented economic method [43]. Still, it is also used to calculate Return on Investment (ROI), i.e. how much is produced by how much is invested. The cost of the systems under study is based in actual prices of this kind of installations.

An additional way of incorporating the economic feasibility study is to study the Net Present Value (NPV) as a more robust measure of economic calculation. The NPV represents the discounted value of all cash flows at the source at a discount rate that matches the cost of capital. For this study, what it is done is to value at a given point in time the unrealized cost of the investment project (i.e. the initial outlay) and the expected higher satisfaction in the future (i.e. the expected cash flows). It is applied a process of choosing the current point in time as the point at which both the payout and the cash flows should be valued, so a discounting process is applied. To apply this discounting process, it is incorporated the discount rate, which is the opportunity cost of the project, known as the cost of capital. These calculations are performed considering a 25 lifespan of the PVSC installation, with a 0.8% yearly degradation rate and an inverter replacement on the 13th year (also valid for IRR and LCOE calculations). The discount rate is selected as 1% based in the economic indicators for Spain and the Euro zone.

Another criterion to make the study more robust is the so-called Internal Return Ratio or IRR. It is defined as the discount rate that equals the NPV of the investment to 0. This is a study of relative profitability to provide a final argument for the TROI and NPV. The IRR provides us with one of the most widespread measures of profitability as it provides a more intuitive idea of the adequacy to what is expected from an investment, as it is a value that can be easily compared with interest rates, which is one of the main components that determine the cost of capital in a given project.

Finally, the Levelized Cost Of Electricity (LCOE) is a metric that informs about the cost of electricity independent of the technology used for generation. From the costs of the different installations, the LCOE will be calculated following the procedure as exposed in [44] and expressed in equation (9).

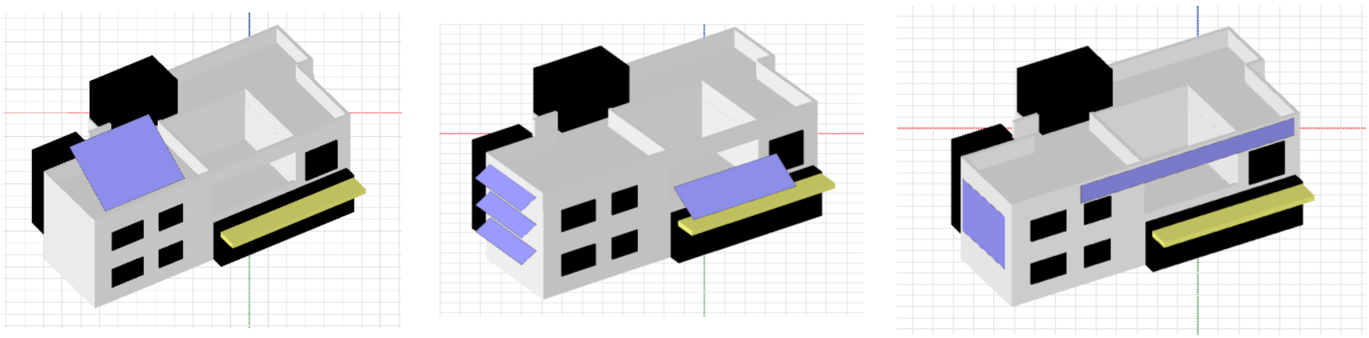
$$LCOE = \frac{\sum_{t=0}^{T} C_t/(1+r)^t}{\sum_{t=0}^{T} E_t/(1+r)^t} \quad (9)$$

$$where\ C_t\ are\ the\ costs, E_t\ the\ energy\ produced\ and\ r\ the\ discount\ rate.$$

2.1.3. Description of the alternative PVSC layouts

This PVSC is built in a single-home detached building with no important shadings from nearby constructions. There are several options for installing a PVSC on it. The orientation is 30°E for the larger façade and 60°W for the shorter one. The roof is flat, and it is divided into two sections connected through a corridor. The owners decided to install the PV modules on the southern part of the roof in two rows of 5 modules each with portrait orientation, as it is shown in Figure 3 (a). For this study, three alternatives will be considered: the first one using canopies with an inclination of 30° on the southeast and southwest façades shown in Figure 3 (b), the second one using modules attached over the same façades, shown in Figure 3 (c) and the third will be a mixed one using a canopy on the southeast façade and modules attached on the southwest façade.

The original PVSC uses power optimizers (one for each PV module), and they are connected to the inverter in a single string configuration. For the other options is also possible to a single string configuration, but two strings are preferred. In this case, a minimum length of 6 modules is mandatory for this inverter and power optimizers. It is important to note that for the two orientations configurations, the peak power is flattened so the inverter can easily accommodate the sum of both strings. These inverters can drive a peak power (DC) up to 50% higher than the nominal AC output. Thus, the cost of the alternatives using several orientations is only increased by the additional modules needed.



(a) (b) (c)

**Figure 3.** Residential PVSC plant PVSYST Models (a) Original layout (b) Design using canopies (c) Design using modules attached to the façade.

