UNIVERSIDADE DE LISBOA
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High Power PV Pumping Systems:
Two Case Studies in Spain

Isaac Afonso Barata Carrêlo

Dissertação

Mestrado Integrado em Engenharia da Energia e do Ambiente

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Trabalho realizado sob a supervisão de

Luis Narvarte Fernández (IES-UPM)

Miguel Centeno Brito (FCUL)

2014

“*Living is a constant process of deciding what we are going to do*”

José Ortega y Gasset

ABSTRACT

Nowadays there is an energy revolution, the electricity price is increasing and fossil fuels are depleting. These facts are leading to an investment in renewable energies. In agriculture there is a huge necessity to change the electricity source as well as using a more efficient way to pump water. This Master thesis pretends to demonstrate economic viability and technical feasibility of incorporating Photovoltaics (PV) to cover these needs. The aim of this study is to create a way to simulate photovoltaic pumping systems with IESPRO, a tool developed by the Institute of Solar Energy. To do this simulation, the pump model describes the dynamic evolution of the output variable, the water flow rate, as a function of the input variables such as the head, the power and the efficiency. The present work looks at two different case-studies, for two types of irrigation: pumping to water pools and pumping to the grid at constant pressure, Villena and Zújar's cases, respectively. In addition to the PV sizing, an economic study was done to understand the viability of these systems. In this study different PV systems penetration rates were represented in order to comprehend the real impact of the investment on it. For this it was created an economic tool that optimizes the power fee according to the real consumption as well as the use of PV.

The analysis showed that these two types of water pumping are not only technically available, but also economically. Relatively to the first case, the more profitable is a 100% PV penetration. On the other hand, for the second case (Zújar) the substitution of one or two motor-pump systems is the choice that provides more savings. In this case, more PV penetration is not also advisable, since the application is at constant pressure and PV alone cannot provide that, as well as the fact that this community only irrigates in a few months of the year and because of that the investment in PV systems is more difficult of being amortized.

Relatively to the last chapter of this work, it will be developed a tool (in Matlab) to find the relationship between the additional energy needed to irrigate at constant pressure and the resource variability. The results from this study show us that it is not needed a huge additional capacity to maintain the constant production if were used the threshold strategy.

Keywords: PV Pump, Communities of Irrigation, IESPRO, economic study, energy, PV systems, energy stored.

Resumo

Hoje em dia assiste-se a uma revolução energética, o preço da eletricidade tem vindo a aumentar e os combustíveis fósseis estão a esgotar-se. Estes factos levam a um investimento em energias renováveis. Na agricultura há uma grande necessidade de alterar a fonte de energia e de utilizar uma maneira mais eficiente para bombear água. Esta dissertação de mestrado pretende demostrar a viabilidade económica e técnica de incorporar energia fotovoltaica (PV) para cobrir estas necessidades. O objetivo deste estudo é criar uma metodologia de simulação de sistemas de bombagem fotovoltaica com o IESPRO, uma ferramenta desenvolvida pelo Instituto de Energia Solar. Para realizar esta simulação, o modelo de bombagem descreve a evolução dinâmica da variável de saída, o caudal, em função das variáveis de entrada como a queda, a potência e a eficiência. O presente trabalho inclui dois casos de estudo, para dois tipos de irrigação: bombagem para reservatórios de água e bombagem para a rede a pressão constante, Villena e Zújar, respetivamente. Para além do dimensionamento fotovoltaico, um estudo económico foi feito para se entender a viabilidade destes sistemas. Neste estudo diferentes taxas de penetração de sistemas fotovoltaicos foram consideradas para compreender o impacto real deste investimento. Com este objetivo foi criada uma ferramenta económica que otimiza a tarifa de potência de acordo com o consumo real e o uso do PV.

A análise demonstrou que os dois tipos de bombagem de água são viáveis dos pontos de vista técnico e económico. Relativamente ao primeiro caso, o mais rentável é uma penetração de PV de 100%. No segundo caso, a substituição de um ou dois sistemas motor-bomba é a escolha que gera maiores poupanças. Neste caso, uma maior penetração de PV não é aconselhável porque a aplicação é a pressão constante e o PV sozinho não consegue garantir isto, para além de que esta comunidade apenas irriga em poucos meses do ano o que faz com que o investimento em sistemas PV seja mais difícil de amortizar.

Relativamente ao último capítulo deste trabalho, uma ferramenta (em Matlab) foi desenvolvida para descobrir a relação entre a energia adicional necessária para irrigar a pressão constante e a variabilidade do recurso. Os resultados deste estudo mostram que não é necessário uma grande capacidade adicional para manter constante a produção se for usada a estratégia da definição de um limite.

Palavras-chave: bombagem fotovoltaica, comunidades de regantes, IESPRO, estudo económico, energia, sistemas fotovoltaicos, energia armazenada.

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List of acronyms

DR	**Discount Rate**
Eff	**Efficiency**
FL	**Friction Losses**
GVA	**Gross Value Added**
H	**Head**
H_{DT}	**Dynamic Head**
H_{ST}	**Static Head**
I	**Investment**
IES	**Solar Energy Institute**
IR	**Interest Rate**
IRR	**Internal Rate of Return**
NCY	**Number of Credit Years**
NOCT	**Nominal Operation Cell Temperature**
NPV	**Net Present Value**
NSH	**Number of Sun Hours**
P	**Density**
P2	**Mechanical Power**
PV	**Photovoltaic**
Q	**Water Flow Rate**
REL	**Lifting**
SP_i	**Sized Power Installed**
TCC	**Total Cost Considered**
VAT	**Value-added tax**
V_w	**Water Volume**
W_p	**Watt-Peak**
Y	**Year**
YEIT	**Yearly electricity increment tax**

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CHAPTER 1. INTRODUCTION

The aim of this thesis is to prove the viability of incorporating PV at existing grid-connected pumping systems and to demonstrate their technical and economic competitiveness with the partial or complete substitution of the grid. It will be presented two study cases that represent the major types of irrigation, to a pool and at constant pressure, Villena and Zujar's cases, respectively. Another fact that will be discussed in this thesis is the relationship between the additional and the stored energy needed to irrigate at constant pressure, and the variability of the solar resource.

1.1. Water Pumping

Water pumping has a long history. As far as man knows, since 2000 BC[1] [1], when the Egyptians invented the shadoof[2] to raise water (Figure 1), different ways to pump water have been developed. This first system consists of a long pole balanced on a plank placed over a meter above the ground. It has a basin and a counterweight, which helps reaching the water. It is a comfortable invention to minimize human effort, particularly when the needed water amount is small. Today the shadoof still can be seen in many places, mainly in the African continent.

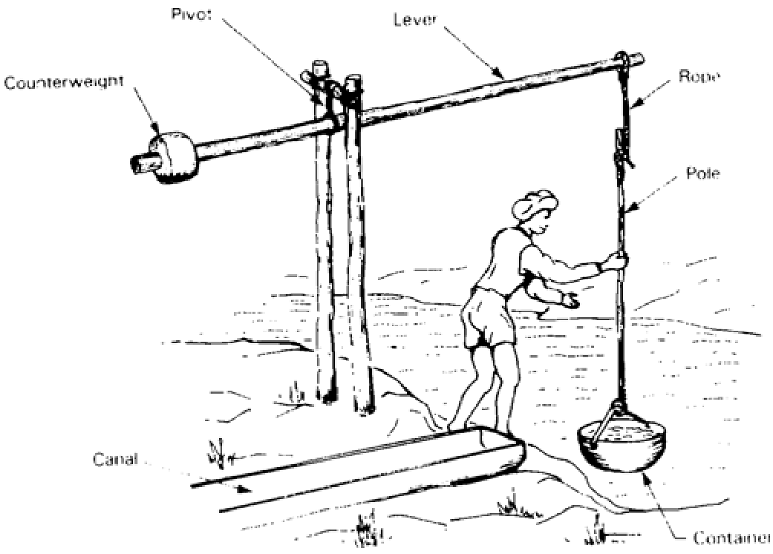

Figure 1 – Shadoof[3]

In the third century BC, the use of the Archimedes' screw was widespread (Figure 2). It is essentially a screw inserted in a hollow cylinder. The bottom of the cylinder is placed in water and the screw rotates. This movement will slide up the water along the screw until it comes out from the upper end of the cylinder. Even today it is quite common to see this type of pump in wastewater treatment plants [2].

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[1] Before Christ
[2] Irrigation tool
[3] http://www.fao.org/docrep/010/ah810e/AH810E05.htm

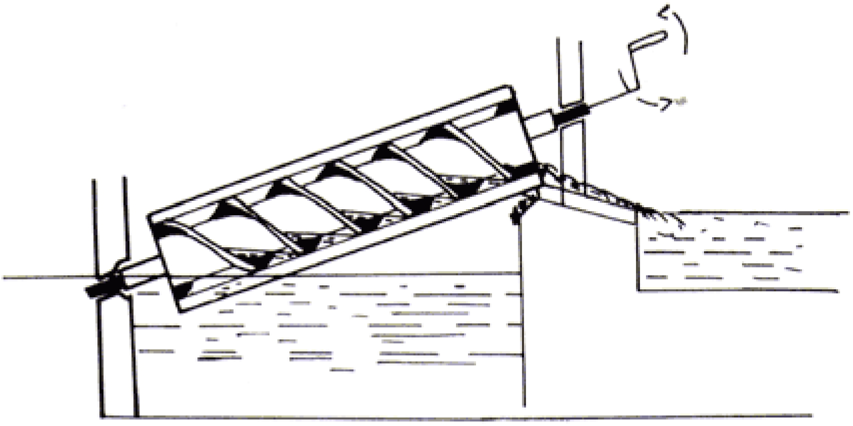

Figure 2 - Archimedes' screw[4]

Although the wheels and hydraulic wheels (Figure 3) were invented in the third century BC, their usage only arised in the eleventh century AD[5]. The system consists on wheels that took advantage of the strength of men or animals to draw water [2].

Figure 3 - Hydraulic Wheel[6]

At the end of the nineteenth century AD all pumps were powered by steam. In the middle of 20th century these pumps were replaced by electric pumps (Figure 4) [2].

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[4] http://fineartamerica.com/featured/archimedes-screw-granger.html

[5] Anno Domini, After Christ

[6] http://pixabay.com/pt/roda-hidr%C3%A1ulica-idade-madeira-168465/

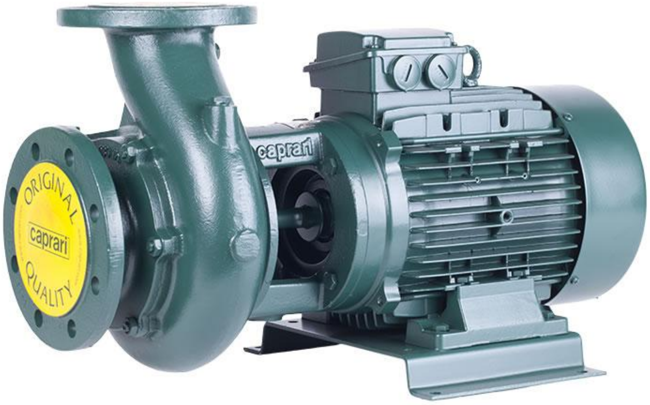

Figure 4 - Electric pump[7]

The shadoof, the Arquimedes' screw and the hydraulic wheel are still in use. However, today´s pumps, the electric ones, are more efficient and some of them are also "environment friendly" if powered by solar or wind energy instead of fossil fuels [2]. The present work is about solar photovoltaic water pumping, which will be thoroughly analyzed in the next subchapter.

1.2. PV Water Pumping

The water pumping powered by photovoltaic (PV) energy is in progress since 1978 [3]. Firstly, it was considered as stand alone systems and it has been used to provide drinking water. Since the price of the electricity soared, as well as the price of the oil, PV solutions are increasingly competitive not only for drinking water supply in isolated areas but also to livestock watering and irrigation/agriculture.

According to Kyocera Solar [4], there are issues besides the cost of energy that also contribute to this development such as the low maintenance, the reliable long life, the fact that this kind of projects are easy to install, the low recurrent costs and its modular characteristic (as they have the possibility to increment the system power by adding more modules).

The PV water pumps are used mainly in regions with good levels of solar irradiation and where the transport of fuel or the grid connection is too expensive. However, this work shows that these criteria are not so strict. The South European countries can be part of this development due to its high irradiation levels and to the growth of electricity and oil prices.

To understand the importance of this kind of systems in photovoltaic industry, according to literature [5], in 1994, $70MW_p$ had been sold, from which 17% were to be used in PV Pump application [6]. As already mentioned, this kind of system appeared as standalone applications. Most of this deployment was the result of many investments programs. There were two relevant cases where the Institute of Solar Energy took apart, one of them as a partner, the PRS [7][8], and the other as director, in one MEDA project [7][8].

The PRS (SRP or Sahel Regional Program, in English) [7][8] was a program supported by the European Union that had the goal to install 600 PV pumps (1.2MW), between 1990 and 1998, in the Sahel[8]. In this the responsibility of the Institute was the development of technical

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[7] http://www.caprari.it/en/_products/products.jsp?idType=89

[8] The Sahel is the ecoclimatic and biogeographic zone of transition in Africa between the Sahara desert to the north and the Sudanian Savanna to the south.

specifications to guarantee the quality of the PV pumps [7][8]. All the others responsibilities, such as supply and installation were done by a regional group. The related hydraulic infrastructure was to be provided by each country, which delegated to the local authorities. The problem here was that they did not have any experience with this kind of projects, and for that reason later evaluations demonstrated that important defects were found in two thirds of the pumps [8][7].

The MEDA program (MEsures D'Accompagnement, French meaning for accompanying measures) was coordinated by the Institute of Solar Energy. This program [7][8] consisted in the sizing and installation of 52 PV Water pumping systems, in a total of 256kW, distributed in Algeria (10 systems/59kW), Morocco (29 systems/138.7kW) and Tunisia (13 systems/58.3 kW). In this case, the installation of the water pumps was done by Isofotón and executed by local teams. The hydraulic infrastructure was responsibility of the local authorities [8][7].

Other relevant examples include Mali (40 systems, in 1990), India (500 systems, in 1995 and 3320, in 2000) and Filipinas (150 systems) [3].

According to Murdoch University, there are more than 10000 solar powered water pumps in use in the world today[9]. In developing countries they are used extensively to pump water from wells and rivers to villages for domestic consumption and irrigation of crops. Nowadays, companies such as Lorentz, Grundfos or Caprari, for example, are able to commercialize PV water pumping solutions. Because of this, this kind of systems are now scattered throughout the world. However, It was not possible to get real numbers in the principal institutions, such as the Euro – Mediterranean Irrigators Community, the International Commision on Irrigation and Drainage, the Food and Agriculture Organization, the International fund for Agricultural Development and the World Water Partnership.

In order to fully understand the PV water pumping is essential to know their components and main features.

1.3. PV Water Pumping System

A photovoltaic pump system is constituted by the photovoltaic arrays, with or without tracking, the motor and the pump, the water storage - that is often elevated - and the water point (Figure 5).

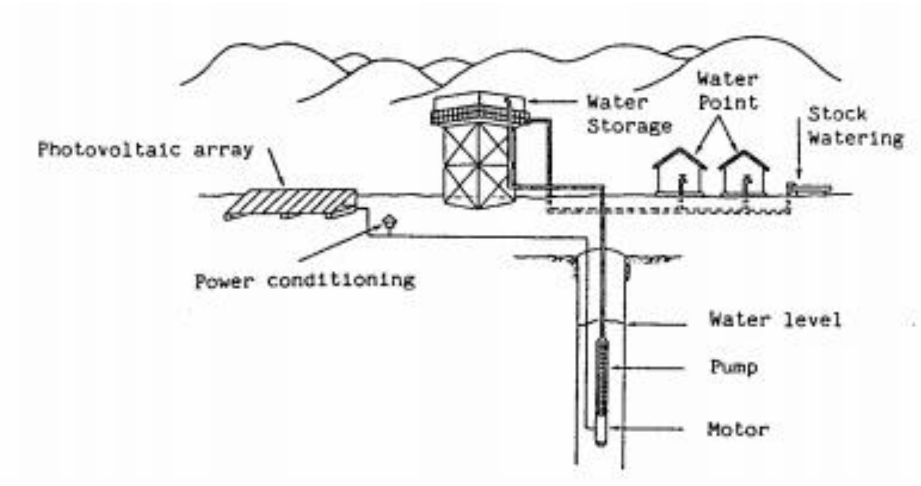

Figure 5 - PV Water Pumping System

The pump normally used to agriculture applications is the centrifugal pump, because of its robustness, effectiveness, the fact that it is well-described and it is produced in any part of the world at an inexpensive cost. Technically, the capacity of pumping at low water flow rates (2 or 3m^3/h) and high rates (5700 m^3/h) and total heads in maximum around the 300 m made them perfect to this kind of application. In this family of pumps, it is used the vertical turbine pumps, because it saves floor space [10].

Figure 6 - Vertical Pump [10]

The principle of these machines [11] consists in the increase of pressure by mechanical energy produced by the motor to the water over the rotor. The water falls from the center of the rotor to their blades, which leads to a fluid velocity increases by the centrifugal effect. This kinetic energy is converted in pressure, which will raise the water.

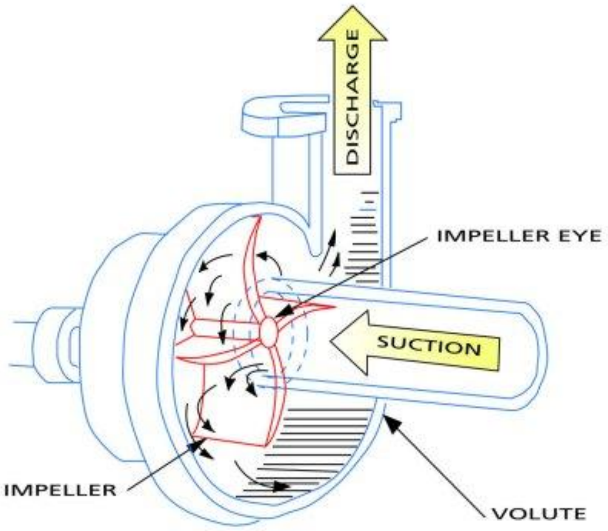

Figure 7 – Scheme of Pump Operation[9]

Besides the centrifugal pumps, it also exists the positive displacement pumps, which have an expanding cavity on the suction side and a decreasing cavity on the discharge side. Liquid flows into the pumps on the suction side that expands and the liquid flows out of the discharge and the cavity collapses, for this reason, the volume is constant. However this kind of pump must not be operated against a closed valve on the discharge side of the pump because it has not a shut-off head like centrifugal pumps, and for that reason it will continue to flow water until the pressure in the discharge line are increased until the pump is severely damaged. A relief or safety valve on the discharge side of the positive displacement pump is therefore absolute necessary. The problem of these pumps is the range of water flow rate, the maximum is around 200 m^3/h [10], that is not enough to this kind of applications that will be analyzed.

Normally, these systems work in alternating current (AC), so the PV arrays that work in direct current (DC) have to use a frequency converter, which invert the tension from DC to AC and vary the frequency.

The PV generator [8] is formed by a set of PV modules electrically connected to inject the power that was sized in direct current coupled with a support structure. The PV generator can have a tracking device or being fixed. For the PV Water Pumping systems that I will study the type of tracker considered is a single axis (North-South) that tracks the sun from East to West. This is considered because its production curve is the one that better fullfil the irrigator's community needs. The solution of a dual axis tracker allows tracking along both axis, not only East-West but also North-South, however the investment cost is higher and it will produce more than the need[12].

The third part that has to exist is the motor. This is an induction electrical motor that will be connected with the pump.

It is important to know the daily required water volume, which is related not only to the pump or the water pool but also to the water supply. It is important to take into consideration the

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[9] http://ffden-2.phys.uaf.edu/212_spring2011.web.dir/Crockett_ColeT/Physics%20of%20Fireground%20Hydraulics%20Pump%20Construction.html

rebound effect. As there is more water available, the people's water use changes and it is therefore necessary to pay attention to the possible consumption increase that could contribute to an unexpected water restriction.

Relatively to the well [8], it is necessary to know the static water level (H_{ST}) which is the water level without pumping. Another value that is important to size (or to know) is the dynamic water level (H_D), related to the level of water decreased with the consumption, as can be seen in Figure 8. According to literature [8], this decrease of the water level could also be related to the permeability of the soil, the percolation of the well or the length of the aquifer.

