

# Comparative analysis of the economic feasibility of five large-power photovoltaic irrigation systems in the Mediterranean region

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## Abstract

The electricity costs for agricultural applications is dramatically increasing in the last years, making the solutions based on photovoltaics more attractive once the technological barriers that impeded high-power PV irrigation systems (PVIS) have been removed. But the data available in the literature are restricted to small-power PVIS what limits the feasibility assessment of the investment in this kind of systems for agricultural applications. This paper presents a comparative economic feasibility analysis of five large-power PVIS in the range from 40 to 360 kW<sub>p</sub> in the Mediterranean region, considering the investment required for each installation and the savings that they produce based on the real data of their performance during the years 2016 and 2017. The results show that the investment in PVIS in the Mediterranean region is always profitable, for all of the PVIS configurations and the powers considered in this study and even with frequent occurrences of events of lack of water that obliges the PVIS to stop, showing *IRR* values between 10-28%, and *LCOE* values ranging from 0.04 to 0.20 €/kWh. Moreover, the results allow concluding that PVIS that has a seasonal water pool and a strong water source show the best results in the feasibility analysis and, therefore, in order to segment the market for the introduction of large-power PVIS, the substitution of conventional power in this kind of existing irrigation networks, would be the priority.

Keywords: photovoltaic, irrigation system, economic assessment, renewable energy.

## **1. Introduction**

Irrigation for agricultural applications is an intensive water and electricity-consuming activity as a result of modernization [1]. The majority of the agricultural irrigation systems are currently powered from the electric grid or by diesel generators [2], [3]. However, the increase in the price of electricity [4], [5], as well as the trend to phase out fossil fuels [6], has boosted the search of alternatives to power the irrigation systems.

The decrease of prices of photovoltaic (PV) technology [7] and the removal of the technological barriers that limited the power of PV irrigation systems (PVIS) [8], [9] have made possible that this kind of systems reach the market. This is a new scenario since, to date, only low power systems had been implemented and, therefore, economic studies had been restricted to them. The table 1 includes the references of the most relevant implementations of PVIS in the world throughout history, since Dominique Campana made the first realization in 1975 in Corsica, France [10], in which it is observed that the power was always less than 26 kW<sub>p</sub>. Table 2 shows the most relevant publications on feasibility studies on PVIS, which include experimental and theoretical studies that present peak powers always lower than 25kW<sub>p</sub>. It is also possible to find references to PVIS up to 37kW<sub>p</sub> in some catalogues of pump manufacturers [11] although

43 scientific reports about their performance in any real implementation have not been able to be  
 44 found. Furthermore, other economic feasibility studies were recently published [12], [13] that  
 45 prospect different criteria for the implementation of PVIS in raising markets. So, it could be said  
 46 that the literature is restricted to small-power PVIS with less than 40kWp. And this is precisely  
 47 the motivation of this article: present an economic analysis of real large-power PVIS, based on  
 48 experimental performance data that contributes to answering their profitability and their  
 49 suitability to enter into the market.

50 **Table 1. Most relevant publications regarding PV Water pumping systems installations**

Reference	PVPS location	Publication Year	PVIS power (kWp)
[14]	Worldwide	1981	< 0.5
[15]	Worldwide	1982	< 26
[16]	Egypt	1988	< 10
[17]	Sahel Countries	1989	< 4
[18]	Worldwide	1993	< 13
[19]	Australia	1996	< 1
[20]	Brazil	2002	~ 0.3
[21]	Sahara Regions	2003	< 1.5
[22]	India	2003	< 1
[23]	Mexico	2004	< 0.9
[24]	Morocco	2005	< 5.3
[25]	Morocco	2006	< 11
[26]	Saudi Arabia	2013	< 2
[27]	India	2015	< 1
[28]	India	2015	< 1
[29]	Turkey	2016	< 2
[30]	Nicaragua	2016	< 3
[31]	Chile	2018	< 3

51

52 **Table 2. Most relevant publications regarding economic analysis of PV Water Pumping Systems**

Reference	PVPS location	Publication Year	PVIS power (kWp)
[32]	Jordan	1990	< 8
[18]	Worldwide	1993	< 13
[33]	Brazil	1996	< 2
[34]	Jordan	2006	< 16
[35]	India	2007	< 2
[36]	Croatia	2009	Not available
[37]	Tunisia	2010	< 9
[38]	Bangladesh	2013	Not available
[39]	Worldwide	2014	< 25
[40]	China	2015	< 3.2
[41]	Bangladesh	2015	< 1.5
[5]	Mediterranean Countries	2016	Not available
[42]	Worldwide	2017	< 20
[43]	Bangladesh	2017	< 20
[44]	Spain	2019	Not available
[45]	Morocco	2019	<1

53

54

55 Feasibility studies have two main pillars: the necessary investment and the benefits based on the  
56 productivity of the system. And here lies the problem: that the lack of large-power PVIS means  
57 that the real CAPEX and its real performance are unknown. Unlike grid-connected PV systems,  
58 which always that they are in a position to produce, they inject electricity into the grid, in the  
59 case of PVIS there are many occasions in which, being able to produce, they do not do so due to  
60 factors external to their quality (lack of water in the well, absence of need to water the crop,  
61 etc.). Therefore, the experience of the performance of the grid-connected PV systems cannot be  
62 directly transferred to the case of the PVIS. This lack of experimental knowledge of its cost and  
63 its performance (and therefore, of its real benefit) prevents in practice a useful study of the  
64 viability of this type of systems. To this is added the great variety of existing irrigation  
65 infrastructures and, therefore, of the PVIS designs needed to power them: “only” PV or hybrid  
66 designs; working at variable frequency and power (if a water pool exists) or working at constant  
67 pressure and water flow and therefore constant power (if pumping directly to the irrigation  
68 network composed of sprinklers, pivots or drip systems). The influence of these different  
69 configurations in the feasibility of the PVIS is still an open question without answering.

70 The objective of this paper is to contribute to answering the previous questions by studying the  
71 economic feasibility of five real large-power PVIS, on a real scale and in real operating  
72 conditions, based on their investment costs and on the experimental data of their performance  
73 for two years. The five analyzed PVIS, which were installed in the framework of the European  
74 project MASLOWATEN [8], [9] cover a wide range of powers (from 40 to 360kW<sub>p</sub>) and  
75 different configurations: "only" PV and also hybrid designs; pumping at variable power but also  
76 at constant power; and with robust sources of water but also with weak sources that produced  
77 events of lack of water forcing the systems to stop. So, the significance of this economic study  
78 is based on the use of experimental data from 5 real large-power PVIS with different powers  
79 and configurations that cover most of the needs of the market for the different existing irrigation  
80 networks.

81 The five PVIS are in the Mediterranean area and only experimental data of 2 years of operation  
82 are available. Therefore, the results and conclusions are limited by these two restrictions and are  
83 not intended to be general. However, these results allow drawing conclusions that may be useful  
84 for the high power PVIS market that is already taking off. Thus, to give more generality, a  
85 sensitivity analysis has been made with respect to CAPEX (which would allow the conclusions  
86 to be extended to other regions with other costs of investment) and with respect to the cost of  
87 electricity supplied by the grid or by diesel generators (which would allow the conclusions to be  
88 extended to countries with other costs of the replaced power sources).

89 This paper is structured as follows: after this introduction a methodology section details the  
90 available performance data for the years 2016 and 2017 together with the description of the  
91 main indices used for the feasibility analysis. Section 3 is devoted to the brief description of the  
92 pre-existing irrigation networks and of the new PVIS installed. Section 4 presents the results of  
93 the economic feasibility analysis and also of the sensitivity analysis and Section 5 shows the  
94 discussion of these results. The last section summarizes the main conclusions of the work.

95

## 96 **2. Methodology**

97 The methodology applied to this analysis is based on the use of real data from five large-power  
98 PV irrigation demonstrators installed in the Mediterranean region, ranging from 40 kW<sub>p</sub> to 360

99 kW<sub>p</sub> and covering all of the possible needs of the market: pumping at a variable frequency and  
 100 power to a water pool, direct pumping at a constant pressure and power to irrigation networks  
 101 using drip systems, sprinklers or pivots, irrigation networks whose sizing allows irrigating in  
 102 just few hours that can use “only PV” irrigation systems and, on the other hand, irrigation  
 103 networks requiring more irrigation hours than the number of the daily sun hours where hybrid  
 104 PV-grid or PV-diesel irrigation systems must also be considered. The five PVIS are in different  
 105 locations in the Mediterranean area listed in Table 3, while the different characteristics of each  
 106 PVIS are detailed in Table 4.