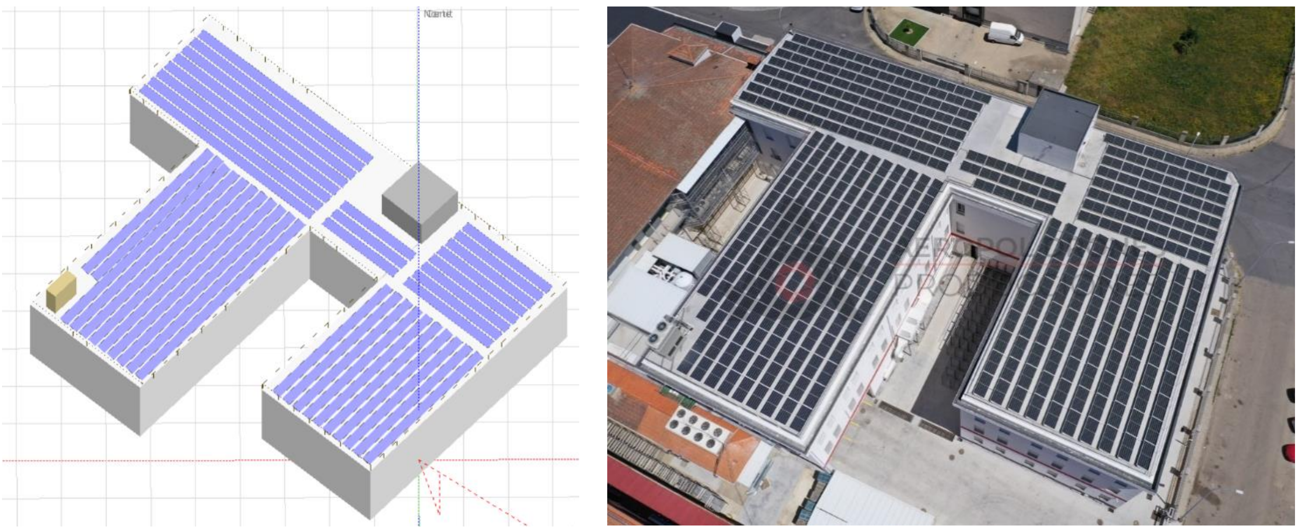
The three alternative layouts and the energy optimal one are simulated in PVSYST as was detailed before and the energy and economic analysis will be performed and presented in the next section. One issue when comparing these different orientations is that the yearly production varies for each case. Different yearly PV production is the result of different instantaneous PV power and means that as the electricity consumption is the same, the balance of self-consumption and surplus are different, affecting the economic results. In fact, for a less-producing layout there will be a higher share of self-consumption and lower proportion of surplus energy. As long as self-consumed electricity is valuated at retail price (equation (5)) and the surplus near at wholesale price (equation (6)), the less-producing layouts will give economic results better than real.

The method that will be used for a proper comparison is as follows. For all the different layouts the former PVSYST simulations will be rescaled for yearly productions between 5,000 kWh and 15,000 kWh and the energy and economic balances will be performed. In this way, we will be able to make a fair comparison and distinguish the effect of the different hourly PV production profiles of each layout.

### *2.2. Case study #2: Industrial PVSC*

The second case under study is an industrial PVSC for a meat-processing plant in Guijuelo (province of Salamanca). This installation has a peak power of 169 kW. It comprises 386 Canadian Solar CS3W-440MS PERC 440 W modules with 193 power optimizers and two 82.5 kW three-phase Solar Edge inverters for a maximum active power of 165 kW, as it is shown in Figure 4. The modules are distributed in 12 strings of 16 or 17 power optimizers (32 or 34 modules/string). The estimated yearly production is 270 MWh with a specific yield of 1,597 kWh/kWp and a performance ratio of 82%. This PVSC corresponds to a factory expansion, with a new building using a flat roof.

During the design stage of this plant, several layouts were considered and the main results from the PVSYST simulations are presented in Table 3. The simulations used the PVGIS database due to more accurate temperature data for this location than the Meteonorm 7.3 database. The models for the PV modules, power optimizers are the inverters are provided with version 7.1 of PVSYST. Modules and strings allocation and orientation are as close as projected as is allowed by the software. The oversizing of DC PV power over inverter nominal power is small for the three options, because the SolarEdge 82.5 kW inverters are composed of three 27.5 kW units. As there are few shadings and PV modules are half-cell type and power optimizers are used, the linear shading option is selected for the simulations.



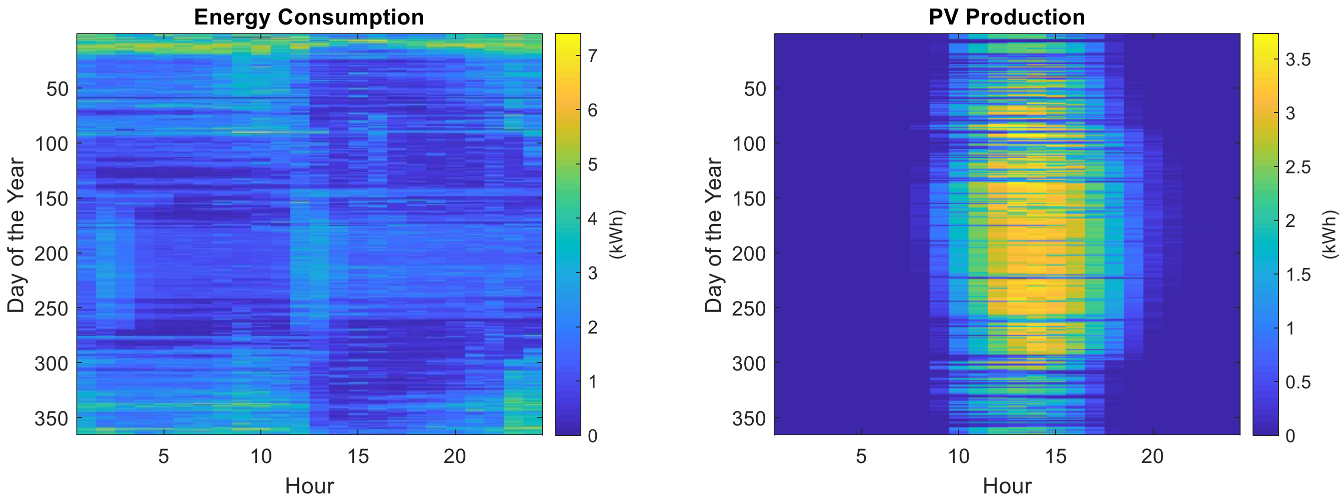
(**a**) (**b**)

**Figure 4.** Industrial PVSC plant (a) PVSYST Model, view from the South. (b) Photograph of the plant.

## 3. Results

*3.1. Residential PVSC*

First, we will start presenting the behavior of the building and the PVSC using heatmaps. Figure 5 (a) represents the hourly consumption profile of the home. It can be observed that there are two usual patterns: in the summertime, the consumption is higher from 12 p.m. to 3 p.m. due to cooking and in the afternoon due to the use of air conditioning. The rest of the year is higher from 8 p.m. to 12 a.m. due to the use of the heat pump for heating. Exceptions are in spring, with low consumption all day, and in some weeks in winter the consumption is very high due to the colder weather. In Figure 5 (b) the PV production is represented and can be seen that it fits well with the peak consumption in summer.