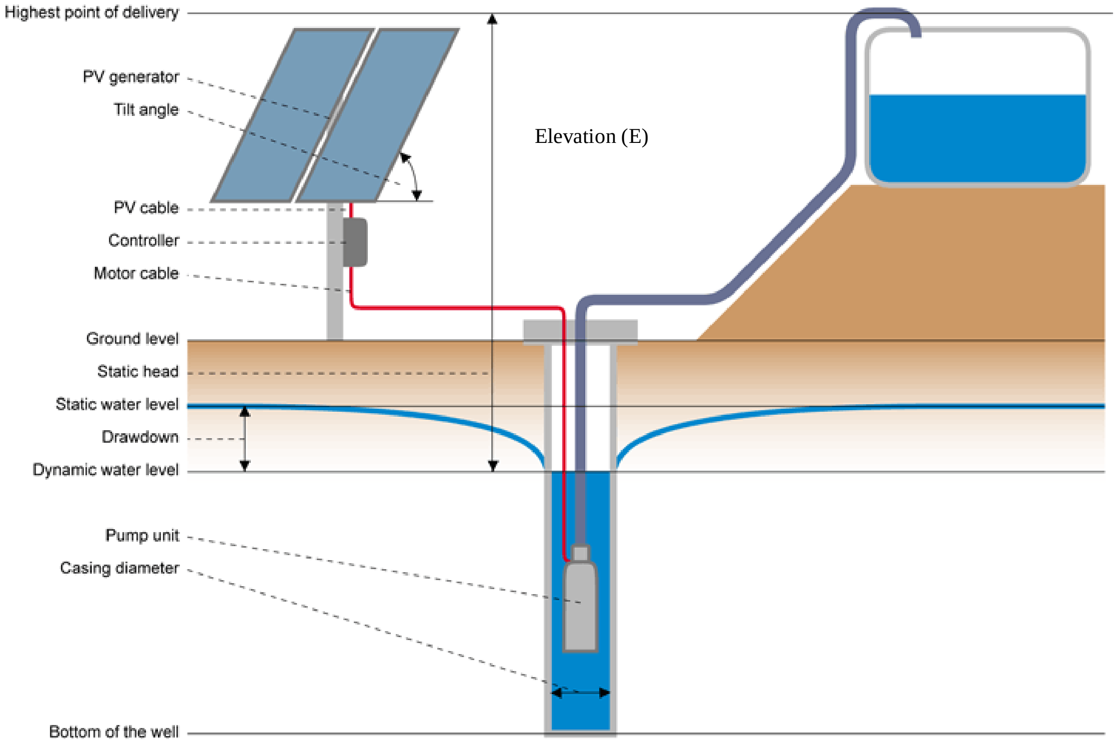

Figure 8 - Water PV Pumping System [13]

According to M. Alonso Abella [14] there are 3 types of PV Water Pumping, systems, classified according to the range of power:

1. Low power systems (50-400W_p), that use a DC motor connected to a positive displacement pump. Between the photovoltaic generator and the motor a DC/DC converter to improve their coupling is inserted.
2. Medium power systems (400-1500W_p) may use a centrifugal pump connected to a frequency converter or can be based on a brushless motor.
3. High power systems (>1500W_p), using frequency converters. These systems are particularly suitable for irrigation.

This thesis will be about this third group. The use of frequency converters allows the utilization of standard motor pumps and thus the use of high power pumps. But other challenges arise, such as the compatibility between high power and the variability of the sun irradiation, which results in instability in the control and thus low system efficiency. Problems in the hydraulic system (such as water hammer[10]) and the impossibility of using these converters for constant pressure irrigation applications are also unresolved issues.

The use of large PV pumping systems for irrigation requires mitigating or even eliminating its variability and, also, the adaptation of the control of standard frequency converters to the specific requirements of PV without the need of extra devices.

The elimination of this variability of PV generation is being addressed for other applications, e.g. grid-connected PV plants to avoid disturbances to the grid using converters [15], or through the integration of batteries, but this solution is still too expensive for market solutions.

According to [15], these converters use transistors that permit to increase the power by switching frequency in order to extract more energy and fulfill the connecting standards. These converters must have a PID[11] control that able to detect situations and take the appropriate measures in order to protect persons and equipment.

UPM has proposed an alternative approach developing a small scale prototype (20 kW PV) pump with a frequency converter like the ones refered before that was validated in a real borehole of 250 m pumping to a 50,000 m^3 pool.

However another propose of this master thesis is to verify the relationship between the additional and the stored energy needed to irrigate at constant pressure, with the variability of the solar resource. Until now, it is referred that this source variability is a huge problem in this kind of application, however it is important to quantify this. This will be done in the last chapter of this work.

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[10] Pressure variations due to flow variations caused by some disturbance, voluntary or involuntary, which is imposed to the flow of liquids in pipes, such as opening transactions or closing valves, mechanical failure of devices protection and control [29]

[11] A proportional-integral-derivative controller (PID controller) is acontrol loopfeedback mechanism(controller)

CHAPTER 2. IRRIGATION

2.1. Irrigation in Europe

Agriculture is considered the principle responsible for water consumption. In Europe, water demand for agriculture depends essentially on the climatic conditions of the country and the type of crop. In the European Union, in 2003, the total area equipped for irrigation was 16 million ha on a total of 182 million ha of agricultural land [16]. It is important to notice that the Mediterranean countries (Portugal, Spain, France, Italy and Greece) account for 75% of the first value, 12 million ha (Table 1), with a corresponding yearly energy demand of about 24000 GWh [17] . In these countries, irrigation is an essential element of agricultural production but it could lead to exceed the natural limit of the availability of the water resources.

Table 1 – Irrigable and irrigated areas by country and irrigated areas finally used for compilation of the EIM in 2006 [16]

Country	Country	Irrigable Area (ha) 2000	Irrigated Area (ha) 2000	Irrigable Area (ha) 2003	Irrigated Area (ha) 2003	Irrigated Area (ha) EIM	AWA (%)
AT	Austria	95240		90420	34230	35900	2.7
BE	Belgium	31970		21110	1610	1610	0.1
BG	Bulgaria			124480	79370	79370	19.6
CH	Switzerland					43820*	74.5
CY	Cyprus			44930	35410	35410	0.8
CZ	Czech Republik			39380	16450	16850	26.4
DE	Germany					234587*	2.9
DK	Denmark	446930		448810	201460	201460	2.2
EE	Estonia					0	14.9
ES	Spain	3475560	3233020	3135930	2849830	3233020	0.5
FI	Finland	88140		100480	0	0	87.8
FR	France	2633350	1575520	2233110	1656780	1575520	3.9
GR	Greece	1321340	1161000	1487210	1278950	1161000	13.7
HU	Hungary	308110	67080	242160	148680	67080	-
IE	Ireland	0	0	0	0	0	18.3
IT	Italy	3855960	2453440	2902000	1746990	2453440	1.9
LT	Lithuania			250		0	0.3
LU	Luxemburg	0	0	0	0	0	-
LV	Latvia	450	0	450	0	0	0.8
MT	Malta			2000	1850	1850	9.7
NL	Netherlands	498280		350560	62150	62150	80.1
PL	Poland			98450	46920	46920	11.8
PT	Portugal	792000		674820	229910	229912	7.8
RO	Romania			1510830	400420	400420	2.1
SE	Sweden	136730		188440	53450	53450	64.9
SI	Slovenia	2230		1880	1880	1880	5.6
SK	Slovakia	225310	110670	209060	104540	110670	
UK	United Kingdom	950(1)		96120(1)	96120(1)	148019*	-
(1) Statistics were complete							
* National sources							

For the particular case of Spain, the area that is used for agriculture is 248000 km^2 (Table 2) which corresponds to 49% of the total territorial area. In this farming land, 13% of the agricultural production of all member states of the European Union is produced [18].

Table 2 - General Distribution of Land by type of culture (2005) [18]

Spain			
Culture type	**Area [ha]**	**Culture type**	**Area [ha]**
Cereal grain	6 840 985	Citrus fruit	306 557
Legumes	410 730	No citrus fruit	1 062 142
Tubercle	72 420	Vineyard	1 149 749
Industrial	728 898	Olives	2 456 719
Fodder	852 630	Other Woody crops	59 940
Vegetables	199 668	Greenhouses	16 218
Flowers and plants	1 707		
Total arable crops	**7 107 038**	**Total Woody crops**	**5 051 325**
Fallow	3 319 193	Surface greenhouse	65 218
		Kitchen gardens	100 904
Other farmland	**3 319 193**	**Other farmland**	**166 122**
Total arable land	**12 426 231**	**Total cropland**	**17 643 678**
		Grassland	7 329 335
		Surface wooded forest	11 546 276
		Other surfaces	13 968 521
		Geographic area	**50 487 836**

According to the National Irrigation Plan, Horizon 2008, published by the Ministry of Agriculture, Fisheries and Food in 2001, the number of existing Irrigation Communities in Spain stood at 7196.

2.2. Electricity cost for irrigation

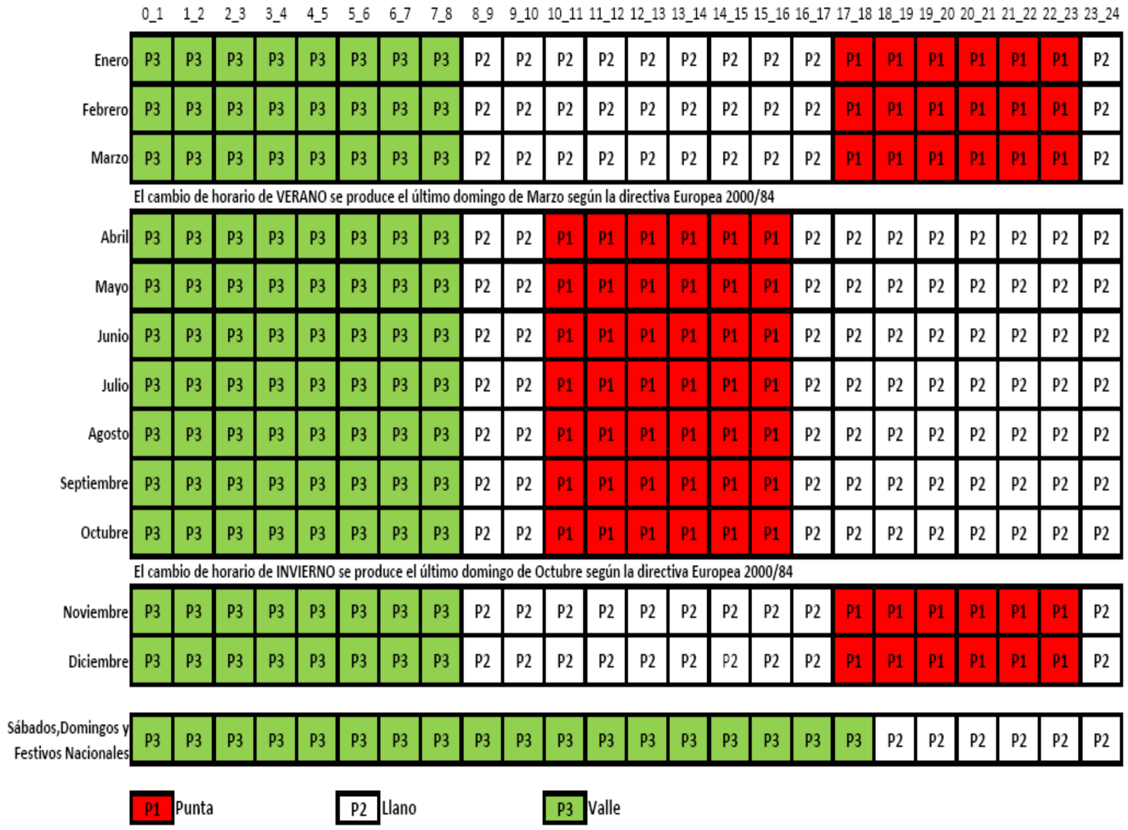
“Energy is essential for Europe to function, but the days of cheap energy for Europe seem to be over. The challenges of climate change, increasing import dependency and higher prices are faced by all EU members” [19].

Irrigation is more and more dependent on energy, due to the modernized irrigation systems [20] that exist in the present. More specifically in Spain, there were things that contributed to this dependence, such as, the abolition of the special electricity of high and low voltage for irrigation (2008), as well as the liberalization of the Spanish electricity market (2007)[20]. Accordingly to literature [21], the energetic consumption had increased from 206 kWh/ha in 1950 to 1560 kWh/ha in 2007. And the energetic price since the liberalization of electricity has increased 80% [22].

The user, as in every electricity contract, has to pay two major fees: the power fee and the active energy fee. There are two major types of tariffs that the communities of irrigators in Spain can contract, one is the model 3.1 (Figure 9) and the other, the 6.1 (Figure 10). The first digit corresponds to the number of periods that it has. These ones correspond to the divisions that the day has and each one has a different price.

The active energy fee that the user will pay is the product between the energy that was consumed (measured by the electricity meter) and its price for the correspondent period.

The power fee is the fee that the user has to pay for having a guarantee of power, this is, to be sure that at any time of the day it is possible to access to a maximum amount of power. However, it is important to note that if they exceed the contracted power, the grid will give it, but paying a penalty. Finally, it is important to mention that the user can contract any power term as long as the last period is greater or equal than the previous one and that it is possible for the user to change these terms in a yearly basis. This can be calculated as the sum of product of the contracted power in each period.



	0_1	1_2	2_3	3_4	4_5	5_6	6_7	7_8	8_9	9_10	10_11	11_12	12_13	13_14	14_15	15_16	16_17	17_18	18_19	19_20	20_21	21_22	22_23	23_24
Enero	P3	P3	P3	P3	P3	P3	P3	P3	P2	P2	P2	P2	P2	P2	P2	P2	P2	P1	P1	P1	P1	P1	P1	P2
Febrero	P3	P3	P3	P3	P3	P3	P3	P3	P2	P2	P2	P2	P2	P2	P2	P2	P2	P1	P1	P1	P1	P1	P1	P2
Marzo	P3	P3	P3	P3	P3	P3	P3	P3	P2	P2	P2	P2	P2	P2	P2	P2	P2	P1	P1	P1	P1	P1	P1	P2

El cambio de horario de VERANO se produce el último domingo de Marzo según la directiva Europea 2000/84

	0_1	1_2	2_3	3_4	4_5	5_6	6_7	7_8	8_9	9_10	10_11	11_12	12_13	13_14	14_15	15_16	16_17	17_18	18_19	19_20	20_21	21_22	22_23	23_24
Abril	P3	P3	P3	P3	P3	P3	P3	P3	P2	P2	P1	P1	P1	P1	P1	P1	P2	P2	P2	P2	P2	P2	P2	P2
Mayo	P3	P3	P3	P3	P3	P3	P3	P3	P2	P2	P1	P1	P1	P1	P1	P1	P2	P2	P2	P2	P2	P2	P2	P2
Junio	P3	P3	P3	P3	P3	P3	P3	P3	P2	P2	P1	P1	P1	P1	P1	P1	P2	P2	P2	P2	P2	P2	P2	P2
Julio	P3	P3	P3	P3	P3	P3	P3	P3	P2	P2	P1	P1	P1	P1	P1	P1	P2	P2	P2	P2	P2	P2	P2	P2
Agosto	P3	P3	P3	P3	P3	P3	P3	P3	P2	P2	P1	P1	P1	P1	P1	P1	P2	P2	P2	P2	P2	P2	P2	P2
Septiembre	P3	P3	P3	P3	P3	P3	P3	P3	P2	P2	P1	P1	P1	P1	P1	P1	P2	P2	P2	P2	P2	P2	P2	P2
Octubre	P3	P3	P3	P3	P3	P3	P3	P3	P2	P2	P1	P1	P1	P1	P1	P1	P2	P2	P2	P2	P2	P2	P2	P2

El cambio de horario de INVIERNO se produce el último domingo de Octubre según la directiva Europea 2000/84

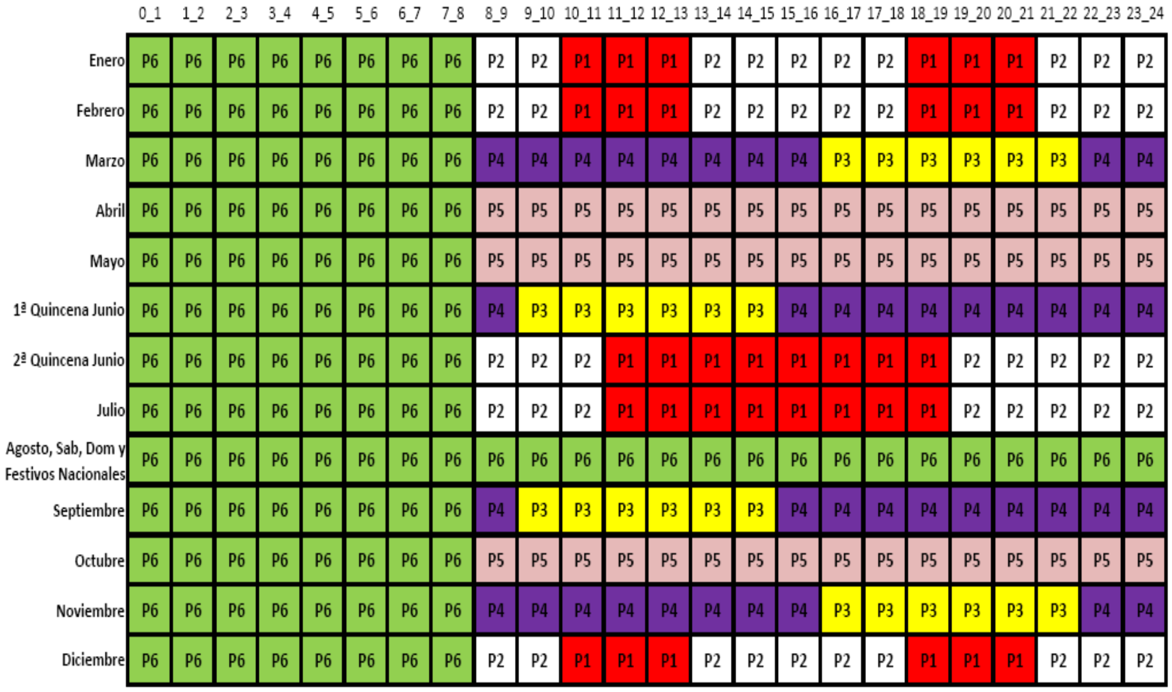
	0_1	1_2	2_3	3_4	4_5	5_6	6_7	7_8	8_9	9_10	10_11	11_12	12_13	13_14	14_15	15_16	16_17	17_18	18_19	19_20	20_21	21_22	22_23	23_24
Noviembre	P3	P3	P3	P3	P3	P3	P3	P3	P2	P2	P2	P2	P2	P2	P2	P2	P2	P1	P1	P1	P1	P1	P1	P2
Diciembre	P3	P3	P3	P3	P3	P3	P3	P3	P2	P2	P2	P2	P2	P2	P2	P2	P2	P1	P1	P1	P1	P1	P1	P2
Sábados,Domingos y Festivos Nacionales	P3	P3	P3	P3	P3	P3	P3	P3	P3	P3	P3	P3	P3	P3	P3	P3	P3	P3	P2	P2	P2	P2	P2	P2

P1 Punta

P2 Llano

P3 Valle

Figure 9 - Matrix with the three payment periods throughout the day (from left to right) and for each month (from top to bottom). Should also be noted that the last line is referred to Saturday, Sunday and national holidays, Model 3.1



	0_1	1_2	2_3	3_4	4_5	5_6	6_7	7_8	8_9	9_10	10_11	11_12	12_13	13_14	14_15	15_16	16_17	17_18	18_19	19_20	20_21	21_22	22_23	23_24
Enero	P6	P6	P6	P6	P6	P6	P6	P6	P2	P2	P1	P1	P1	P2	P2	P2	P2	P2	P1	P1	P1	P2	P2	P2
Febrero	P6	P6	P6	P6	P6	P6	P6	P6	P2	P2	P1	P1	P1	P2	P2	P2	P2	P2	P1	P1	P1	P2	P2	P2
Marzo	P6	P6	P6	P6	P6	P6	P6	P6	P4	P4	P4	P4	P4	P4	P4	P4	P3	P3	P3	P3	P3	P3	P4	P4
Abril	P6	P6	P6	P6	P6	P6	P6	P6	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5
Mayo	P6	P6	P6	P6	P6	P6	P6	P6	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5
1ª Quincena Junio	P6	P6	P6	P6	P6	P6	P6	P6	P4	P3	P3	P3	P3	P3	P3	P4	P4	P4	P4	P4	P4	P4	P4	P4
2ª Quincena Junio	P6	P6	P6	P6	P6	P6	P6	P6	P2	P2	P2	P1	P1	P1	P1	P1	P1	P1	P1	P2	P2	P2	P2	P2
Julio	P6	P6	P6	P6	P6	P6	P6	P6	P2	P2	P2	P1	P1	P1	P1	P1	P1	P1	P1	P2	P2	P2	P2	P2
Agosto, Sab, Dom y Festivos Nacionales	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6
Septiembre	P6	P6	P6	P6	P6	P6	P6	P6	P4	P3	P3	P3	P3	P3	P3	P4	P4	P4	P4	P4	P4	P4	P4	P4
Octubre	P6	P6	P6	P6	P6	P6	P6	P6	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5
Noviembre	P6	P6	P6	P6	P6	P6	P6	P6	P4	P4	P4	P4	P4	P4	P4	P4	P3	P3	P3	P3	P3	P3	P4	P4
Diciembre	P6	P6	P6	P6	P6	P6	P6	P6	P2	P2	P1	P1	P1	P2	P2	P2	P2	P2	P1	P1	P1	P2	P2	P2

Figure 10 - Matrix with the six payment periods throughout the day (from left to right) and from the top to the bottom with following order (January; February; March; April; May; 1stFortnight of June; 2ndFortnight

of July; August, Saturday, Sunday and National Holidays; September; October; November and December, Model 6.1

For the particular case of irrigation, the price of energy (€/kWh) is increasing very fast: from 2008 to 2013 it increased 1250% in Spain, 226% in Portugal and 32% Italy [23]. This increase in the price of energy creates the conditions for change of behavior of irrigators.

