

1 Article

# 2 Analysis of different scenarios to include PV Rooftop systems 3 with battery energy storage systems in olive mills

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11 **Abstract:** The industrial sector is not only one with the highest energy consumption but represents,  
12 together with the transport sector, the most polluting ones. Photovoltaic Rooftop systems and bat-  
13 tery energy storage systems are proposed as candidates to include renewable energy, allowing  
14 greater grid autonomy and greenhouse gases mitigation. Therefore, this work will try to provide a  
15 methodology based on monitored data to analyse the potential of photovoltaic Rooftops with bat-  
16 tery energy storage system regarding self-consumption and self-sufficiency indices in the industrial  
17 sector. Direct self-consumption and self-sufficiency indices either with and without storage will be  
18 analysed. In addition, the *iso self-consumption* and *iso self-sufficiency* curves are used, which allow to  
19 evaluate the matching between the generation and consumption profiles considering either direct  
20 self-consumption and the use of batteries. A large, medium and small olive mills were selected in  
21 order to cover the entire spectrum of these industries. It can be considered that olive mills are suit-  
22 able candidates for the incorporation of photovoltaic systems, since generation profiles matches  
23 with the consumption profiles. However, the size of these systems is highly dependent on the period  
24 of consumption to be faced. Regarding batteries, both during the *harvest* and *off-harvest periods*, the  
25 impact on self-sufficiency becomes significant, reaching increases up to 10 %, depending on the bat-  
26 tery capacity used.

Citation: Lastname, F.; Lastname, F27  
Lastname, F. Title. *Energies* 2023, 15,28  
x. <https://doi.org/10.3390/xxxxx> 29

**Keywords:** Olive mill; self-consumption; PV Rooftops; batteries; iso self-sufficiency curves; iso self-  
consumption curves

Academic Editor: Firstname Last-  
name

Received: date 30

Accepted: date 31

Published: date 32

33  
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35 tral with regard to jurisdictional  
36 claims in published maps and institu-  
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45

## 1. Introduction

In recent years, improved natural resource management and globalization have had a positive impact on the growth of the global economy [1]. However, this economic growth is one of the main drivers of pollution [2,3]. This is due to the fact that the economically productive sectors (primary, secondary and transportation) still rely on highly polluting primary energy sources [4]. The transition from conventional energy sources, such as natural gas or coal, to renewable sources such as solar and wind energy for electricity production could lead to a considerable reduction in greenhouse gas (GHG) emissions [5–7]. The consolidated Renewable Energy Directive 2018/2001/EU sets a new binding renewable energy target for 2030 in the EU of at least 32 % to enable self-consumption of renewable energy, an expanded target of 14 % for the contribution of renewable fuels in transport by 2030 and Enhanced criteria to ensure the sustainability of bioenergy [8]. In fact, the objective of the European Union's Green Pact is to become the world's first emission-neutral continent by 2050.

In this context of sustainable development, factors such as GHG emissions, gross domestic product, population and labour force growth are directly related to primary and

46 final energy consumption [9]. In Spain, in 2021, the transportation sector was the main  
47 contributor to GHG emissions (29.9 %), followed by industrial activities (22.6 %), agricul-  
48 ture and livestock as a whole (11.4 %), electricity generation (10.9 %), fuel consumption in  
49 the residential, commercial and institutional sectors (9.1 %), and waste management (4.6  
50 %) [5]. On the other hand, final energy consumption in Spain in 2021, excluding non-en-  
51 ergy uses, increased by 8.9 %. In the total final energy consumption, transportation stands  
52 out as the largest final energy consumer, with 37.8 %, followed by the industrial sector  
53 with a 30.2 % [10]. It could be said that there is a direct relationship between the most  
54 polluting sectors and their final energy consumption [11]. Further in this classification,  
55 within the industrial sector in Spain, one of the most important is the agri-food sector and  
56 the manufacture of food products, since they are not only large emitters of GHGs, but also  
57 induce more emissions in other sectors [11]. The efficient use of their energy resources  
58 becomes crucial in increasing agricultural production, the competitiveness of the agricul-  
59 ture and food industry and environmental sustainability. Reducing its reliance on increas-  
60 ingly limited fossil energy resources by understanding the energy consumption profiles  
61 and analysing the energy balance of these industries is increasingly necessary [12]. There-  
62 fore, the implementation of energy measures that introduce renewable energies in the  
63 agri-food industrial sector can significantly contribute to the reduction of GHG emissions  
64 and improve its economic competitiveness.

65 Solar photovoltaic (PV) energy and storage systems are key technologies to enable a  
66 higher share of renewable energy and grid autonomy [13]. In countries such as Spain, in  
67 2022, renewable electricity generation accounted for 42.2 % of the national electricity sup-  
68 ply, with wind energy as the second most important source (22.2 % of the total) and solar  
69 photovoltaic energy as the fourth (10.1 %), which contributed to the reduction of GHG  
70 emissions [14].

71 However, renewable energy generation sources have a stochastic behaviour that  
72 makes it difficult to manage and control them within the generation mix. During their  
73 operation, peaks and valleys of production are generated and must be compensated to  
74 maintain system stability [15]. This situation has driven the industry's interest in battery  
75 energy storage systems (BESS) as a possible solution [16–21]. In this sense, batteries are a  
76 key instrument for the transition to the climate-neutral economy that is expected to be  
77 achieved by 2050, in order to enable the integration of increasing shares of variable renew-  
78 able energies.

79 In the short term, most projections foresee an increment in the use of storage systems,  
80 reaching 100 GWh in 2025. Beyond 2025, strong growth continues: the lowest estimates  
81 range from 8 to 100 GWh and the highest estimates reach 400 GWh in 2030, reaching 1300  
82 GWh in 2040. At present, global demand for lithium-ion batteries is expected to exceed  
83 2,000 GWh by 2030. Under the most optimistic scenario, it could reach 4000 GWh by 2040  
84 [22].

85 The expected growth stems from the expected significant technological improve-  
86 ments and further cost reductions. Lithium-ion battery prices, which were above  
87 \$1100/kWh in 2010, fell to \$156/kWh in 2020 [23]. In 2022, the estimated average battery  
88 price stood at about \$150/kWh, with the cost of pack manufacturing accounting for about  
89 20 % of total battery cost, compared to more than 30 % a decade earlier [24]. These factors  
90 are essential in order to make the transition to a cleaner and more sustainable economy,  
91 which in turn contributes to the reduction of carbon emissions and the promotion of re-  
92 newable energy sources in industry.

93 In this sense, the renewable energy systems with BESS in industries is a topic of grow-  
94 ing relevance in today's energy landscape. **It is important to note that a balance must be  
95 established between ecosystem conservation, integration with the natural heritage and the  
96 energy productivity of these systems. The debate on the architectural and landscape inte-  
97 gration of these systems is extensive [25]. Therefore, policies, recommendations and de-  
98 sign criteria should be identified to promote energy transition in the rural environment,  
99 preserving also the cultural and natural heritage, as is being done in [26], where a full**

discussion of policy-related design criteria for the integration of photovoltaic systems is presented. By increasing the aesthetic, functional and environmental value of a building or natural environment, photovoltaic technologies can lead to new market growth and social acceptance [27–31].

In this context, a benefit-cost analysis of PV and BESS planning for an industrial site, with the objective of maximizing the solar resource, is illustrated in [32]. A study to size the BESS of a particular customer using the generic load profile for industrial customers located in northern Taiwan is performed in [33]. As well as in [34], where the impact of different regulations on the optimal sizing of a solar hybrid system is studied, comparing systems under net metering and zero export schemes, located in an industrial township in Delhi. In [35], a two-level stochastic programming model is proposed to determine the optimal power and capacity of the BESS for industrial consumers. In particular, in the agriculture and agri-food industry, photovoltaic (PV) Rooftop systems, with or without batteries, is one of the most widely used renewable energy sources with various applications [36–38], as water pumping systems for irrigation purposes [39], or electricity production in the agri-food sector [40–42].

These studies provide very interesting findings, but even so, research gaps have been identified. The studies found in the industrial sector do not provide an exhaustive analysis of the consumption profiles of the industries which constitutes a key issue in order to provide a proper analysis of the potential of PV Rooftops and no specific industries have been studied. Moreover, few of them use real performance data and, in many cases, consumption averages or statistics are used instead of real monitored power consumption profiles throughout a year. This means that the detail of when and how the energy is consumed is lost because previous studies typically focus on cumulative energy consumption values, which may illustrate the total amount of kWh consumed but do not provide insights into the energy behaviour of the industry. While studies without real performance data may provide valuable insights under controlled conditions, they often face limitations in terms of external validity, practical applicability, and the ability to account for the complexities of real-world scenarios.

The proposed work aims to illustrate the potential of incorporating renewable energy to the industry through PV Rooftop systems with batteries. For this purpose, a previous energy characterization of the real consumption profiles of these industries will be carried out. Industries usually have very different consumption profiles. Therefore, this work will try to provide a methodology based on monitored data to analyse the potential of PV Rooftops with BEES regarding their consumption profiles together with self-consumption and self-sufficiency indices either with and without storage system (direct self-consumption) in the industrial sector. This methodology is based on an analysis of the consumption profile through a year where either power and energy data will be considered and may be very useful in order to maximize the self-consumed energy and therefore, the self-consumption and self-sufficiency indices. Moreover, to illustrate this methodology will be used within the olive mill agri-food industrial sector to analyse the matching between consumption and photovoltaic generation in three olive mills considering the daily consumption profiles monitored throughout a year. Each of the analysed olive mills belong to a type according to the classification published in [43]: small, medium and large. This classification is made considering the different size or productive scope. Although initially direct self-consumption will be considered, the study is extended by taking into account the effect of incorporating BESS into the PV Rooftop system. In this sense, it will be provided an analysis which will illustrate the potential of PV Rooftops with or without BEES in this type of industry as it will be considered the different types of olive mills that cover the whole spectrum of this sector. It must be highlighted that although it can be found studies regarding PV Rooftops in olive mills, they only consider direct self-consumption [44] and the study is only focused on a determined olive mill. For the analysis of the potential of PV Rooftop systems with batteries, there will used the *iso self-consumption* and *iso self-sufficiency* curves which allow to evaluate the matching between the generation and

consumption profiles considering either direct self-consumption and the use of BEES [45]. Direct self-consumption analysis will be made taking into account not only global self-sufficiency but self-sufficiency in solar hours [46]. In this sense, it will be analysed the suitability of PV Rooftops with or without BEES in olive mills. Moreover, it will be provided different scenarios to take advantage of this type of systems when facing energy consumption. It must be said that in most cases olive mills are located very near of urban zones in rural areas which would allow the use of collective PV Rooftops facilities through energy communities. This opens up new and profitable opportunities in these rural areas to access energy based on renewable sources, thus having not only a very positive impact on the environment but on the own olive mills economic activities.