(**a**) (**b**)

**Figure 5.** Heatmaps of measured hourly energy consumption (a) and PV production (b) for the period under study.

3.1.1. Energy analysis

As was explained in the previous section, different configurations were simulated in PVSYST and compared with the real data obtained from the PVSC. The size and specific yield are shown in Table 3, where it can be seen that the difference between the simulation and the real data is less than 1% for the original configuration. This is a fair result considering the natural variability of yearly irradiation. The yearly optimum is a 11% better than the original installation. Still, for the configurations over the façades, the results range from a 10% less yield for the configuration using canopies and a 30% less for the configurations with coplanar modules attached to the façades.

**Table 3.** Energy yield of the different configurations for the PVSC.

| Configuration | # Modules | PV Power (W) | Yield (kWh/kWp) | ΔYield[1] |
|---|---|---|---|---|
| Original (Real Data) | 10 | 3850 | 1582 | 1% |
| Original | 10 | 3850 | 1560 | 0% |
| Yearly optimum | 10 | 3850 | 1725 | 11% |
| Canopy (SE & SW) | 12 | 4620 | 1375 | -12% |
| Coplanar on façade (SE & SW) | 12 | 4620 | 1097 | -30% |
| Canopy & Façade (SE) & (SW) | 12 | 4620 | 1325 | -15% |

[1] Refereed to the simulated original configuration.

The energy balances are presented in Table 4. The PV production for the original configuration (both simulated and measured) and for the canopy and façade configuration are very close. Nevertheless, the simulated PV self-consumed energy differs from the measured: 3.4 MWh vs. 3.0 MWh. This can be explained due to different hourly profiles for the irradiance in the weather data and the reality. So, in the following the comparisons will be made with the original simulated configuration. The canopy and the energy optimal configuration have similar PV production and self-consumption, bearing in mind that the canopy configuration has a 20% more installed PV power. The façade configuration has the lower PV production, a 16% lower than the original simulated, but the self-consumed energy is only a 2% lower.

**Table 4.** Energy performance with the building and the grid of the different configurations for the PVSC.

| Configuration | PV Production[1] | Energy Consumption[1] | PV Self-Consumption[1] | Surplus Energy[1] | Energy from the Grid[1] | SCD[2] | SSD[3] |
|---|---|---|---|---|---|---|---|
| Original (Real Data) | 6.1 | 13.5 | 3.0 | 3.1 | 10.5 | 49% | 22% |
| Original | 6.0 | 13.5 | 3.4 | 2.6 | 10.1 | 56% | 25% |
| Energy optimal | 6.6 | 13.5 | 3.6 | 3.1 | 9.9 | 54% | 26% |
| Canopy (SE & SW) | 6.4 | 13.5 | 3.6 | 2.8 | 9.9 | 56% | 27% |
| Façade (SE & SW) | 5.1 | 13.5 | 3.3 | 1.7 | 10.2 | 66% | 25% |
| Canopy & Façade (SE) & (SW) | 6.1 | 13.5 | 3.5 | 2.6 | 9.9 | 58% | 26% |

[1] All energies are expressed in MWh; [2] SCD - Self Consumption Degree; [3] SSD - Self Sufficiency Degree.

With this data is not clear enough the effect of the PV orientations on the self-consumption variation because if a particular configuration produces less energy, it is easier to consume it in the building, improving the self-consumption degree. For removing this effect, the PV production for each configuration has been rescaled to match annual energy productions ranging from 5,000 kWh to 15,000 kWh and the energy balances are calculated in each case, simulating PV installations of different power. In this way it is possible to distinguish the effect of the different orientations on the self-consumption and self-sufficiency indexes. In Figure 6 are represented (a) the self-consumption and (b) the self-sufficiency degree (defined in equations 3 and 4). The non-optimal configurations provide a self-consumption index 4% better than the original and a 2% better self-sufficiency. This is a consequence of the flatter time profile of the PV production for the configurations based on modules coplanar with the façades and on canopies.