Figure 11 and 12 present [15] the evolution of the price of the electricity in Spain for the most common two types of fee used to irrigation the term 3.1, in the Figure 11 and the 6.1 in Figure 12, for two irrigator's communities.

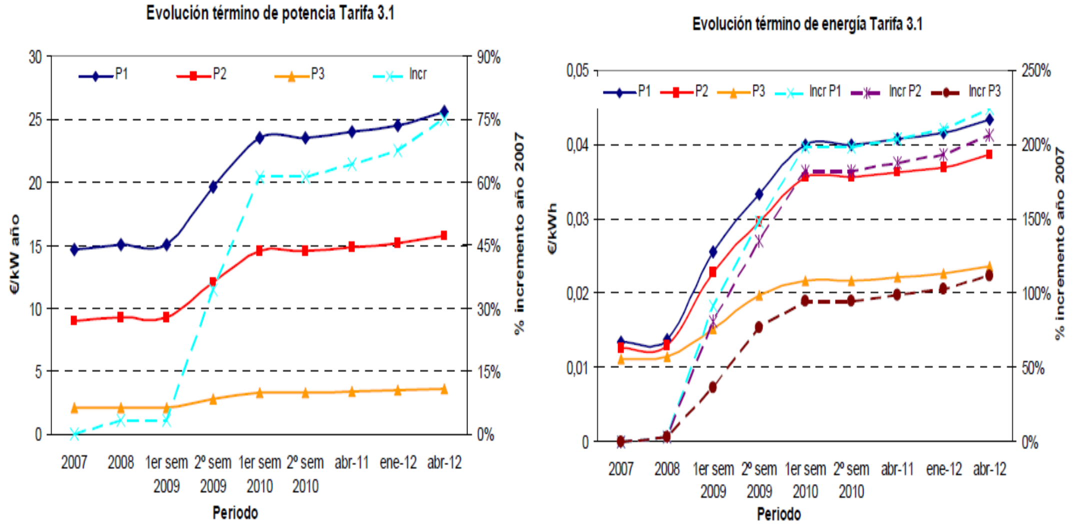


Figure 11 - Evolution of the Active Energy and the Power fees for 3.1A [15]

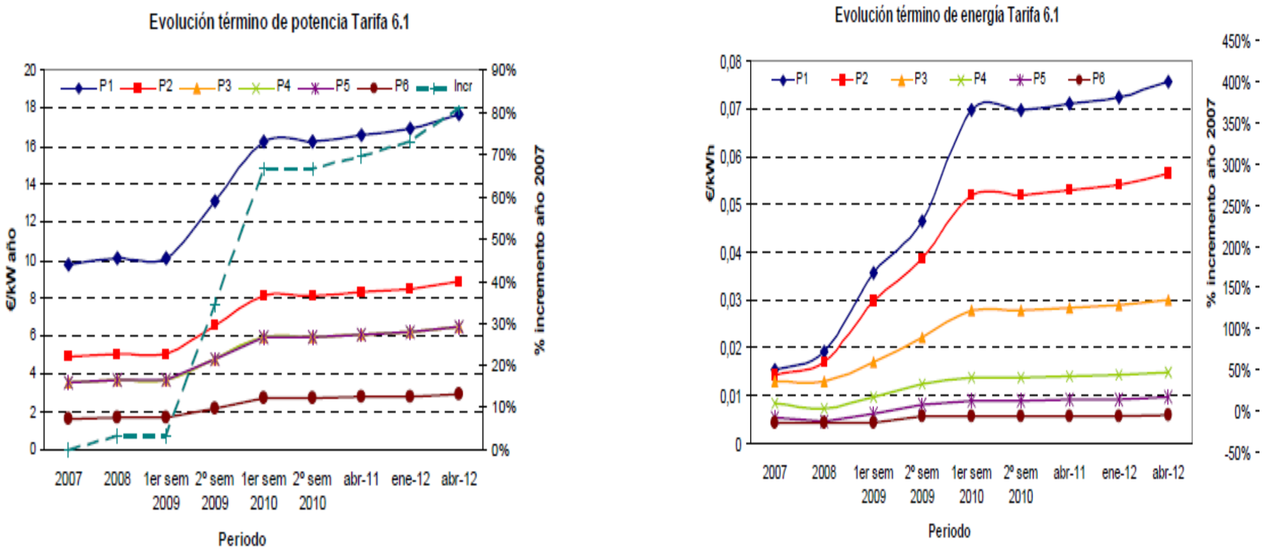


Figure 12 - Evolution of the Active Energy and the Power fees for 6.1. [15]

More detailed, it is possible to verify that between 2007 and 2012, relatively to the Figure 11, an increasing of the power fee of 75.2% for all the periods and 224%, 207% and 112% for all the periods of the active energy fee.

Relatively to the Figure 12, it is possible to see the evolution of the both costs. Relatively to the power fee, this increment is around the 81% for all the periods and the 390.1%, 291.8%, 134.1%, 76.3%, 81.4% and 41.3%, to all the periods, respectively for P1, P2, P3, P4, P5 and P6 periods.

As it was referred before, these results are only for two irrigator’s communities but are expected to reflect a more general description of irrigation energy costs in Spain and perhaps in the others Mediterranean Countries.

On the other hand, it highlights the importance to the communities to consume the energy in the right time to pay less. It is in here that PV systems earn more importance because the hours of more solar production correspond to the periods that are more expensive (Power and Active Energy fees), for that it is possible to the communities to contract a power term in this period of a lower power.

To emphazise the impact of the irrigation communities, after ADIF (Administrador de Infraestructuras Ferroviarias in Spanish, or Railway Infrastructure Administrator, in English) they are the major consumers of electricity in Spain. In the irrigation, as time goes by, it is necessary more energy (in this case electricity) to pump the water because not only the necessities are increasing but also it is necessary to pump from deeper wells. This case brings us to the real importance of the energy.

2.3. European Market

As already known, the electricity price has dramatically increased year after year and, currently, the mean price paid for the electricity supplied by the grid is 100€/MWh. If this number is taking into account and as referred before, the consumption is about 24000GWh/year, irrigators spend about 2400M€ per year.

Take into account the annual consumption considered before, with the intention of satisfying this electrical demand, it would be needed to install 16 GW of PV pumps. Considering an estimated cost of 1.5€/W_p, this could represent a latent market in the South of Europe of 24000M€ in terms of high power PV pumps to supply this electrical need. Without considering the interest rates of the credits or the increase of the price of the electricity, in 10 years this investment was sold. It is important to refer that these systems are prepared to work for 25 years.

Instead, the water that is consumed year after year for irrigation is reducing, once the industry is modernizing the irrigation technologies. For example, in the last years in Spain the water consumption has reduced from 7000 m^3/ha to 5000 m^3/ha (28% of reduction). The price to pay for this modernization is the use of more energy as seen before. The lack of water, along with the need to maintain the agricultural activity, is forcing the need for the use of more efficient technologies for irrigation. The objective is, with low energy irrigation systems, to reach a mean figure of 3500 m^3/ha. It is estimated that for this application the market is estimated in 800 M€/year during the next ten years in the South of Europe.

Moreover the fact that this work is about the previous case, the market for photovoltaic irrigation is not restricted to the South of Europe but also to many other regions in the world where the electrical grids are not extended or even in places that use diesel pumps, with a high cost, related not only with the increase of the cost of the oil, but also the transport of that to remote areas.

As referred previously, this work is about high power PV pumping. For instance, the Institute of Solar Energy in conjunction with the Polytechnic University of Madrid produced a small scale prototype with 20kW PV pump, financed by the Spanish Government able to pump 50000 m^3 to a water pool or an amount of them. The problem related to PV power variability was solved and comparing the previous cost of pumping with the grid with the actual cost with the PV prototype, the kWh cost reduction was around 60%. According to that, the Institute of Solar Energy pretend to extrapolate the use of a system like this one, to others communities of irrigators, and be able to reduce their costs with electricity. The first study of this master thesis will have as basis this prototype.

CHAPTER 3. METHODOLOGY

3.1. Technical Analysis

The technical performance of PV pumping systems was developed using the IESPRO tool. This is a software tool developed in Matlab, which can analyze the energy produced by any photovoltaic system, of any technology, in any place in the world. In this software, factors as shadows or dust, or even spectral response in the modules, are taken into account.

In the last year, a new functionality was also developed by the Institute (see Figure 13) oriented to PV Water Pumping. It uses geographical and meteorological data, PV modules and generator characteristics and motor and pump characteristic curves as input to give the user the following information: energy production, water volume pumped, Sankey diagram and the intermediate parameters.

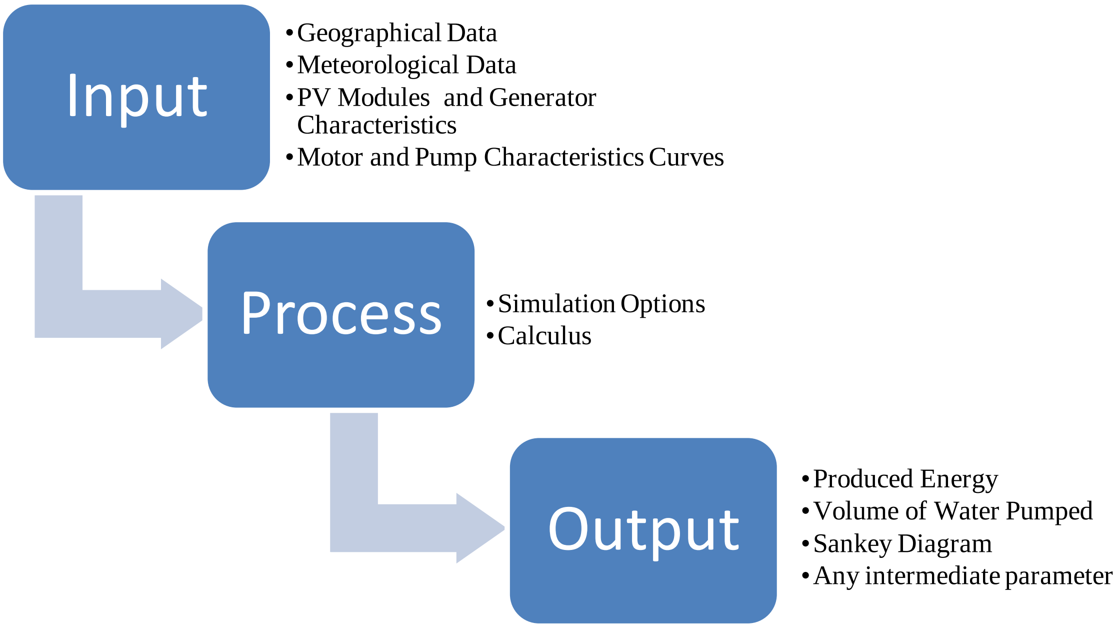


Figure 13 - IESPRO Diagram oriented for PV Water Pumping

The software works as follow:

1. It calculates the electrical power delivered by the generator assembly to the pump motor.

$$\boxed{P_{\mathrm{DC}}(G,T_{\mathrm{C}}) = P^{*} \times P_{\mathrm{RVN}} \times \frac{G}{G^{*}} \times [1-\gamma(T_{\mathrm{C}} - T_{\mathrm{C}}^{*})] \times \frac{\eta_{\mathrm{G,25}}}{\eta^{*}} \times (1 - PER_{\mathrm{CAB\_DC}})} \qquad (1)$$

2. Where, P* is the nominal power of the generator, P_{RVN} is the relationship between the output power and the power for STC. G is the irradiance in the generator and G* is the 1000 W/m^2. The γ is the coefficient that permits to calculate the power variation with the temperature. T_c is the current cell temperature and the T_c* is 25ºC. Finally, the PER_{CAB_DC} that represents the losses in the cables.
3. It uses information about solar radiation and ambient temperature of the place (provided, for example, by the PVGIS database); photovoltaic generator (rated power, coefficient of variation with temperature, Nominal Operation Cell Temperature

(NOCT), layout of bypass diodes, type of activity and geometry) and inverter (relationship between efficiency and power).

4. It calculates, for a given height, the relation between the electrical power delivered to the motor and the water flow to the pump outlet. It uses the information provided by the manufacturer of the pump on the H-Q curves (see Figure 14).

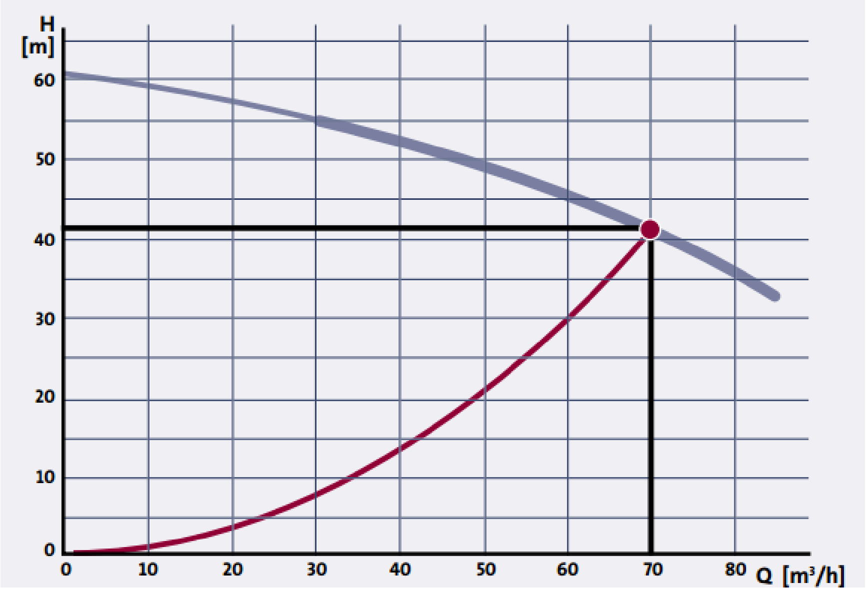


Figure 14 - A typical QH-curve for a centrifugal pump: low flow results in high head and high flow results in low head

Also from the manufacturer it is possible to get the P2-Q curve (see Figure 15) at rated speed and engine efficiency in terms of its mechanical output power that the user had introduced.

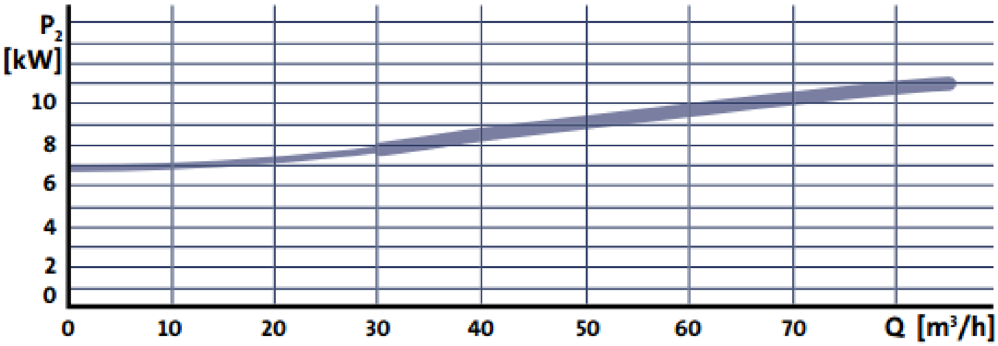


Figure 15 - The power consumption curve of a typical centrifugal pump

5. Through the results of the previous step, it can calculate the water flow. The water pumped in each month will correspond to the integral of that water flow during the period considered.

3.1.1. Input

In the IESPRO, there are inputs related to the whole system and others only related to the motor-pump system. First of all, the user has to define the geographical data, such as the coordinates and its elevation. These data could be obtained, for example, through the PVGIS[12] platform. Next, it is necessary to define the meteorological data for the area in question. From the Meteorological Agencies, or again from PVGIS, it is possible to get all the information needed, such as monthly average daily irradiance, monthly average maximum daily temperature, monthly average minimum daily temperature, link turbidity and wind speed. After this, the user has to parameterize the generator data, where all the standard test conditions have to be defined, as well as the efficiencies at different irradiances, and the technology. There is also a parameter for the losses that are divided in AC and DC components. It is possible for the user to get this data from the datasheet of every element or even using the predefined ones. Then the user has to define some simulation options that are available in the next table, Table 3.

Table 3 – Options of Simulation and Typical value

Option of Simulation	Possible Values
Tracking Type	Static Structure, **Horizontal Axis**, Azimuthal Axis, 2 Axis
Degree of contamination of the PV generator	Degree of Contamination (0,**2**,3,8%)
Simulation of a static generator oriented to Equator and the optimal slope	Yes, **No**
Time range to the calculation	**15** minutes (it can be chosen any value)
Spectral Response	**Yes**, No
Daily Correlation KD-KT	**Page**, Erbs, Macgnan
Hourly Correlation KD-KT	**Orgill-Hollands**, Erbs
Diffuse Model	**Isotropic**, Anisotropic (Hay), Anisotropic (Peréz)
Simulation for the average day, clear day or input data	**Clear**, Mean, Worst day
Simulation with wind data (PV Concentration)	Yes, **No**
Shading models	Optimist, Pessimist, **Classic**, Martinéz et al
Day time change from summer to winter	**Yes**, No
Day time change from winter to summer	**Yes**, No

All these options of simulation have a variety of selections, for example in the first case, once the user choose the type of tracker, he or she will have to define other parameters related to that, such as the inclination, the distance between generator or even the maximum inclination.

Once all these parameters are defined it is necessary to specify the motor-pump system parameters. These parameters are described in Table 4. And their value depends from well to well.

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[12] PVGIS can be seen in http://re.jrc.ec.europa.eu/pvgis/

Table 4 – Characteristics of the pumping system

Static height
Friction losses
Water density
Nominal speed
Water flow
Nominal height
Motor nominal power

Through the characteristic curve with variations of the water flow, height, power and motor efficiency, with six points of each parameter across the application range, the software does a polynomial fit to these data.

If not all parameters are known, by knowing the demand of water that the irrigator's community wants to pump, it is possible to start the selection of the system. First it is necessary to define the mean flow rate (Q that is expressed in m^3/h) of the application that is calculated with the following equation (Equation 1):

$$Q = \frac{1}{365}\sum_{n=1}^{12}\frac{V_m}{NSH_m} \tag{2}$$

where V_m (in m^3) corresponds to the volume of water pumped in each month, and NSH_m (in hours) is the daily average number of sun hours, for every month. With this value, the total head (H_t), can be calculated as the sum of the Dynamic Head (H_D, expressed in meters and the elevation (E) expressed in meters as well, as it is stated in the Equation 2.

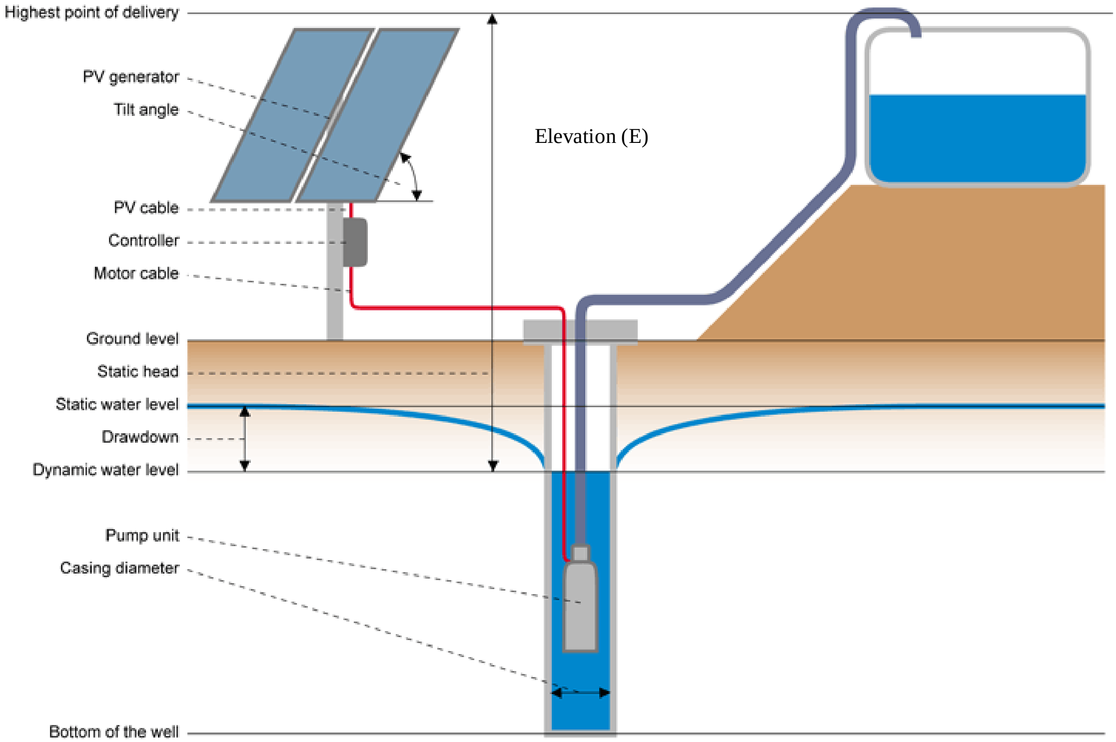
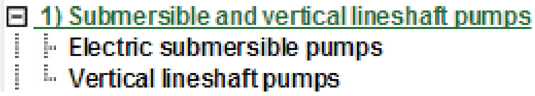


Figure 16 - Water PV Pumping System [13]

$$H_T = H_D + E \quad \text{(See 16)} \qquad (2)$$

Then it is possible to choose the motor-pump system. This could be done by finding it in a catalogue or using a tool that many motor-pump system brands have on the internet. This tool is a graphical user interface that the user only has to fill some parameters. For this work, the internet tool of Caprari[13], named as IPUMP, was used. Once the user has done registration in the IPUMP platform, it is necessary to choose the type of system that he or she wants. Figure 17 lists all the types of systems that it is possible to use. They are classified in submersible and vertical lineshaft, drainage and sewage pumps, monobloc and horizontal shaft pumps and flow accelerators and mixers.