Finally, the methodology here provided can be extended to any type of industry when analysing the matching capability and suitability of PV Rooftops systems with or without BEES. Special attention must be paid to the consumption analysis given the wide variety of consumption profiles that already exist in the industrial sector. This fact demands an *ad hoc* analysis not only to estimate the potential of PV Rooftops systems properly but to provide a proper analysis of the PV array and BEES.

In order to approach this study, the article is structured as follows: section 2 will analyse the methodology used in the study and the data required; section 3 will show the results of the study and the discussion of these results when plotting the curves of self-consumption, self-sufficiency and self-sufficiency in sunshine hours; finally, section 4 will show the most relevant conclusions.

## 2. Materials and Methods

In this section, the materials and methods employed in this study are detailed with a particular focus on the description of the industries under analysis, together with their monitored electricity consumption data. Figure 1 summarizes the subsequent stages of the study, identifying each phase of the proposed methodology. This methodological approach aims to provide an understanding of the factors influencing the energy consumption of these industries and their potential for incorporating rooftop PV systems with batteries.

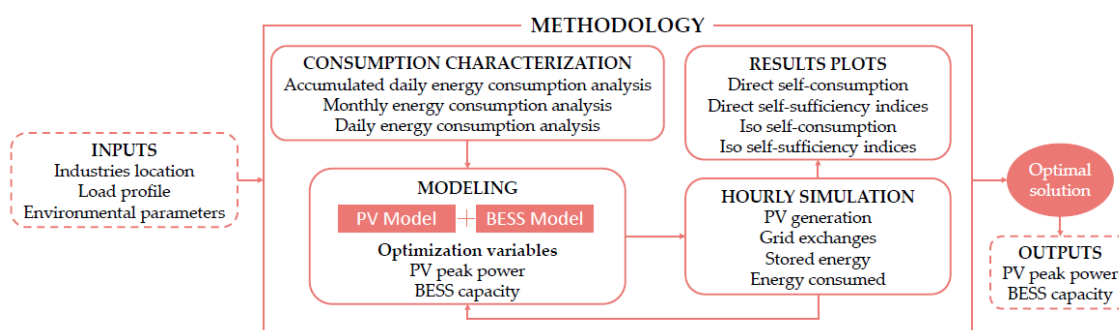


Figure 1. Methodology implemented in the development of the study.

### 2.1. Description of the industries

Olive oil mills play a crucial role in Spain, making the country the largest producer of olive oil in the European Union and a crucial part of its economy [47]. According to the Olive Oil Market Information System (SIMO) managed by the Ministry of Agriculture, Fisheries and Food (MAPA), Andalusian cooperatives play an essential role in the production of olive oil in Spain, being responsible for the production of 80 % of the country's total oil [48]. These mills are a significant part of the industrial framework in Andalusia, accounting for 35.8 % of the food sector turnover in the region, which underlines their relevance in this region. Moreover, these industries are scattered throughout the region, from the largest urban areas to the most remote rural areas [49].

195 These industries, due to the fact that in most cases they are located in rural areas, may  
196 have favourable access to renewable energy sources, such as solar, wind, hydro and bio-  
197 mass, among others [50,51]. In rural areas, in fact, the population's options for remaining  
198 in these areas are highly conditioned by the evolution of this productive sector [52]. The  
199 new distributed generation technologies, on a medium and small scale, can help to avoid  
200 the total reliance of these industries on an energy supply that, until now, has had a high  
201 environmental impact [53]. A clear example can be the energy communities. In Spain it is  
202 regulated by Royal Decree 244/2019 [54]. It establishes that in order to connect collective  
203 self-consumption facilities, the condition is that generation and consumption must be con-  
204 nected at a distance less than 500 meters from each other. In the particular case of photo-  
205 voltaic facilities, this distance may be up to 2000 meters. In most cases, in rural areas, the  
206 olive mills are integrated very close to the urban centre, which would allow the use of this  
207 consumption option. This opens up new and profitable opportunities to access energy  
208 based on renewable sources in olive oil mills, thus having a very positive impact on the  
209 environment and on their economic activities. In Andalusia, due to the high level of solar  
210 irradiation available throughout the year (avg.: 5.11 kWh/m<sup>2</sup>/Day [55]), PV Rooftop sys-  
211 tems can be considered as a potential energy solution to cover part of the electricity con-  
212 sumption of olive oil mills, as well as being an alternative technical solution to face chal-  
213 lenges such as the reduction of GHG and the use of renewable energies in these industries.

214 The electrical energy consumed by oil mills can be characterized in two periods: a  
215 first period in which the mill is producing oil, called the *harvest period*, and a second period  
216 in which no oil is produced, called the *off-harvest period*. During the first period, in this  
217 type of industry, electricity consumption is mainly related to the processes of cleaning the  
218 fruit (conveyor belts, bar screens, washing machines, motors, etc.) and milling (mills and  
219 centrifugal pumps). In addition to the phases of the fruit cleaning process, the "horizontal  
220 technologies" installed in the mill, such as offices, lighting and air conditioning, also con-  
221 sume electricity. Air conditioning consumption is significant because it allows the ambi-  
222 ent temperature of the cellar to be maintained between 15 °C and 20 °C, thus preserving  
223 the properties of the oil until it is sold. Therefore, there is energy consumption throughout  
224 the year due to auxiliary needs, such as air compressors, computer systems, lighting sys-  
225 tems, etc. However, there is some equipment that is only used during the *harvest period*  
226 and is used in several stages of the olive oil production process, such as cleaning and  
227 crushing of the olives.

228 The amount of olive oil production is the first factor that can be directly related to the  
229 electrical energy consumption of the mill. In this sense, there is a proposed classification  
230 [43] that considers as large mills those with an annual production of more than 5,000 tons  
231 and an average annual electricity consumption equal to or greater than 1000 MWh; on the  
232 other hand, medium mills are those with a production between 1000 and 5000 tons and  
233 an average consumption between 500 and 1000 MWh; and finally, small mills are those  
234 with a production of less than 1000 tons and an electricity consumption less than 500  
235 MWh.

236 The following subsections describe the data acquisition used and the characteristics  
237 of the electrical energy consumption of the olive mills under study during one year of  
238 operation.

#### 239 2.1.1. Monitoring and characterization of the electricity consumption of the industries 240 analysed

241 The data gathering has been carried out through the smart electricity meter reading,  
242 which allows to obtain the electrical power consumed every 60 minutes [56–58]. These  
243 devices allow to efficiently measure and record the electrical energy consumption, i.e., the  
244 energy flowing from the electrical network to the user's installation (consumption). In the  
245 absence of sensors, it is possible to use databases to obtain solar radiation and ambient  
246 temperature such as NASA database, Meteonorm or even Andalusian Energy Agency for  
247 local data. In this case, the global solar irradiation database, PVGIS, was used to obtain

these parameters [59]. Power consumption has been monitored over a year, showing a complete operating cycle and the processes carried out in this industry will be visualized: oil production, bottling and storage.

Table 1 shows the size category of each olive mill under study.

**Table 1.** Annual energy consumption and classification of monitored mills.

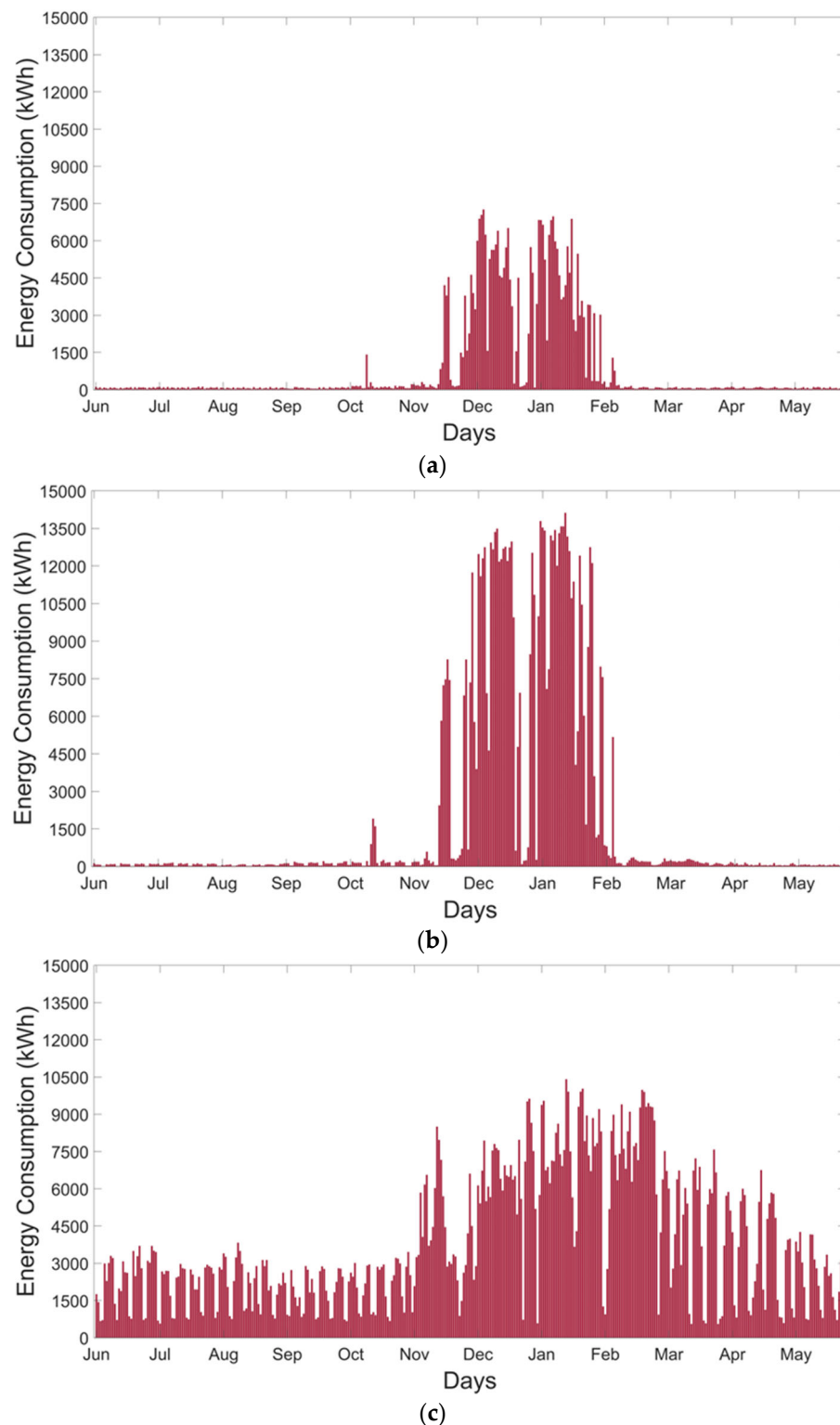
Industry	Annual energy consumption (kWh)	Classification
Olive mill 1	313	Small
Olive mill 2	699	Medium
Olive mill 3	1407	Large

According to the above-mentioned olive oil production classification criteria, olive mill 1 is considered small, olive mill 2 is considered medium and olive mill 3 is classified as large. The electricity consumed by these industries is obtained from the power grid. These energy consumptions can be divided into electrical and thermal. The two consumption periods mentioned above, *harvest* and *non-harvest*, make it necessary for most of these industries to have a different electricity tariff for each period of operation. The tariff associated with the *off-harvest period* is characterized by reduced power capacity, since it is only necessary to supply electricity to the offices and cellars. At the beginning of the *harvest period*, the tariff is changed and the electricity contract is made exclusively for the high electricity supply required for this period.