107 **Table 3. Location of the 5 PVIS in study.**

PVIS	Country	Latitude	Longitude
Villena	Spain	38°41'16'' N	0°50'33''W
Alaejos	Spain	41°16'26'' N	5°16'47''W
Uri	Italy	41°37'24'' N	8°28'14''W
Tamallalt	Morocco	31°47'56'' N	7°31'20''W
Alter do Chão	Portugal	39°09'56'' N	7°41'41''W

108

109 **Table 4. Characteristics of the 5 PVIS in the study.**

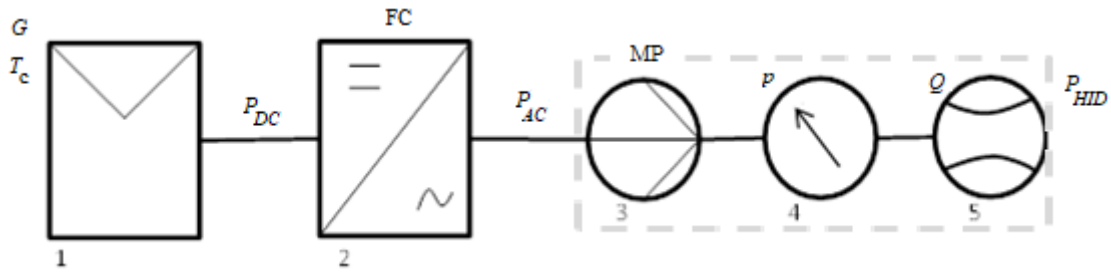
PVIS	Power (kW <sub>p</sub> )	Climatic region	Power supply	Well robustness	Irrigation network	Irrigation device
Villena	360	Mediterranean	Only PV	Strong	Variable power	-
Alaejos	160	Mediterranean	Only PV	Strong	Constant power	Pivot
Uri	40	Mediterranean	Only PV	Weak	Constant power	Sprinkler
Tamallalt	120	Arid - Desert	Hybrid PV/grid	Weak	Constant power	Drip
Alter do Chão	140	Mediterranean	Hybrid PV/diesel	Weak	Constant power	Drip

110

111 It is worth to underline that these different characteristics of the 5 PVIS cover most of the  
 112 irrigation systems present in the market and will allow the comparison of their feasibility  
 113 depending on their power, performance, configurations, and reliability of the water source.  
 114 However, it can be observed that all the PVIS are installed in the similar climatic regions so,  
 115 this study is limited to the climatic conditions of the Mediterranean area. In order to give more  
 116 generality to this study, a sensitive analysis to assess the impact of the initial investment and the  
 117 price of the previous source of electricity (grid or diesel) on the economic feasibility of PVIS  
 118 has been carried out.

119 The basic concept of the PVIS installed in all of them is shown in Figure 1. The main  
 120 components of a PVIS are: the PV generator, the frequency converter (FC), the centrifugal  
 121 motor-pump (MP), the pressure gauge to measure the pumping pressure ( $p$ ) and the water flow  
 122 meter to measure the water flow rate ( $Q$ ). Figure 1 also shows the main operation variables that  
 123 have been collected and recorded every minute by monitoring systems also installed in each  
 124 demonstrator. Other sensors have been integrated into the system to allow the monitoring of the  
 125 available solar irradiance ( $G$ ) and the solar cell temperature ( $T_c$ ), the actual DC power produced

126 by the PV generator ( $P_{DC}$ ), the AC power ( $P_{AC}$ ) delivered to the motor-pump and the final  
 127 hydraulic power ( $P_{HID}$ ) at the output of the system.



128

129 **Figure 1. PV Irrigation System made up of: 1) PV generator, 2) Frequency Converter, 3) Centrifugal Pump, 4)**  
 130 **Pressure gauge and 5) Water flow meter.**

131 This methodology has been sequenced in three steps:

- 132 1) Collection and analysis of the actual performance data for two complete irrigation  
 133 campaigns (2016 and 2017) and the definition of two different performance scenarios  
 134 for the economic analysis.  
 135 2) Calculation of the main economic indices for the feasibility analysis: the normalized  
 136 Net Present Value ( $NPV$ ), the Internal Rate of Return ( $IRR$ ), the Payback Period ( $PBP$ )  
 137 and the Levelized Cost of Energy ( $LCOE$ ).  
 138 3) Processing a sensitivity analysis with two parameters: the initial investment cost and the  
 139 price of the electricity or the diesel.

140

141 *2.1. Actual performance data in 2016 and 2017 and the definition of scenarios for the*  
 142 *economic analysis*

143 The following tables summarize the actual values of the main performance indices [46], [47] for  
 144 the two complete irrigation campaigns of 2016 and 2017. The PV Energy Yield is shown in  
 145 Table 5 and Table 6 shows the Performance Ratio ( $PR$ , [48], [49]) given by the following  
 146 equation:

$$PR = \frac{E_{AC}}{P^*/G^*} \times \frac{1}{\int G dt} \quad (1)$$

147

148 where  $E_{AC}$  is the energy supplied by the frequency converter,  $P^*$  is the nominal power of the PV  
 149 generator,  $G$  is the irradiance on the PV generator surface, and  $G^*= 1000 \text{ W/m}^2$ .

150 **Table 5 – PV Energy Yield for the two irrigation campaigns**

Year	Energy Yield [kWh/kW <sub>p</sub> ]				
	Villena	Alaejos	Uri	Tamallalt	Alter do Chão
2016	1662	1254	751	1919	833
2017	1575	1240	450	1093	280

151

152 **Table 6 – Performance Ratio ( $PR$ ) for the two irrigation campaigns**

Year	Performance Ratio
------	-------------------

	Villena	Alaejos	Uri	Tamallalt	Alter do Chão
2016	0.71	0.55	0.35	0.82	0.36
2017	0.65	0.54	0.21	0.33	0.12

153

154 It is worth noting that the PV energy yield varies from 280 to 1662 kWh/kW<sub>p</sub> and the most used  
 155 performance indicator in the PV community, the *PR*, ranges from 0.12 to 0.82. This is for two  
 156 main reasons:

- 157 - 2016 and 2017 were two very different years from the climatologic point of view.  
 158 While 2016 was a standard year in terms of pluviometry, 2017 was characterized by a  
 159 lower rate of rain. For example, in the demonstrator of Alter do Chão, in 2017 the  
 160 pluviometry was 46% less than the average [50], [51], and this situation was similar in  
 161 the whole Mediterranean area. These different climatological conditions affect in  
 162 different ways to the five PVIS, depending on the robustness of the water source. The  
 163 PVIS in Villena and Alaejos are practically not affected because they have strong water  
 164 sources (deep wells with high capacity) while the rest of PVIS are highly affected (for  
 165 example, the PVIS in Alter do Chao, reduces dramatically its energy yield from 833 to  
 166 280kWh/kWp) because they have weak water sources. In these cases, events of lack of  
 167 water in the source obey the PVIS to stop.  
 168 - While in the well-known PV grid-connected systems *PR* values are usually close to 0.8  
 169 [52], [53], these five demonstrators show values well below this figure. The reason is  
 170 not only that PVIS, even if they show a high quality, are highly influenced by external  
 171 factors such as the mentioned lack of water in the source but also the requirements of  
 172 the irrigation network, such as the water needs of the crop throughout the year and the  
 173 behavior of the irrigator [8].