1) Submersible and vertical lineshaft pumps
  - Electric submersible pumps
  - Vertical lineshaft pumps

Figure 17 - IPUMP general menu

Once the user chooses the most suitable type of system, a duty point menu (Figure 18) appears. Here, it is necessary to fill the flow rate (Volume of water pumped per hour), the total head and the static head. All the other parameters remain unchanged.

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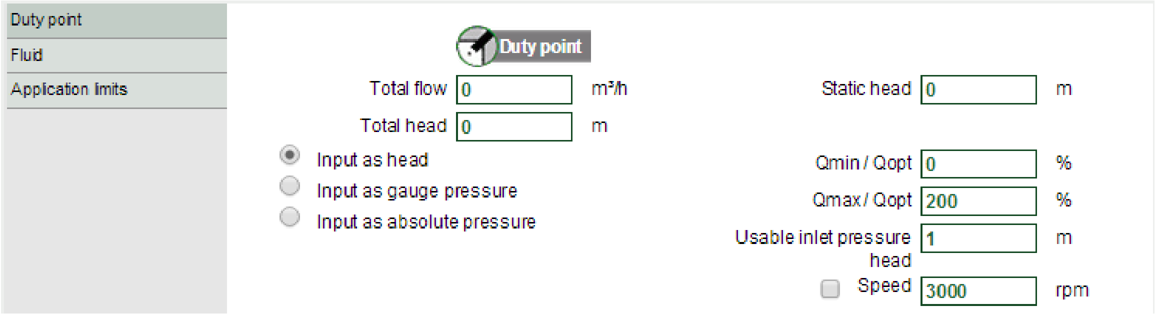
[13] Caprari is a leading international manufacturer in the production of centrifugal and electric pumps and in the creation of advanced solutions for management of the integrated water cycle.



Total flow 0 m³/h

Total head 0 m

● Input as head

○ Input as gauge pressure

○ Input as absolute pressure

Static head 0 m

Qmin / Qopt 0 %

Qmax / Qopt 200 %

Usable inlet pressure head 1 m

☐ Speed 3000 rpm

Figure 18 – IPUMP duty point menu

Since this is filled, all the motor-pumps systems that satisfy all the conditions that the user had decided will appear. An example of this can be seen in the next figure, Figure 19.

Type / Coding	Pump	n [rpm]	Discharge size	Δ Q/Q [%]	Δ H/H [%]	η [%]	P [kW]	Energy costs [EUR]
E8SX57/3I + MACX625-8V	E8SX57	2900	DN125	1.5	3	79.7	18.5	43,610.18
E9S55N /3C + MAC625-8V	E9S55	2900	DN125	0.61	1.2	78.4	18.5	44,046.44
E9S50N /3A + MAC625-8V	E9S50	2900	DN125	0.33	0.65	78.1	18.5	43,732.94
P8L/5/20/3A	P8L	2900	DN125	1.7	3.4	78.1	11	39,998.48
P8C/5/20/3C	P8C	2900	DN125	0.61	1.2	77.3	15	39,367.63
E8SX60/3C + MACX630-8V	E8SX60	2900	DN125	0.08	0.16	77	22	43,601.26
E8SX55/4P + MACX625-8V	E8SX55	2900	DN100	0.84	1.7	75.6	18.5	45,476.47
E8S64N /3A + MAC630-8V	E8S64	2900	G5"	4.3	8.9	74.8	22	48,996.40
P9L/6/24/3H	P9L	2900	DN150	6.8	14	73.6	30	47,001.72
P9C/6/24/3G	P9C	2900	DN150	1.8	3.7	71.4	30	43,621.54
E10S50N /2E + MAC630-8V	E10S50	2900	DN150	1.1	2.1	71.2	22	47,891.66
P7C/4/20/4A	P7C	2900	DN100	0	0	69.8	11	42,947.12
P8F/4/20/4B	P8F	2900	DN100	-0.74	-1.5	69.5	15	42,443.96
E10S55N /2B + MAC840-8V	E10S55	2900	DN150	5.8	12	67.3	30	53,588.22
E8S55N /5I + MAC630-8V	E8S55	2900	DN100	2.2	4.4	66.9	22	51,246.94
P10L/6/24/2F	P10L	2900	DN150	1.1	2.2	65.6	30	46,796.75
P12C/7/30/6F	P12C	1450	DN175	3.8	7.8	64.6	37	50,465.01
P10C/6/24/2G	P10C	2950	DN150	1.6	3.3	59.9	30	51,178.46

Figure 19 – List of motor-pumps for an example

As there are plenty of motor-pumps systems for the same characteristics, it is required to analyze all of them, according to the specifications that the user (that in this case are the irrigation communities) want to their fields. Parameters such as the application range, the nominal power, the efficiency or even the motor characteristics will modify the curve [head-flow rate], shown in Figure 20. The idea is that the maximum and the minimum water flow rate produced by the motor-pump system, from the available irrigator's data, to be contained in the application range (marked in red in the Figure 20).

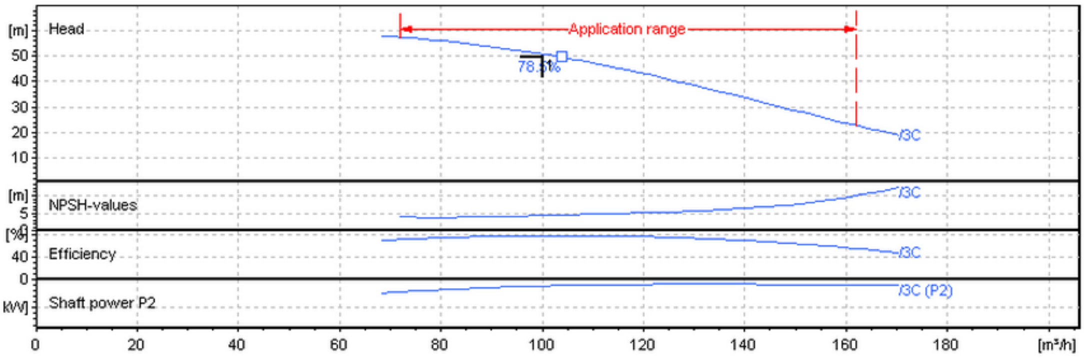


Figure 20 – Example of Head, NPSH, Efficiency, Shaft Power curves in function of the flow rate

The platform permits to the user to see all the points of the curve, and give the information of the water flow, the efficiency and the power. With six disperse points, as well as the nominal values, it is possible to fill all the inputs related with the Water Pumping System.

3.1.2. Output

Once you run the program in the Matlab platform, 4 options are available, as can be seen in the next table (Table 5).

Table 5 - IESPRO Menu

0	Exit
1	Report
2	Sankey Diagram
3	Characteristics Curves

Option 0 gives the user the possibility of using any array, any parameter or any variable calculated along the simulation and with that to output the water flow or to plot anything that the user desires. The principal parameters analyzed are the water flow rate, the frequency, the efficiency of the system, the produced energy and the irradiance.

Option 1 generates a report (as well as the diagrams and the curves).

Option 2 allows the user to have an idea whether the system is well sized. In the Sankey diagram, the user has access to the input and output of energy. It starts with the horizontal global irradiation and the production at reference conditions and the output is the produced AC energy, the hydraulic energy and the cubic meters pumped. There are also represented losses, divided in the pump, the motor, the cables, the inverter, the temperature, the power, the spectrum and finally the reflection.

Option 3 generates four different graphics. Two of them, are in function of the flow rate (Q), one represents the height (H-Q) and the other the mechanical power (P2-Q) at the output of the motor. The next one is the motor efficiency in function of the mechanical power (Eff-P2) and the last one is the flow rate in function of the electrical power (Q-P).

3.2. Economic Study

In addition to the technical study, another point of this work was to verify the economic viability of this kind of investment. Therefore, the return on investment as a result of total or partial replacement of the exclusive use of the grid by a photovoltaic system will be calculated.

To do that, it is necessary to know the cost of a PV Water Pumping system, the price of the electricity from the grid, if the community pumps exclusively with that and finally the electricity price that the user will pay if theyreplace partial or totally their current system by PV.

3.2.1. PV Water Pumping System cost

The IES tested a 20kWp system in Villena (nowadays it is working in Ouarzazate, in Morroco) and the costs that will be considered for the economic studies will be from this case study. It will be also considered an adjustment, to actualize the costs of all the components, related with a large scale production of all the elements. Table 6 shows the costs for W_p of all the components.

Table 6 – Costs per W_p installed for all water pumping system components

Component	Prototype Cost [€/W_p]	Cost considered in the scenario [€/W_p]
PV Generator	0.92	0.75
North-South Tracker	0.77	0.50
Pump	0.18	0.10
Electrical Cabinet	0.20	0.16
Hydraulic Kit	0.11	0.10
Electrical + Installation Kit	0.25	0.20
Total	**2.43**	**1.81**

As can be seen, the photovoltaic system represents 69% of the entire installation (41% for the PV array and 28% for tracking system). It should be noted that the investment in the pump only represents 5% of the total investment. And it must be referred that many pumps do not have to changed.

3.2.2. Cost of grid electricity for irrigation

Beside the initial investment, it is necessary to know the price of the energy from the grid for water pumping solutions.

One thing that is possible to note is that the hours of PV production correspond to the higher period cost. It means that the user could pay less for the energy and contract a low power guarantee in that period, for example. On the other hand, the periods where the price is cheaper, are the ones in which the PV does not produce.

The economical studies were done based on the two types of data considered, monthly bills, with the total value of energy consumed for each month, and bills with more detailed information, which include the hourly consumed energy.

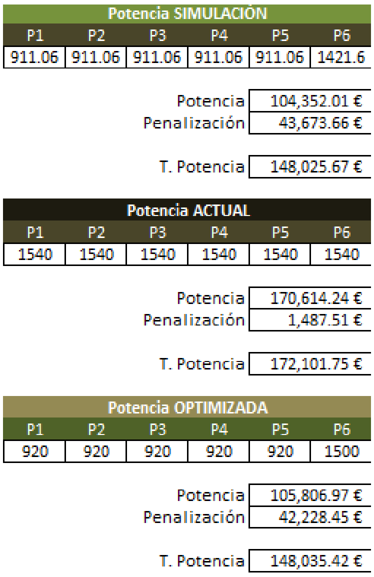
For the first case the average of the values was considered, and it was considered a mean value for the active energy fee and the power fee, whereas for the second case the hourly consumption was used and because of that were calculated the cost considering the power fee and the energy fee for each period.

3.2.3. Electricity Price considering the total or partial replacement with PV

The economic study will be done according to the information provided by the community. If the information is only the monthly values (case A), the savings considered by using PV Water Pumping Systems result of the product from the mean value of the price of electricity in the year by the energy produced by the PV application. On the other hand, if the data provided by the community is more detailed (hour per hour or even 30 minutes in 30 minutes) it is possible to do a different study. To do this one it was developed an excel tool that permits to calculate the savings by the optimization of the contracted power as well by the reduction of the energy consumed by the utilization of the PV.

3.2.4. Economical tool

In this tool once we had access to the consumed energy, as well as, the money that they have paid for it and the quantity in cubic meters of water that was pumped, for example in the previous year, it is possible to extract two important data for an economic test, the cost of energy (€/kWh) and the cost of water pumped (€/m^3). Furthermore, if the user enters the PV energy production, the tool can optimize the contracted power to minimize the grid electricity cost, and can calculate the cost of the electricity with the PV system, considering also penalties by surpassing the value of the contracted power. In the first sheet, called summary for optimization, the user has to insert the current contracted power on each term, P1, P2, among others, depending on the type of tariff (3, in the 3.1.fee and 6, in the 6.1), Figure 21.



Potencia SIMULACIÓN					
P1	P2	P3	P4	P5	P6
911.06	911.06	911.06	911.06	911.06	1421.6

Potencia	104,352.01 €
Penalización	43,673.66 €
T. Potencia	148,025.67 €

Potencia ACTUAL					
P1	P2	P3	P4	P5	P6
1540	1540	1540	1540	1540	1540

Potencia	170,614.24 €
Penalización	1,487.51 €
T. Potencia	172,101.75 €

Potencia OPTIMIZADA					
P1	P2	P3	P4	P5	P6
920	920	920	920	920	1500

Potencia	105,806.97 €
Penalización	42,228.45 €
T. Potencia	148,035.42 €

Figure 21 – Summary of the optimization tool. The first group is the optimized by the program, the second is the actual that they have and the third will be the considered one

The first parameter (Potencia SIMULACION) is the contracted power that will be optimized. Whereas, the second parameter (Potencia ACTUAL) is the information provided, ie it is the power that the user hired in each stretch. As it is not possible to hire exactly the power that the user wants, the third menu (Potencia OPTIMIZADA) is the closest nominal power value which can be hired.

Afterwards, it is also necessary to input the actual energy consumed in one year, as well as the normalized PV production in terms of kWh/ kW_p simulated by the IESPRO tool. Based on these two data sets, this excel file subtracts the energy used and the energy from the PV. In the case of a photovoltaic generation is greater than the consumed electricity, and there is no capacity to store water, the excess is disregarded.

3.2.5. Return of the Investment

With the results provided from the last calculation, it is necessary to do an analysis of the return of the investment, this is, it is necessary to calculate the Net Present Value (NPV) as well as the Internal Rate of Return (IRR). The NPV is the difference between the present value of cash inflows and the present value of cash outflows. On the other hand, the IRR is the discount rate that makes the net present value of all cash flows from a particular project equal to zero, and thus the higher a project's internal rate of return, the more desirable it is to undertake the project.

Communities of irrigators prefer to contract longterm loans (typically 25 years), in order to reduce the monthly expenses. To obtain these two parameters (NPV and IRR) it is necessary to calculate the investment (I), expressed in € (equation 3).

$$\mathrm{I} = \mathrm{TCC} \times \mathrm{SP}_i \tag{3}$$

where the TCC is the total cost considered, in €/W_p, and the SP_i the Sized Power to be installed, in W.

As it is not known how much the user is willing to invest, this study considered that the claim that would be asked for the bank would be the total amount. Assuming an interest rate (IR) charged by the bank expressed in percentage, it is possible to calculate how much the community will pay annually (P_y), considering a number of years (Y) of payment, by using the following equation:

$$\mathrm{P}_y = \left(\frac{I}{NCY}\right) \times (1 + ((NCY - (Y - 1)) \times IR)) \tag{4}$$

where NCY is the number of years that they will have to pay the credit, in years, and the Y is the year that is analyzed.

However, the value of money today is not the same of tomorrow and therefore it was considered a discount rate (DR), which is expressed in percentage. Through the following equation the upgrade of the money can be verified.

$$\mathrm{C}_y = \frac{P_y}{((1 + DR)^Y)} \tag{5}$$

To know whether the investment is viable or not, it is necessary to make a comparison with the cost of electricity from the grid. Considering an annual rate of increase in the price of electricity (YEIT) expressed in percentage, it is possible to simulate how much the community would pay for it during the years of credit. This increase in annual cost could be calculated by the following equation:

$$\mathrm{GC}_{yi} = \mathrm{GC}_y \times (1 + \mathrm{YEIT}) \tag{6}$$

where the GC_y is the cost expressed in € before the rate of increase and GC_{yi} is that parameter but after that consideration.

With all these data it is possible to calculate the net present value (NPV) and check the profitability of the project.

The NPV was calculated according to the following equation:

$$\mathrm{NPV} = \sum \mathrm{GC}_a - \sum \mathrm{C}_y \tag{8}$$

Through the NPV, and based on an excel tool that calculates the IRR, it is possible to get this value and finally, evaluating the profitability of the system.

CHAPTER 4. Study Cases

Until this chapter it has been presented the methodology used to make a study about a Water PV Pumping system. There will be analyzed two real cases, one in Villena (pumping to a water pool) and the other Zújar (pumping at constant pressure). These studies emerged following a request from the communities of irrigators who increasingly look for alternatives to their systems. For that reason, the Solar Energy Institute was requested to do them.

4.1.Villena

4.1.1. Site location and characterization

The site is located in the Irrigation Community of Villena, in Alto Vinalopó, in the province of Alicante (N38.36, W0.52 and altitude: 81m). This irrigation community pumps to water pools thanks to a big store capacity of 3.5 hm^2. In Alto Vinalopó, according to data from the AEMET (Meteorological Agency, in Spanish), the mean monthly higher temperature varies between 30.6ºC, in August and 16.8ºC, in January. Minimum temperatures vary between 20.4ºC (August) and 6.2ºC (January). Table 7 lists monthly maximum and minimum temperature and horizontal irradiation.

Table 7 – Maximum and minimum temperatures[14] and Irradiation[15] parameters for this local

Month	Maximum Temperature [ºC]	Minimum Temperature [ºC]	Mean Daily Horizontal Irradiation[Wh/m^2]
January	16.8	6.2	2430
February	17.8	7.0	3320
March	19.2	8.2	4530
April	20.9	10.1	5700
May	23.6	13.3	6610
June	27.2	17.1	7680
July	30.1	19.7	7770
August	30.6	20.4	6760
September	28.4	17.8	5110
October	24.4	13.7	3770
November	20.4	10.0	2610
December	17.6	7.3	2350

This irrigation community has 22 wells divided into 7 zones and it has a total a storage capacity of 3.5hm^3, spread across several water pool (Table 8).

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[14] Data from the AEMET

[15] Data from PVGIS

Table 8 - Technical characteristics of this field

Zone	Well	Power [kW]	Static Height [m]	Dynamic Height [m]	Elevation[m]
1	CALERA	101	261	263	58
	CANDELA	361	242	253	35
	PEÑETES BIS	158	217	247	15
	BALDONA	152	252	254	31
	ROSITA	427	258	259	0
2	CERRUCHÓN	295	196	198	12
	BOQUERA	184	198	200	15
	SERRATA	187	215	226	12
	TINTORERAS	214	230	276	20
3	BOQUERON1	190	436	478	0
	BOQUERON2	333	437	440	0
	PINAR	341	375	381	45
	LA MINA		Does not work		47
4	ALORINES 2	98	205	188	12
	ALORINES 3	191	205	224	10
	ALORINES 4	247	169	176	34
5	QUEBRADAS	268	200	207	25
	PATOJO 1	185	192	194	30
	PATOJO 2	156	192	189	30
6	BARR-PONS	349	215	219	25
	ROMERAL	212	259	275	35
7	NOGUERAL	214	225	267	0

For every well, this irrigator’s community gave access to the monthly amount of water pumped, as well as the consumed energy and its cost, as summarized in Table 9.

Table 9 – Yearly Consumed Energy, the Volume of Pumped Water and the Cost for each well in 2012

Zone	Well	Energy [kWh]	Cost [€]	Volume of Pumped Water [m^3]
1	CALERA	181125	18322	102687
	CANDELA	958939	78918	738445
	PEÑETES BIS	376013	44756	300312
	BALDONA	229779	22957	129890
	ROSITA	2054426	165727	1806997
2	CERRUCHÓN	1132109	120943	1154973
	BOQUERA	618717	64496	655331
	SERRATA	616460	64026	612891
	TINTORERAS	927769	101456	656214
3	BOQUERON1	1657803	141862	719918
	BOQUERON2	Does not have information		
	PINAR	650273	62754	318775
	LA MINA	Does not work		
4	ALORINES 2	260225	27163	215848
	ALORINES 3	542020	57173	531074
	ALORINES 4	860521	92831	835001
5	QUEBRADAS	533343	55232	594841
	PATOJO 1	629919	64584	444057
	PATOJO 2	468849	50166	394807
6	BARR-PONS	1396196	152926	1375664
	ROMERAL	598496	57043	456466
7	NOGUERAL	358308	37521	308477
TOTAL		14338985	1404205	11554474

As it is possible to see, the consumption energy is around 1.44GWh/year, which corresponds to a cost of almost 1.5M€. Furthermore, the production is not distributed in an equal way. For example, the well named Rosita represents 14% of the pumped water of the entire community but Calera represents just 0.9%.