The first step to characterize the energy consumption of these industries is to identify their consumption profiles during a complete annual operating cycle. Fig. 2 shows the daily accumulated energy consumption data for the entire year.

In Fig. 2, the ordinate axis corresponds to energy consumption in kWh and the abscissa axis to the corresponding day of the year. In this case, the months of the year have been indicated on the abscissa axis to show in a more representative way how consumption evolves, since these industries have clearly seasonal consumption. Two different consumption periods can be distinguished in these industries. Throughout the months that typically correspond to the olive harvesting season, which is the *harvest period* (December, January, February, and March), daily electricity consumption is significantly higher than the consumption that occurs during the off-season period. Likewise, during the same *harvest period*, consumption stands out in the months of December and January, while in the months of February and March, consumption decreases in small and medium olive mills.

It's important to emphasize that the *harvest period* may vary depending on the weather conditions of the chosen year, as well as the characteristics of the olive mill itself, but always following this pattern of differentiated consumption in two periods. Therefore, it can be said that there is an irregular consumption structure [60].



281 **Figure 2.** Accumulated daily energy consumption of the olive mills studied: (a) Consumption of  
282 small olive mill; (b) Consumption of medium olive mill; (c) Consumption of large olive mill.

283 In Figure 2, can be observed the difference in production processes among the three  
284 typical sizes of these industries. During the *harvest season*, peak consumption values are  
285 reached by all three olive mills, primarily due to the fruit cleaning and milling processes.  
286 However, the medium olive mill shows the highest consumption values. Nevertheless,  
287 when considering the annual total consumption, the small and medium-sized olive mills  
288 have a lower consumption than the large olive mill. This is because, in the large olive mill,

in addition to fruit cleaning and milling, oil bottling processes take place, resulting in significantly higher consumption during the *off-harvest period*.

Synthesizing the data provided in Fig. 2, Table 2 classifies the electricity consumption according to time, specifically in months. In addition, this table provides different ratios: the monthly energy consumption ( $E_{L,month}$ ) and the monthly consumption rate (MCR) which is the ratio between the energy consumed for a complete month compared to the annual energy consumption ( $E_{L,year}$ ):

$$MCR = \frac{\text{Monthly energy consumption}}{\text{Annual energy consumption}} = \frac{E_{L,month}}{E_{L,year}} \cdot 100 \quad (1)$$

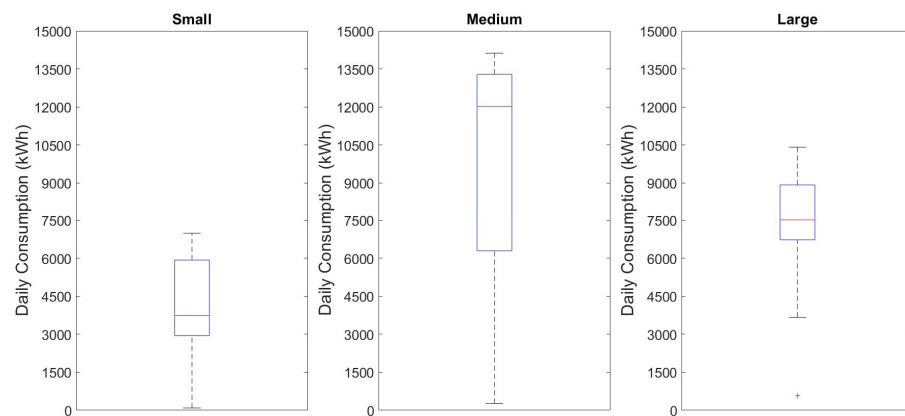
Figure 2 clearly shows the two operating periods graphically but the MCR parameter is used to quantify in a simple way the relative weight of each month in the complete operating cycle and to evaluate the greater or lesser homogeneity in consumption profiles.

**Table 2.** Monthly energy consumption, monthly consumption rate for each olive mill under study.

Period	$E_{L,month}$ (kWh/period)			MCR (%)		
	Small	Medium	Large	Small	Medium	Large
June	2140.6	2296.0	68283.0	0.7	0.3	4.9
July	2361.3	2794.7	64509.0	0.8	0.4	4.6
August	2002.4	1904.9	67635.0	0.6	0.3	4.8
September	1981.4	3535.9	52970.0	0.6	0.5	3.8
October	4709.4	8083.3	67194.0	1.5	1.2	4.8
November	28388.8	66756.0	125344.0	9.1	9.6	8.9
December	129409.0	277884.0	198244.0	41.3	39.8	14.1
January	127661.0	299849.0	233352.0	40.7	42.9	16.6
February	8206.5	27073.7	208175.0	2.6	3.9	14.8
March	2149.2	5377.5	139263.0	0.7	0.8	9.9
April	2246.3	1668.8	107102.0	0.7	0.2	7.6
May	2101.4	1501.0	75133.0	0.7	0.2	5.3
<b>Total</b>	<b>313357.1</b>	<b>698724.8</b>	<b>1407204.0</b>	<b>100</b>	<b>100</b>	<b>100</b>

Electricity consumption differs widely from one month to another and among the three olive mills. In December, there is an extremely high consumption for every olive mill, while in April and May, the consumption is considerably lower. Large olive mill has a similar electricity consumption in most of the periods, but small and medium olive mills usually consume less during the *off-harvest period*. It shows how the relative contribution of each month to the total annual consumption of small and medium olive mills is concentrated in months corresponding to *harvest period* (November, December and January). For example, December represents more than 40 % of the total annual consumption in these olive mills. These data, together with their graphical representation, are useful to evaluate electricity consumption profiles throughout the year and to compare consumption between the different sizes of olive mills.

The characteristics of the two representative periods of these industries can be seen in Figures 3 and 4. In them, a comparative analysis of the distribution of multiple data sets is carried out, in this case, the daily energy consumption for a month within the *harvest period* (January) and another within the *off-harvest period* (May). This tool provides information about the median and the interquartile range (IQR), which is represented within a boxplot containing values between the first quartile (25 %) and the third quartile (75 %), as well as data dispersion. Outliers are represented by the symbol "+", effectively visualizing the distribution of numerical data for each of the olive mill energy consumptions.



**Figure 3.** Cumulative daily consumption for January of the studied olive mills. Harvest month.

In this case, during the month within the *harvest period* (January), it is observed that the data consumption asymmetry is greater for small and medium olive mills, where medium olive mill shows the greatest one. In contrast, large olive mill is characterized by having reduced asymmetry. It can be inferred that the dispersion of consumption values for small and large olive mills is lower than medium olive mill. The origin of this high dispersion for medium olive mill may be attributed to its high raw material (olive) processing capacity, which is greatly affected by the variability in the raw material income. On the other hand, small and large olive mills are less affected, possibly due to their lower processing capacity. However, large olive mill has higher annual consumption. During this month, 50 % of the daily consumption for small olive mill falls between 3000 and 6000 kWh, between 6200 and 13400 kWh for medium olive mill, and between 7000 and 9000 kWh for large olive mill.

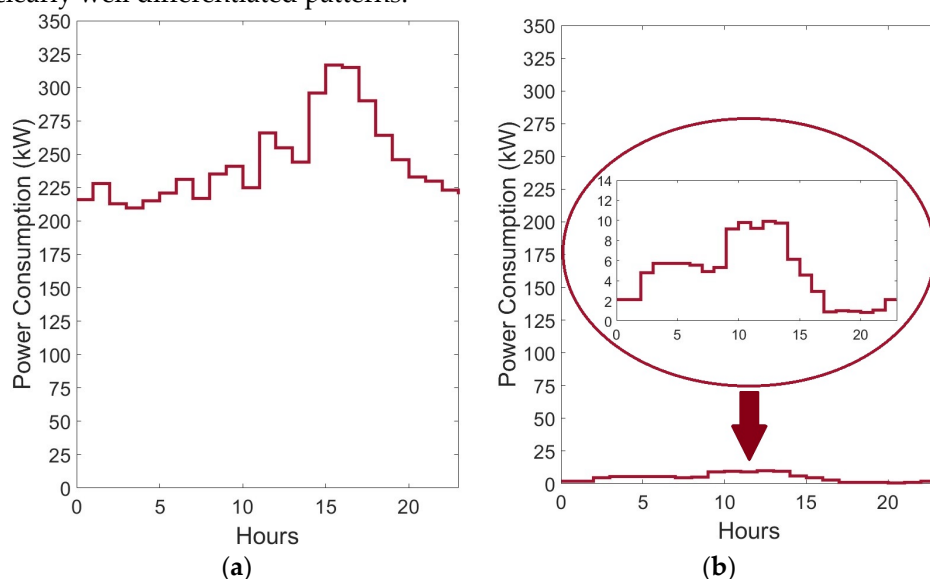
The month of May, corresponding to the *off-harvest period*, has been chosen to characterize the energy consumption for this period. Figure 4 displays the corresponding box plot for the three olive mills under study.