174 Taking these data as the input, we propose three different scenarios for the economic feasibility  
 175 analysis for a period of 25 years (the warranty of the PV modules, normally used for PV  
 176 investments). An optimistic scenario considers that the PVIS have no events of lack of water in  
 177 the source and, therefore, all the 25 years are equal to 2016. This scenario will allow to compare  
 178 the performance and the economic feasibility of the five PVIS considering that all of them have  
 179 strong water sources. The pessimistic scenario is defined as a combination of 2016 and 2017  
 180 data and considers that every 5 years there is a year like 2017 whilst the remaining ones are like  
 181 2016. This way, the pessimistic scenario considers the occurrence of events of droughts every 5  
 182 years that could affect the performance of the different PVIS due to lack of water depending on  
 183 the robustness of the water source. This scenario will allow to compare the economic feasibility  
 184 of the five PVIS considering the influence of the different characteristics of the water sources. It  
 185 is worth to note that the lack of water is affecting in a different way to three of the five PVIS  
 186 considered in this paper, with reductions in the energy yield from 40% to 67%. Finally, as  
 187 pointed out in [54], in one out of ten years, in semi-arid areas, there is a drought event caused by  
 188 the seasonal rainfall being below the minimum seasonal plant water requirement. So, we  
 189 propose a realistic scenario which considers the occurrence of events of droughts, and therefore  
 190 of lack of water, every 10 years. It can be observed that the proposed pessimistic scenario  
 191 considers a double occurrence of this situation and this is way it is denominated “pessimistic”.  
 192 The results corresponding to the range between the realistic and the pessimistic scenarios could  
 193 be seen as the range of the possible expected results.

194 *2.2. Main indices for the economic feasibility analysis*

195 The economic feasibility analysis is made by taking as incomes the savings produced due to the  
 196 total or partial substitution of the previous power sources. The annual Cash Flows ( $CF$ ) [55] are  
 197 calculated for the period of 25 years considered in this analysis. Therefore, the feasibility of the  
 198 PVIS is evaluated in terms of the variation in the  $CF$  before and after the substitution of the  
 199 previous existing power source by the PV.  $CF$  for the year  $n$ , is given by equation (2):

$$CF_{pv,n} = \begin{cases} -IIC, & n = 0 \\ S_n - OPEX - DI, & n \neq 0 \end{cases} \quad (2)$$

200 where  $IIC$  is the Initial Investment Cost also known as  $CAPEX$  – Capital Expenditures,  $S_n$  is the  
 201 annual savings by not using grid electricity or the diesel generator,  $OPEX$  (operating expense) is  
 202 the annual operational expense and  $DI$  is the debt interest. In more detail,  $S_n$  is given by  
 203 equation (3):

$$S_n = PVE_n \times CEC_n \quad (3)$$

204 where  $PVE_n$  is the energy which, after the installation of the PV system, is not produced by the  
 205 conventional source of electricity (grid or diesel generator) but by the PV generator; and  $CEC_n$   
 206 is the annual price of the conventional energy source.  $CEC_n$  is calculated by the following  
 207 equation:

$$CEC_n = CEC_{n-1} \times (1 + h + s) \quad (4)$$

208 where  $h$  is the inflation rate [55] and  $s$  is an additional spread of the cost of the conventional  
 209 electricity. The additional spread is defined as an additional tax in order to reflect the most exact  
 210 price evolution of that commodities throughout the years that goes above the annual inflation  
 211 rate. According to [56] since 2008 to 2015, in the European Union the electricity price  
 212 incremented, on average, 3% per year, while the inflation rate was close to zero. Thus, we have  
 213 considered the additional spread of 3% and applicable to both the electricity and diesel price.

214 As regards the  $OPEX$ , only those costs related to maintenance, insurance and security associated  
 215 to the PV system were considered. Finally, in order to calculate the  $DI$ , the following equation  
 216 was used [55]:

$$DI_n = IIC \times D - CR \quad (5)$$

217 where  $CR$  is the Capital Repayment [55] and is associated with the loan maturity ( $l$ ) [55] which  
 218 is defined as the time in which the loan is paid off and, in this case, was considered as 6 years.  
 219  $D$  is the debt ratio [55] which was considered as 70% and the  $CR$  is given by the following  
 220 equation [55]:

$$CR = \frac{IIC \times D}{l} \quad (6)$$

222 The variation in  $CF$  for the year  $n$  ( $\Delta CF_n$ ) when substituting the conventional source of energy  
 223 is given by [55]:

$$\Delta CF_n = \frac{CF_{pv,n}}{(1+r)^n} \quad (7)$$

224 where  $r$  (real interest rate) can be calculated by the following equation [55]:

$$r = \frac{(i-h)}{(1+h)} \quad (8)$$

225 where  $i$  is the interest rate. According to [55], the difference between  $r$  and  $i$  is that the first one  
 226 has been adjusted to remove the effects of inflation.  
 227

228 Table 7 shows the price of the conventional electricity source in year 0, while Table 8 shows the  
 229 initial investment cost ( $IIC$ ) or  $CAPEX$  of the PV part of the systems.

230 **Table 7 - Price of the conventional electricity source in year 0**

	Villena	Alaejos	Uri	Tamallalt	Alter do Chão
$CEC_0$ [c€/kWh]	10.5	11.3	27.0	10.4	16.6

231

232 **Table 8 - The Initial Investment Cost for each PV Irrigation System in absolute terms and normalized by the**  
 233 **peak power of the PV generator.**

	Villena	Alaejos	Uri	Tamallalt	Alter do Chão
$IIC$ [€]	433098	200351	57778	148704	170277
$IIC/W_p$ [€/W <sub>p</sub> ]	1.20	1.25	1.44	1.24	1.22

234

235 In terms of the  $OPEX$  of each plant (see Table 9), the most expressive items are  
 236 electricity/diesel, water, maintenance and insurance costs.  $OPEX$  was considered as 1.5% of the  
 237 total  $IIC$  of each PVIS, with the exception of the Italian and Morocco plants for which it was  
 238 considered more suitable to take the annual amount of 2000 € and 3000 € respectively into  
 239 account due to their lower size and the need to cover a minimum of maintenance costs.

240 **Table 9 - OPEX for each PV Irrigation System**

	Villena	Alaejos	Uri	Tamallalt	Alter do Chão
$OPEX_0$ [€]	6496	3005	2000	3000	2554
$OPEX_0/kW_p$ [€/kW <sub>p</sub> ]	18.04	18.78	50.00	25.00	18.24

241

242 In the case of the hybrid PVIS with diesel generators or grid connection, Table 10 shows the  
 243 corresponding  $OPEX$  as a function of the  $OPEX$  values of Table 9.

244 **Table 10 - The OPEX for the current system ( $OPEX_{CS}$ )**

Items	Diesel	Grid
$OPEX_{CS}$	$1.2 \times OPEX_0$	$OPEX_0$

245

246 Table 11 shows the rates considered [57], in which the inflation rate and the interest rate are the  
 247 average value of the last 10 years as indicated in [58].

248 **Table 11 – Rates (which are country-dependent variables) for the 5 PVIS.**

PVIS	$h$ [%]	$i$ [%]	$r$ [%]	$s$ [%]
Villena	1.39	0.81	-0.57	3
Alaejos	1.39	0.81	-0.57	3

Uri	1.36	0.81	-0.55	3
Tamallalt	1.46	2.86	1.38	3
Alter do Chão	1.19	0.82	-0.37	3

249

250 2.2.1. Net Present Value, Internal Rate of Return and Payback Period

251 With the  $\Delta CF_n$ , it is possible to calculate the *NPV* with equation (9), [55]. The *NPV* is the sum  
 252 of all the cash flows discounted to the present using the time value of the money [55]. A value  
 253 of *NPV* greater than zero means that profits will be created for the investor. The normalized  
 254 *NPV* is the result of the division of the *NPV* by the peak power of the PVIS,  $P^*$ .

$$NPV = \sum_{n=1}^{25} \frac{CF_{pv,n}}{(1+r)^n} = \sum_{n=1}^{25} \Delta CF_n \quad (9)$$

255

256 Finally, it is possible to calculate the *IRR* as well as the *PBP*. The former is defined as the real  
 257 interest rate that would make the *NPV* equal to zero after the 25-year lifetime of the project (i.e.  
 258 the real interest rate at which the initial investment is returned at the end of the lifetime of the  
 259 project). On the other hand *PBP* is defined as the number of years ( $n$ ) for which *NPV* is equal to  
 260 zero (i.e. the period required for the initial investment to be returned with the present value of  
 261 cash flows, disregarding the real interest rate).