4.1.2. Technical simulation for a singular well

The objective of this subchapter is to propose and simulate a scenario of substitution of the current pumping systems by a PV pumping system.

In order to show the detail of the simulation for every well in Villena's Irrigation Community, here we are going to present the study of a representative well (the Serrata well). The same study was done for every single well of this field.

Table 10 lists the characteristic parameters of the Serrata well and the corresponding selected pump.

Table 10 – Characteristics of the Pump System

Parameter	Value
H_{ST}	215
Flow Losses	22
Pump+Motor Model	E12S55 /10A + M14380-9V
ρ [kg/m^3]	998
Nominal Velocity [rpm]	2900
Q [m^3/h]	290
Nominal Height [m]	264
Motor Nominal Power [kW]	277

By running the simulation on the IESPRO platform it is possible to access four curves (Figure 22). In the top on the left, there is a curve of height in function of the water flow rate. On its right, the mechanical power output as a function of flow rate. On the bottom left, the curve of the motor efficiency as a function of the mechanical output power. The flatness of the curve is due to the fact that Caprari just give information of the average efficiency. Finally, on bottom right, the water flow rate as a function of on the demanded electric power.

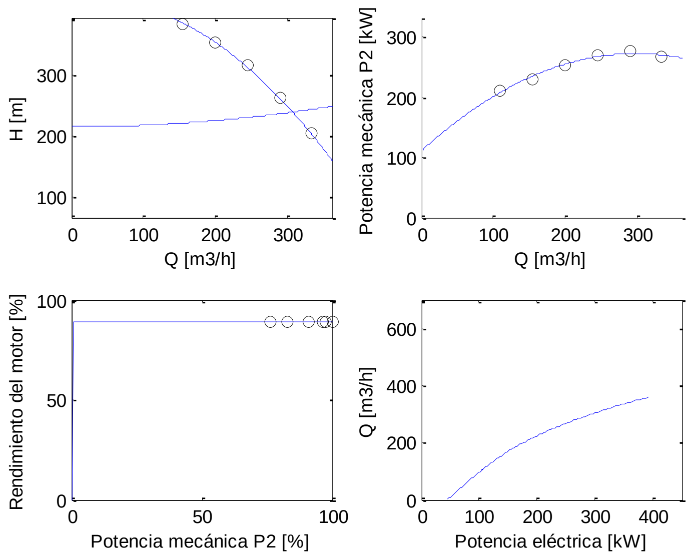

Figure 22 – Characteristics curves to the selected Pump System

The result of the simulation in terms of incident irradiation, the electrical production and pumped water is shown in Table 11.

Table 11 –Parameters related with Irradiation and production

Parameter	Value
Irradiation [kWh/m^2]	
Horizontal	1787
Normal	2568
Effective (dust and incidence)	2477
Effective with adjacent shadows	2477
Total effective with shadows	2477
Production [kWh/kW]	
DC	2119
AC	2006
Hydraulic	1327
Pumping [m^3/kW]	2173

The shadow losses parameter the value is zero since the tracking system includes back tracking mechanism, which adjusts the tracker position so that no shade from neighboring systems exist, reducing losses by shadow at a cost of less than optimum incidence angle, thus increasing the incidence losses .

Note also that for DC-AC conversion the losses were considered negligible while AC to hydraulic power, the losses are quite significant, losing nearly 25%.

The water pumped per unit of installed PV peak power is, approximately $2m^3$ per W_p installed.

In order to analyse the losses of the system in a more detailed way the Sankey diagram is shown in Figure 23.

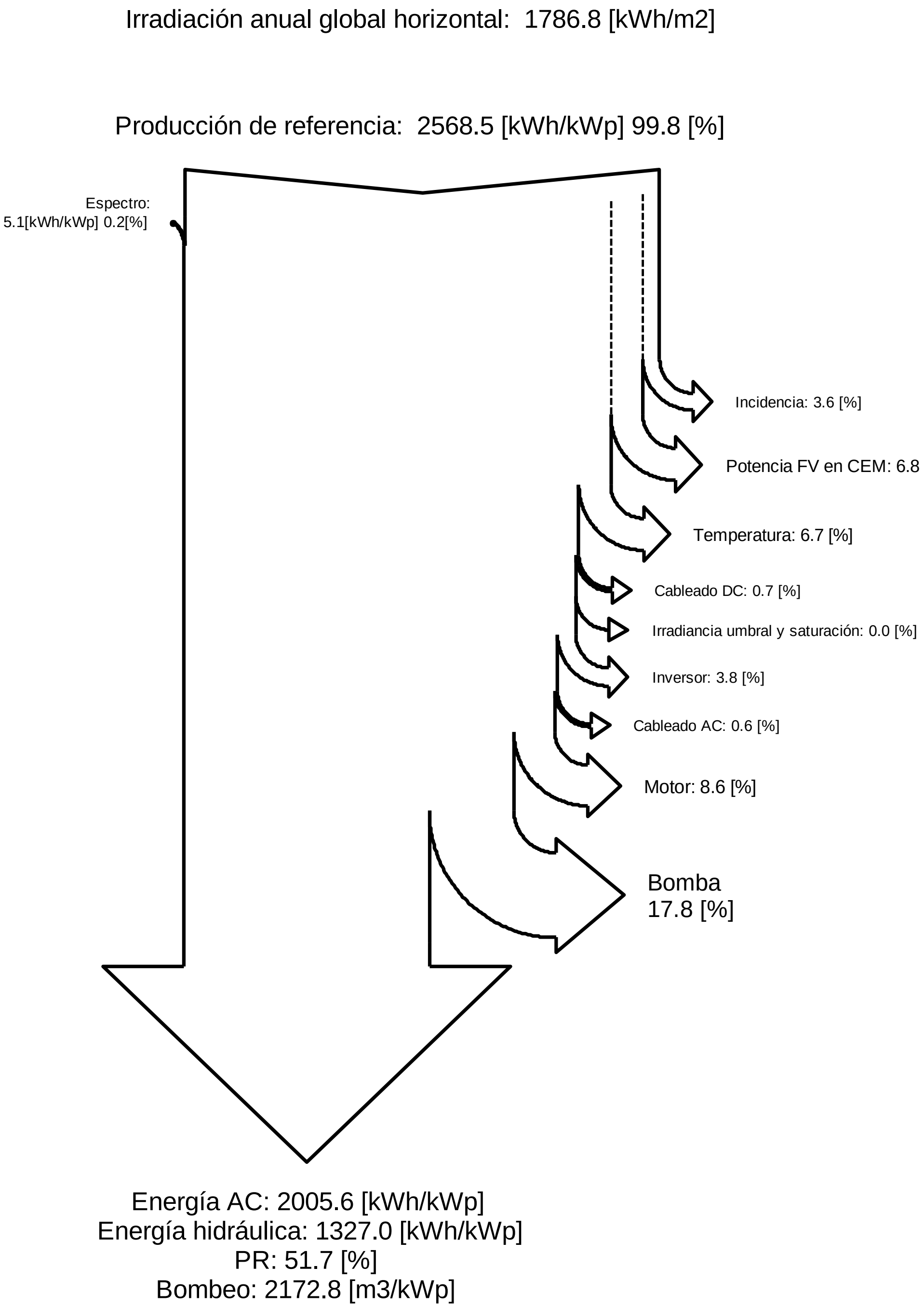

Figure 23 - Sankey Diagram

It is possible to observe that the entry point has two values, one corresponding to the global annual horizontal irradiation and the other for the production of reference, in units of energy per PV power installed for the PV peak system chosen.

It can be seen that the greatest losses occur at the pump, about 18 %, followed by the motor, with 9 %. Other losses can occur in the inverter (4%), or due to high temperature (7%).

Table 12 shows the daily production for a typical day of each month for the year.

Table 12 – Daily energy and hydraulic production, as well as the volume of pumped water

	DC [kWh]	AC [kWh]	Hydraulic Energy [kWh]	Volume of water pumped [m^3]
January	952	904	560	935
February	1243	1179	770	1273
March	1610	1524	1032	1683
April	1894	1789	1216	1973
May	2091	1974	1338	2169
June	2337	2208	1484	2413
July	2349	2220	1490	2426
August	2086	1974	1320	2156
September	1655	1568	1039	1706
October	1344	1275	835	1378
November	996	946	590	984
December	924	878	526	881
Mean value	1625	1539	1018	1665

Figures 24 and 25 show the operating curves for two typical days of August and December, respectively.

They show the incident irradiance on the generator (considering the dirt, shadows and spectral correction), the pump efficiency (strictly considered, ie, the relation between hydraulic energy and mechanical energy provided by what gives the engine), its rotational frequency and flow rate (Q).

From some interesting marked points, for a typical day of August, we can say that:

- Pumping begins after the 6:30^{AM}.

- The irradiance at that moment it starts to pump is 160.3 W/m^2.

- The frequency of rotation in the same hour is 33.68Hz.

- Flow rate at noon is 205.7 m^3/h.

- The irradiance at noon is 902.8 W/m2.

- The frequency of rotation at the same hour is 40.88Hz.

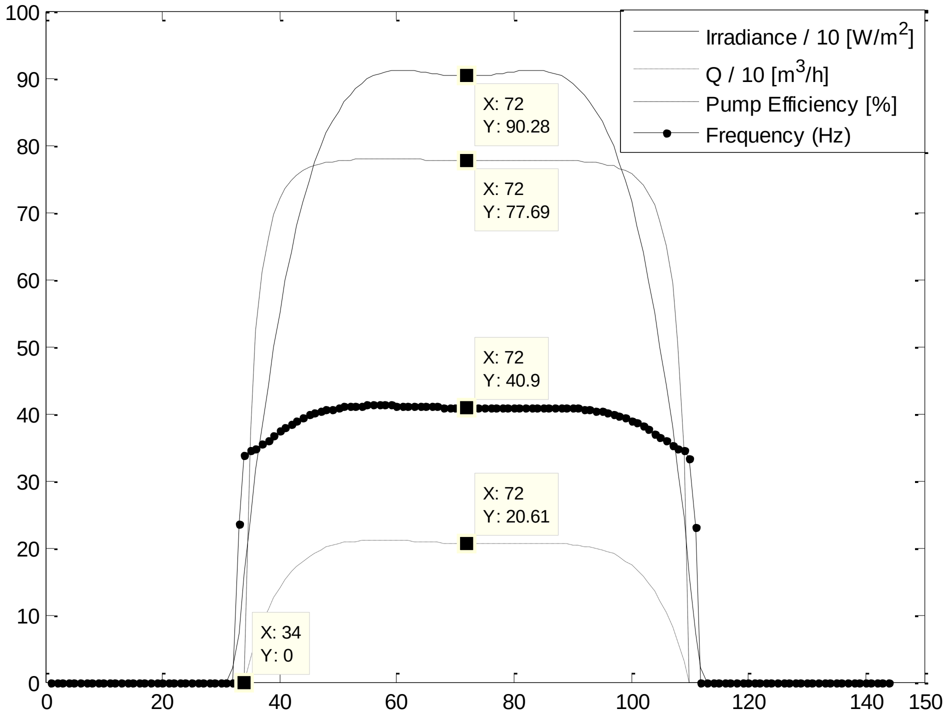

Figure 24 - Curves of Irradiance, Water flow rat, Efficiency of the Pump and Work Frequency for a typical August day. The horizontal axis represents an entire day where each value represents 10 minutes.

From some interesting marked points, for a typical day of December, we can say that:

- Pumping begins after the 7:30^{AM} hours

- The irradiance at that moment is 103.8 W/m^2.

- The frequency of rotation at the same hour is 26.5Hz.

- Flow at noon is 101.1 m^3/h.

- The irradiance at noon is 480.5 W/m^2.

- The frequency of rotation at noon is 35.8Hz.

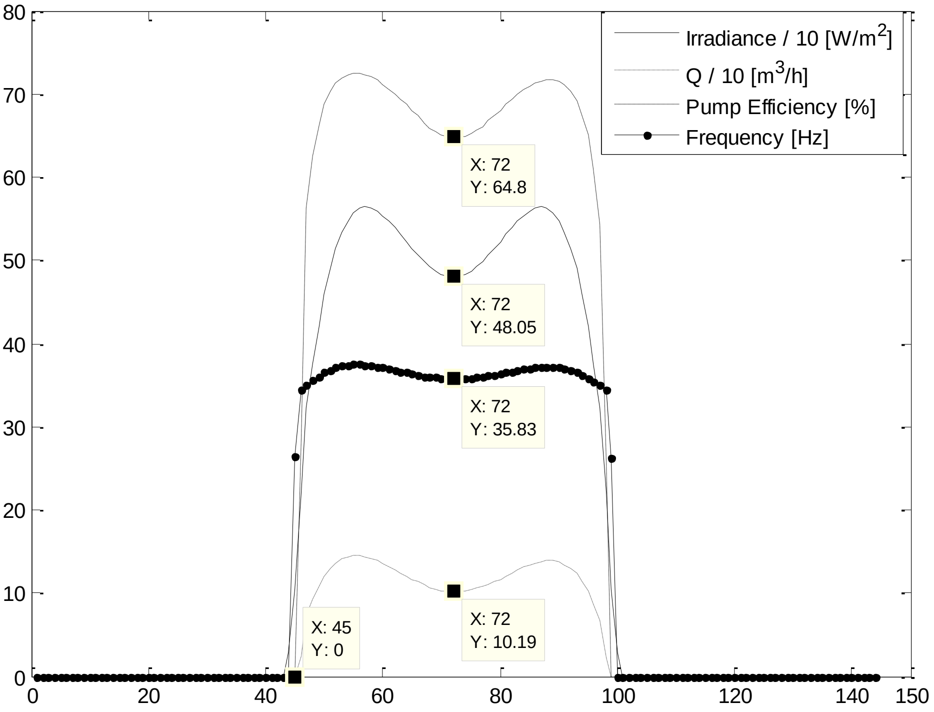

Figure 25 - Curves of Irradiance, Water flow rate, Efficiency of the Pump and Work Frequency for a typical December day. The horizontal axis represents an entire day where each value represents 10 minutes.

As shown above, the results are quite different for these two months. The flow rate at noon in December is about half of that in August, although the monthly irradiation is only 30% less in December that in August. Even with less irradiation, the frequency converter permits that the pumps does not stop but pumps with less rotation velocity. It is important to refer that the slope that is possible to verify at noon is caused by the type of tracking used. As it was referred before, it is a horizontal axis N-S, that in December, when the sun is in a lower position, the irradiance is not perpendicular and for that, occurs that decay.

4.1.3. Technical Results

Table 13 represents the result of the application of the methodology explained in the previous chapter, including the name of the well, the quantity and model of motor-pumps and the power of the PV generator. It is also shown the match of the volume of water pumped for 2012 as a result of the simulation by the IESPRO with horizontal North-South axis tracker.

Table 13 - Characteristics of the PV Water Pumping system for all station of Villena

Well	**Number of Pumps**	**Match in m^3/Year (%)**	**Peak PV power per pump [kW_p]**	**MODEL**[16]
PENETES	1	99%	165	**E12S50 /8I + MAC10220-8V**
BALDONA	1	97%	75	**E8SX57/14A + MACX8125-8V**
BOQUERA	1	95%	280	**E12S58 /8AB + M14380-9V**
SERRATA	1	99%	280	**E12S55 /10A + M14380-9V**
TINTORERAS	1	102%	370	**E14SE50 /7Q + M14500-9V**
ALORINES3	1	106%	280	**E12S58 /7A + M14380-9V**
QUEBRADA	1	108%	280	**E12S55 /10A + M14380-9V**
NOGUERAL	1	104%	150	**E10S50 /10B + MAC10200-8V**
CALERA	1	111%	75	**E8S50N /23A + MAC8100-8V**
ALORINES4	1	90%	370	**E14SE55 /5BC + M14500-9V**
PATOJO2	1	108%	110	**E10S55 /7A + MAC10150-8V**
ALORINES 2	1	99%	59	**E8SX57/9A + MACX880-8V**
CANDELA	2	106%	200	**E10S55 /13A + MAC12330-8V**
PATOJO1	2	97%	92	**E8SX57/14A+MACX8125-8V**
ROMERAL	2	98%	125	**E9S55 /17A + MAC10200-8V**
PINAR	2	101%	150	**E9S50 /22A + MAC10200-8V**
ROSITA	3	96%	410	**E14SE50 /7Q + M14500-9V**
CERRUCHON	2	107%	270	**E14SE50 /6I + M14460-9V**
BOQUERONES	3	106%	340	**E12S42 /9M + M14500-9V**
BARR-PONS	3	102%	240	**E12S42 /5A + MAC12330-8V**
Total	31	102%[17]	7138[18]	

Results shows that more than 1 pump was required in eight wells. This is due to the fact that Caprari does not have pumps that are able to provide the required volumes. Table 14 shows the total pumped water for each month, in every well. The last two columns represent the actual and simulated volume of water pumped in 2012.

---

[16] All from Caprari brand

[17] Mean Value

[18] This value is the sum of the product of the number of pumps by the peak PV power per pump for all wells

Table 14 - Volume of Water Pumped [m^3] for each month

Well	Jan [m^3]	Feb [m^3]	Mar [m^3]	Apr [m^3]	May [m^3]	Jun [m^3]	Jul [m^3]	Aug [m^3]	Sep [m^3]	Oct [m^3]	Nov [m^3]	Dec [m^3]	V_{med} [m^3]	V_{calc} [m^3]
PENETES	12766	17536	26211	30264	34357	36537	37755	33248	24888	20358	13152	11504	300312	298575
BALDONA	5681	7529	10959	12547	14254	15240	15776	13966	10559	8723	5831	5244	129890	126308
BOQUERA	27804	37161	54343	62289	70730	75549	78201	69167	52188	43075	28569	25482	655331	624556
SERRATA	28991	36917	52189	59193	67233	72384	75206	66839	51186	42730	29520	27323	612891	609711
TINTORERAS	26834	38808	59548	68937	78201	82887	85532	75169	55785	45142	27783	23231	656214	667856
ALORINES3	23492	32883	49616	57546	65212	69360	71449	63004	46860	38173	24267	20854	531074	562715
QUEBRADA	31202	39147	54647	61857	70255	75855	78858	70187	53973	45282	31674	29661	594841	642597
NOGUERAL	14040	18986	27922	32037	36344	38775	40145	35470	26730	22016	14442	12750	308477	319658
CALERA	5026	6784	9996	11463	13011	13884	14388	12705	9566	7879	5164	4574	102687	114439
ALORINES4	30792	43546	66241	76839	87188	92514	95390	83871	62355	50617	31812	27187	835001	748351
PATOJO2	20345	25819	36484	41451	47086	50712	52660	46760	35799	29890	20682	19232	394807	426921
ALORINES 2	9442	12696	18583	21287	24149	25789	26711	23623	17832	14717	9706	8605	215848	213139
CANDELA	37384	47498	67030	76002	86311	92972	96609	85873	65807	54979	38046	35279	738445	783790
PATOJO1	18677	25586	37851	43473	49267	52543	54364	48029	36130	29684	19236	16801	444057	431642
ROMERAL	21366	26987	38172	43498	49754	53180	55460	49066	37872	31341	21726	20164	456466	448586
PINAR	13671	18815	28167	32548	36954	39288	40593	35731	26735	21846	14080	12302	318775	320730
ROSITA	61136	97435	159065	186783	212126	223011	228917	199492	144943	114020	64395	49259	1806997	1740583
CERRUCHON	59379	74924	105634	120275	136774	147301	152842	135734	103793	86714	60340	56399	1154973	1240107
BOQUERONES	25581	42258	70393	83112	94460	98994	101460	88120	63556	49531	27071	19996	719918	764530
BARR-PONS	59316	82219	122877	141655	160582	170964	176633	155803	116695	95454	61159	52989	1375664	1396345
TOTAL	532923	733535	1095924	1263055	1434247	1527739	1578947	1391857	1043253	852172	548655	478837	12352668	12481143

Figure 31 represents the total water pumped in 2012 (shown in the graph as *Grid*) and the water pumped curve according to the simulation of the PV pumps.

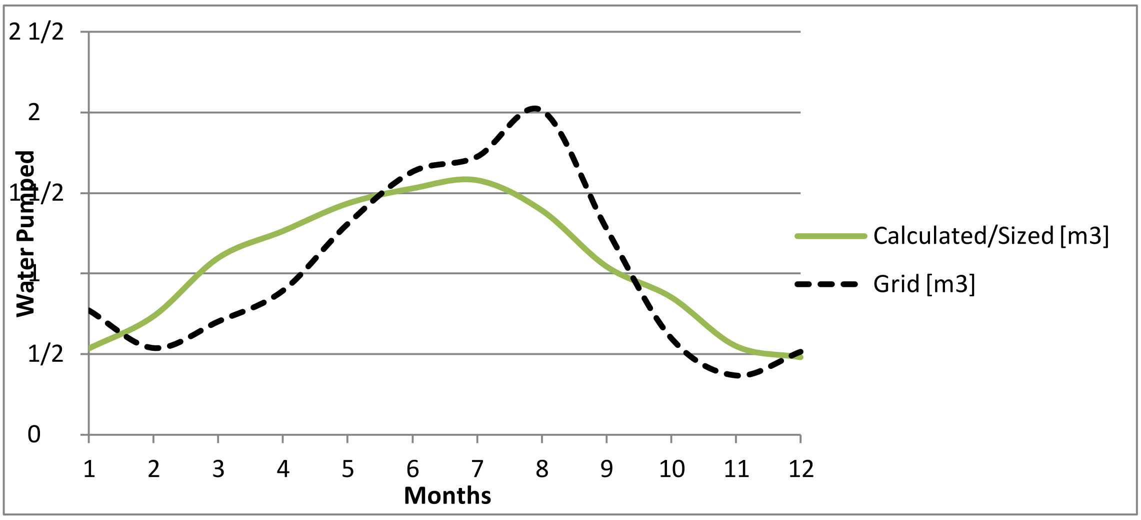

Figure 26 - Curve of the Water Pumped during one year

The mismatch between the two curves can be overcome by the use its storage capacity of 3.5 million of m^3, which is more than sufficient to store this difference. This is clearly shown in figure 27.