**Figure 4.** Cumulative daily consumption for January of the studied olive mills. Off-harvest month

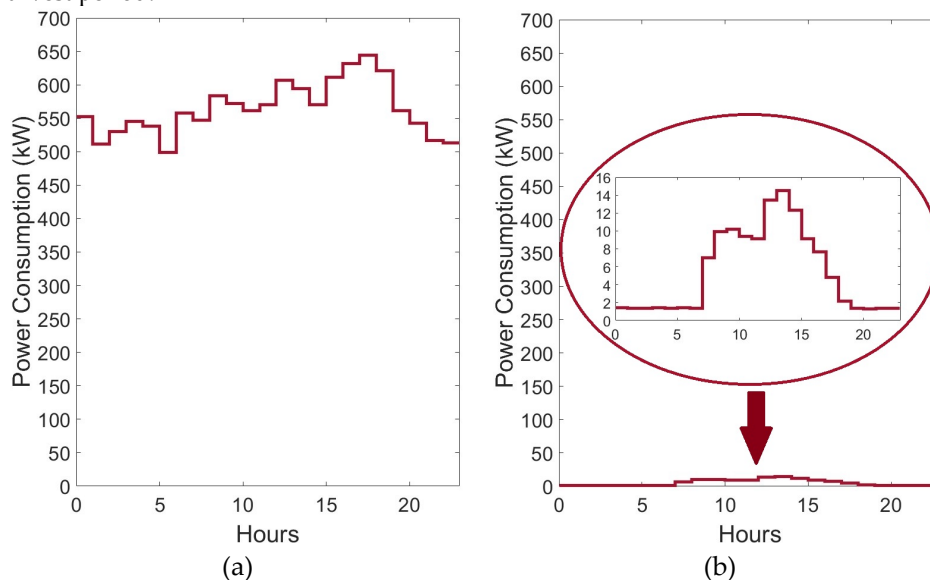
In this case, in order to observe the consumption distribution of large olive mill, it was necessary to adjust the scale range, as previously mentioned, this industry has significant electricity consumption due to the bottling activity. An important factor is the high similarity in the median value between small and medium olive mills, approximately 60 kWh, although the asymmetry in small olive mill is greater. These figures indicate that, in these industries, there are not only differences in the energy consumption profiles between the *harvest and off-harvest periods*, but notable differences are also observed within each size category during these periods. During the *harvest period*, medium olive mill

shows the highest variability in daily consumption, whereas during the *off-harvest period*, the consumption of small and medium olive mills is very similar, since only the office and the equipment that keeps the temperature of the cellar where the oil is stored are active. The charts for each month and olive mill category can be found in Appendix 1.

However, it is important to know not only the cumulative daily consumption values over a year but also the daily consumption profiles that they may present. Fig. 5 and 6 show the electricity consumption profile of small and medium olive mills during a typical day corresponding to the *harvest period* and another day of the *off-harvest period*. Thus, it can be seen that, between a *harvest day* and *off-harvest day*, the consumption profiles show clearly well differentiated patterns.



**Figure 5.** Hourly consumption profile for a typical day at small olive mill: (a) harvest period; (b) off-harvest period.

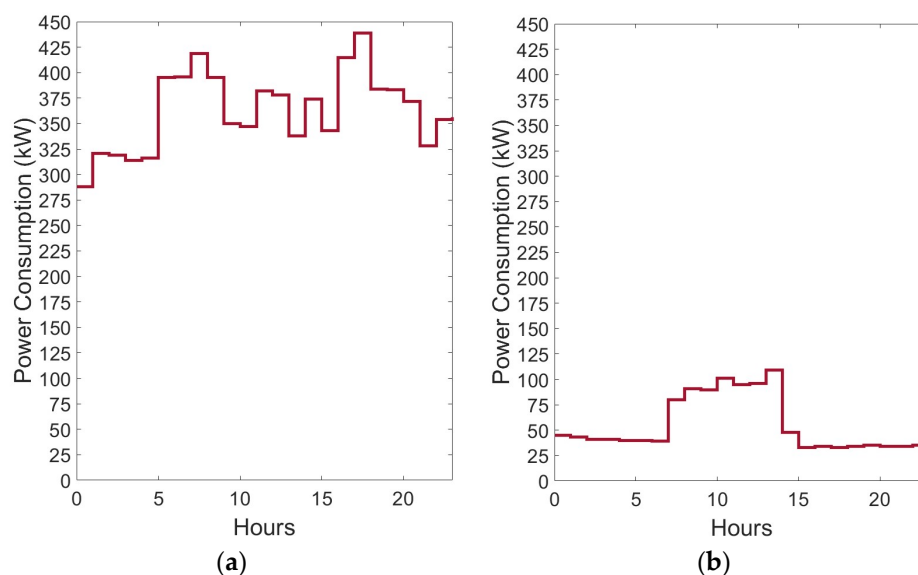


**Figure 6.** Hourly consumption profile for a typical day at medium olive mill: (a) harvest period; (b) off-harvest period.

It can be seen that, for both small and medium olive mills, during the *harvest period*, Fig. 5(a) and 6(a), the daily power consumption shows low variability throughout the day, which is more pronounced during sunshine hours. Small olive mill shows an average consumption of 240 kW, with power peaks from midday to the end of the afternoon reaching

a maximum of 317 kW, which corresponds mainly to energy needs due to the olive cleaning and transport processes. The same applies to medium olive mill, although it reaches an average consumption of 550 kW and peaks of up to 650 kW. In both figures, the consumption profile of a day in the *off-harvest period* has been incorporated as a detail with a different background scale in order to appreciate the electricity consumption in that period, Fig. 5(b) and 6(b). It can be seen that during sunshine hours, when generation is at its maximum, consumption is higher.

In this case, during the *off-harvest period*, the highest consumption take place during office hours, between 9 am and 2 pm, with an average power of 4.7 kW and 6 kW, with a maximum of 9.9 kW and 14.4 kW, corresponding to the hottest hours when refrigeration is activated for small and medium olive mills, respectively. In these olive mills, power consumption during the *harvest period* is between forty and fifty times higher than *off-harvest period* power consumption. Both the *harvest* and *off-harvest periods* show an increased consumption during sunshine hours. This characteristic can facilitate the matching between the generation and consumption profiles in this type of industry. This behaviour can also be seen for the large mill in Fig. 7.



**Figure 7.** Hourly consumption profile for a typical day at large olive mill: (a) harvest period; (b) off-harvest period.

During the *harvest period*, Fig. 7(a), the daily power consumption also shows little variations throughout the day. An average consumption of 375 kW is reached, with a maximum of 440 kW. In this olive mill, during the *off-harvest period*, the highest consumption also occurs during office hours, between 7 am and 2 pm, with an average power consumption of 60 kW, and a maximum of 120 kW. This olive mill, due to its particular production processes, does not show such a significant difference between both periods as small and medium olive mills.

## 2.2. Photovoltaic generator and storage systems. Modeling and analysis parameters.

### 2.2.1 Photovoltaic generator

To assess the suitability of using a PV Rooftop system in olive mills, it will be necessary to consider a mathematical procedure that, for certain meteorological conditions obtained from databases (solar radiation and ambient temperature), calculates the power obtained from the photovoltaic generator. There are a wide variety of methods to estimate the power output of a photovoltaic generator [61]. Among them, we have selected a method that offers a compromise between simplicity of implementation and accuracy of results and has been used in several scientific studies [62–66]. This approach is based on

calculating the DC power obtained at the generator output by applying the Osterwald method:

$$P_{PV,DC} = P_0 \cdot \frac{G_{i,k}}{G_{STC}} \cdot [1 + \gamma \cdot (T_c - T_{c,STC})] \quad (2)$$

Where  $P_0$  is the nominal power of the generator under STC (W),  $G_{i,k}$  the effective irradiance incident on the generator in-plane and  $G_{STC}$  is the standard reference irradiance of the system (STC, radiation 1000 W/m<sup>2</sup> and cell temperature of 25 °C). On the other hand,  $\gamma$  represents the power coefficient by temperature and  $T_c$  the cell temperature at standard conditions, which is dependent on the ambient temperature.

Then, to obtain the AC power output of the inverter, an overall loss factor of 15 % has been considered to take into account losses due to inverter efficiency, wiring losses, mismatch, spectral losses, etc. [67,68]

These losses are introduced into the system performance ( $\eta$ ).

$$P_{PVgen} = P_0 \cdot \frac{G_{i,k}}{G_{STC}} \cdot [1 + \gamma \cdot (T_c - 25)] \cdot \eta \quad (3)$$

In order to analyse the sizing of the photovoltaic generator, an algorithm will be used to perform a wide scan of photovoltaic generator power in order to obtain the curves of self-consumption, self-sufficiency and self-sufficiency in sunshine hours [46]. The last parameter may be interesting to evaluate the level of matching between the consumption and generation during the sunshine hours, since these industries shows an increased consumption during that time. This scan starts with a 0.01 kWp photovoltaic generator and iterates with a step that depends on the system to be analysed and the period of analysis (annual period, *harvest period* and *off-harvest period*). These indices, self-consumption, self-sufficiency and self-sufficiency in sunshine hours, are defined by Eq. 4, 5 and 6:

$$\phi_{SC,direct} = \frac{E_{PVcon,\tau}}{E_{PVgen,\tau}} \quad (4)$$

$$\phi_{SS,direct} = \frac{E_{PVcon,\tau}}{E_{L,\tau}} \quad (5)$$

$$\phi_{SSSH,direct} = \frac{E_{PVcon,\tau}}{E_{LSH,\tau}} \quad (6)$$

The self-consumption index ( $\phi_{SC}$ ) is the ratio of self-consumed photovoltaic electricity in the industry itself ( $E_{PVcon,\tau}$ ) and the electric energy generated by the photovoltaic system ( $E_{PVgen,\tau}$ ). On the other hand, the self-sufficiency index ( $\phi_{SS}$ ) provides the percentage of the energy consumption ( $E_L$ ) that is covered from the generated photovoltaic energy. While the self-sufficiency index in sunshine hours provides the self-sufficiency of the olive mill industry when the PV Rooftop system is operating, from dawn to dusk ( $\phi_{SSSH,direct}$ ) and will illustrate the ratio of power consumption during sunshine hours ( $E_{LSH,\tau}$ ) that is covered by the energy coming from the generator ( $E_{PVcon,\tau}$ ) [46,69,70].

### 2.2.2. Storage system

Due to the irregular consumption of these industries, and in order to increase and optimize their self-sufficiency, it is proposed not only to analyse the PV generator, but also to analyse the effect of incorporating a storage system. For this purpose, a simplified model is used to maximize self-consumption [71,72]. This simplification assumes that the battery does not self-discharge and that the charge and discharge efficiencies of the battery are equal and constant [73]. At the same time, and taking into account the state of charge, when PV generation exceeds industry consumption, the battery will be charged, and discharged when consumption exceeds generation. If there is photovoltaic generation once the battery state of charge is at its maximum value, this energy will be fed into the grid.

437 However, to perform this storage system analysis, it is possible to consider different bat-  
438 tery modelling, as well as different battery charge management algorithms.