262 2.2.2. Levelized Cost of Energy

263 *LCOE* is the most common indicator used by entities in order to compare different energy  
 264 technologies. According to [59], the sum of the annual values of the *LCOE* ( $LCOE_n$ ) multiplied  
 265 by the energy generated annually ( $E_n$ ) should be equal to the sum of the values of the costs of  
 266 the project – see equation (10).

$$\sum_{n=0}^N \frac{LCOE_n \times E_n}{(1+r)^n} = \sum_{n=0}^N \frac{Costs_n}{(1+r)^n} \quad (10)$$

267 If we carry out the same rearrangement as in [59] and [60], assuming a constant value per year,  
 268 the *LCOE* is given by the following equation:

$$LCOE = \frac{\sum_{n=0}^N \frac{Costs_n}{(1+r)^n}}{\sum_{n=0}^N \frac{E_n}{(1+r)^n}} \quad (11)$$

269 where the numerator in equation (11) is the total lifecycle cost of the system and the  
 270 denominator, the lifetime energy production. Based on this equation we are able to calculate  
 271 different *LCOEs* according to the energy source(s) used. The *LCOE* for an only PV application  
 272 ( $LCOE_{PV}$ ) is calculated as follows:

$$LCOE_{PV} = \frac{IIC + \sum_{n=1}^N \frac{OPEX_n}{(1+r)^n}}{\sum_{n=0}^N \frac{PVE_n}{(1+r)^n}} \quad (12)$$

273 On the other hand, the *LCOE* of the previous system ( $LCOE_{PS}$ ), with an only-diesel or only-grid  
 274 systems, is calculated as:

$$LCOE_{PS} = \frac{\sum_{n=0}^N \frac{CEC_n \times (PVE_n + PE_n) + OPEX_n}{(1+r)^n}}{\sum_{n=0}^N \frac{(PVE_n + PE_n)}{(1+r)^n}} \quad (13)$$

275 where  $PE_n$  is the energy which, after the installation of the PV system, was provided by the  
 276 previous energy source. So, the sum between  $PVE_n$  and  $PE_n$  represents the total energy  
 277 consumed by the irrigation system.

278  $LCOE_{PV}$  can be generalized as  $LCOE$  of the current system ( $LCOE_{CS}$ ) to include hybrid systems  
 279 or systems with contributions from the previous system. It is calculated as:

$$LCOE_{CS} = \frac{IIC + \sum_{n=0}^N \frac{CEC_n \times PE_n + OPEX_{CSn}}{(1+r)^n}}{\sum_{n=0}^N \frac{(PVE_n + PE_n)}{(1+r)^n}} \quad (14)$$

280

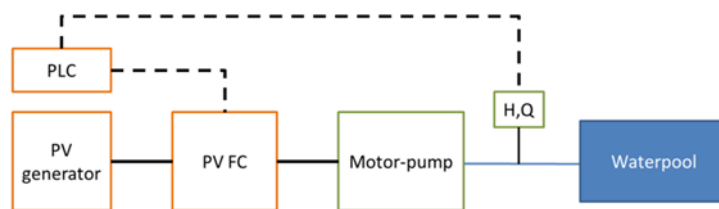
### 281 3. Description of the pre-existing irrigation networks and of the new PVIS

282

283 The pre-existing system and the new PVIS installed in each demonstrator are described below  
 284 for each one of the systems:

- 285 • Villena, Spain – Figure 2: This system belongs to the Irrigator’s Community of Alto  
 286 Vinalopó and operates throughout the year. The pre-existing system was made up of a 250  
 287 kW submersible pump fed by the national grid which pumped water from a 400 m deep-  
 288 borehole to a water pool of 173000 m<sup>3</sup>. This water is then distributed to other reservoirs in  
 289 the Irrigator’s Community. The new PV irrigation system was designed to substitute the  
 290 grid entirely. A 360 kW<sub>p</sub> stand-alone PVIS is currently installed and the system is able to  
 291 pump water from the borehole at a variable water flow according to the PV power available  
 292 [61].

293

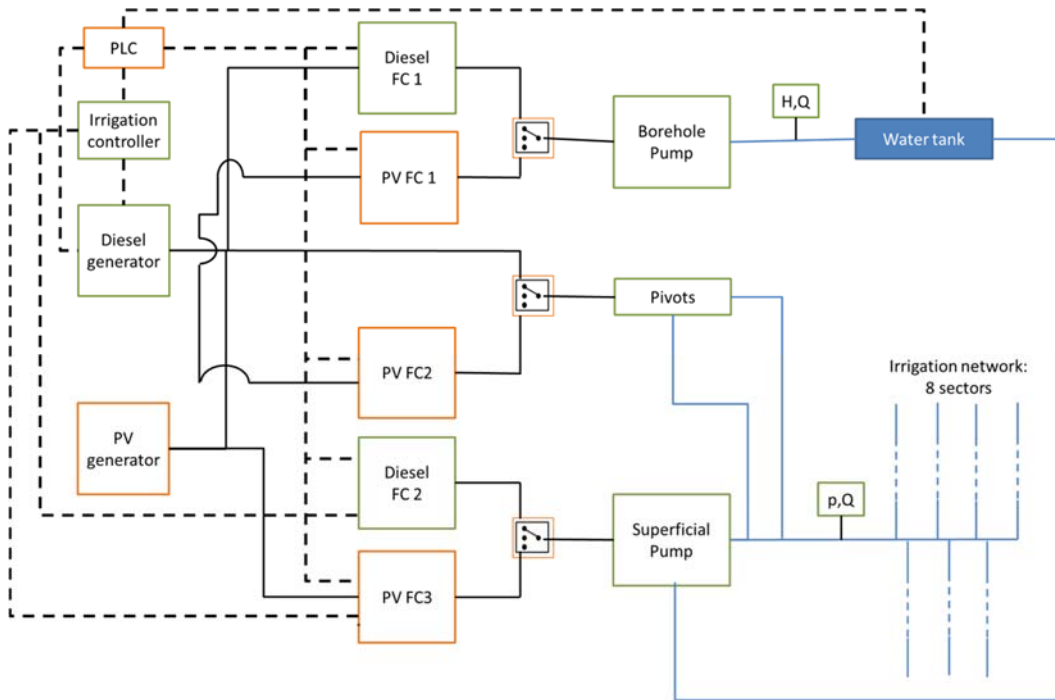


294 **Figure 2. Villena’s PVIS configuration. A PV generator, a new FC and a PLC have been added**  
 295 **to the pre-existent configuration, where the grid has been totally substituted. The new**  
 296 **components are marked in orange, while the previous ones are in green.**

- 297 • Alaejos, Spain – Figure 3: It is an 80 ha farm mainly devoted to the intensive cultivation  
 298 of beetroot and potatoes. The irrigation takes place from March to October. The  
 299 irrigation is divided into ten sectors, in which 4 of them are pivots and 6 are sets of  
 300 sprinklers. The farmer establishes the irrigation schedule on a daily basis, according to  
 301 the recommendations received by a local institution [62]. The pre-existing system was  
 302 made up of two pumps fed by a 150 kVA diesel generator, one pump of 92 kW  
 303 elevating water from a 150m deep-borehole to an intermediate tank of 1000 m<sup>3</sup> of  
 304 capacity and a 30 kW surface-pump to irrigate at a constant pressure from the tank  
 305 through pivots or sprinklers. The new PV irrigation system was designed to substitute

306  
307

the diesel generator by a 160 kW<sub>p</sub> PV generator but the diesel system was kept to irrigate during the night in the peak periods.