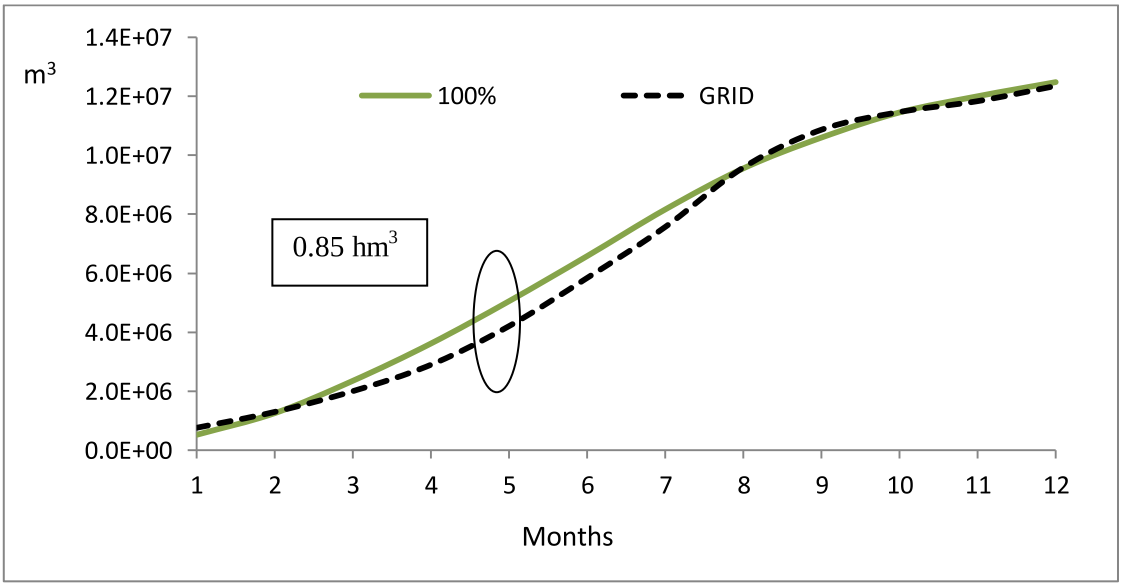

Figure 26 - Accumulated water along a year

4.1.4. Land Occupation

In order to see the impact of the installation of the PV generators, the occupied area has to be considered. The system proposed is based on single horizontal axis (North-South) which has a ground cover ratio of 1/3.5 [24].

As shown in Table 13, the required power is 7.138MW. Assuming, for example, a Sunmodule Plus SW 275 mono, and each tracking system has 20 modules of this kind, for example, with a 2x10 configuration (Figure 28) the total area may be calculated as follows.

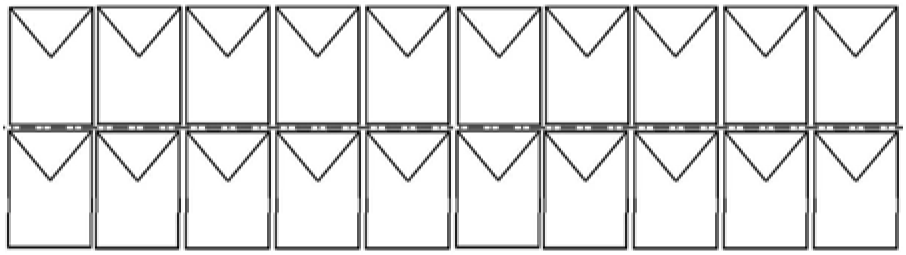

Figure 27 – Example of a possible scheme of a generator

Knowing the value of the total power (P_t), the number of modules considered can be calculated using the following equation.

$$N_m = \frac{P_t}{P_m} \tag{9}$$

where P_m is the power of a single module, in W.

Then, the land occupation by the modules is

$$A_{Land} = 3.5 \times N_m \times A_m \tag{10}$$

where A_m is the area of a single module, in m^2.

In a lineal way, for different rate of substitution of the current system, the area will be:

$$A_{\%penetration} = A_{Land} \times \%_{penetration} \tag{11}$$

Thus, for this system, the land occupation is roughly 2ha/MW. Figure 29 represents the occupied area for different percentages of penetration.

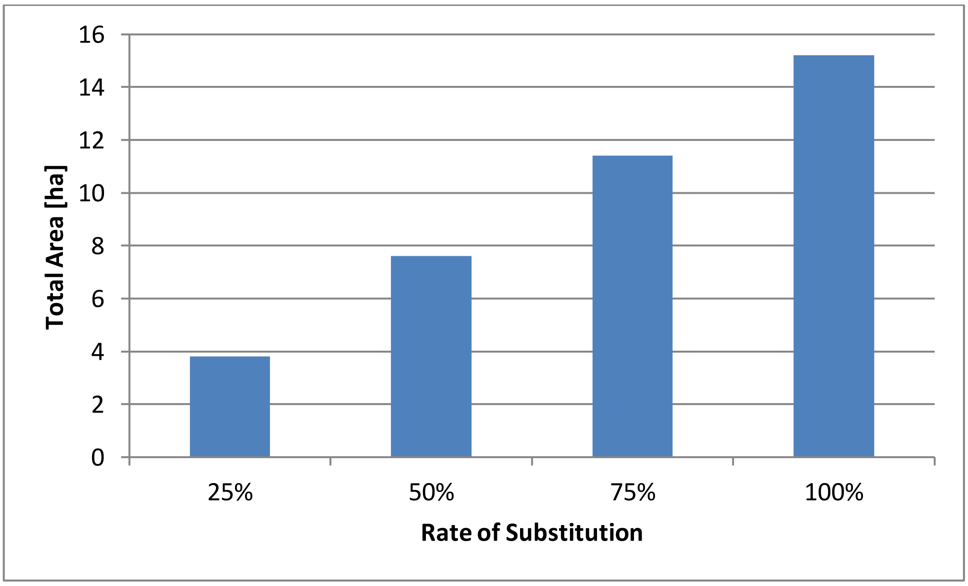

Figure 28 - Occupied area in function of PV penetration

As it is expected total area increased linearly with rate of substitution, however, the PV installation has to be next to each well. Table 15 shows the required land for each well.

Table 15 - Occupation Land for each well

Well	Number of Pumps	Peak PV power per pump [kW_p]	Land Occupation [ha]
PENETES	1	165	0.4
BALDONA	1	75	0.2
BOQUERA	1	280	0.6
SERRATA	1	280	0.6
TINTORERAS	1	370	0.8
ALORINES3	1	280	0.6
QUEBRADA	1	280	0.6
NOGUERAL	1	150	0.3
CALERA	1	75	0.2
ALORINES 4	1	370	0.8
PATOJO2	1	110	0.2
ALORINES 2	1	59	0.1
CANDELA	2	200	0.9
PATOJO1	2	92	0.4
ROMERAL	2	125	0.5
PINAR	2	150	0.6
ROSITA	3	410	2.6
CERRUCHON	2	270	1.2
BOQUERONES	3	340	2.2
BARR-PONS	3	240	1.5

It can be observed that Rosita is the well that needs more land while Alorines 2 requires less land area for the PV field.

4.1.5. Economical Results

After having already established the technical design it remains to test if it is feasible from the economical point of view.

The initial parameters considered for this evaluation are listed in Table 16:

Table 16 – Initial Villena's case parameters

Number of wells	20
Annual Production [hm3]	12.4
Annual Electrical Consumption [GWh]	15
Annual Cost of Electricity [M€]	1.48

Table 17 presents the cost of every PV system according to the PV system design presented in Figure 28.

Table 17 – The investment in PV Water systems needed

Well	Number of Pumps	Peak PV power per pump [kW]	MODEL[19]	Cost [k€]
PENETES	1	165	E12S50 /8I + MAC10220-8V	299
BALDONA	1	75	E8SX57/14A + MACX8125-8V	136
BOQUERA	1	280	E12S58 /8AB + M14380-9V	507
SERRATA	1	280	E12S55 /10A + M14380-9V	507
TINTORERAS	1	370	E14SE50 /7Q + M14500-9V	670
ALORINES3	1	280	E12S58 /7A + M14380-9V	507
QUEBRADA	1	280	E12S55 /10A + M14380-9V	507
NOGUERAL	1	150	E10S50 /10B + MAC10200-8V	272
CALERA	1	75	E8S50N /23A + MAC8100-8V	136
ALORINES4	1	370	E14SE55 /5BC + M14500-9V	670
PATOJO2	1	110	E10S55 /7A + MAC10150-8V	199
ALORINES 2	1	59	E8SX57/9A + MACX880-8V	107
CANDELA	2	200	E10S55 /13A + MAC12330-8V	724
PATOJO1	2	92	E8SX57/14A+MACX8125-8V	333
ROMERAL	2	125	E9S55 /17A + MAC10200-8V	453
PINAR	2	150	E9S50 /22A + MAC10200-8V	543
ROSITA	3	410	E14SE50 /7Q + M14500-9V	2226
CERRUCHON	2	270	E14SE50 /6I + M14460-9V	977
BOQUERONES	3	340	E12S42 /9M + M14500-9V	1846
BARR-PONS	3	240	E12S42 /5A + MAC12330-8V	1303
Total	31	7138		12920

Results show that the required investment to cover all the needs is 13 M€. Table 18 present the remaining input parameters to the economical model which were determined based on conversations with local irrigator communities and the Energy Ministry of Spain.

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[19] All from the brand Caprari

Table 18 – Economical Input Data

Cost[€/W_p]	1.8
Interest Rate in the PV credit [%]	5.0
YEIT of the grid cost [%]	7.0
DR [%]	3.5
Credit Years	25

Table 19 presents the economic model results for different penetration scenarios.

Table 19 – PV Cost and Grid Cost and its investment

PV Pumps Substitution Rate	PV Power [MW_p]	PV Investment [M€]	PV Cost in 25Y [M€]	Grid Cost 25Y [M€]	Cost PV + Grid (25Y) [M€]
0%	0	0	0	58.7	58.7
25%	1.9	3.4	3.9	46.5	50.4
50%	4.2	7.6	8.7	27.9	36.6
75%	5.7	10.2	11.7	13.7	25.4
100%	7.1	12.9	14.8	0	14.8

It is possible to get from here that the savings for using PV are significant, as shown in Figure 30.

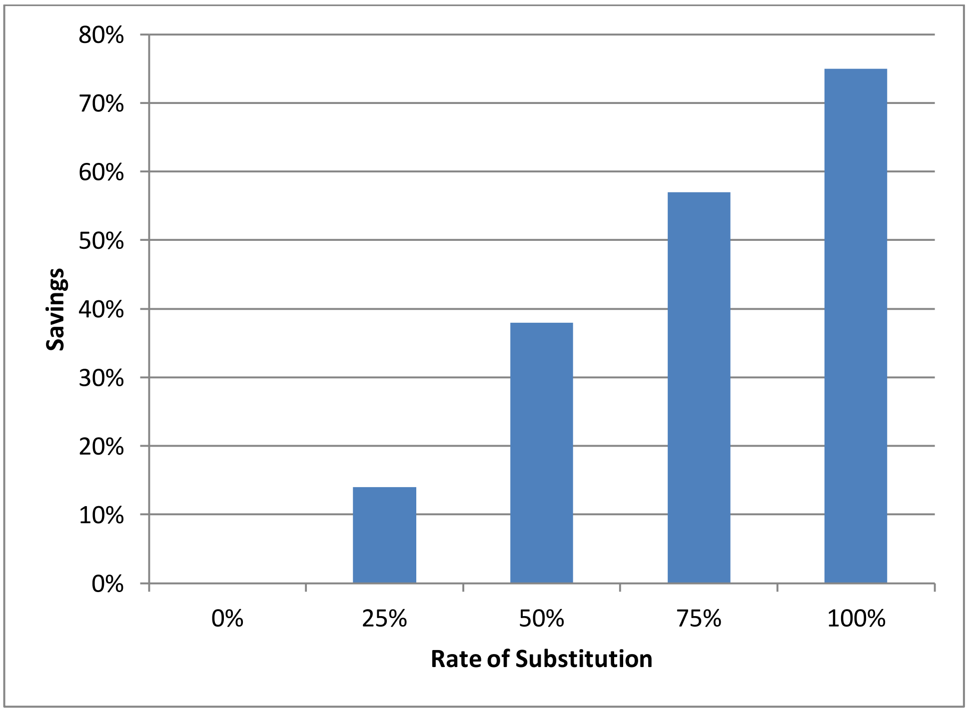

Figure 29 - The Savings, when compared with the actual case

From Figure 30, it is possible to observe that increased investiment in PV will lead to increasing savings. In the case of full substitution, the saving is 75%.

The costs per unit of energy and per pumped cubic meter is shown in Table 20.

Table 20 – Mean Leveled Cost of Energy as well as the same but represented in m^3 pumped for the all 25 years

PV Pumps Substitution Rate	Grid+PV Cost [€/kWh]	Grid + PV Cost [€/m3]
0%	0.156	0.190
25%	0.132	0.163
50%	0.097	0.117
75%	0.069	0.082
100%	0.041	0.067

Considering all the taxes, figure 31 shows the evolution of the energy cost during the 25 years for different PV penetrations.

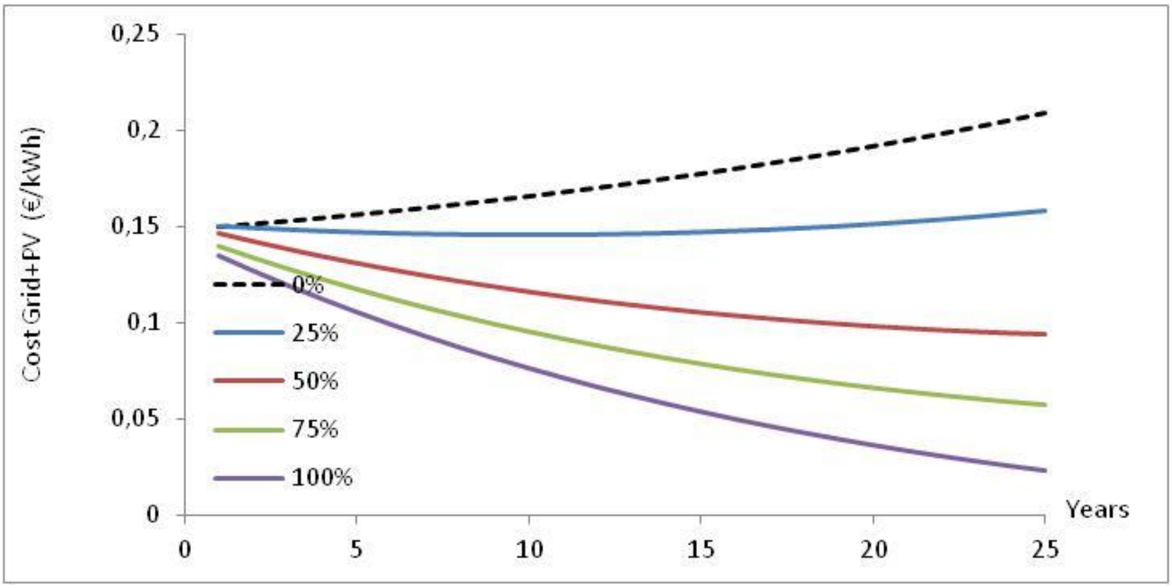

Figure 30 - Evolution of the energy cost (€/kWh) in 25 years, where grid corresponds to the actual scenario of only grid and the percentages correspond to the different PV penetrations

In order to test less favourable economic conditions, the economic model was run with the parameters listed in Table 21.

Table 21 - Economical Input Data

		Variation
TCC [€/W$_p$]	1.8	=
Interest Rate in the PV credit [%]	8	+3
YEIT of the grid cost [%]	3	-4

Discount Rate [%]	3.5	=
Credit Years	25	=

The results are shown in Table 22.

Table 22 – Cost of energy if the all 25 years

PV Pumps Substitution Rate	Cost PV (25Y) + Grid (25Y) [M€]	Savings [M€]	Savings in Percentage [%]
0%	34.8	- €	0%
25%	32.4	2.4 €	7%
50%	27.4	7.4€	21%
75%	22.8	12.0 €	34%
100%	18.6	16.2 €	47%

In this less than optimum economic environment, the saving is still 47% of the total investment. Figure 32 shows the evolution of energy costs during the project duration. Unlike the reference scenario, in the first five years, the exclusive use of the grid has a lower cost than the cases which include 25% (until the 5th year), 50% (4th year) and 75% (2th year) of PV penetration, For the stand alone system (100% PV penetration) the energy cost will always be cheaper than the grid cost.

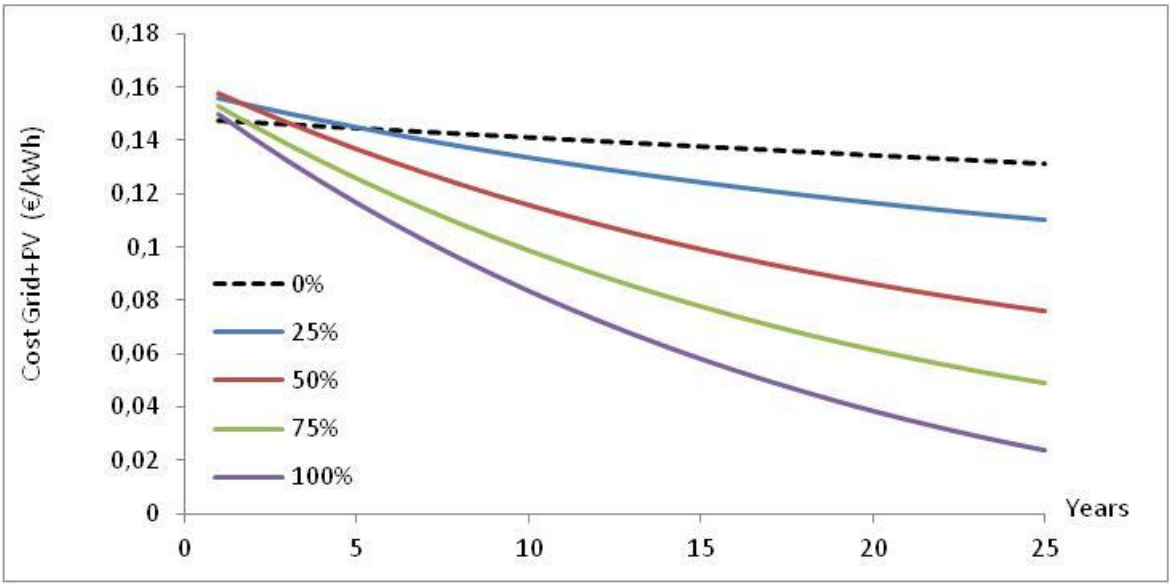

Figure 31 - Evolution of the energy cost (€/kWh) in 25 years, where grid corresponds to the actual scenario of only grid and the percentages correspond to the different PV penetrations

4.2.Zújar

In this case, the question to be answered is if it is more economically profitable to stay as it is currently or to install PV with the corresponding decrease of the contracted power and the consumed grid energy. Since the storage capacity of water does not exist, the under-use of the PV system could affect the economical viability of the system. To assess this will be one of the main objectives of this section.

For this study 3 cases were considered in which the last one was divided in another two (varying the PV installed power). We have considered a credit of 10 and 25 years which are the most used in this kind of applications. In opposite to the first study, this irrigator's community asks us to do these two credit scenarios.

The definition of each case is shown below:

- Case 1: unoptimized contracted power: current case.
- Case 2: optimized contracted power without PV
- Case 3: optimized contracted power with PV
    - Case 3.1: 300 kW_p of PV
    - Case 3.2: 600 kW_p of PV

Each case is evaluated in two different conditions: "current consumption scenario" and "the use of 100% of PV production".

4.2.1. Site location and characterization

The site is located in the Irrigation Community Canal of Zújar, in Don Benito, in the province of Badajoz (N38.98, W5.65 and altitude: 303m). The irrigation community has a very small tank, only to to keep constant the pressure and offer to its farmers the service of water for irrigation at 5 bars at any hour of the day. For this analysis, the irradiance and temperature data were provided by SIAR (Agriculture Information System for Irrigation), the platform of the Ministry of Agriculture, Food and Environment, data intervals are 30 minutes. From the AEMET it was used the normal values, the annual maximum temperature varies between 34.3ºC, in July and 13.9ºC, in January. Relatively to the minimum ones, the higher is also in August, with 17.0ºC and 3.2ºC in January. There are 61 days/year with precipitation levels above 1mm.