439 If the energy storage system is taken into account, the energy consumed ( $E_{PVcon,\tau}$ )  
440 must consider not only the overlapping part of the generation and charging profiles  
441 ( $E_{PVdirect,\tau}$  and  $E_{L_{SH},\tau}$ ), but also that corresponding to the photovoltaic energy delivered  
442 to the inverter-charger or bi-directional inverter (BDI) to charge the battery ( $E_{TPac,\tau}$ ). Fur-  
443 thermore, the  $E_{PV-BAT}$ , which is the energy given by the array and the battery to the loads,  
444 should take into account  $E_{PVdirect,\tau}$  and the energy given by the BDI from the batteries to  
445 the loads ( $E_{FPac,\tau}$ ), (Eq. 10), as shown in [45].

$$\varphi_{SC} = \frac{E_{PVcon,\tau}}{E_{PVgen,\tau}} = \frac{E_{PVdirect,\tau} + E_{TPac,\tau}}{E_{PVgen,\tau}} = \frac{E_{PVdirect,\tau}}{E_{PVgen,\tau}} + \frac{E_{TPac,\tau}}{E_{PVgen,\tau}} \quad (7)$$

$$\varphi_{SSSH} = \frac{E_{PV-BAT,\tau}}{E_{L,\tau}} = \frac{E_{PVdirect,\tau} + E_{FPac,\tau}}{E_{L,\tau}} = \frac{E_{PVdirect,\tau}}{E_{L,\tau}} + \frac{E_{FPac,\tau}}{E_{L,\tau}} \quad (8)$$

$$E_{PVcon,\tau} = E_{PVdirect,\tau} + E_{TPac,\tau} \quad (9)$$

$$E_{PV-BAT,\tau} = E_{PVdirect,\tau} + E_{FPac,\tau} \quad (10)$$

$$E_{FPac,\tau} = E_{TPac,\tau} \cdot \eta_{BDI}^2 \cdot \eta_{BAT} \quad (11)$$

446  $\eta_{BDI}$  y  $\eta_{BAT}$  provide the bi-directional inverter and battery efficiencies, respectively. In  
447 addition, in  $\eta_{BAT}$  includes the charge, storage and discharge efficiencies.  $\tau$  refers to the  
448 study period. In this case, the curves of self-consumption and self-sufficiency for a year  
449 will be studied, also considering the *harvest period* and *off-harvest period* of the olive mills  
450 analysed.

### 2.3. Applied methodology for the analysis of the potential of photovoltaic systems with batteries

451 The analysis of the potential of PV Rooftop system with battery can be carried out  
452 using 2D figures that combine the self-sufficiency and self-consumption indices as a func-  
453 tion of the power of the photovoltaic generator and the storage system. For this purpose,  
454 the tool provided by [45] is very useful, since it not only simplifies the analysis, but also  
455 makes the sizing of this type of systems even easier and more intuitive through the use of  
456 the *iso self-consumption* (isoSC) and *iso self-sufficiency* (isoSS) curves. The iso curves are con-  
457 tour plots containing the iso-lines of the SS and SC indices as a function of the PV gener-  
458 ator power and the nominal capacity of the batteries. In the plane, the isolines are plotted  
459 with the self-sufficiency and self-consumption values, where abscissa is the PV generator  
460 power and ordinates represents the nominal capacity. The first step is to find the maxi-  
461 mum and minimum values of both indices. Starting with the maximum value, the next  
462 steps are to find the range of iso-curves from the maximum value to the minimum value  
463 with the desired step.  
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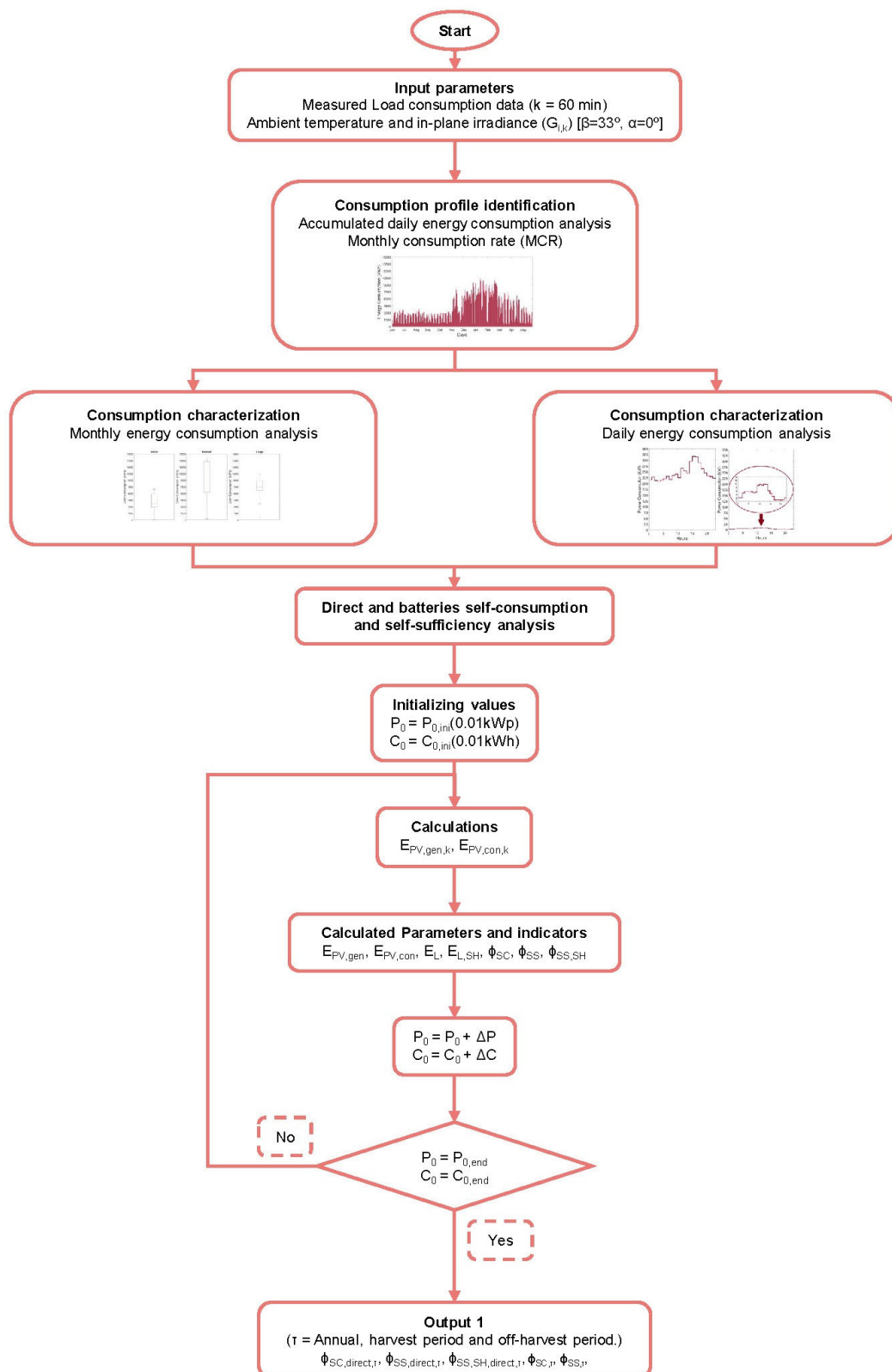


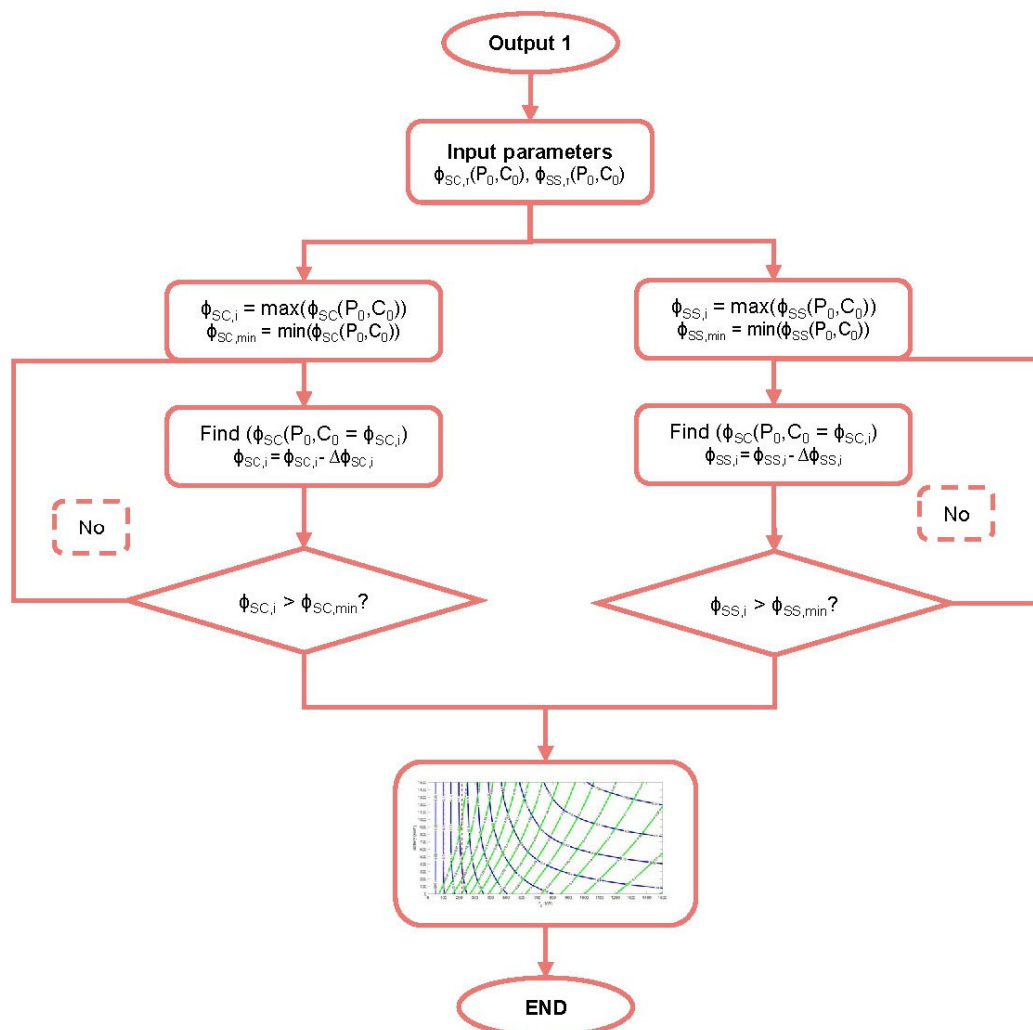
Figure 8. Flow chart of the applied methodology for the analysis of direct self-consumption and self-sufficiency indices.

After this procedure, the self-consumption and self-sufficiency indices are obtained in order to analyse direct self-consumption and with batteries. Then, the iso curves of the self-consumption and self-sufficiency indices are calculated as shown in the Fig. 9 [45]. A

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minimum self-consumption index of 50 % has been selected for the simulations, therefore, the final simulated size of the PV generator and batteries is related to this value.



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**Figure 9.** Flow chart of the applied methodology for the analysis of the PV generator and battery [45].

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### 3. Results and discussion

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#### 3.1. Direct Self-consumption and self-sufficiency

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Firstly, the analysis of the direct self-consumption and self-sufficiency indices has been carried out. Figure 10 shows the self-sufficiency and self-consumption curves for each period and each olive mill.