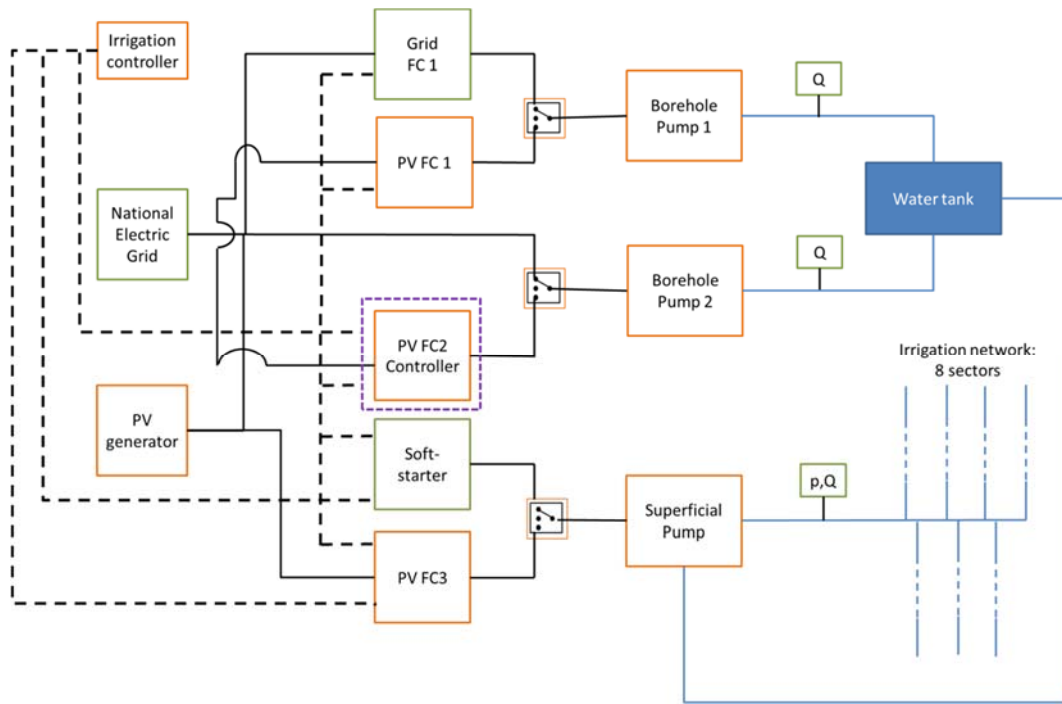


308

309 **Figure 3. Alaejos' PVIS configuration. A PV generator, three FCs, and a PLC have been added to the**  
310 **pre-existent configuration. The new components are marked in orange, while the previous ones are in**  
311 **green.**

312

- 313
- Uri, Italy – Figure 4: It is a 5.4ha farm dedicated to the ecological cultivation of artichokes. The irrigation season is from May to the end of October [63].The pre-existing system included two different boreholes, with 4 kW and 3 kW pumps respectively, elevating water to the same 2000 m<sup>3</sup> water pool. The irrigation was carried out using a third surface pump of 7 kW to irrigate through sprinklers from this water pool. The three pumps were fed by the grid. A 40 kW<sub>p</sub> stand-alone PVIS was designed to substitute the grid but the grid connection was kept to have the confidence of the farmer.
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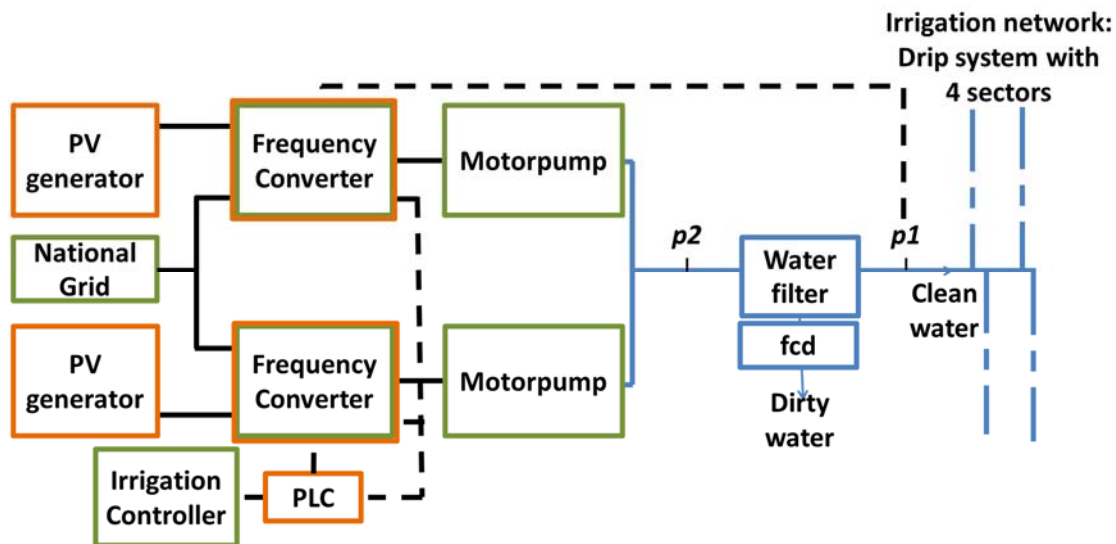


321

322 **Figure 4. Uri's PVIS configuration. A PV generator, three FCs, an irrigation controller, and three motor-**  
 323 **pumps have been added to the pre-existent configuration. The new components are marked in orange,**  
 324 **while the previous ones are in green.**

325

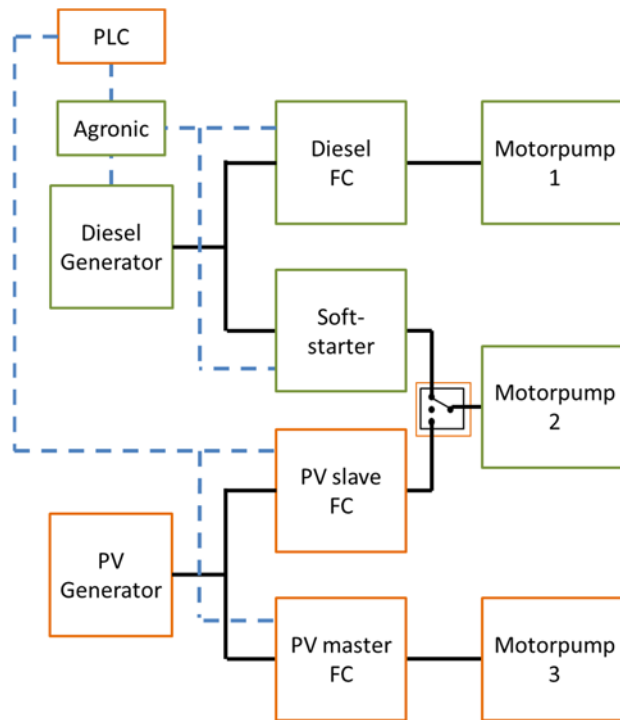
- 326 • Tamallalt, Morocco – Figure 5: It is a 233 ha farm devoted to the intensive cultivation  
 327 of olive trees. The irrigation is carried out throughout the year, May and June being the  
 328 months with the highest consumption. The pumps work with a pressure set-point of 4  
 329 bars after the bank of filters used to clean the water before reaching the drip irrigation  
 330 system, giving each one a water flow rate of between 180 and 200 m<sup>3</sup>/h according to the  
 331 irrigation sector [64]. The pre-existing system was made up of two 45 kW centrifugal  
 332 surface pumps fed from the national grid. The new PVIS was designed to partially  
 333 substitute the grid. A 120 kW<sub>p</sub> PV generator was added to the previous system and two  
 334 frequency converters are now fed at the same time by the PV generator and the grid.  
 335 Consequently, the current system is a 120 kW<sub>p</sub> hybrid PV-grid drip irrigation system  
 336 with hybridization in the electric part of the system.



337

338 Figure 5. Tamallalt's PVIS configuration. A PV generator and two FCs have been added to the pre-  
 339 existent configuration. The new components are marked in orange, while the previous ones are in  
 340 green.  
 341

- 342 • Alter do Chão, Portugal – Figure 6: It is a 195 ha farm devoted to the super-intensive  
 343 cultivation of olive trees. The irrigation period is from March/May (depending on the  
 344 availability of water) to October, June being the month with the highest consumption.  
 345 The irrigation is carried out through a drip system in 7 different sectors with a pressure  
 346 set point of 5.7 bars [65]. The pre-existing system included a diesel generator and two  
 347 45 kW surface centrifugal pumps. In order to partially substitute the diesel  
 348 consumption, the current system includes a 140 kW<sub>p</sub> PV generator, as well as an  
 349 additional pump. This third pump was added because, in this case, hybridization takes  
 350 place in the hydraulic part of the system, although just two of the three pumps run at the  
 351 same time. Now the system is able to work in three different modes according to the  
 352 available PV power: “Only PV”, “Hybrid” and “Only Diesel”.