Table 23 – Maximum and minimum temperatures[20] and Irradiation[21] parameters for this local

Month	Maximum Temperature [ºC]	Minimum Temperature [ºC]	Mean Daily Horizontal Irradiation[Wh/m^2]
January	13.9	3.2	2210
February	15.9	4.7	3340
March	19.4	6.0	4720
April	20.9	8.1	5860
May	24.8	11.1	6860
June	30.3	14.7	7890
July	34.3	17.0	8150
August	34.0	16.7	7100

---

[20] Data from the AEMET

[21] Data from SIAR

September	30.3	14.8	5440
October	23.8	11.0	3800
November	18.1	6.8	2600
December	14.5	4.8	2150

This community has many stations; however this study will be focused on one of them, that has seven 220kW pumps. Its characteristics are listed in Table 24.

Table 24 – Station Data

Pump System Characteristics	7 pumps, 220 kW each one
Contracted Power	1540 kW
Power Fee[22]	6.1
Yearly Energy Consumption (2012-2013)	2.861.839 kWh

Figure 33 represents the energy onsumption profile during 2012; the period of irrigation focuses between mid-May to mid-September.

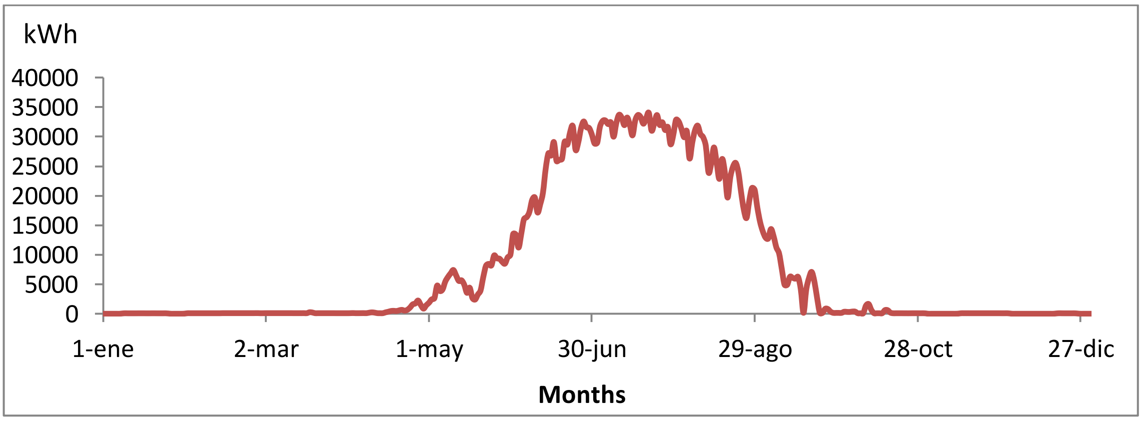

Figure 32 - Energy consumption along the considered year (2012)

This irrigator's community gave access to their detailed consumption for 2012, with values for every 30 minutes. With this kind of data it was possible to use economic tool developed.

The type of fee contracted by this community is the 6.1, and in the next table (Table 25), its costs are shown.

Table 25 – Considered terms for the considered fee [25]

	Active Energy Fee [€/kWh]	**Power Fee [€/kW.day]**
P1	0.12846	0.10973
P2	0.11016	0.05491
P3	0.09521	0.04019
P4	0.08322	0.04019
P5	0.08062	0.04019
P6	0,06894	0,01834

4.2.2. Technical Results

The idea in this subchapter is to find out which PV power is sufficient to decrease the contracted power, so it would be profitable. Zújar community, due to its type of service pays an amount for the power's tariff for only 4 months of use of that. So the idea would be to substitute with PV a significant part of the grid pumps and decrease the amount of the contracted power.

For the substitution of the grid pumps, we have selected multiples of 300kW$_p$ per pump and we have simulated for a North-South Axis, as it can be seen in the next table (Table 26).

Table 26 - Technical Characteristics

PV Generator	300 or 600 kW$_p$
Tracker	1 Axis N-S
Yearly Production	2260 kWh/kW$_p$

We considered only 300 kW$_p$ and 600 kW$_p$, not only for the economical aspect but essentially for technic issues. We know already that the solar souce is not constant along the day, and for that reason it is impossible to water pump in a constant way, it needs always an additional source that could be the grid or a diesel generator to maintain the pressure. Economically, since this community only pumps 4 months per year, it will be difficult to amortize the investment if the PV component was greater.

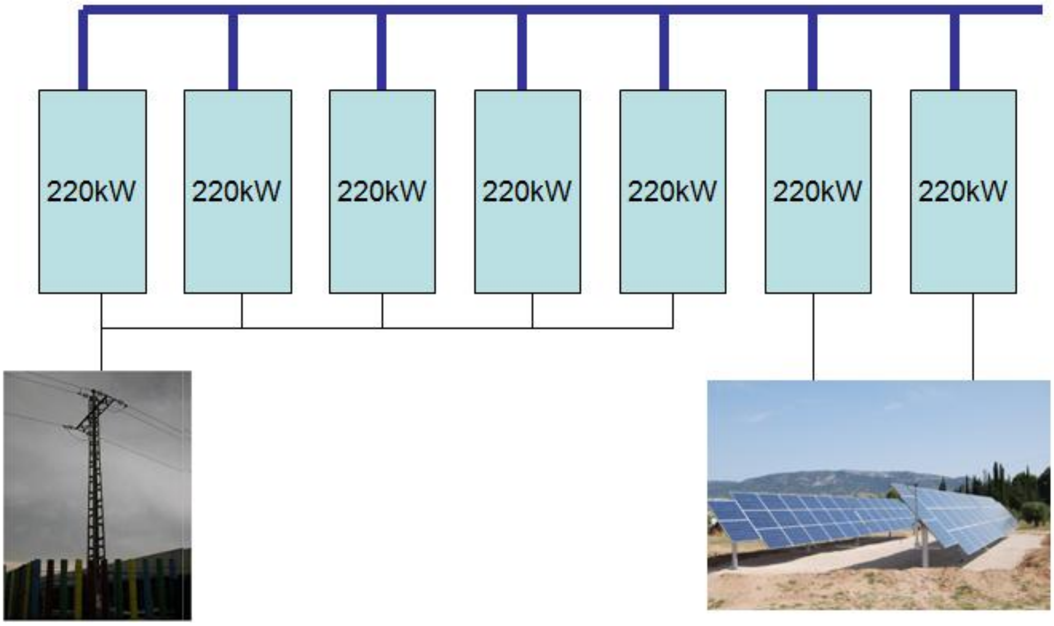

Figure 33 - Possible Configuration for the case 3.2 [26]

The results of this simulation for a year were the following:

Table 27 – Irradiation and production characteristics

Parameter	Value
Irradiation [kWh/m^2]	
Horizontal	1818
Normal	2626
Effective (dust and incidence)	2525
Effective with adjacent shadows	2525
Total effective with shadows	2525
Production [kWh/kW]	
DC	2235
AC	2119
Hydraulic	1408
Pumping [m^3/kW]	3230

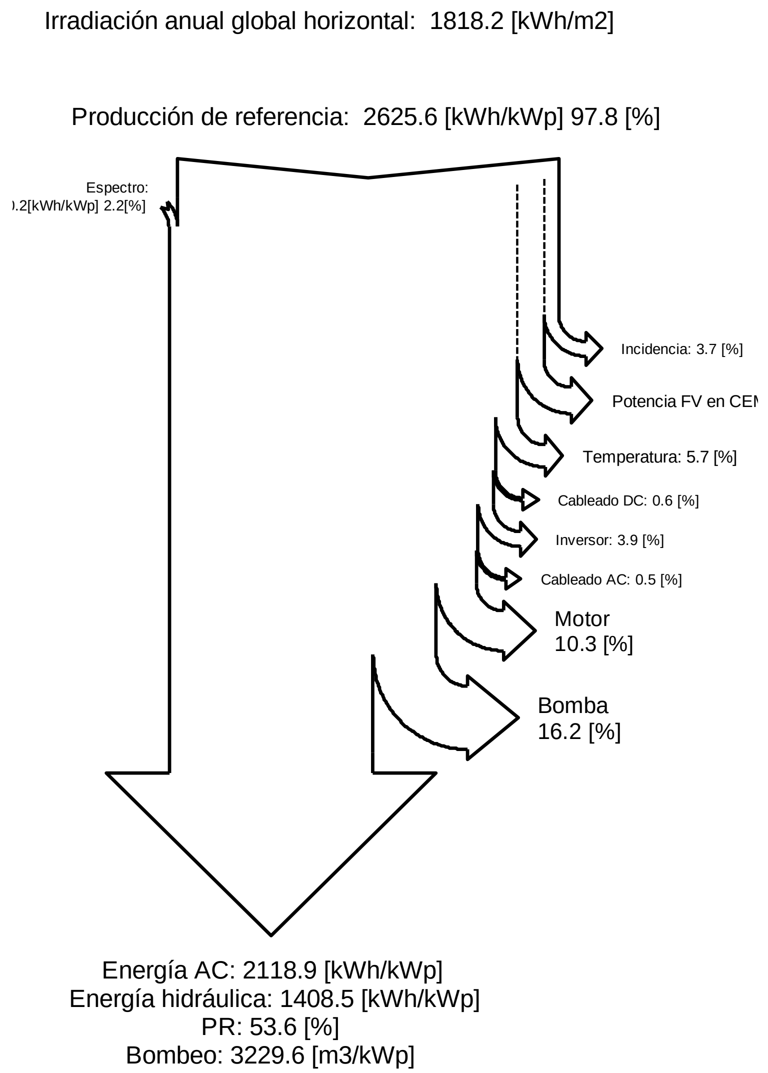

Figure 34 - Sankey Diagram

It can be seen that the greatest losses occur at the pump, about 16% followed by the motor (10%). There is why there is a big difference between the hydraulic power and the AC one, as it can be visualized in Table 28. In it is shown the daily production for a typical day of each month for a year.

Table 28 – Daily energy and hydraulic production and the volume of water pumped

	DC [kWh]	AC [kWh]	Hydraulic Energy [kWh]	Volume of water pumped [m^3]
January	884	838	532	1275
February	1343	1275	838	1965
March	1781	1692	1148	2641
April	2173	2063	1391	3182
May	2348	2220	1491	3388
June	2752	2605	1730	3908
July	2786	2633	1729	3885
August	2507	2375	1590	3587
September	1964	1860	1233	2815
October	1522	1447	976	2279
November	1033	982	648	1537
December	926	879	565	1351
Mean value	1837	1742	1158	2769

It is possible to verify that as expected, the energy produced in the months of June and July is the higher in the entire year, for example being more than the triple of the produced energy in January or December.

4.2.3. Land Occupation

Using the same reasoning of the Villena’s case, the area that is occupied by the PV system should be taken into account. Considering that each system has 300kW of PV peak power and using the same generator and equations of the previous study (Villena’s case), the area of the possible system is presented in the next table (Table 29). It is important to refer that were used the same equations, that in Villena’s case.

Table 29 – Occupied area in function of the PV penetration

PV Installed [kW]	Area [ha]
300	0.64
600	1.28

4.2.4. Economic/Financial Study

To verify the profitable of this application it was used the excel tool developed and explained in the other chapter. In the next table are represented the economical characteristics taken into account about the economic rates.

Table 30 – Economical characteristics

Cost	1,8 €/W_p
Interest Rate	5,0%
YEIT	7,0%
Discount Rate	3,5%

4.2.4.1.Current consumption scenario

In this scenario the energy produced by the PV during the months that the community does not irrigate and the energy produced that exceed demand are curtailed because there is no storage capacity.

As can be seen in Figure 36, the least expensive solution is case 3.2.

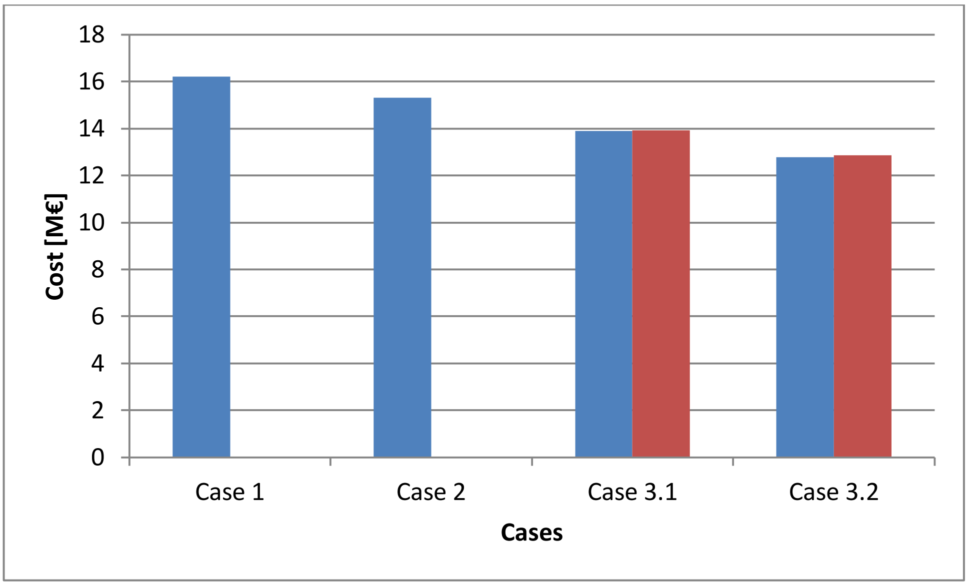

Figure 35 - Simulation of the cost in 25 years, for the case 3.1 and 3.2, the blue is the 10 years credit and the red, the 25 years credit

It is possible to conclude that in case of the loan in 10 years when compared with the other the difference between the total cost is almost the same, having a little bit more savings with 10 year loan.

In the following table (Table 31) are presented values that demonstrate the profitability of the project.

Table 31 – IRR and NPV to the Current consumption scenario

	IRR	NPV [M€]
Case 3.1	17,94%	1.5
Case 3.2	16,57%	2.7

The interest rate of return are similar in the two cases, however the NPV is very different. So the community has to choose what is best to them. Both of the cases are very profitable.

The energy management strategy (PV excess curtailment) considered for these scenarios yields important losses, reaching 40% of the annual production as shown in Table 32,

Table 32 - Penetration profile of PV electricity consumption

PV Power installed [kW]	Energy lost [MWh]
300	266.6 (39%)
600	588.8 (43%)

4.2.4.2.Use of 100% of PV production

It was also done the same simulations that for the previous scenario. In Figure 37 is presented the cost simulated at the final of the 25 years. It is important to refer that the values for the Case 1 and Case 2 does not have any credit associated. When it is referred that it is used all the PV production, what was done in this scenario was to consider that the excedent was sold to the grid at same price of that period. This is, all the energy was used to amortize the investment.

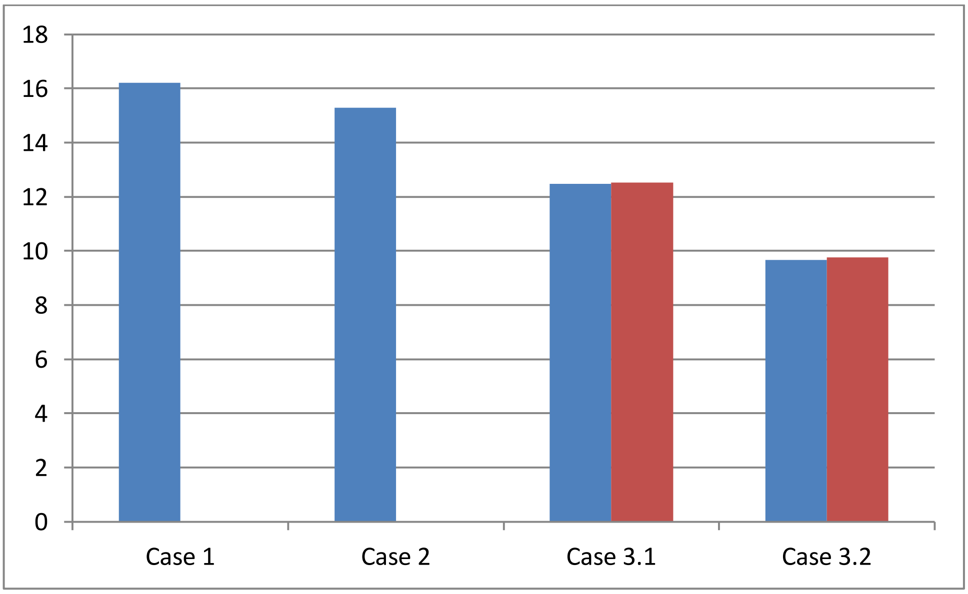

Figure 36 - Simulation of the cost in 25 years, for the case 3.1 and 3.2, the blue is the 10 years credit and the red, the 25 years credit

As it can be observed, in this scenario the savings are higher and it is easy to justify, once it is considering all the production.

In Table 33 are presented the financial parameters as the Investment Rate of Return as well as the Net Present Value.

Table 33 - IRR and NPV to the Use of 100% of PV production

	IRR	NPV [M€]
Case 3.1	24,36%	2.3
Case 3.2	23,68%	4.5

Comparing these values with the ones from the previous scenario, it is possible to verify that the IRR is as high as 24%.

CHAPTER 5. SOLUTIONS FOR STABLE PV PUMPING AT CONSTANT PRESSURE

The requirement of constant pressure pumping makes necessary to solve the problem of solar irradiance variability. This chapter, focus on the external energy required to mitigate these fluctuations. Based on the last case-scenario analyzed (Zújar), that we could only substitute 2 of the motorpumps for PV ones, the problem that we had in there was that, since this irrigator's community only irrigate for 4 months, the investment needed in PV was not economical feasible. For that reason, it was created a tool that permits to know this amount of additional energy needed.

5.1. Analysis of the additional energy for constant pressure PV pumping

PV applications that have to work continuously are strongly affected by clouds variability [27]. Based on it, if the idea is to irrigate at constant pressure, and in order to maintain this one, it is necessary to find a way to compensate this variability.

To analyze the relationship between the additional energy needed to irrigate at constant pressure and the variability of the source, it was created a tool that reads the information of the irradiance that PV receives and then converts it to energy. For this study, besides the constant pressure we will also consider a constant water flow rate, in order to assure a good distribution of the water that goes out from the sprinkles into the soil. In addition two parameters were created, the constant working threshold and the inferior threshold. The constant working threshold can be 850 W/m^2 or 1000 W/m^2, and represents the irradiance for which the motorpump will work (at a constant pressure and water flow rate). The inferior threshold is the threshold for which the pump is stopped. It is firstly defined as 150 W/m^2, then as 200 W/m^2 and then a stepwidht of 100 W/m^2 is used until the previously defined working threshold. If the constant working threshold is 850 W/m^2 this value is also considered as an inferior threshold. Obviously, the lower the threshold, the greater the additional energy is needed.

For each inferior threshold the system starts to establish a pressure and a water flow rate at a constant way when the irradiance is higher that this limit. Until that time, all the energy from the PV generator will be stored. This parameter will increase from this value to the constant working power. If the irradiance is higher than 850W/m^2 or 1000 W/m^2 (where it will work the system), the excess of PV power will be stored. When any cloud causes an inflection in the amount of energy produced, the stored energy will supply that need. If it is not enough, additional energy from an external source will be used. Energy stored can be kept in a battery or in a tank. In this work only the second option were considered.

The Figure 38 shows the methodology for a day. It was considered for example 300 W/m^2 as inferior threshold and 850 W/m^2 as constant working threshold. Between the two black lines is represented in orange the required power to keep the pressure and the flow rate constant. With this inferior threshold (300 W/m^2), only after 9^{AM} the system starts to establish a pressure and a water flow rate in a constant way. In addition, if the irradiance is higher than constant working threshold (850W/m^2), the excess of PV power would be stored.

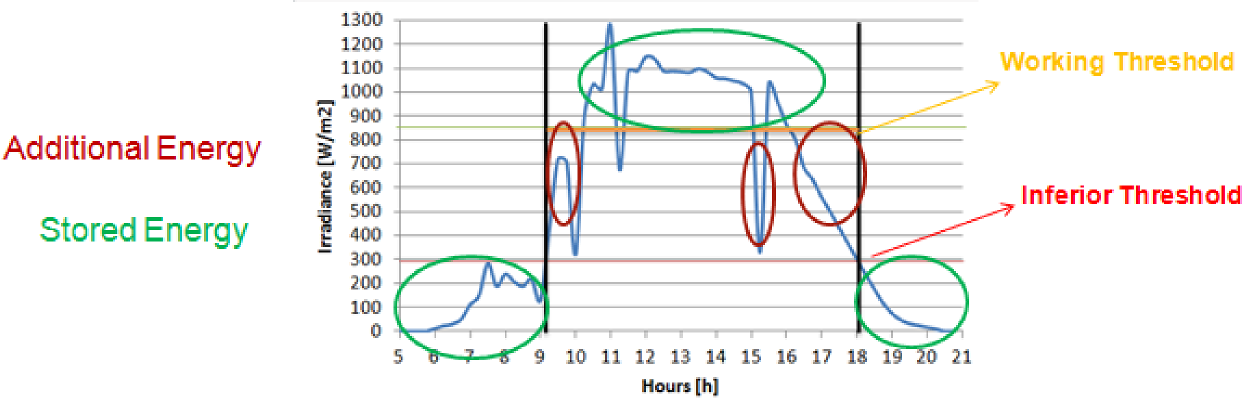

Figure 37 - Orange is the power for a pressure and a water flow rate constant, red the threshold and black the limits considered by the threshold

However this tool was developed to analyze an entire year of data. The following examples will represent that for an entire year of 15 minutes production data.