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It can be seen how for small and medium olive mills, and on annual basis, initially, direct self-consumption is not appropriate for these industries. For high values of self-consumption, around 80 and 90 %, the self-sufficiency indices obtained are very low, Fig. 10(a). However, if the study is carried out separately for the harvest and off-harvest periods, for the same self-consumption values, the self-sufficiency indices increase considerably, Fig. 10(b) and (c). Note that the background scale is different for the *harvest period* to clearly appreciate the curves. This already shows the difference in consumption between the two periods.

(a)

(b)

(c)

**Figure 10.** Self-consumption and self-sufficiency curves for each olive mill size; (a) Annual; (b) Harvest period; (c) Off-harvest period.

As expected, for every olive mill and every period considered, the self-sufficiency indices in solar hours are higher than the self-sufficiency index. The  $\phi_{SS_{SH}}$ , serving as a supplementary metric to increase the insights provided by the self-sufficiency index in the

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literature, assesses the impact of PV Rooftop systems when meeting energy requirements exclusively during sunshine hours which corresponds to the time frame in which photovoltaic energy is generated. Also, it provides a more accurate characterization of PV Rooftop systems, particularly in the industrial sector, where energy consumption profiles tend to have a high degree of variability and non-uniform distribution throughout the whole day.

Table 3 summarizes the most significant results obtained from the different curves aforementioned. The analysis of direct self-consumption and self-sufficiency curves was carried out by selecting two high self-consumption values, 80 and 90 %; the aim is to maximize self-consumption in order to obtain maximum energy use. As mentioned above, the high difference between the power consumption of both periods results in very low self-sufficiency indices when the study is carried out on an annual period. This is due to the fact that the *harvest period*, although it corresponds to a reduced period of time, between 3 and 4 months, concentrates between 60 and 80 % of the annual consumption of the mills, depending on their size. Although most of the consumption is concentrated in the *harvest period*, the rest of the time corresponds to the *off-harvest period*, between 8 or 9 months. The reduced consumption in this period has an impact on the self-consumption and self-sufficiency indices. Therefore, it is necessary to carry out an individual study for both periods in order to study the suitability of the PV Rooftop systems.

**Table 3.** Self-consumption and self-sufficiency in sunshine hours indices together with its corresponding array power for each olive mill and each period studied.

	Annual			Harvest period		Off-harvest period	
	$\phi_{SC,direct}$ (%)	$\phi_{SS_{SH}}$ (%)	$P_0$ (kW)	$\phi_{SS_{SH}}$ (%)	$P_0$ (kW)	$\phi_{SS_{SH}}$ (%)	$P_0$ (kW)
Small	90	4	4	10	53	15	3
	80	6	7	36	176	21	5
Medium	90	1	2	10	120	5	3
	80	2	5	34	460	10	6
Large	90	24	107	32	247	32	85
	80	43	218	66	560	52	154

Taking into account high self-consumption indices, 80 and 90 %, the self-sufficiency indices in sunshine hours are obtained, as well as their corresponding array power. Considering the *harvest period*, the array power should be between 53 and 176 kW for small olive mill, between 120 and 460 kW for medium olive mill, and between 247 and 560 kW for large olive mill. For the *off-harvest period* the PV generator size drops significantly, especially for the small and medium olive mills, and very close to the annual sizes. This fact highlights the impact of this period when considering an annual reporting period. However, the self-sufficiency in sunshine hours index increases in the study of both periods for all the olive mills. In this case, the highest indices are found in *harvest period* and *off-harvest period* for large olive mill, being able to obtain a self-sufficiency in sunshine hours of 66 and 52 %, respectively.

The study of direct self-consumption shows that these systems are suitable for large olive mills. This is not the case for small and medium olive mills. However, during the *harvest period*, the 32 % renewable energy target that the EU wants to achieve by 2030 is reached in all olive mills [8]. In this case, a collective consumption solution may be chosen in order to use the generation surplus during the *off-harvest period* and increase self-sufficiency.

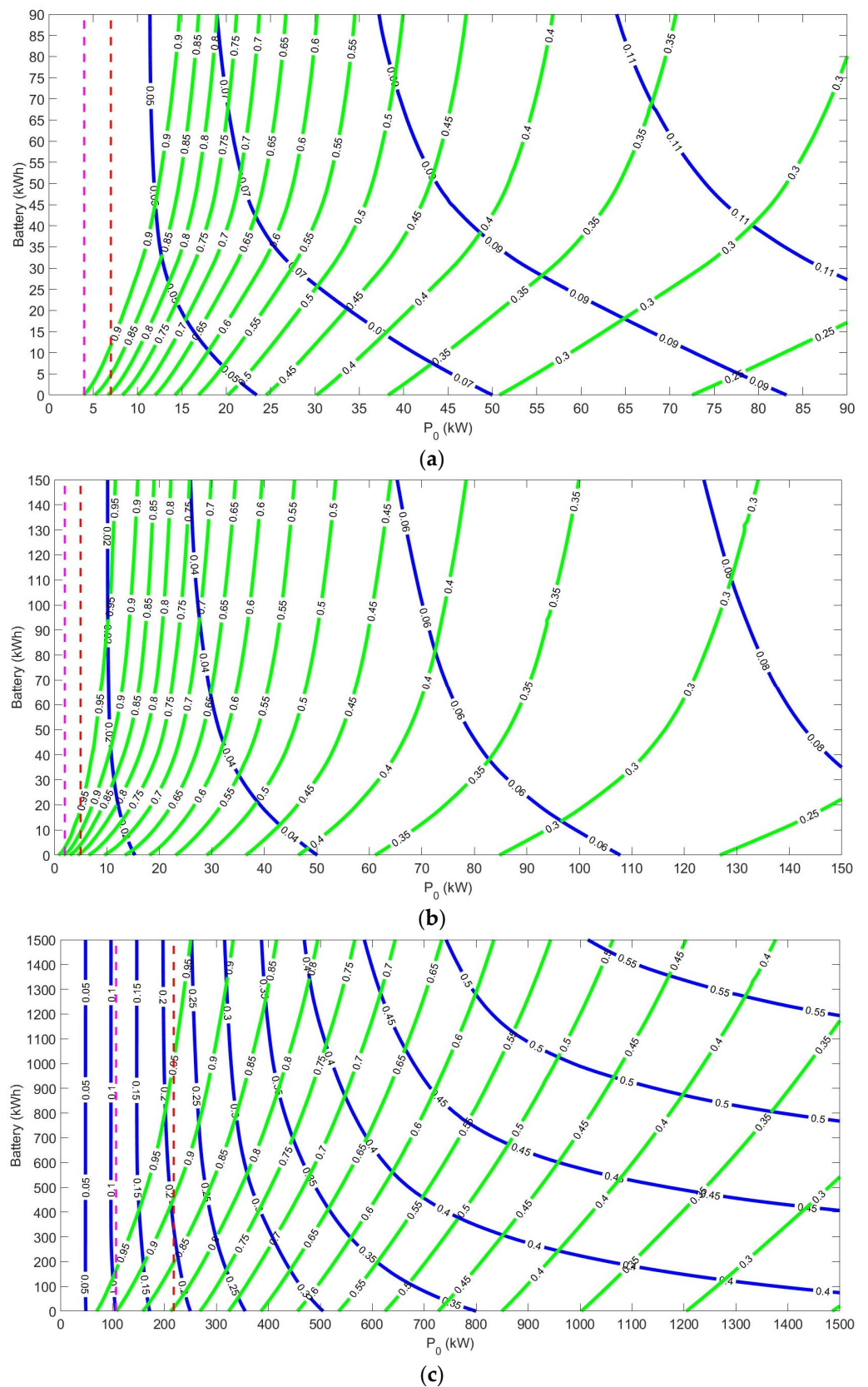
### 3.2. Self-consumption and self-sufficiency indices with batteries

This section will apply the methodology described above and use a graphical tool that will assess the role of the array power together with the storage system. Fig. 11 shows the annual global isoSC and isoSS curves described in section 2.3. In this case, since the influence of the storage system is being analysed, it is more convenient to use the self-sufficiency index rather than the self-sufficiency index in sunshine hours, as the effect of the batteries may be significant during the hours when there is no photovoltaic generation.

These curves provide different array power and nominal capacity of the battery to get determined self-consumption and self-sufficiency indices. The intersection of the isoSC curves (green) with the abscissa axis provides the value of the PV generator for a given direct self-consumption index. For example, in this case, the values of 80 and 90 % of direct self-consumption have been selected as a reference, characterized by the red and magenta dashed lines respectively. This is done to obtain a comparative baseline of the results obtained with the battery sizing tool and the results of the sizing without batteries, direct self-consumption, since the purpose is also to quantify the batteries impact on the self-consumption and self-sufficiency indices.

It is noted that, both for small and medium olive mills, the values of the self-consumption index are very low from 30 kWp of PV generator power onwards, below 50 %. For small olive mill, it can be seen that the maximum self-sufficiency index that can be reached with 50 % self-consumption is barely 5 to 9 %, depending on the battery capacity. Even if the size of the PV generator and batteries is increased, the improvement in self-sufficiency is very small and self-consumption is greatly reduced. This means that the consumption of this industry will have a high grid reliance, even if batteries of the order of 70 kWh are incorporated. This may indicate that a study of consumption profile in annual period for this type of industries is not accurate, due to its high variability from one period of operation to another.

It is observed that, for the PV generator power considered to harness most of the PV energy generated, between 4 kWp (magenta dashed line) and 7 kWp (red dashed line) for 90 and 80 % self-consumption respectively, self-sufficiency indices near 3 % are achieved, Fig. 11(a), without the use of storage systems. Also, considering the use of a storage system is irrelevant, as the curves tend to be vertical. To obtain a self-sufficiency index of 10 % and if it is required to harness a large part of the photovoltaic energy generated (i.e., a self-consumption index higher than 75 %), it is noted that there is no combination of PV generator power and capacity that provides these values (these values would be obtained as the intersection between the isoSC curves of 75 % and isoSS of 15 %) for the olive mill under consideration.



**Figure 11.** isoSC (green) and isoSS (blue) annual curves. (a) Small olive mill; (b) Medium olive mill; (c) Large olive mill.

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In this case it is possible to achieve a self-sufficiency index of 11 % with PV generator power and nominal capacity ranges up to 65 kWp and 80 kWh, respectively. Very low

576 grid autonomy and poor energy efficiency in this case. To obtain a high energy yield (self-  
577 consumption indices higher than 75 %), a PV generator power and a nominal capacity of  
578 10 kWp and 10 kWh respectively could be used.