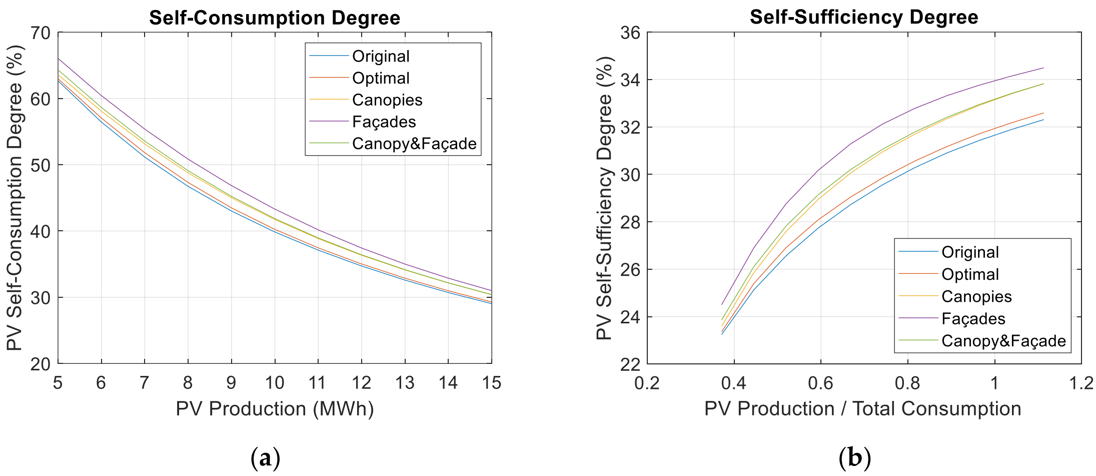
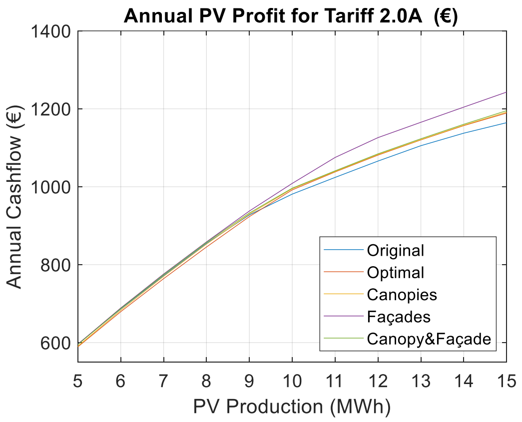
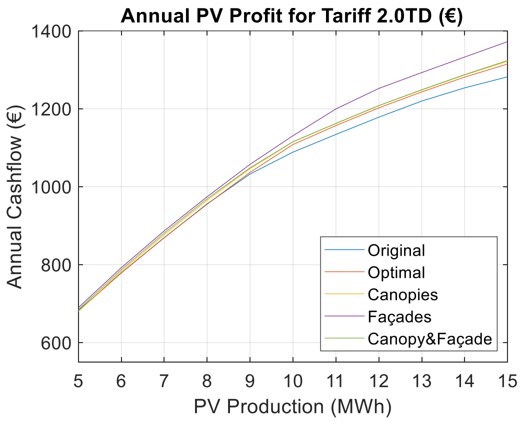



**Figure 6.** Self-consumption (a) and Self-sufficiency (b) degree vs PV production relative to the consumption for the simulated configurations.

The hourly energy balances are valuated with the pricing data for the two tariffs, as was detailed before, and the annual PV profits are calculated for all configurations. The results are shown in Figure 7 and can be seen that for the same energy production, the most profitable configuration is the one with modules coplanar with the façades. This is due to the better self-consumption of PV produced electricity, that is valuated at a higher price than the surplus energy exported to the distribution grid. It is also visible in Figure 7 that the annual profit rises linearly with the PV production up to 9 MWh and beyond this annual production, the profit increases at a lower pace. This is due to the Spanish simplified compensation expressed in equation (6) that stablish that during the one-month billing period the energy term cannot be negative. In fact, for higher PV productions, in some months it is possible for the value of the energy exported to the grid to be higher than the consumption, despite the lower price of the exported energy and thus reducing the profits. In addition, comparing the profits for the two tariffs, the new tariff displays a profit of approximately 100 € higher than the older one for all configurations and sizes.




(a)




(b)

**Figure 7.** Economic profit for older and new electricity tariffs in Spain: (a) Annual profit for older tariff 2.0A; (b) Annual profit for the new tariff 2.0TD. Taxes of 5.11% of electricity and 21% VAT are included in the calculations.

The annual profits calculated are used as the cashflow for the economic analysis. The other input are the costs of the installations. We have estimated the following costs: 1.55 €/W for PV powers lower than 4 kW, 1 €/W for PV powers higher than 8 kW and a linear variation of costs between these powers. This pricing scheme is supported on the information of PV installers, and it is representative of the Spanish PV residential market in the year 2021. We have applied a cost increase of 11% for the configuration based on façades, a 12.5% for the mixed one and a 14% for the canopies. In Figure 8 are presented the results for the Net Present Value ((a), (d)), Internal Rate of Return ((b), (e)) and Time of Return of Investment ((c), (f)). These results are plotted versus the annual PV production ((a), (b), (c)) and versus the installed PV power ((d), (e), (f)). The economic indicators are favorable in all cases, being the optimal case the best economic performer and the façades the worst. The best maximum NPV is for the optimal case with 12,271 € and 8.1 kW installed at a cost of 8,116 €. The lowest NPV is maximum at 7,616 €, being almost flat for a range of powers between 8 kW and 11 kW. The IRR is very favorable also, always over 7%. The best performer is the optimal, between 14% and 17% and the worst the façades, between 6.9% and 10.8%. The optimal PV power is around 8 kW in all cases. The time of return of investment is minimum for PV power of 8 kW in all cases and ranges from 6.3 years for the optimal case to 8.6 years for the façades.