353

354 **Figure 6. Alter do Chão PVIS configuration. A PV generator, two FCs and a motorpump have been added to**  
 355 **the pre-existent configuration. The new components are marked in orange, while the previous ones are in**  
 356 **green**

357

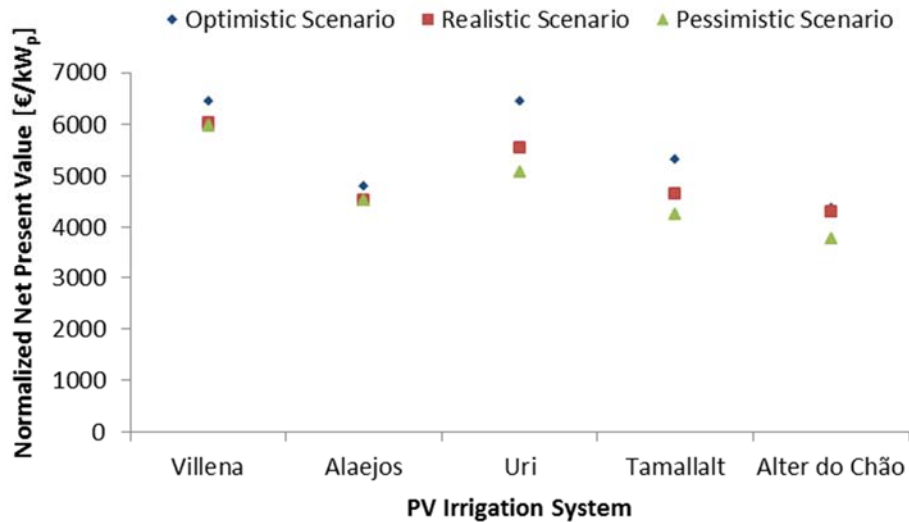
358 The PV modules of the 5 PV Irrigation demonstrators were installed on North-South horizontal  
 359 axis trackers. The use of this kind of tracker has numerous advantages. Not only is there a match  
 360 between the annual production and the annual water needs, but also, if we analyse the daily  
 361 irradiance profile of this kind of tracker, its constancy allows the wells not to be stressed out and  
 362 to reach the pumping start threshold earlier in the morning and later in the afternoon than a fixed  
 363 south-oriented structure, allowing more hours of irrigation per day [66].

364

#### 365 **4. Results**

##### 366 *4.1. Economic feasibility analysis*

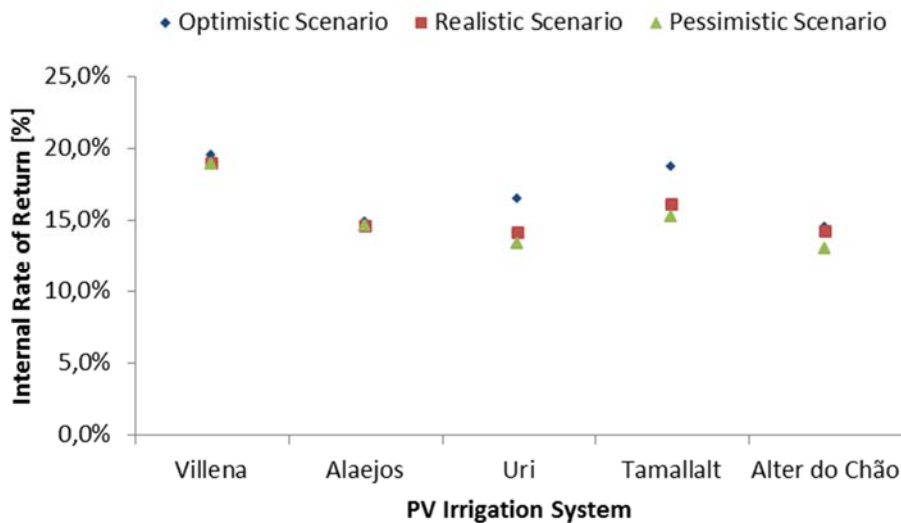
367 The *NPV*, the *IRR* and the *PBP* obtained for each PV Irrigation demonstrator for the three  
 368 proposed scenarios is presented in this section. It is important to clarify that to be cost-effective,  
 369 the *NPV* should be positive, the *IRR* must be higher than the discount rate of the country and the  
 370 *PBP* lower than the lifetime of the project (25 years). Figure 7 shows the *NPV* normalized by  
 371 the PV peak power for the 5 demonstrators, regarding the two scenarios. Their values range  
 372 from 3778 €/kW<sub>p</sub> (pessimistic scenario of Alter do Chão) to 6453 €/kW<sub>p</sub> (optimistic scenario of  
 373 Uri).



374

375 **Figure 7. Net Present Value normalized by the peak power of the PVIS [€/kW<sub>p</sub>] for the 5 PV irrigation**  
 376 **demonstrators considering the optimistic, realistic and pessimistic scenarios**

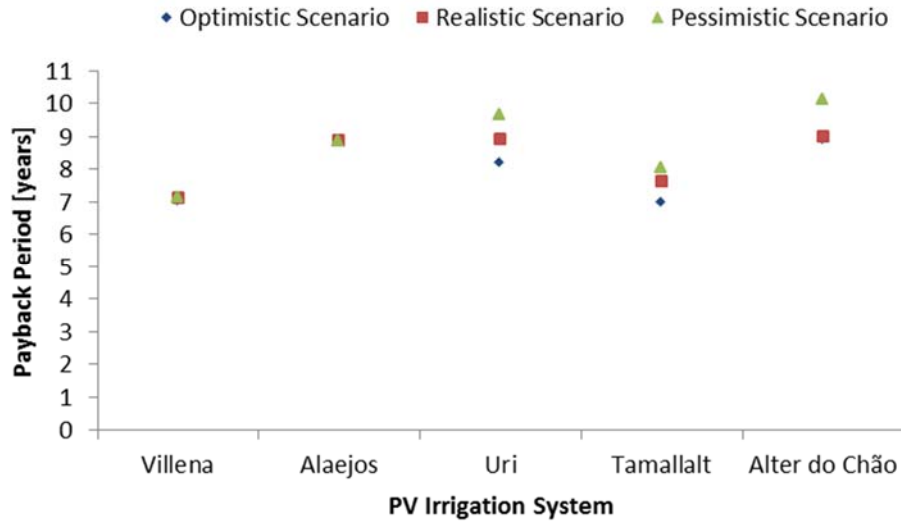
377 In terms of *IRR* (Figure 8), the values vary from 13% to 19%. Villena's demonstrator is the one  
 378 which offers the best profitability in both scenarios. On the other hand, 13% is the lowest value  
 379 that corresponds to the pessimistic scenario in Uri and Alter do Chão.



380

381 **Figure 8. Internal Rate of Return [%] for the 5 PV irrigation demonstrators considering the optimistic,**  
 382 **realistic and pessimistic scenarios.**

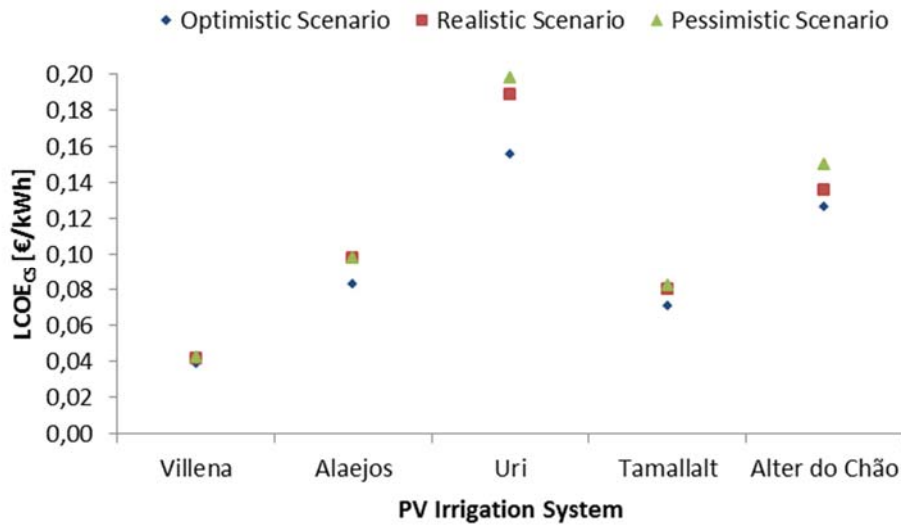
383 As regards *PBP* values (Figure 9), they are all less than or equal to 10 years for both scenarios.  
 384 In the optimistic scenario, it ranges from between 7 and 9 years.