579 It should also be noted how the isoSS curves are very similar to those obtained in Fig.  
580 11(b) for medium olive mill. It can be found that the maximum self-sufficiency index that  
581 is possible to achieve with 50 % self-consumption is close to 5 %. This means, again, that  
582 the consumption of this type of industry will have a high reliance on the grid regardless  
583 of the size of the PV generator and batteries to be used.

584 Likewise, increasing the size of the PV generator has little impact on achieving a high  
585 self-sufficiency index. It is necessary to increase the power from 50 kWp to 110 kWp to  
586 increase self-sufficiency from 4 to 6 %. In order to obtain a high energy use in this mill  
587 (self-consumption indices higher than 75 %), a PV generator power and a nominal capac-  
588 ity of 15 kWp and 20 kWh respectively should be considered.

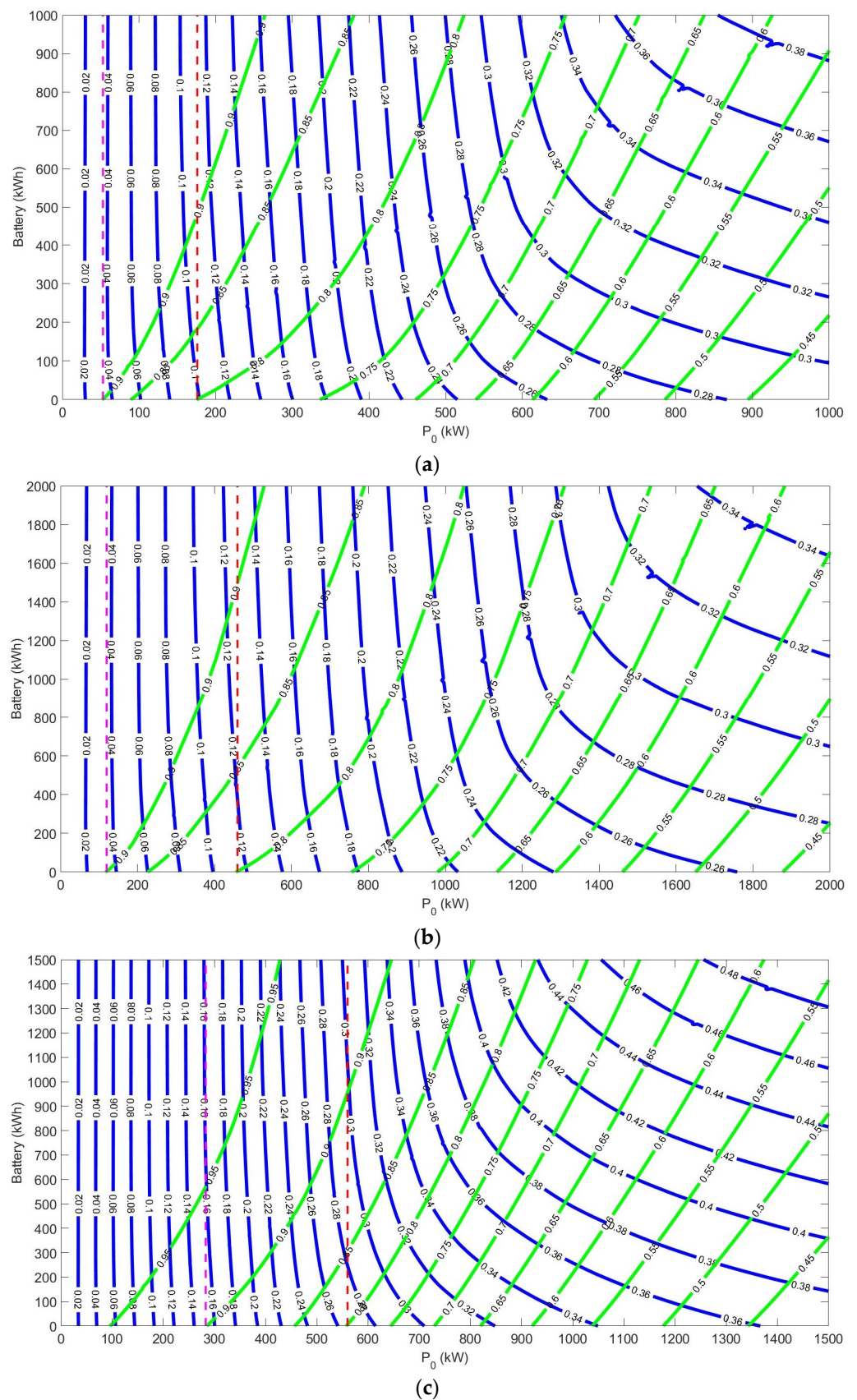
589 Fig. 11(a) and (b) show the low self-consumption index for large PV generator sizes,  
590 which shows the poor match between generation and load profiles if the study is per-  
591 formed on an annual basis. Moreover, the incorporation of batteries, in these cases, does  
592 not influence the achievement of high self-consumption indices.

593 Finally, the isoSC and isoSS curves have been included for large olive mill. As indi-  
594 cated in section 2, the electricity consumption of this mill was much higher than that of  
595 the other two industries and differed in that it was relatively constant over time due to its  
596 characteristic productive activities. This industry has the best self-consumption and self-  
597 sufficiency indices among all three, Fig. 11(c). This may be due to the fact that it has a  
598 remarkable baseline electricity consumption, as is the case with other industries, making  
599 them strong candidates for the incorporation of this type of system [46].

600 In this olive mill, it can be noted that the maximum self-sufficiency index that is pos-  
601 sible to reach with 50 % of self-consumption is 55 %, higher than the other two mills. In  
602 this case, the increasing size of the photovoltaic generator and batteries produces an im-  
603 provement in self-sufficiency up to a certain value. This suggests that the consumption of  
604 this industry can reach a relatively high level of independence from the grid depending  
605 on the size of the PV generator and batteries used.

606 It is observed that, if PV generator power considered to harness most of the PV power  
607 generated (between 107 and 218 kWp for 90 and 80 % self-consumption respectively),  
608 overall self-sufficiency indices between 10 and 18 % are achieved, Fig. 11(c), without the  
609 incorporation of storage systems. However, as can be seen in the 10 and 20 % isoSS curves,  
610 the same applies as in small and medium olive mills. Considering the incorporation of a  
611 storage system for low PV generator power is irrelevant, since the curves tend to be ver-  
612 tical.

613 As mentioned above, since these industries have such a characteristic consumption  
614 profile, divided into two well differentiated periods (*harvest* and *off-harvest*), it is necessary  
615 to study both separately. Fig. 12 and 13 show the isoSC and isoSS curves for the *harvest*  
616 and *off-harvest periods*, respectively.



**Figure 12.** isoSC (green) and isoSS (blue) harvest period curves. (a) Small olive mill; (b) Medium olive mill; (c) Large olive mill.

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619 In Fig. 12 the analysis period is restricted to the *harvest period*. During this period, the  
620 estimated size of the PV generator is higher for every olive mill compared to the annual  
621 analysis, Fig. 11. The same behaviour observed in the annual analysis is observed for the  
622 three olive mills. If the size of the batteries is increased, the value of the self-sufficiency  
623 index remains practically unaffected below 600 kWp for small olive mill Fig. 12(a), 1000  
624 kWp for medium olive mill (b) and 600 kWp for large olive mill (c) regardless the battery  
625 capacity. However, it can be seen how the value of the self-sufficiency index is increased  
626 compared to the annual analysis. For small olive mill, Fig. 12(a), if a high energy use is  
627 desired (self-consumption indices higher than 75 %), the self-sufficiency indices reach val-  
628 ues up to 30 %. For medium olive mill, Fig. 11(b), it can be seen that the maximum self-  
629 sufficiency index that is possible to achieve with 75 % self-consumption is 30 %, the same  
630 as small olive mill.

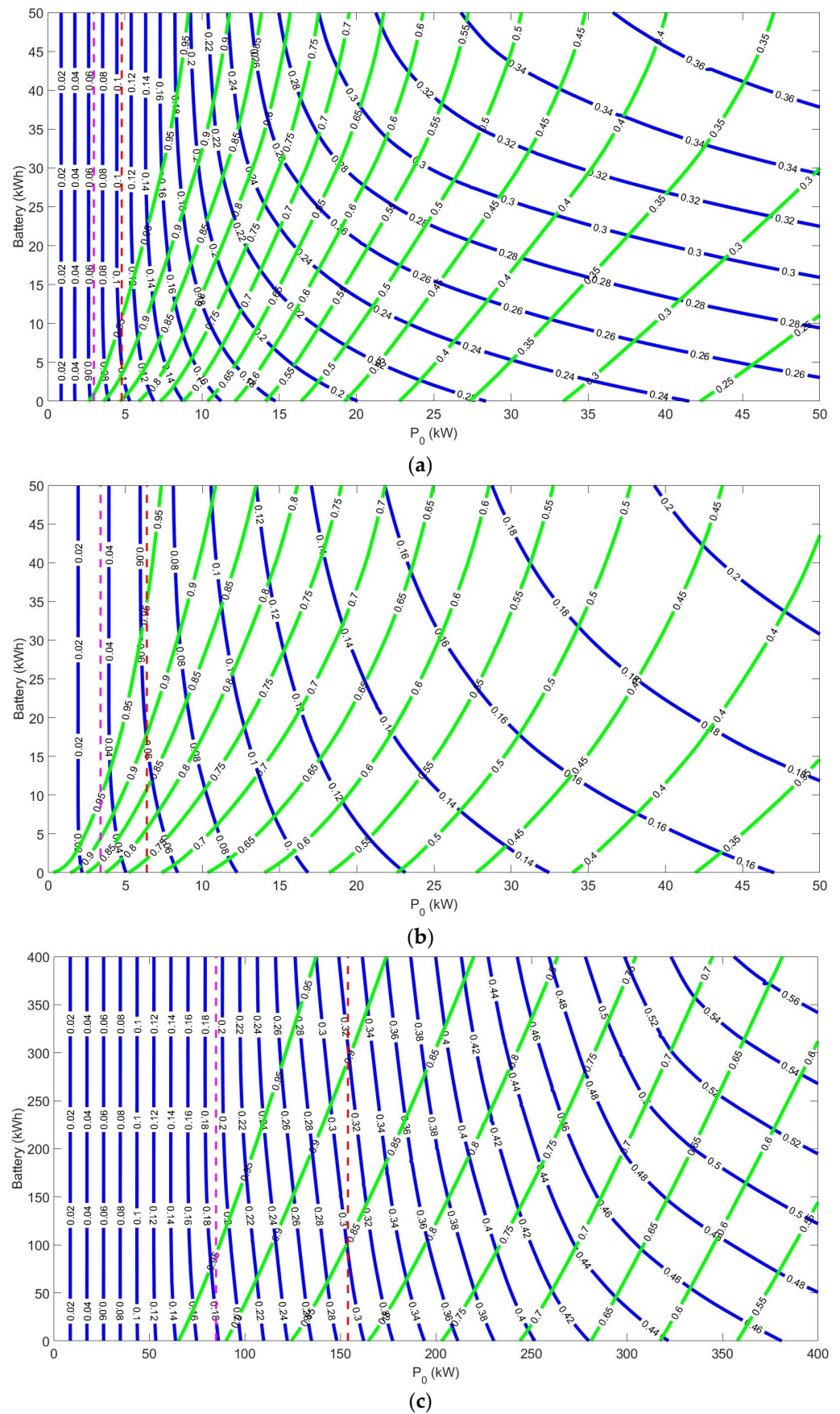
631 The isoSC and isoSS curves for large olive mill during the *harvest period* have also  
632 been included, Fig. 12(c). For this olive mill, it can be seen that the maximum self-suffi-  
633 ciency index that is possible to reach with a high use of generation, 75 % of self-consump-  
634 tion, is 45 %, higher than the small and medium olive mills. Therefore, it could be said  
635 that for the *harvest period*, the indices increase considerably for the entire spectrum of olive  
636 mills.