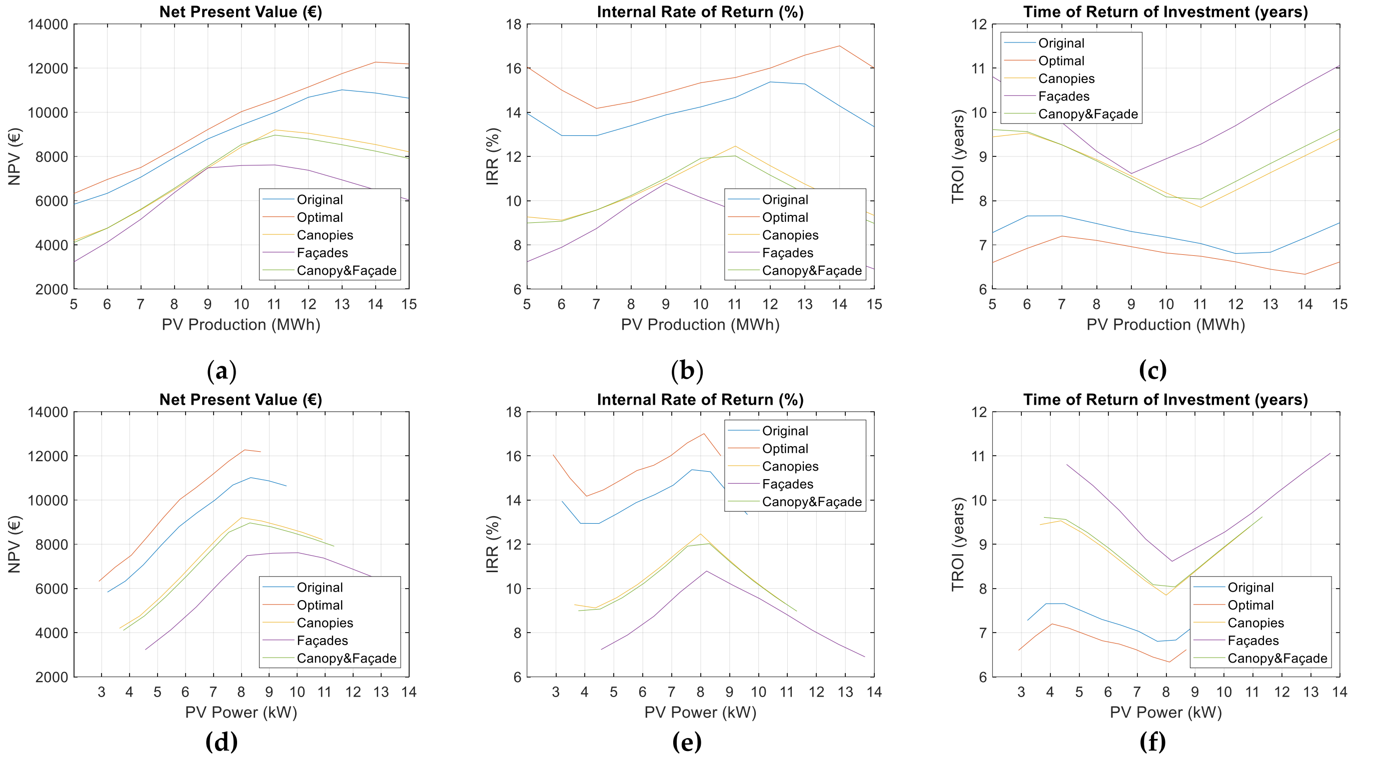



**Figure 8.** Economic balance. (a) Net present value vs annual PV production; (b) Internal Rate of Return vs annual PV production; (c) Time of return of investment vs PV installed power.

Finally, the levelized cost of electricity is calculated according with equation 9 and it is shown in Figure 9 (a) and (b). For PV powers under 8 kW, the LCOE reach maximum values of between 6.3 c€/kWh and 10.3 c€/kWh and the minimum values are between 4.0 c€/kWh and 7.0 c€/kWh. All these minimum values are well below current retail electricity prices in Spain.

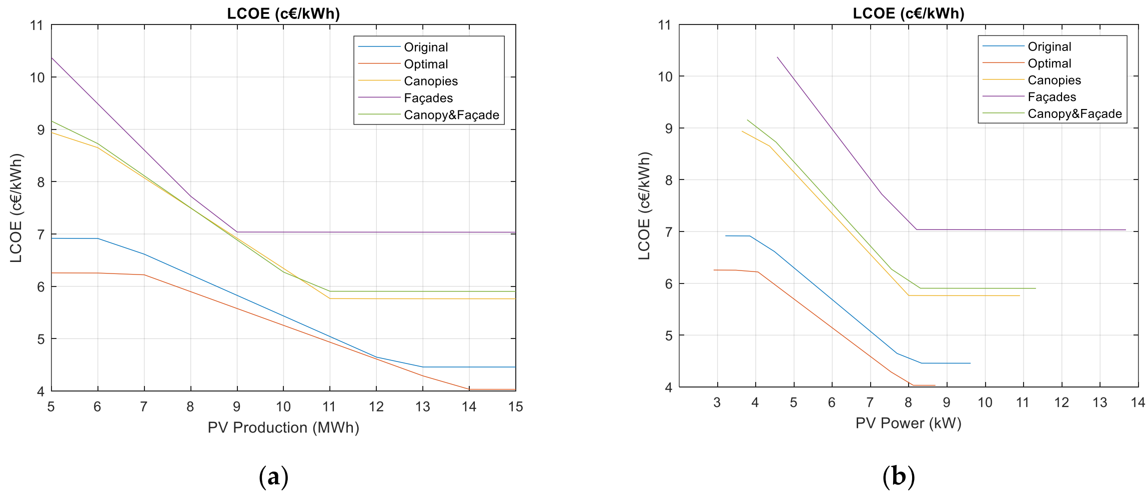



**Figure 9.** Levelized Cost of Electricity for all configurations. (a) LCOE vs annual PV production; (b) LCOE vs PV installed power.

*3.2. Industrial PVSC*

This PVSC is in operation since October 2020, and there are data for almost a year, so the analysis is not as complete as for the residential example. Figure 10 shows the heatmaps for the hourly consumed energy 10 (a), PV-produced 10 (b) and imported from the grid 10 (c). It can be appreciated the good fitting between the factory peak load before noon and the PV production. Also, in Figure 10 (c) can be seen near zero consumption periods due to the PVSC production. The horizontal band in the center of all figures correspond to the period of unavailable data due to the recent construction of this PVSC. It is important to note the reduction in the maximum hourly energy demanded from the grid in periods of high prices of electricity.