385

386 **Figure 9. Payback Period [years] for the 5 PV irrigation demonstrators considering the optimistic, realistic**  
 387 **and pessimistic scenarios**

388 Figure 10 shows the  $LCOE_{CS}$  obtained for the 5 PV irrigation demonstrators in this study. The  
 389 values range from 4 c€/kWh (Villena's PVIS) to 20 c€/kWh (pessimistic scenario of Uri).



390

391 **Figure 10. Levelized Cost of Energy of the current system [€/kWh] for the 5 PVIS considering the optimistic**  
 392 **and pessimistic scenarios.**

393 The  $LCOE_s$  of the previous and current systems ( $LCOE_{PS}$  and  $LCOE_{CS}$  respectively), as well as  
 394 the differences between both of them for each scenario, are presented in Table 9. The difference  
 395 can be seen as the savings in the cost of the kWh due to the total or partial substitution of the  
 396 previous conventional source of energy by PV. In all of the cases, the savings are more than  
 397 60%, achieving 80% in the case of Villena.

398

399

400 Table 12. Comparison of the  $LCOE$  of the previous system ( $LCOE_{PS}$ ) and the current system ( $LCOE_{CS}$ ) as well  
 401 as its difference.

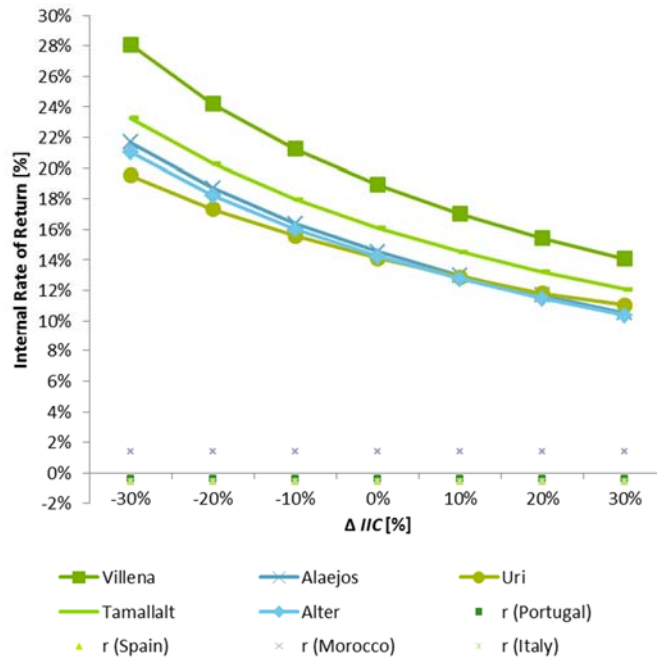
PVIS	$LCOE_{PS}$ [€/kWh]	$LCOE_{CS}$ [€/kWh]					
		Optimistic Scenario	% Difference	Realistic Scenario	% Difference	Pessimistic Scenario	% Difference
Villena	0.20	0.04	-80	0.04	-79	0.04	-79
Alaejos	0.23	0.08	-64	0.10	-57	0.10	-57
Uri	0.55	0.16	-72	0.19	-66	0.20	-65
Tamallalt	0.20	0.07	-64	0.08	-59	0.08	-59
Alter do Chão	0.32	0.13	-61	0.14	-58	0.15	-53

402

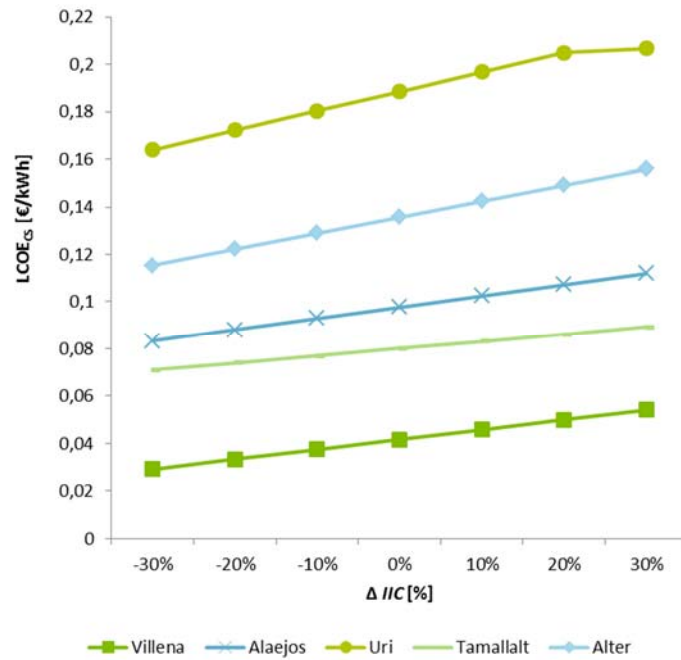
403 4.2. Sensitivity analysis

404 A sensitivity analysis of the realistic scenario has been carried out considering the variation of  
 405 two parameters: the  $IIC$  and the annual price of the conventional energy source,  $CEC_0$ . In both  
 406 cases the variation in  $IRR$  and  $LCOE$  regarding these parameters is presented. The  $IIC$  is varied  
 407 by  $\pm 30\%$  of the base case value with an interval step of 10% and  $CEC_0$ , from -30% to 30%, with  
 408 an interval step of 10%.

409 In what concerns the variation in the  $IIC$ , Figure 11 (a) shows that the variation in  $IRR$  has a  
 410 decreasing slope, in which the minimum and maximum values occur for Alter do Chão (10%)  
 411 and Villena (30%) respectively. For all PVIS,  $IRR$  is higher than the real discount rates of each  
 412 country. Regarding the variation in the  $LCOE_{CS}$ , it increases in a linear way. The minimum  
 413 value is for the Villena PVIS, 2.9 c€/kWh, and the maximum for Uri PVIS, 20.7 c€/kWh  
 414 (Figure 11b).



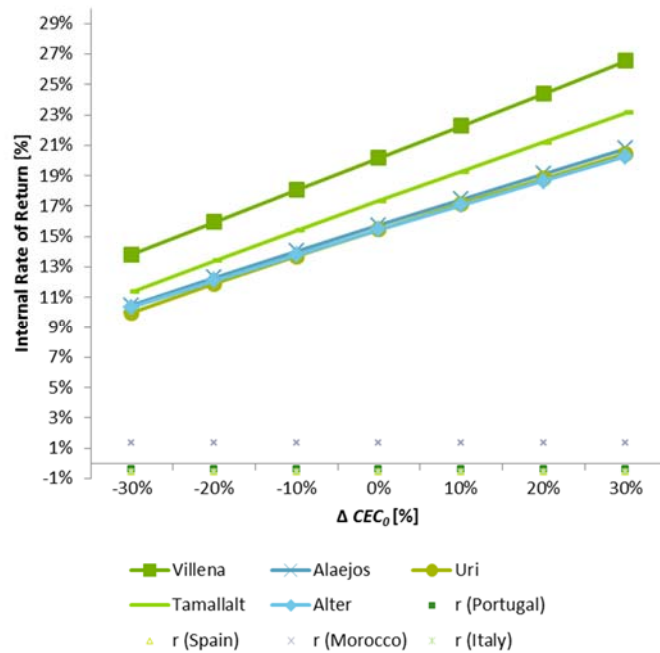
(a)