637 Finally, Fig. 13 plots the same curves for the *off-harvest period*. In this case, the sizes of  
638 the PV generators and batteries are reduced as expected, since consumption during this  
639 period is much lower. In this sense, all olive mills continue showing the same behaviour  
640 as during the *harvest period* for reduced PV generator ranges. If the size of the batteries is  
641 increased, the value of the self-sufficiency index remains nearly unaffected below 5 kWp  
642 for small olive mill (a), 10 kWp for medium olive mill (b) and 150 kWp for large olive mill  
643 (c). However, it can be seen again how the value of the self-sufficiency indices increases  
644 with respect to the annual analysis.

645 In small olive mill, Fig. 13(a), in order to obtain a high use of energy (self-consump-  
646 tion indices higher than 75 %), the self-sufficiency indices reach values up to 30 %. It would  
647 be necessary to use a PV generator power and rated capacity of 18 kWp and 50 kWh,  
648 respectively, to obtain self-consumption and self-sufficiency indices of 75 and 30 %, re-  
649 spectively. In the case of medium olive mill, Fig. 13(b), it can be seen that the maximum  
650 self-sufficiency index that can be achieved with 75 % self-consumption is nearly 15 %,  
651 lower than in small olive mill.

652 The isoSC e isoSS curves for large olive mill during the *off-harvest period* are shown in  
653 Fig. 13(c). In the case of this olive mill, it can be observed that the maximum level of self-  
654 sufficiency that can be reached with a high use of self-consumed energy (75 %) is 52 %  
655 with 305 kWp and 375 kWh. It is therefore concluded that, if the photovoltaic generator  
656 and the battery capacity are analysed for the *off-harvest period*, the indices increase for all  
657 olive mills, which supports the concept that the annual analysis of this type of industries  
658 is inaccurate due to their peculiar consumption profile.

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**Figure 13.** isoSC (green) and isoSS (blue) off-harvest period curves. (a) Small olive mill; (b) Medium olive mill; (c) Large olive mill.

669 After this study, to improve the understanding of the integration of PV Rooftop sys-  
670 tems with batteries in olive mills, the next phase would involve the exploration of different  
671 studies to further analyse other aspects of these systems. In this sense, the existing re-  
672 search regarding PV systems with BESS could be broadly categorized into six types. These  
673 are Lifetime Improvement, Cost Reduction Analysis, Optimal Sizing, Mitigation of Power  
674 Quality Issues, Optimal Control of Power System and Peak Load Shifting and Minimizing  
675 [74]. One of the most widely studied is the economic feasibility. Future research works  
676 should evaluate key financial parameters, such as return on investment (ROI) and pay-  
677 back periods (PBP). Through economic analysis, it is possible to quantify the long-term  
678 economic benefits and feasibility of these systems. Several research studies have con-  
679 ducted in recent years, focusing on the techno-economic evaluation of these systems in  
680 different countries such as Egypt [75], Italy [76], Belgium [77], or other different European  
681 countries [78]. Most studies focus exclusively on economic profitability, mainly through  
682 parameters such as net present value (NPV) and internal rate of return (IRR) [79–81].  
683 However, some authors opt for other economic parameters such as ROI and PBP [82,83].  
684 In spite of this predominant orientation, it is essential to consider other parameters in the  
685 analysis, such as self-consumption and self-sufficiency indices, as other authors consider  
686 [84,85].

687 In a first approach, a simple but illustrative economic study has been carried out. A  
688 specific size of photovoltaic generator and battery is evaluated for each of the olive mills,  
689 using the ROI and PBP as economic indicators. These are two acknowledged indicators to  
690 evaluate the economic performance of renewable systems. ROI refers to the economic re-  
691 turn investors get from investment activity. As an important economic index, the ROI can  
692 reflect the comprehensive profitability of investment projects [83]. The ROI is the gain  
693 made from an investment, in this case, the amount saved by using a solar PV system com-  
694 pared to standard electricity divided by the initial start-up costs. Besides, PBP represents  
695 the first year when the NPV reaches zero and defines the period it takes to recover the  
696 initial investment [86].

697 In the analysis, a low penetration of renewable energy scenario in olive mills has been  
698 developed, compared to the EU target of 32 % [8]. This scenario represents more unfa-  
699 vourable conditions (greater technical and administrative difficulties, higher costs, lower  
700 availability of alternatives, offers and business models for the promotion of self-consump-  
701 tion, etc.). Firstly, the analysis is conducted without batteries and secondly, a specific bat-  
702 tery size is incorporated so that all the olive mills reach at least 20 % self-sufficiency. A  
703 literature review has been conducted to gather the necessary economic information about  
704 the systems involved: PV and BESS. Out of this literature review, a PV capital expenditure  
705 of 806 €/kW and 7 €/kW/year have been selected [87]. A BESS capital expenditure of 275  
706 €/kWh was considered [83]. The cost of energy was established at 0.215 €/kWh [88] and  
707 the cost of sale at 0.110 €/kWh [89]. Finally, a PV and BESS lifetime of 25 and 15 years,  
708 respectively, was chosen.

709 Comparing these two scenarios for each mill, the PV systems without battery were  
710 the most feasible to implement with payback periods of 3.7 years for the small mill, 3.3  
711 years for the medium mill and 5.5 years for the large mill, while the scenarios with battery  
712 had slightly longer payback periods, 4.3, 4.1 and 6 respectively. The same is applicable to  
713 ROI, going from 337 % without batteries to 285 % with batteries for the small olive mill,  
714 from 390 % to 303 % for the medium olive mill and from 222 % to 198 % for the large olive  
715 mill.

716 Overall, the ROI is lower for systems with battery compared to systems without bat-  
717 tery for all olive mill sizes. The payback period is also longer for battery systems at all  
718 sizes. Based on these data, it could be concluded that, in strictly economic terms, the non-  
719 battery systems are more cost-effective in the short term. However, it is also important to  
720 consider other factors such as sustainability, energy autonomy and possible government  
721 incentives or subsidies in renewable energies. The government incentives can promote  
722 the profitability and growth of this type of systems, because in the absence of economic

incentive policies there is a lower probability of economic viability of this kind of renewable energy generation [90]. Economic profitability may not be the only factor to consider when taking decisions. In addition, energy storage technologies may improve and costs may decrease in the future, which could change the economic dynamics. In summary, although battery systems have an economic impact, other factors must also be taken into account when making decisions, and a more detailed analysis with additional considerations could be useful.

#### 4. Conclusions

This study has addressed the analysis of the incorporation of PV Rooftop systems with storage in three olive oil mills. Olive oil mills are identified as industries with high suitability for these systems from an energetic point of view. This work has provided a methodology based on monitored data to analyse the potential of photovoltaic Rooftops with battery energy storage system regarding self-consumption and self-sufficiency indices in the industrial sector. Two types of olive mills can be identified, according to the consumption analysis performed. One type has year-round industrial activity and the other one has a high activity only during the *harvest period*. In the *off-harvest period*, all studied olive mills show small, PV generator sizes, with adequate self-sufficiency in sunshine hours. PV generator sizes increase significantly during the *harvest period*, and with new consumption trends like collective consumption, these industries can improve the sustainability of their environment.

For small and medium olive mills, by placing a PV generator of 3 to 6 kWp can result in direct self-consumption indices up to 80 % and 10 to 21 % self-sufficiency in sunshine hours during the *off-harvest period*. Consumption similarities between small and medium olive mills during the *off-harvest period*, to auxiliary needs (air compressors, computer systems, lighting systems, etc.) rather than production processes, are noted.

Differences in energy consumption become evident during the *harvest period*, requiring larger PV generators for higher self-consumption and self-sufficiency in sunshine hours.

Large olive mill shows the best results, both for the *harvest period* and the *off-harvest period*, with self-sufficiency indices in sunshine hours of 66 and 52 %, respectively. The smaller gap between consumption periods, *harvest* and *off-harvest*, leads to a greater use of photovoltaic generation, compared to medium and small olive mills, making PV Rooftop systems ideal for this type of industry.

In a preliminary analysis, batteries enhance the self-sufficiency indices for every olive mill studied above a certain PV generator power threshold. Lower PV generator power (< 5 kWp) provide no additional value, while higher powers lead to significant self-sufficiency indices increases, up to 10 %, depending on the capacity.

Large olive mill consumption profile matches well with generation due to their high basal consumption throughout the year. However, decision-making for small and medium olive mills depend on the period studied and the desired energy management strategy of the industry. It is possible to install a small generator to face the *off-harvest period* consumption or install a large generator to cover the consumption during the *harvest period*. In the latter case, it may be interesting to explore the opportunities offered by collective consumption, since the mills are usually located in rural areas but close to urban centres.

Based on the analysis carried out, the economic variables related to these systems deserve a further study. Nevertheless, the reductions in non-renewable energy expenditure and GHG emissions suggest olive oil mills as strong candidates for distributed energy generators, given their favourable surface area for energy generation. Olive oil mills, influential in the Spanish economy and present globally such as in Italy, Portugal, Greece, Africa, Asia, America and Oceania, make this study applicable to regions with this type of agri-food industries.

775           On the other hand, the study has shown that the difference between the consumption  
776 of their operating periods, *harvest* and *off-harvest*, requires further analysis including eco-  
777 nomic scenarios that, together with the energy analysis performed, can propose new in-  
778 dices based on PV generator and battery sizes . In addition, governments' proposals, in-  
779 cluding storage systems and energy sharing through the creation of energy communities,  
780 could benefit industries with unbalanced power consumption.  
781

782 **Appendix A**

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784

**Figure 14.** Cumulative daily consumption for small olive mill.

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786

**Figure 15.** Cumulative daily consumption for medium olive mill.

787  
788 **Figure 16.** Cumulative daily consumption for large olive mill.

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