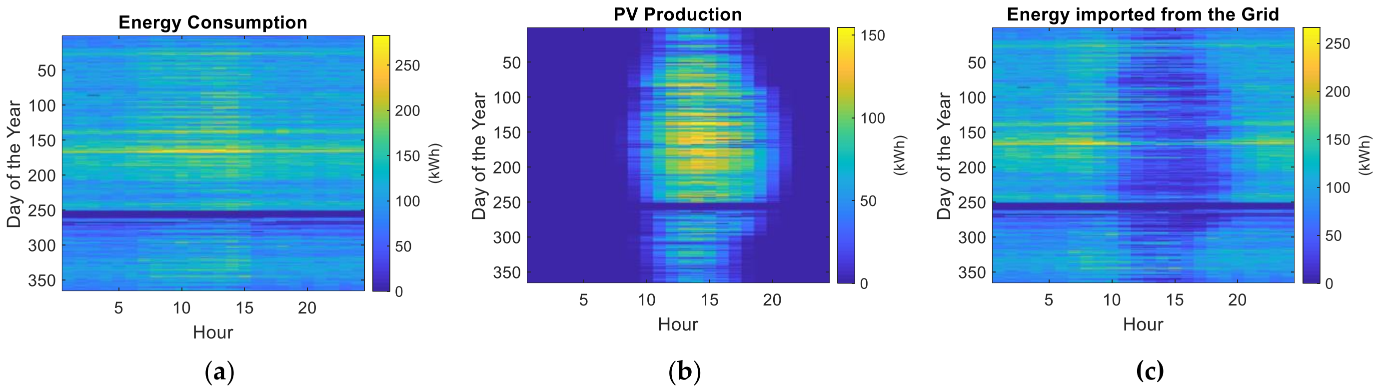



**Figure 10.** Heatmaps for industrial PVSC plant (a) Electricity consumption (b) PV Production (c) Energy imported from the grid.

The annual electricity consumption for the factory was of 665 MWh before the expansion, so the owners wanted to generate the most electricity as possible. The electricity consumption estimated for the first year after the expansion is of 1,000 MWh. In Table 5 are presented the results of the PVSYST simulations for the four layouts considered. The optimal orientation (South, 35° inclination) was discarded due to the lower annual production. The wider distance between different rows due to the higher inclination causes a poor occupancy of the available area in the roof. The east-west orientation (15° inclination) allows a higher installed power but the increment in the energy produced is low, so it was also discarded. Finally, the yearly production is very similar for the south (15°) and the two orientations layouts. It is important to note that due to the high winds present in winter, modules should be placed in landscape orientation and with the lower inclination possible.

One of the reasons to discard the south orientation was due to the study of consumption patterns and considering the Spanish regulation. This regulation allows a fast-permitting process for PVSC without surplus for installations of nominal power above 100 kW. For installations with a surplus, there is mandatory to obtain permits for grid connection so there are several permitting stages that would delay the process both before and after building the PVSC installation. On the other side, the biggest portion of energy consumption is the cooling inherent to the meat-processing. Moreover, the energy consumption in summer doubles that of in winter. In this way, the first option (south orientation) was discarded because it yields a maximum at solar noon, so there is the risk of frequently producing more electricity than the consumption, so the inverters would curtail the production. For energy non-optimal orientations, the daily production presents a lower peak around midday and produces electricity a longer time in spring and summer.

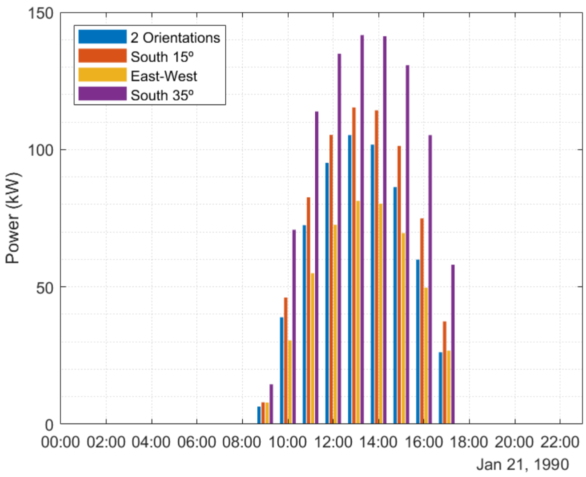
**Table 5.** Summary of configurations for PVSC industrial plant. The increments are relative to the optimal orientation.

| Configuration | # Modules | Peak Power | Δ Power | Annual Production | Δ Production | Specific Yield kWh/(kWp.yr) |
|---|---|---|---|---|---|---|
| South, (35° optimal incl.) | 224 | 98 kW | 0% | 170 MWh | 0% | 1,729 |
| South | 336 | 148 kW | 51% | 248 MWh | 46% | 1,675 |
| Two orientations aligned with the building | 386 | 169 kW | 72% | 270 MWh | 59% | 1,597 |
| East-West | 280 | 123 kW | 26% | 184 MWh | 8% | 1,495 |

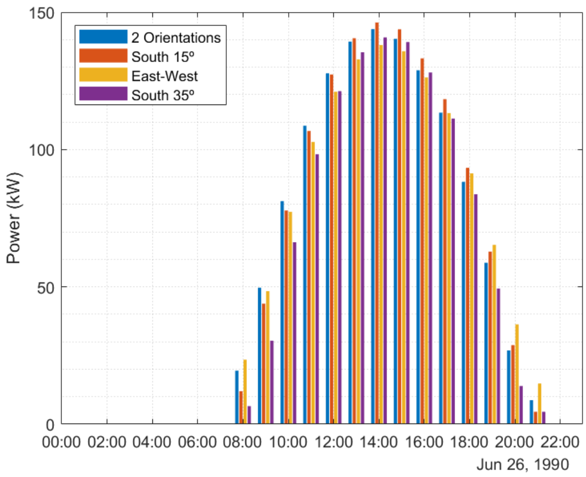
[1] Modules inclination is 15° in all configurations except the optimal energy producing.