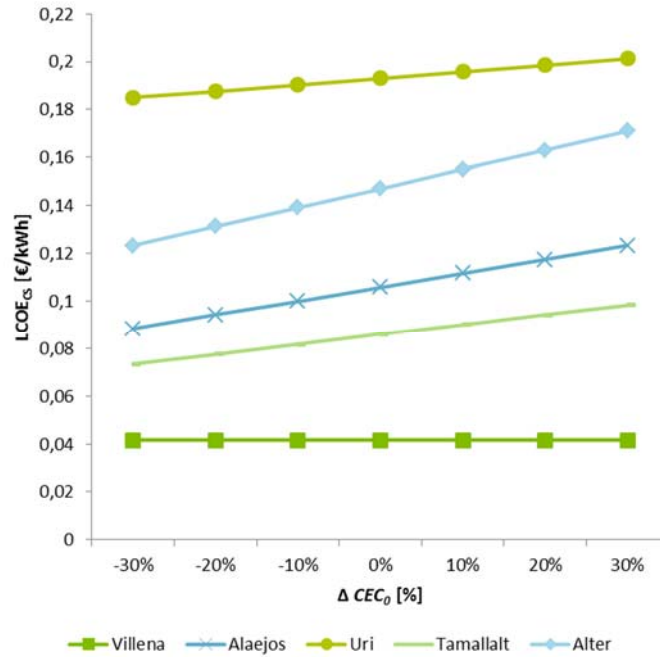
(b)

415 **Figure 11. Variation in the  $IRR$  (a), and in  $LCOE_{CS}$  (b) for the 5 PVIS in the realistic scenario, regarding the**  
 416 **variation in Initial Investment Cost (IIC) of each PVIS.**

417 For the  $CEC_0$  sensitivity analysis, the variation in the  $IRR$  (Figure 12a) has a positive linear  
 418 slope, varying from 10% if  $\Delta CEC_0$  is -30% (Uri PVIS) to 27% (Villena PVIS) with a  $\Delta CEC_0$  of  
 419 30%. As regards the variation in the  $LCOE_{CS}$ , it can be seen that its behavior is different for  
 420 each PVIS (Figure 12b). The minimum and maximum values also occur for Villena and Uri  
 421 PVIS. In Uri  $LCOE_{CS}$  goes from 18.5c€/kWh to 20.1c€/kWh considering the variation of the  
 422  $CEC_0$  from -30% to 30%. Villena has the lowest  $LCOE_{CS}$ , 4c€/kWh. However there is an aspect  
 423 that stands out which is the fact that the slope is more pronounced in the systems in which there  
 424 is more presence of the previous energy source.



(a)



(b)

425 **Figure 12. Variation in the *IRR* (a) and in *LCOE<sub>CS</sub>* (b) for the 5 PVIS in the realistic scenario, regarding the**  
 426 **variation of the price of the conventional electricity, *CEC*, from the grid or the diesel generator.**

427

## 428 5. Discussion of the results

429 The main finding from the results and the sensitivity analysis is that the investment in large-  
 430 power PVIS in the Mediterranean region is profitable in any existing grid or diesel-powered  
 431 irrigation system: in the case of substituting the grid, the *IRR* ranges from 10% in the worst case  
 432 (considering  $\Delta CEC_0 = -30\%$ ) to 28% (optimistic scenario and  $\Delta IIC = -30\%$ ). In terms of LCOE,  
 433 this investment leads to savings in the electricity cost from 80% to 53%, and in terms of PBP  
 434 the investment is returned in all of the cases in less than half of the 25 years considered as the  
 435 PVIS lifetime in this study. It is worth to underline that we obtain these good results for all of  
 436 the PVIS configurations and even in the scenario that considers frequent events of lack of water  
 437 in the source and, therefore, the PVIS is obliged to stop.

438 Another important finding is the influence of the use of the PVIS in the feasibility of the  
 439 investment. The PVIS that has a seasonal water pool and a strong water source (Villena) and,  
 440 therefore, it is independent from the water needs of the crop and from events of lack of water,  
 441 the best results considering the three scenarios regarding the normalized *NPV* (5965 to 6436  
 442 €/kW<sub>p</sub>), the *IRR* (18.8% to 19.5%) and the *PBP* (7 years). This leads to the important conclusion  
 443 that, in order to segment the market for the introduction of large-power PVIS, the substitution of  
 444 conventional power in existing irrigation networks with seasonal water pools and strong water  
 445 sources, would be the priority.

446 Another outstanding finding is related to the cost of the previous energy source. Even the  
 447 investment in PVIS is profitable for any configuration of PVIS and for all of the range of  
 448 variation of the cost of the conventional power sources substituted, the economic feasibility of a  
 449 PVIS cannot be generalized as it is highly dependent of the cost of the previous power source.  
 450 This is well illustrated by the Uri PVIS: despite it being the smallest system (40 kW<sub>p</sub>) and also  
 451 the most expensive one considering the normalized cost (1.44€/W<sub>p</sub>), it is the PVIS that presents

452 the highest value for the normalized  $NPV$  ( $6453\text{€}/\text{kW}_p$  in the optimistic scenario) due to it  
453 presents one of the highest savings when comparing the  $LCOE_{CS}$  with the  $LCOE_{PS}$ , and this is  
454 due to it had the highest cost for the grid electricity ( $LCOE_{PS}=0.55\text{€}/\text{kWh}$ ). Therefore, when  
455 analyzing the economic feasibility of a PVIS, the cost of the electricity from the conventional  
456 power to be substituted is one of the key aspects to take into account. For that reason a sensitive  
457 analysis considering the price of electricity supplied by the grid or by diesel generators have  
458 been carried out.

459

## 460 6. Conclusions

461 This paper presents a comparative economic feasibility analysis of five large-power PV  
462 irrigation systems (PVIS) in the range from 40 to 360  $\text{kW}_p$  in the Mediterranean region,  
463 considering the investment required for each installation and the savings that they produce  
464 based on the real data of their performance during the years 2016 and 2017. These PVIS have  
465 different configurations, covering all the possible needs of the market. Three different scenarios  
466 have been considered for the economic feasibility analysis taking into account external factors  
467 that influence the PVIS performance, such as the existence of weak wells leading to events of  
468 lack of water in the source.

469 The results show that the investment in PVIS in the Mediterranean region is always profitable,  
470 for all of the PVIS configurations, for all of the powers considered and even with frequent  
471 occurrences of events of lack of water that obliges the PVIS to stop. The normalized  $NPV$   
472 values are within the  $1.13\text{-}7.68\text{€}/\text{W}_p$  range,  $IRR$  values between  $10\text{-}29\%$ , the  $PBP$  values within  
473 the  $7\text{-}11$  years range and the  $LCOE$  of the PVIS ranging from  $0.04$  to  $0.20\text{€}/\text{kWh}$ , leading to  
474 savings in the electricity costs ranging from  $80\%$  to  $53\%$  regarding the electricity cost from  
475 conventional sources. The sensitivity analysis shows the robustness of the profitability of PVIS  
476 against the variation of the investment cost of PVIS and the different costs of conventional  
477 electricity, which can be used to extend this conclusion to other regions of the world.

478 Finally, it is worth to underline two other remarkable conclusions: first, PVIS that has a  
479 seasonal water pool and a strong water source (like the PVIS in Villena in this study) show the  
480 best results in the feasibility analysis ( $NPV$  from  $5965$  to  $6436\text{€}/\text{kW}_p$ , the  $IRR$  from  $18.8\%$  to  
481  $19.5\%$  and  $PBP$  of  $7$  years) and, therefore, in order to segment the market for the introduction of  
482 large-power PVIS, the substitution of conventional power in this kind of existing irrigation  
483 networks, would be the priority. This is due to that their performance is independent from  
484 external factors such as the water needs of the crop or events of lack of water. Second, the  
485 economic feasibility of a PVIS cannot be generalized as it is highly dependent of the cost of the  
486 previous power source. In this study, the PVIS with the highest cost of the conventional  
487 electricity ( $LCOE_{PS}=0.55\text{€}/\text{kWh}$ ) shows the highest value for the normalized  $NPV$  ( $6453\text{€}/\text{kW}_p$ )  
488 despite it being the smallest system ( $40\text{ kW}_p$ ) and also the most expensive one considering the  
489 normalized investment cost ( $1.44\text{€}/\text{W}_p$ ). Therefore, the cost of the electricity from the  
490 conventional power to be substituted is one of the key aspects to take into account when  
491 analyzing the economic feasibility of a PVIS.

492

493

494 **7. Acknowledgements**

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498 agreement n°640771.

499

500 **8. References**

501

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