To represent this relationship there were analyzed two different variables: the yearly additional energy divided by the yearly energy produced by the PV pump (kWh Additional/kWh Produced) and the yearly energy produced by the maximum yearly energy produced by the PV generator (E/Emax) if the inferior threshold was 150 W/m^2 [23].

Based on this method, there were analyzed two cases, one for Italy, with a static generator and the other in Spain, for a PV generator with a 2 axis tracker.

5.2.1. Study Case: static generator

The first case analyzed was a fixed PV system in the South of Italy (Sicily). In this case it was possible to access an entire year of 15 minutes production data. In Figure 39 it is possible to see the irradiance that arrives to the PV generators in 13th May of 2012, for a PV Central[24].

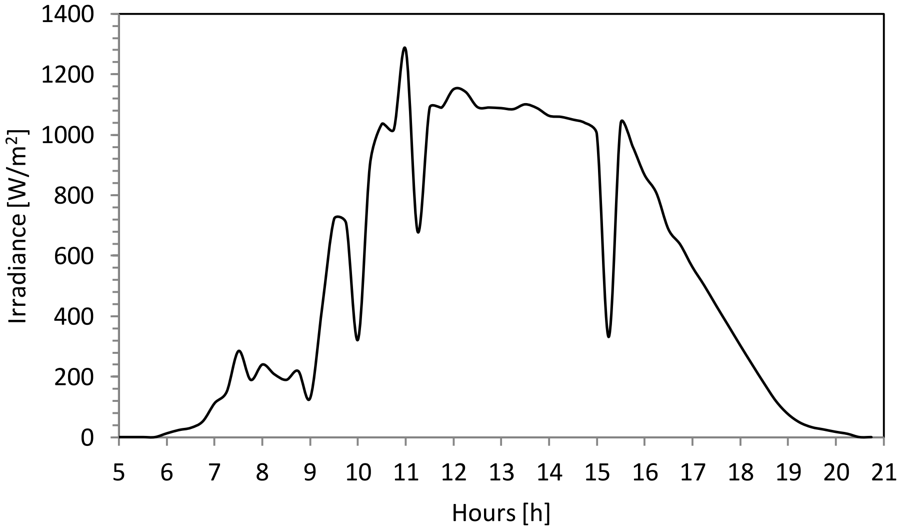

Figure 38 - Irradiance to a random day (13th May) for a PV Generator in a fixed structure, in Italy

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[23] Solar Irradiance which generally starts the motorpump

[24] Measurements made by Rodrigo Moretón, a PhD Student at IES

The irradiance in a day is not constant, neither has the typical bell curve for a clearsky day. From 7^{AM} to 9^{AM} there is no significant irradiance increase, which could correspond to morning mist. At 10^{AM}, 11^{AM} and 3^{PM}, it is possible to observe three abrupt drops in the irradiance. Overall, there are about 45 minutes of important cloud cover. It must be emphasized that in any of this cases the irradiance drops more than 300W/m^2.

A yealy analysis were done for both values of constant working threshold.

A static PV Generator to this local usually produces between 1300 and 1560 kWh/kW$_p$ [28]. For a constant working threshold of 850 W/m^2, Produced Energy, Additional Energy and Stored Energy are presented in the following table for each inferior threshold.

Table 34 - Produced Energy, the Additional Energy and Stored Energy by kW PV power installed for a static PV generator

Inferior Threshold [kW/m^2]	**Produced Energy [kWh/kW$_p$]**	**Additional Energy [kWh/kW$_p$]**	**Stored Energy [kWh/kW$_p$]**
0.15	2431	648.0	0.9
0.2	2185	402.0	1.0
0.3	1813	45.5	1.3
0.4	1542	2.2	1.6
0.5	1346	1.0	1.7
0.6	1149	0.6	2.2
0.7	966	0.3	2.9
0.8	759	0.1	3.6
0.85	544	0.0	4.1

Based on the previous values, the yearly energy additional divided by the yearly energy produced by the PV pump, and the yearly energy produced by the maximum yearly energy produced by the PV generator are presented in the following figure.

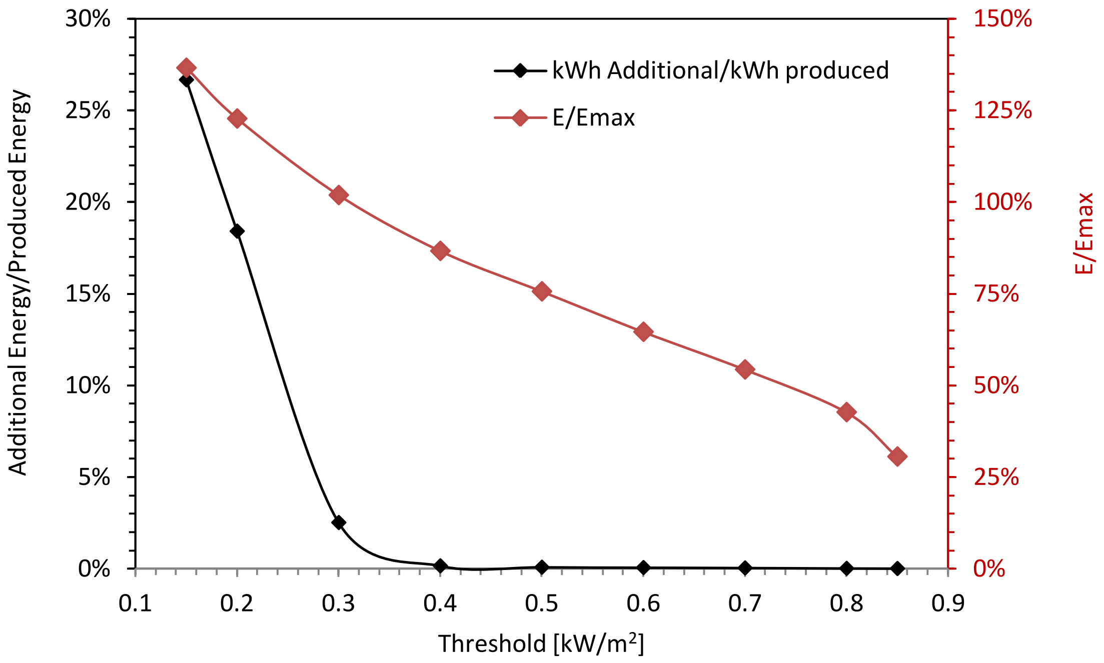

Figure 39 - Curve of the percentage of energy stored in function of the parameter threshold in Italy for a static PV generator

The results presented in figure 40 show that considering a threshold of around 400 W/m^2, the additional energy is residual (0.15%) for a produced energy of 87% of a maximum one.

As an example, if we consider a PV system of 100 kW$_p$ and a threshold of 500 W/m^2 the produced energy was 134.6 MWh and the energy that was necessary to store is 170 kWh. Hence, if it is considered a total head of 30 m, the tank should have a volume capacity of 2040 m^3. For the addional energy, considering that can be provided by a diesel generator, taken into account a 20kW diesel generator with the following consumption.

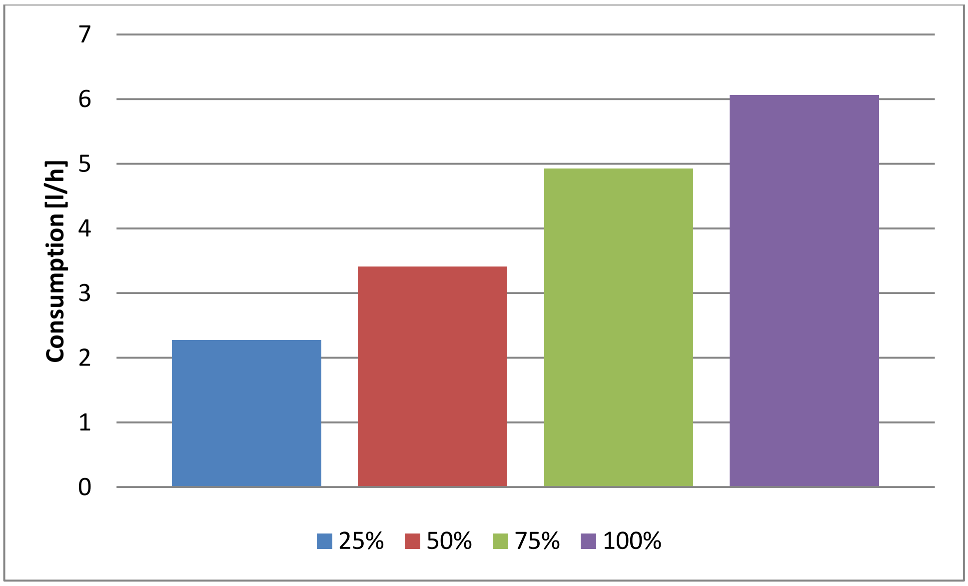

Figure 40 - Specific fuel consumption of a 20 kW Diesel generator [27]

As it can be seen the figure above, and as it was expectable, the diesel consumption grows with the needs of the generator and for that reason, if it is considered the worst case, 100% load, in our case corresponds to only 30 liters of annual consumption.

It was also done for a superior limit of 1000 W/m^2 to see the differences between using this limit up to 850 and to 1000 W/m^2. The results are represented in Table 35 and Figure 42.

Table 35 - Produced Energy, the Additional Energy and Stored Energy by kW PV power installed for a static PV generator

Inferior Threshold [kW/m^2]	Produced Energy [kWh/kW$_p$]	Additional Energy [kWh/kW]	Stored Energy [kWh/kW$_p$]
0.15	2860	1077	0.3
0.2	2570	788	0.4
0.3	2133	353	0.7
0.4	1814	58.7	1
0.5	1583	3.3	1.1
0.6	1352	1.3	1.6
0.7	1137	0.8	2.3
0.8	893	0.5	3.1
0.9	640	0.2	3.9
1	381	0	5.8

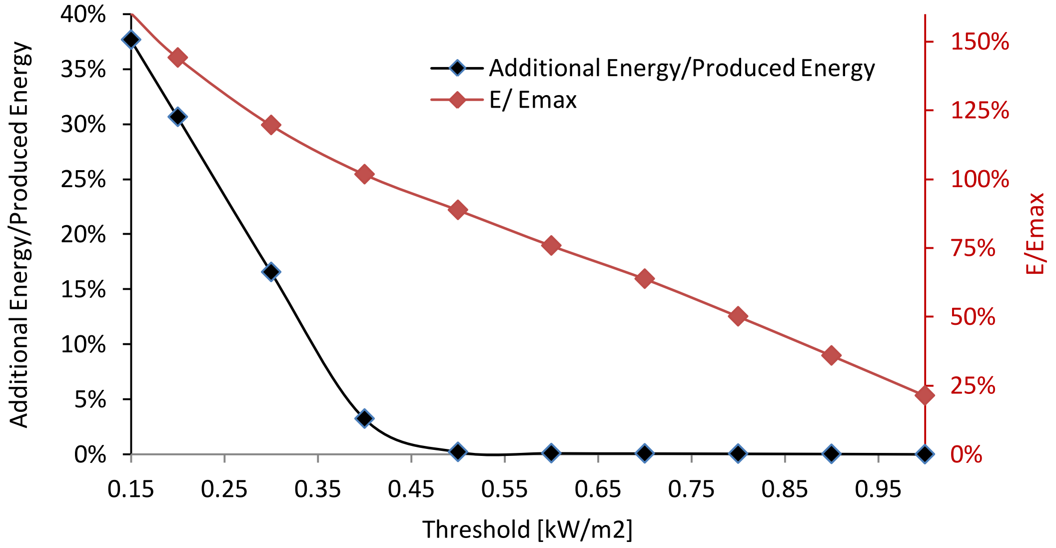

Figure 41 - Curve of the percentage of energy stored in function of the parameter threshold in Italy for a static PV generator

Comparing the two scenarios it can be seen that for thresholds between 0.15 and 0.6 kW/m^2, the second scenario requires less capacity of stored energy however it needs more additional energy.

5.2.2. Study Case: 2 axis tracker

A second case with 2 axis tracking was analysed, for a location in the South of Spain. It was done this analysis to understand if it exists any difference between using a tracker or not. By inputting data for an entire year of 15 minutes production data [25], it was possible to get results that allowed doing the Figure 43. In first it will be presented the study for the first scenario (850W/m^2).

A PV generator with 2 axis tracker to this local usually produces around 2220 kWh/kW$_p$ [28]. In Table 36 is presented the produced, the additional and the stored energy for all the thresholds considered by PV power installed for a 2 axis PV generator.

Table 36 - Produced Energy, the Additional Energy and Stored Energy by kW PV power installed for a static PV generator

Inferior Threshold [W/m^2]	Produced Energy [kWh/kW$_p$]	Addtional Energy [kWh/kW]	Stored Energy [kWh/kW$_p$]
150	2910	353.6	1.2
200	2802	246.5	1.2
300	2608	56.7	1.2
400	2428	7.9	1.5
500	2255	2.2	2.0
600	2060	0.9	2.0
700	1881	0.3	2.0
800	1604	0.1	2.8
850	1409	0.0	3.6

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[25] Measurements made by Rodrigo Moretón, a PhD Student at IES.

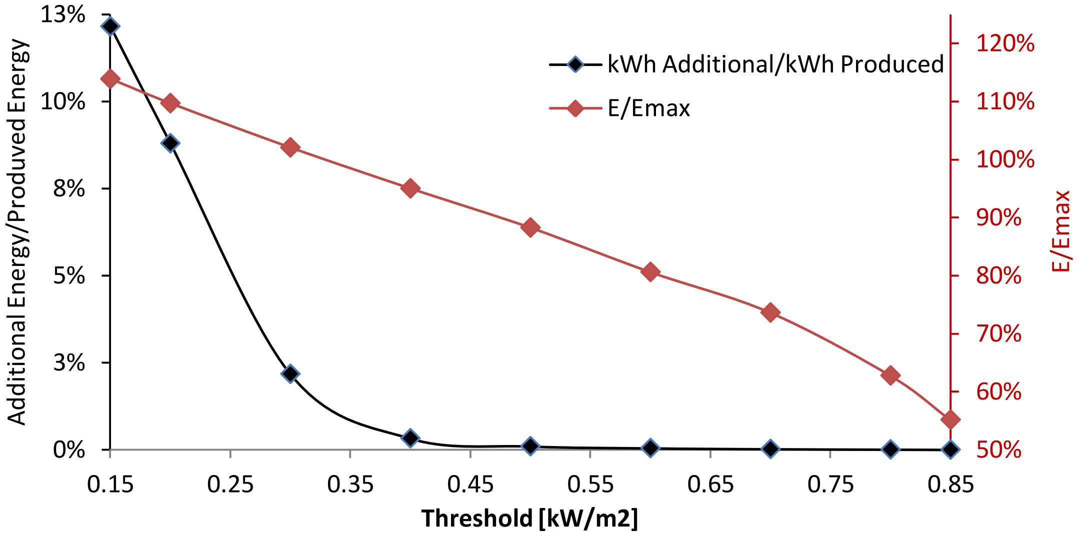

Figure 42 - Curve of the percentage of energy stored in function of the parameter threshold in Spain for a PV generator with a 2 axis tracker

For a 2 axis application is possible to verify in Figure 43 that considering a threshold around 400 W/m^2, the additional energy by all the produced energy is 0.325% for a produced energy of 95% of a maximum one.

If it is considered a threshold around 500 W/m^2 the value of addtional energy by all the produced energy is almost zero (0.1%) and the produced energy by the maximum of it is 88%.

It was also done for a superior limit of 1000 W/m^2 to see the differences between using this limit up to 850 and to 1000 W/m^2. The results are represented in Table 37 and Figure 44.

Table 37 - Produced Energy, the Additional Energy and Stored Energy by kW PV power installed for a static PV generator

Inferior Threshold [kW/m^2]	Produced Energy [kWh/kW$_p$]	Additional Energy [kWh/kW]	Stored Energy [kWh/kW$_p$]
0.15	3423	866.9	0.01
0.2	3297	740.9	0.01
0.3	3068	512.6	0.01
0.4	2856	303.9	0.32
0.5	2653	109.6	0.82
0.6	2423	10.5	0.82
0.7	2213	2.3	0.82
0.8	1887	1.1	1.61
0.9	1658	0.5	2.43
1	292	0.0	5.8

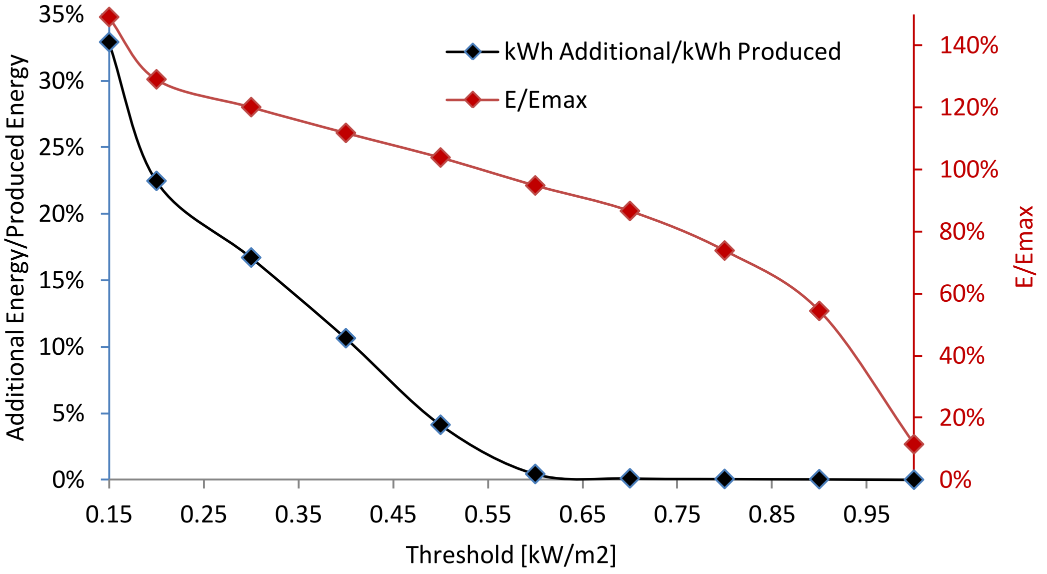

Figure 43 - Curve of the percentage of energy stored in function of the parameter threshold in Spain for a PV generator with a 2 axis tracker

The same conclusion can be taken from this figure, comparing the two scenarios it can be seen that the second scenario requires less capacity of stored energy however it needs more additional energy.

Comparing the first case (Italy-Static) with the second one (Spain-2 Axis), it is possible to conclude that the additional energy needed is greater for the first case, which makes sence because with a tracking system, the production is maximized and the irradiance is higher, and for that, the addional energy needed is almost zero for an inferior threshold of 500 W/m^2 for the first case and 600 W/m^2 for the second one.

CONCLUSIONS

First of all this work consisted in optimizing the design of pumping systems process in technical and economical point of view. It was used the software IESPRO for the technical part, which had proven its viability by the Solar Energy Institute to the prototype that is installed in Morocco, a real scenario. Using this tool it was possible to do the technical studies for the Villena's case as well as the Zújar's one. For both cases, the technical part was feasible. However, in the second case, the substitution could not be total, once the type of irrigation is at constant pressure that could not support the variability of the PV energy.

It was developed an economical tool that permitted to analyse the viability of the case. This tool not only gave access to parameters that permit to know the return of the investment, but also to optimize the power fee with the integration of PV power. Relatively to these two study cases it may be concluded that with the increasing of the electricity's price and the decrease of the cost of the PV Systems installation, as time goes by, more is the certainty that high power PV pumping is an excellent investment. In Villena's case the savings when the penetration of PV Power was 100% were from 47% to 75% changing the taxes considered. For Zujar's case, taken into account their technical specifications, the better option consisted in substitute from 15% to 30% of the actual pumps and reducing the power fee to all the periods. It is important to refer that both of studies were requested by the irrigator's communities and individual reports based on these results were done and gave to them.

Finally, relatively to the relationship between the capacity needed to irrigate at constant pressure and the resource variability, it can be concluded that with a small additional energy and storage capacity it is possible to produce energy in a constant way, using a threshold around 500W/m^2. The study was done for a static and a 2 axis tracker. Comparing these two cases, it could be noted that for the second one, it was necessary less storage capacity because there are less occasions with low irradiance. For this last chapter, thinking in the future, it could be also done an economical analysis comparing the tank/water pool solutions with batteries.

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