The two-orientations option was also selected because it was more convenient for easing the installation process and maintenance, as it is shown in Figure 3. Due to the orientation of the building, the South and East-West orientations generate a saw-tooth pattern in the borders resulting in a poor occupancy of the roof and compromising the clearance distance with the external fence. The east-west layout had a particularly difficult access to all points in the plant.

In Figure 11 is presented the hourly production for two clear-sky days. Figure 11 (a) correspond to a winter day and Figure 11 (b) to a summer day. For a better view of the effect of orientation (azimuth and inclination), the data from the four configurations is rescaled to 169 kW. It can be seen that due to the low inclination of the modules, the variation between the South (15° inclination) orientation layout and the 2-orientations layout is low, but in summer the 2-orientations production profile is more rounded, with a lower peak and higher production at sunrise and sunset. The East-West configuration has a marginally better behavior in summer, but it is poor in winter. On the contrary, the energy-optimal orientation (South, 35° inclination) presents a better performance in winter but a worse one in summer with a sharper profile, with the lowest production in the morning and in the evening. There is important to remind that the installed PV power for the optimal south orientation and the east-west layouts is significantly lower than for the South (15°) and the two orientations.




(**a**)




(**b**)

**Figure 11.** PV production of the different configurations rescaled to the same rated power for industrial PVSC plant on representative days (a) Winter day, (b) Summer day. (1990 is the default year for PVSYST simulations).

The behavior of the real PVSC on one representative day is presented in Figure 12. As can be seen, the energy consumption decreases at lunchtime, between 14:00 and 16:00. This can make the electricity consumption from the grid too low, so the inverters curtail the production. According to the Spanish regulation, if the PVSC is connected under the category without surplus, grid feeding is not allowed in any of the three electricity phases, as can be seen in the production being curtailed around 16:00. So, if the electrical loads into the factory are not well-balanced it could result in higher PV production losses. This fact is important in favor of PVSC layouts that yield the energy with flatter and longer production profiles.

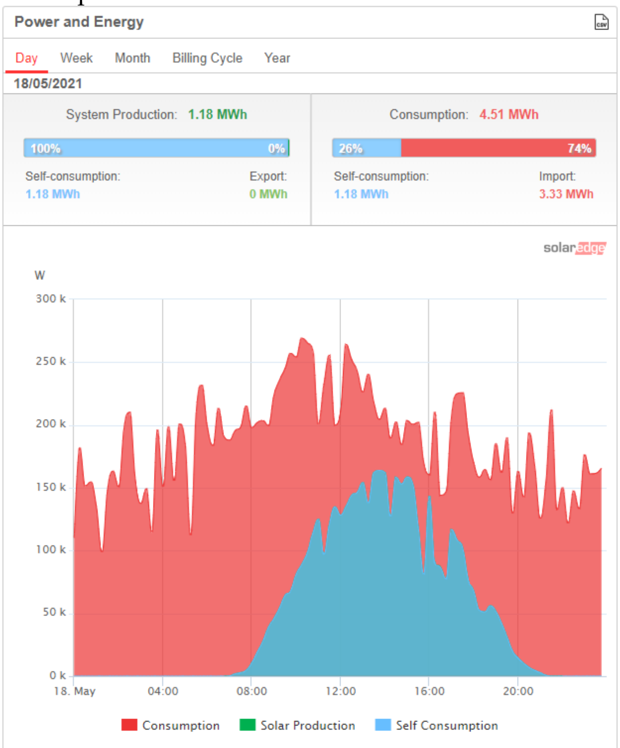



**Figure 12.** Screenshot of the monitoring portal showing the electricity consumption and production on one spring day (18/05/2021). The figure shows the 15-minute average power in watts for the consumption and PV production.

## 4. Discussion

The use of PV orientations non-optimal for energy generation has been presented in residential and industrial cases of study. For the residential case, it is found that the economic yield for the discussed orientations is better than its energy yield. One reason is that using several orientations the energy production spreads more uniformly during the daytime, increasing the self-consumption share of PV-produced electricity. The other reason is found in the variable prices for the retail electricity and the surplus electricity fed into the distribution grid. With the maturity of the PV sector, the actual net-billing schemes, like the current one in Spain, are more appropriate than net-metering policies since the surplus price is indexed to the wholesale electricity market, thus signaling the periods when distributed generation is more valuable [39]. The use of these non-optimal orientations can reduce the electricity interchanged with the grid, especially the energy fed, resulting in a reduction of the energy stress on the grid [40]. Another benefit can be the more stable production for configurations using façades, which can match better the consumption profile during the year.

The introduction of residential tariffs with higher prices in periods of high electricity consumption will add an additional profit to the Southeast orientations, which produce most electricity in the hours before noon, just within one of the two peak tariff periods. From the data shown in Figure 7, the increase in profits over the current one period tariff ranges between 8% and 16% for PV installations of annual productions from 5 MWh to 15 MWh.

For the industrial case, in addition to the considerations discussed for the residential scenario, there are additional factors to take into account. The use of alternative orientations can facilitate larger PVSC installations, reduced curtailment of PV production or energy fed into the distribution grid, and simplified installation and maintenance. Furthermore, it is possible to optimize the periods of energy generation to suit the load patterns of the site. The use of PV reduces the maximum power demanded from the grid, in particular, the analysis of the period of available data shows an important reduction of power surpasses. In Spanish industrial tariffs, a surpass is defined as the power demanded in a quarter hour period exceeding the contracted power. For this industry, the contracted power is of 180 kW and in the period of data available there are 642 quarters with consumption over 180 kW, with a maximum demanded power of 284 kW. For the energy taken from the grid there are 194 quarters with demanded power over 180 kW and with a maximum power of 236 kW demanded from the grid. These figures mean that the use of PV roughly decreases the surpasses by 69% and the maximum power exceeded decreases a 46%, reducing maximum demand penalties and providing additional economic savings.

To realize the potential of alternative orientations it is important to stress the necessity of implementing complementary demand side strategies. For example, in Figure 4 (a) it is clear that the use of air conditioning during the night in summer can be shifted to the hours when PV production is high using self-produced PV electricity and therefore providing greater economic benefit.

From a wider perspective, the use of these orientations can provide an important increase in the suitable area for PV, beyond roofs [21,41]. Traditionally, installations of PV in locations other than roofs are perceived as inefficient or uneconomic and reserved for emblematic or flagship buildings. Our study shows that even when the energy performance is lower than traditional orientations, the economic performance is not so far from them. Considering that PV modules can replace building materials, the overall economic balance can be positive. In addition, the use of PV as shading elements in canopies can be used by architects to improve the user's comfort and the energy performance of the building by reducing cooling needing while increasing the energy production. These facts are relevant to the BIPV concept and can help the expansion of this sector.

Complementarily, these results help us to demystify general rules of thumb of photovoltaic installations, such as: "In the northern hemisphere, the solar panels have to be oriented towards the South" and "For maximum annual energy availability, a surface slope equal to the latitude is best" [42]. More precisely, in an extensive numerical study [43], the optimal fixed tilt and azimuth angles are calculated for the continental USA and it is found that "The optimum tilt was never greater than latitude tilt, but up to 10° less than latitude tilt". In this reference is also pointed that if variable electricity prices are considered, these angles can vary. Moreover, as is stated in [44] "there is a false perception among building professionals that solar modules should be installed on ideally oriented and tilted surfaces". The performance of systems with non-optimal orientations allows further flexibility in the installation of PVSC in residences and industrial buildings. This is achieved without aesthetically distorting the structure and obtaining an acceptable economic benefit with an economic yield that varies only slightly compared to installations with optimal orientations.

Future directions of this work will include a detailed techno-economic analysis of the industrial PVSC with full-year data, systematic research of different orientations for representative residential, commercial, and industrial users, and the development of a methodology for optimal design of PV installations in accordance with hourly-variable electricity prices and consumption patterns.

## 5. Conclusions

The use of orientations different of the traditional orientation optimal for energy production in PVSC installations has been studied in residential and industrial buildings. The aim of this study is to be as close as possible to real built installations and hourly variable electricity prices are used. For the residential case, different PV configurations suitable for the building are studied using the real data from the PVSC simulating the behavior for PVSC installations of different sizes that produce the same range of annual energy. For the industrial case, the PVSC is built using non-optimal orientations and it is compared with 15° inclination South-facing andEast-West orientations, and with South facing and 30° inclination that is the optimal energy-producing for our latitude.

In conclusion, it has been found that PVSC installations in orientations different of the traditional orientation optimal for energy production are a viable option. The economic performance of these orientations it is found to be acceptable under the current net-billing self-consumption scheme in Spain. The data from the residential case shows that for the configuration using canopies, the economic benefit is the same as that of the optimal energy producing orientation. For the configuration with the modules on the façades, the economic benefit is a 14% lower than for the optimal, despite of an energy production a 24% lower. The use of these non-optimal orientations can add-up to conventional orientations in case that there is not enough roof available for PV, for example in condominium with collective self-consumption.

An additional advantage for these orientations is found in the new residential tariffs, that results in an increase up to 16% in the profit over previous tariffs. The new period of highest prices "peak" before noon can be used in orientations with maximum production in this period. There is also a fair economic performance for these orientations, despite of the higher cost assumed in this study for the modules placed on canopies and on the façades.

The data from the industrial PVSC case study suggest that non-optimal PV orientations can be an advantage over traditional south facing orientations optimal for yearly energy production. The main advantages found can be summarized as follows:

- Higher installed power due to more efficient use of available space in roofs, resulting in higher energy production in the available space. The benefit identified in the case study was a 72% more peak power and a 59% increase in energy production.
- Improved economic yield by adaptation to variable electricity tariffs and load patterns of industry using different orientations.
- Reduced curtailment of PV production or energy fed into the distribution grid due to the flattened production profile.
- Higher potential for reducing peaks of consumption due to the extended period of PV production. The reduction in the number of power surpasses reach 69% and the maximum power exceeded is reduced a 45% in this case study.
- More ordered PV Layout, easing installation, operation and maintenance, and overall safety for workers.

With the current outlook of an increased deployment of zero-marginal-cost generation sources, such as PV, wholesale market electricity prices are expected to decline after noon, when consumption is lower. Meanwhile retail prices will remain high during peak periods of consumption and therefore the use of non-optimal orientations can be highly beneficial from the economic point of view.

**Author Contributions:** Conceptualization, E.S. and A.O.; methodology, E.S. and A.O.; software, E.S.; investigation, E.S., A.O. and J.P-D.; resources, E.S and A.S.; data curation, E.S.; writing—original draft preparation, E.S, A.O. and J.P-D.; writing—review and editing, E.S., A.O., A.S., R.G., and J.P-D.; visualization, E.S.; supervision, R.G.; project administration, E.S. and R.G.; funding acquisition, R.G. All authors have read and agreed to the published version of the manuscript.

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**Conflicts of Interest:** One of the authors (A. S.) redacted the engineering project and was responsible of the works direction for the PVSC in the industrial plant. E.S. collaborate in this project with the analysis of the different configurations and the PV design and calculations for the final layout. There is no other conflict of interest.

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